Kansas Geological Survey

High Plains Aquifer Index Well Program: 2012 Annual Report

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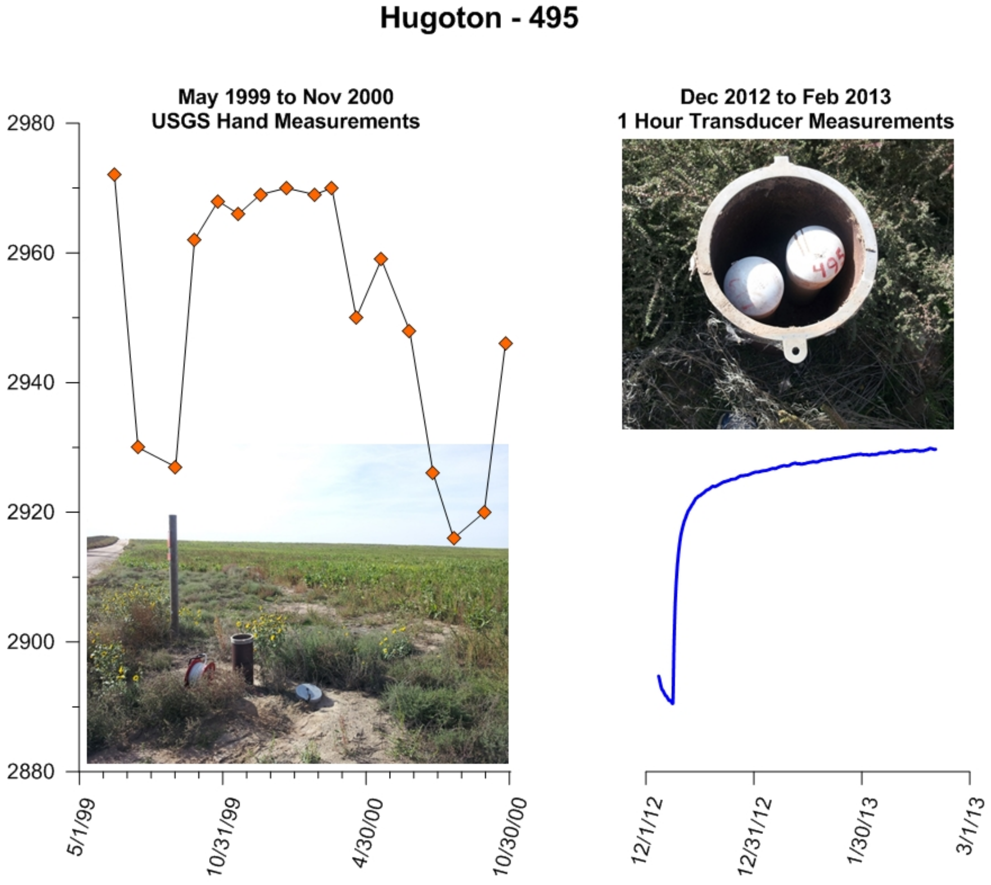

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Acknowledgments

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Executive Summary

The index well program (formerly, calibration monitoring well program) is directed at developing improved approaches for measuring and interpreting hydrologic responses at the local (section to township) scale in the High Plains aquifer (HPA) in western Kansas. The study is supported by the Kansas Water Office (KWO) with Water Plan funding as a result of KWO's interest in and responsibility for long-term planning of groundwater resources in western Kansas. The Kansas Department of Agriculture, Division of Water Resources (DWR), is providing assistance, as are Groundwater Management Districts (GMDs) 1, 3, and 4.

The project began with the installation of three transducer-equipped wells, designed and sited to function as local monitoring wells, in late summer 2007. One of these index wells is installed in each of the three western GMDs, with locations deliberately chosen to represent different water use and hydrogeologic conditions, and to take advantage of related past or current studies. A major focus of the program has been the development of criteria or methods to evaluate the effectiveness of management strategies at the sub-unit (e.g., township) 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 five full recovery and pumping seasons and one ongoing recovery season have been obtained at the three index wells; additional water-level data have been acquired from wells in the vicinity of all three index well sites. In late 2012, four wells along the Kansas-Oklahoma state line were added to the network.

This report provides (a) an update of the hydrographs for the original three index wells; (b) interpretation of hydrographs from the index wells and the wells in the expanded monitoring area in the vicinity of the Thomas index well; (c) a discussion of the new wells added to the network in GMD1 and along the Kansas-Oklahoma border in GMD3 and interpretation of the initial hydrographs from these wells; (d) a discussion of climatic indices and their relationship to annual water-level changes at the original three index wells; and (e) a discussion of a spreadsheet approach for estimating the impact of barometric pressure changes in western Kansas during the time of each annual measurement campaign and its potential effects on annual water-level change estimates.

The major findings of the project are as follows:

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

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

(3) Interpretation of index well hydrographs during both the pumping and recovery periods enables important practical insights to be drawn concerning the origin of

the pumped water and the long-term viability of the aquifer in the vicinity of the index wells;

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

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

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

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

The focus of project activities in 2013 will be on the continuation of the detailed analyses of hydrographs from all project wells, completion of the computer tool for readily identifying susceptibility of water-level change estimates from the annual water-level measurement program to barometric pressure effects, cooperation with GMD4 on the interpretation of water-level data from monitoring wells in the Sheridan-6 subunit, further interpretation of geochemical results of analyses of water samples from the vicinity of the index wells, an assessment of the contribution of the Dakota aquifer to pumping withdrawals in the vicinity of the Haskell County index well, further assessment of the relationship between climatic indices and annual water-level changes in the three western GMDs, and integration of information from drillers' logs in the vicinity of the Thomas County index well into interpretation of water-level responses in that area.

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1. Introduction and Background

The index well program (formerly, calibration monitoring well program) is directed at developing improved approaches for measuring and interpreting hydrologic responses at the local (section to township) scale in the Ogallala–High Plains aquifer (henceforth, High Plains aquifer or HPA). The study is supported by the Kansas Water Office (KWO) with Water Plan funding as a result of KWO's interest in and responsibility for long-term planning of groundwater resources in western Kansas. The Kansas Department of Agriculture, Division of Water Resources (DWR), is providing assistance, as are Groundwater Management Districts (GMDs) 1, 3, and 4.

A major focus of the program is the development of criteria or methods to evaluate the effectiveness of management strategies at the subunit (e.g., township) scale. Changes in water level—or the rate at which the water level is changing—are considered the most direct and unequivocal measures of the impact of management strategies. Because of the economic, social, and environmental importance of water in western Kansas, the effects of any modifications in patterns of water use need to be evaluated promptly and accurately. The project has focused on identifying and reducing the uncertainties and inaccuracies in estimates of year-to-year changes in water level, so that the impacts 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 (or calibration) of the water-level change estimates from the annual measurement program.

At the end of 2012, monitoring data (hourly frequency) from five full recovery and pumping seasons and one ongoing recovery season have been obtained. With increasing data, the index well program has demonstrated that (1) the annual water-level measurement network alone (even with additional semi-annual observations) does not currently produce an adequate dataset to evaluate how management decisions affect water-level changes in the short term (fewer than four to five years); (2) because of uncertainties in both the effects of barometric pressure changes and the degree of well recovery at the time of the annual water-level measurement program, the data from the index wells provide the context needed for interpretation of the results of the annual measurement program; (3) interpretation of index well hydrographs during both the pumping and recovery periods enables important practical insights to be drawn concerning the origin of the pumped water and the long-term viability of the aquifer in the vicinity of the index wells; (4) additional measurements at nearby (local [~township] scale) wells help establish the generality of the conclusions that can be obtained from interpretation of index well hydrographs; (5) local hydrogeologic variations and well construction need to be assessed and considered in the interpretation of well hydrographs for the most effective use of wells of opportunity; (6) continuous monitoring has helped establish the hydrogeologic information conveyed by hydrographs of various forms; and (7) water-level data collected using a pressure transducer and data logger provide a near-continuous record of great practical value that can help in the assessment of the continued viability of the HPA as a source of water for large-scale irrigation. As a result of these findings, the index well network was expanded in 2012 to include two wells in GMD1 and four wells in GMD3 along an east-west line near the Kansas-Oklahoma border. In addition, four wells within the proposed Sheridan-6 Local Enhanced Management Area (LEMA) are in the process of being added to the network.

This report will provide (a) an update of the hydrographs for the original three index wells; (b) interpretation of hydrographs from the index wells and the wells in the expanded monitoring area in the vicinity of the Thomas index well; (c) a discussion of the new wells added to the network in GMD1 and along the Kansas-Oklahoma border in GMD3 and interpretation of the initial hydrographs from these wells; (d) a discussion of climatic indices and their relationship to annual water-level changes at the original three index wells; and (e) a discussion of a spreadsheet approach for estimating the impact of barometric pressure changes in western Kansas during the time of each annual measurement campaign and its potential effects on annual water-level change estimates.

2. Setting and Experimental Design

The foundation of the experimental component of the project consists of three transducer-equipped wells, designed and sited to function as local monitoring wells, installed in late summer 2007. One of these index wells is in each of the three western GMDs, with locations deliberately chosen to represent different water use and hydrogeologic conditions, and to take advantage of related past or current studies (Figure 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, initial findings of the project led to the realization that more extensive measurements and calibration were necessary to develop a suitable measurement protocol. To achieve this, the project was expanded to include “wells of opportunity” in the vicinity of the index wells:

1. Haskell County expansion – with the collaboration of DWR, the project obtained access to water-level records from additional wells. In the vicinity of the Haskell index well, numerous wells that are instrumented by DWR provide 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.

2. Thomas County expansion – with the collaboration of DWR and GMD4, six additional wells (two of which are annual program wells) have been equipped with transducers. Monitoring is continuing at three of these additional wells. The commonly adopted view of the HPA as a single unconfined aquifer appears reasonable in the vicinity of the Thomas County site.

3. Scott County expansion – early in 2012, with the assistance of GMD1, two additional “wells of opportunity” in the vicinity of the Scott County index well were equipped with transducers. The commonly adopted view of the HPA as a single unconfined aquifer also appears reasonable in the vicinity of the Scott County site.

Site characteristics are described and discussed in more detail in previous publications (Young et al., 2007, 2008; Buddemeier et al., 2010) but are briefly summarized below and in Table 1. The three 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 water availability. Although the saturated thickness is large, the thickness of intervals that readily yield water to wells is much less. Probably as a result, well yields have deteriorated and, in the spring of 2012, a lawsuit was filed to curtail pumping by some junior water rights. 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; DWR has installed transducers in a number of nearby wells screened in one or both aquifer zones and these wells have been used by this project. The Haskell County site is in an area of greater saturated thickness than the other sites but with greater lateral variation and a 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 project report (Butler et al., 2012) and a recently published journal article based on that report (Butler et al., 2013 – copy in Appendix B of this report), it is doubtful that large-scale irrigation withdrawals from the High Plains aquifer can be sustained at the current pumping rate in this area beyond the current 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. Both areas have shown long-term declines in water level, so these sites are vulnerable to resource exhaustion. The Scott County site has the only well that directly monitors the level of the northern portion of the Scott-Finney depression, where the aquifer is the major water supply for Scott City. In addition, Scott County has recently been the location of a project that uses analyses of drillers’ logs to determine and map the intervals of the aquifer that readily yield water (Practical Saturated Thickness Plus [PST+] Project). This 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 major extension of the PST+ project.

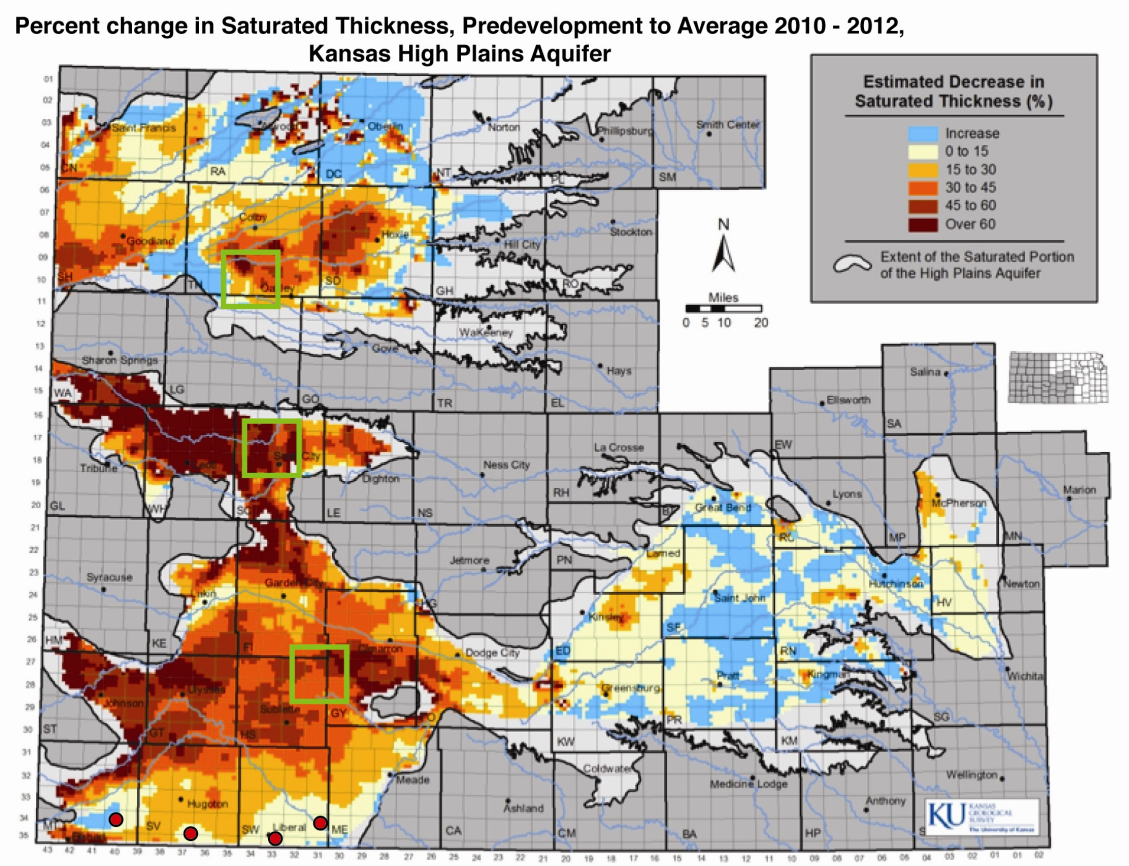


Figure 1: The Kansas portion of the High Plains aquifer, with aquifer and county boundaries shown. Each colored pixel represents one section (1 mi^2), coded to show the degree of groundwater depletion from the beginning of large-scale development to the average of conditions in 2010–2012. The three green boxes surround the three original index well sites; the filled red circles indicate the locations of the new border well sites discussed in Section 4.5. Additional wells are monitored within each of the green boxes, the WH-1 well near Leoti, which will shortly be replaced, is not shown.

Table 1: Characteristics of the index well sites.

Site	2013 WL elev. (ft)[a]	2013 Saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2011 Water Use (ac-ft)		
					1-mi circle	2-mi circle	5-mi circle
Haskell	2553.1[b]	148.3[b]	433	420–430	2155	10,560	59,286
Scott	2830.3	86.2	223	215–225	1078	3596	19,077
Thomas	2970.1	66.7	284	274–284	1256	3299	14,997

[a] 2013 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html)

[b] Suspect annual water-level measurement; elevation and saturated thickness may be overestimated by close to 2 ft.

3. Overview of Index Well Sites and Monitoring Data

This section provides a brief overview of the hydrographs from the three original index well sites. With more than five 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 is defined as the time between pumping seasons. Since water levels increase throughout the recovery period at all three index wells, and full recovery has not been observed at any of the wells, the difference between water levels measured during the recovery season from one year to the next only provides a measure of the year-to-year change in still-recovering water levels. This year-to-year change in recovering water levels must be used cautiously by managers because it can be affected by a variety of factors, such as the duration of recovery at the time of the measurement, that are of little significance for assessing aquifer trends. More importantly, it *does not* involve the final recovered water level, the elevation to which the water level would rise if the recovery were not interrupted by the next pumping season. Efforts to estimate this final recovered water level, which would provide a reliable basis for managers to assess the impact of changes in water use, through various extrapolation procedures have proven difficult because of the variety of mechanisms that can affect the recovery process. Although the recovery extrapolation work has not resulted in reliable estimates of the final recovered water level at the index wells, those efforts, which have been described in previous annual reports for this project, have enabled us to identify recovery "signatures." These signatures allow recognition of some of the mechanisms affecting the recovery data even when only relatively short data records are available.

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

3.1. Haskell County

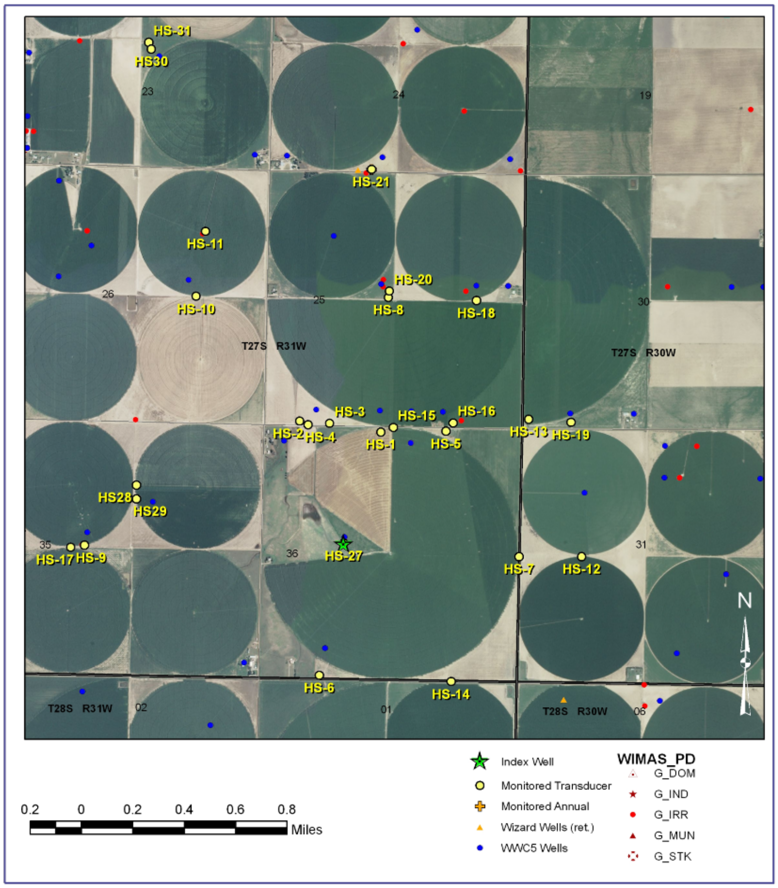


Figure 2: Haskell County site, showing the index well, adjacent monitoring wells, and points of diversion within the area of concentrated DWR studies. Most of the marked wells are equipped with transducers.

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

3.1.1. Hydrograph and General Observations

The complete hydrograph for the Haskell index well is shown in Figure 3 and its general characteristics are summarized in Table 2. The confined nature of the aquifer zone in which the index well is screened is illustrated by the greater than 120-ft change in water level during each pumping season, despite the absence of high-capacity pumping wells in the immediate vicinity of the index well (closest pumping well is almost half a mile away).

The 2011–12 recovery started on August 29, the last date of pumping for the 2011 irrigation season that had a major impact on the index well, and ended on February 23, 2012 when nearby pumping began. However, as is typical for the Haskell site, few periods during the recovery season were completely free of the influence of pumping. Similar to previous years, the pumping season started earlier in the vicinity of the Haskell site compared with the Scott and Thomas sites, with a break during much of the month of April. The early start of pumping is likely due to a combination of winter wheat irrigation and pre-irrigation of other crops, whereas the break in pumping could be caused by decreased water use during planting of summer crops. The 2012–13 recovery season began on August 19, 2012, and was still ongoing at the time of this report (February 20, 2013). However, there was a major period of pumping during the 2012–13 recovery season that lasted for more than a month (October 31, 2012 – December 4, 2012).

Each year, the minimum recorded water-level elevation at the Haskell index well has declined from the previous year. The lowest water level observed was in 2012; the minimum 2012 water-level elevation was 2.7 ft lower than in 2011, 10.6 ft lower than in 2010, 17.5–17.6 ft lower than in 2008 or 2009, and 18.9 ft lower than in 2007. Water-use data for 2012 will be available later in 2013. In 2011, water use within the 2-mile radius surrounding the index well was 10,560 ac-ft, the highest use year during the monitoring period. The 2011 water use was 1,588 ac-ft more than in 2010, 1,840 ac-ft more than in 2009, 629 ac-ft more than in 2008 (the next highest use year during the monitoring period), and 1,796 ac-ft more than during 2007. The 2011 water use was applied on fewer irrigated acres than previous years, resulting in a much higher water use per acre irrigated (Table 2). In 2009, 2010, and 2011, the index well recorded year-to-year declines in the maximum recovered water level of 5.0 ft, 3.9 ft, and 6.8 ft, respectively. In 2012, the decline was 8.7 ft, the largest decline during the monitoring period. Given the only moderately lower water-level minimum recorded in 2012, the expectation is that the decline in the maximum recovered water level in 2013 will not exceed the 2012 decline.

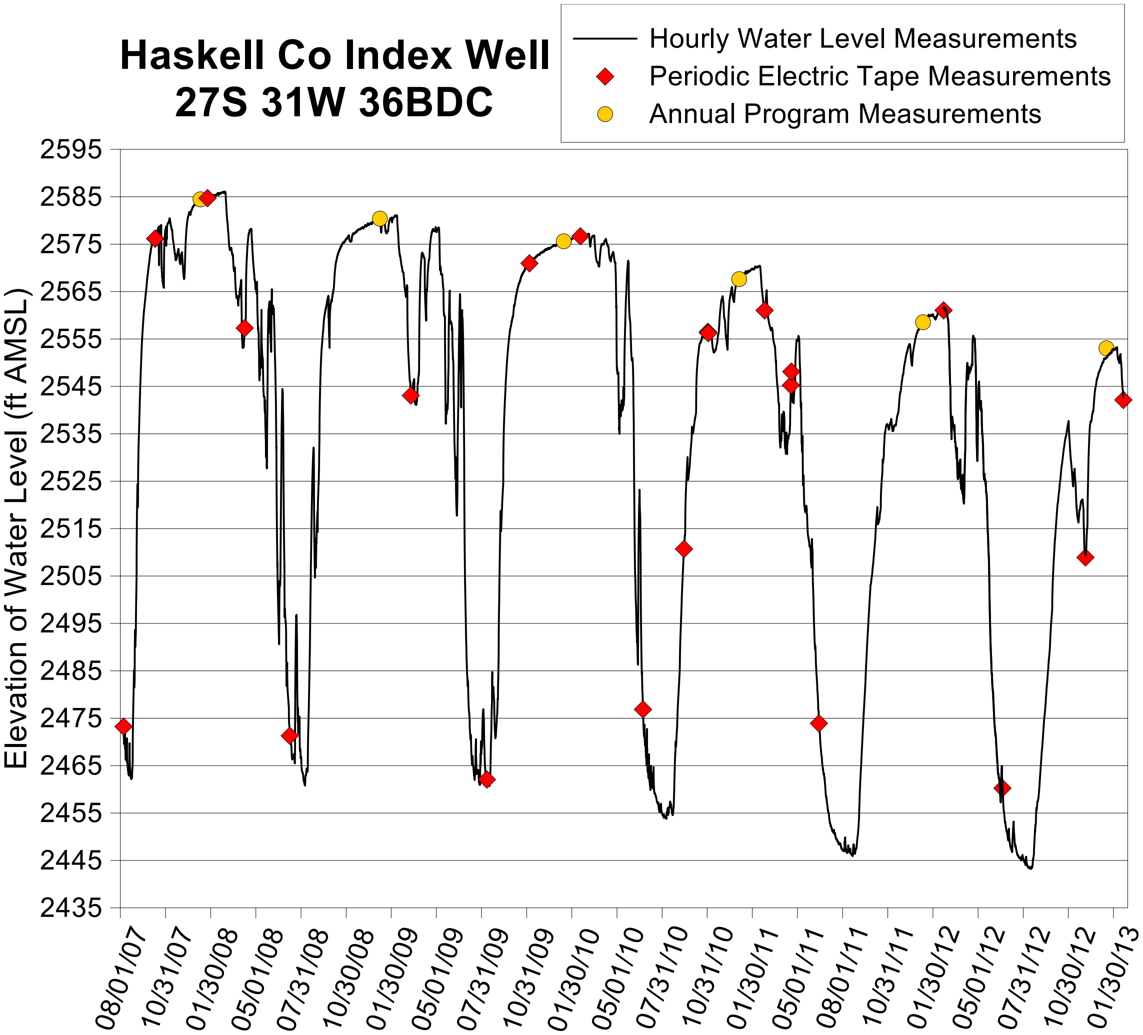


Figure 3: Haskell County index well hydrograph – total data run to 2/19/13. A water-level elevation of 2445 ft corresponds to a depth to water of 392.85 ft below land surface (lsf); the top of the screen is 420 ft below lsf (elevation of 2417.85 ft) and the bottom of the aquifer is 433 ft below lsf (elevation of 2404.85 ft). The screen terminates 3 ft above the bottom of the aquifer.

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

		2007	2008	2009	2010	2011	2012
Minimum Water-Level Elevation	Feet	2462.1	2460.8	2460.7	2453.8	2445.9	2443.2
	Date	8/23/07	8/8/08	8/16/09	8/9/10	8/21/11	8/16/12
Maximum Observed Recovery Elevation	Feet	NA	2586.1	2581.1	2577.2	2570.4	2561.7
	Date	NA	2/28/08	2/9/09	3/5/10	2/13/11	2/23/12
Apparent Recovery	Feet	NA	124.0	120.3	116.5	116.6	115.8
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-5.0	-3.9	-6.8	-8.7
Recovery Season	Start	NA	8/24/07	8/13/08	8/18/09	8/24/10	8/29/11
	End	NA	2/28/08	2/10/09	3/6/10	2/15/11	2/23/12
	Length (Days)	NA	189.2	181.0	200.2	174.9	178.8
Pumping During Recovery Season	Days	NA	41.5	20.0	5.2	25.8[a]	28.9
Length of Pumping Season	Length (Days)	NA	166.1	188.5	171.0	193.7	173.4
2-mi Radius Water Use	Irrigated Acres	6475	7755	6259	6114	6107	NA
	Total Use (ac-ft)	8764.0	9931.7	8720.4	8972.7	10,560.4	NA
	Use per Irrigated Acre (ft)	1.35	1.28	1.39	1.47	1.73	NA

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

3.1.2. Measurement Comparisons

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

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/15/2008	2584.48	NA	Steel tape
	2584.44[c]	-	Transducer
1/7/2009	2580.41	-4.07 (-5.0)	Steel tape
	2580.19[c]	-4.25	Transducer
	2580.10[d]	NA	Transducer
1/14/2010	2575.63	-4.78 (-3.9)	Steel tape
	2575.54[c]	-4.65	Transducer
	2575.51[d]	-4.59	Transducer
1/4/2011	2568.67	-6.96 (-6.8)	Steel tape
	2567.91[c]	-7.63	Transducer
	2567.94[d]	-7.57	Transducer
1/11/2012	2558.57	-10.1 (-8.7)	Steel tape
	2558.82[c]	-9.09	Transducer
	2558.75[d]	-9.19	Transducer
1/16/2013	2553.09[e]	-5.48 (NA)	Steel tape
	2551.22[c]	-7.60	Transducer
	2550.99[d]	-7.76	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.

[e] Suspect annual measurement value.

3.2. Scott County

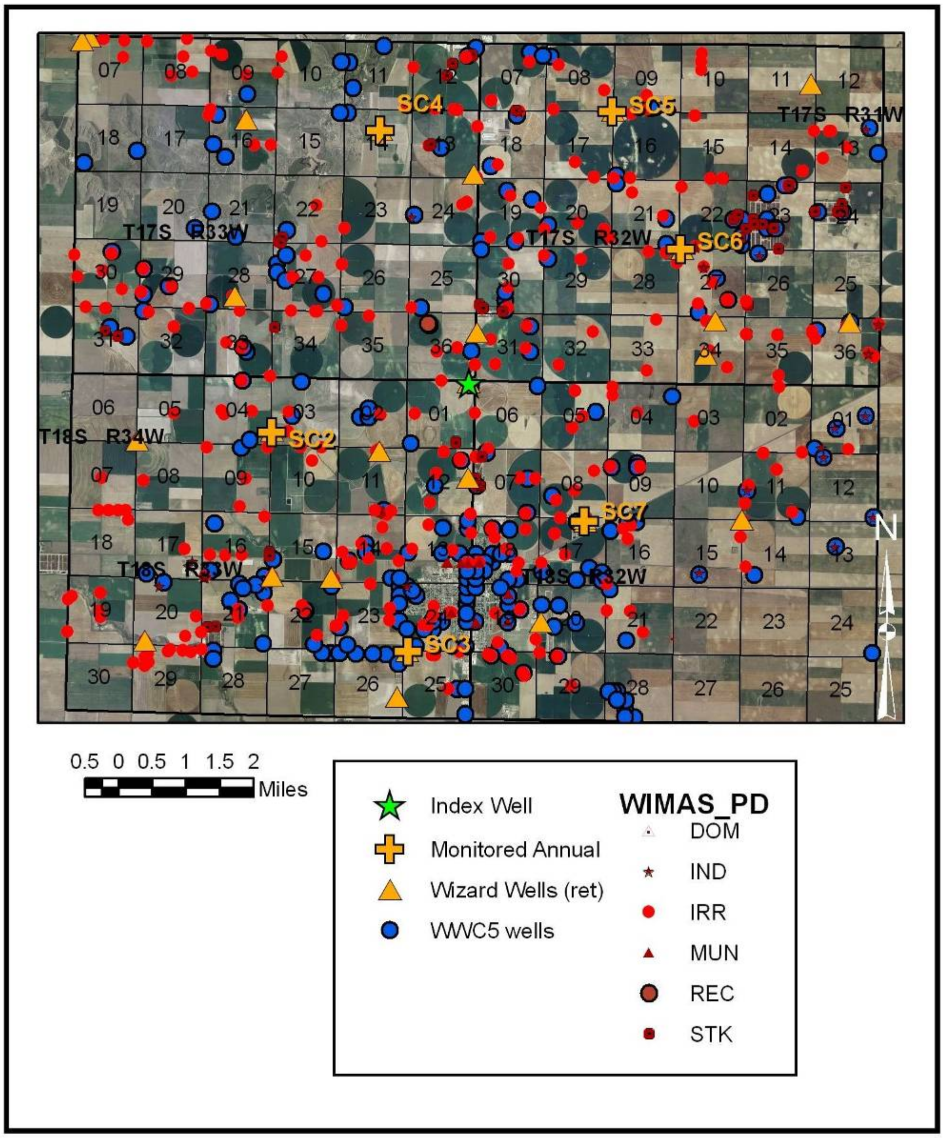


Figure 4a: Scott County site, showing the index well, other monitored wells, and adjacent points of diversion; GMD1 expansion wells shown in Figure 4b.

Figure 4a is an aerial overview of the Scott County site at a scale that shows the index well, the surrounding network of annual program wells, and the location of wells with water rights within the area. Figure 4b shows the GMD1 expansion wells discussed in Section 4.4.

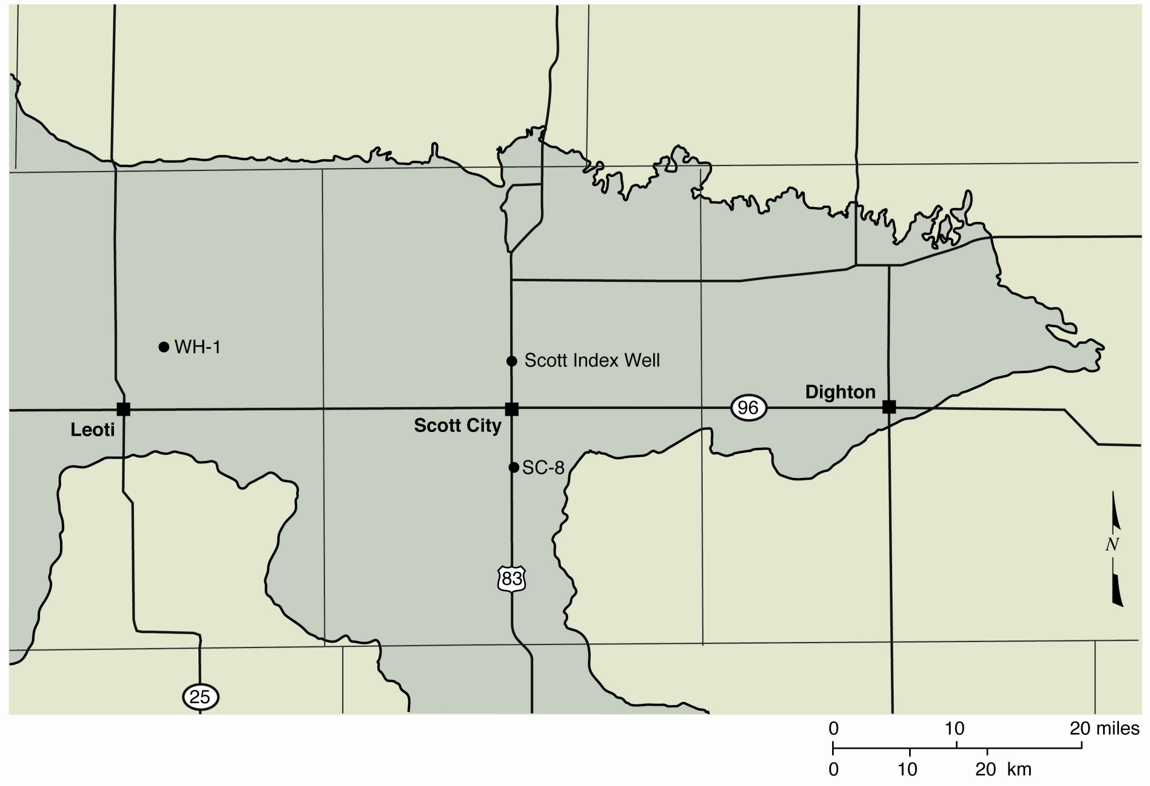


Figure 4b: Scott County Index Well with the SC-8 and WH-1 expansion wells discussed in Section 4.4.

3.2.1. Hydrograph and General Observations

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

The 2011–12 recovery started on September 1, with approximately eight days of pumping beginning on September 22. This pumping period was followed by a quick recovery of almost a foot, followed by a nearly linear recovery before pumping for the next irrigation season started on March 12, 2012. Pumping then continued until a break from April 3 to April 23, most likely for spring planting. Pumping then continued for many wells in the vicinity until late June. After a sudden drop of more than 0.75 ft within 24 hours on June 21–22, pumping appeared to continue at all wells in the vicinity until July 22. Pumping was then more sporadic until the end of widespread pumping on September 7. Sporadic pumping occurred during the first two months of the 2012–13 recovery season through November 10. The recovery was then nearly linear through the time of this report (February 20, 2013).

Each year, the minimum recorded water-level elevation has declined from the previous year. The lowest water level observed was in 2012; the minimum 2012 water-level elevation was 0.8 ft lower than in 2011, 2.2 ft lower than in 2010, 2.5 ft lower than in 2009, and 3.3 ft lower than in 2008. Water-use data for 2012 will be available later in 2013. Water use within the 2-mile radius surrounding the index well in 2011 (3,596 ac-ft) was the second highest over the monitoring period and was 560 ac-ft, 640 ac-ft, and 420 ac-ft greater than water use during 2010, 2009, and 2007, respectively, and 463 ac-ft less than use during 2008 (highest use over the monitoring period). The year-to-year declines in the maximum recovered water level were 1.3 ft, 0.4 ft, 0.7 ft, and 0.9 ft in 2009, 2010, 2011, and 2012, respectively. The expectation, based on the decline in the minimum recorded water-level elevation in 2012, is that the decline in the maximum recovered water level in 2013 will not exceed the 2012 decline.

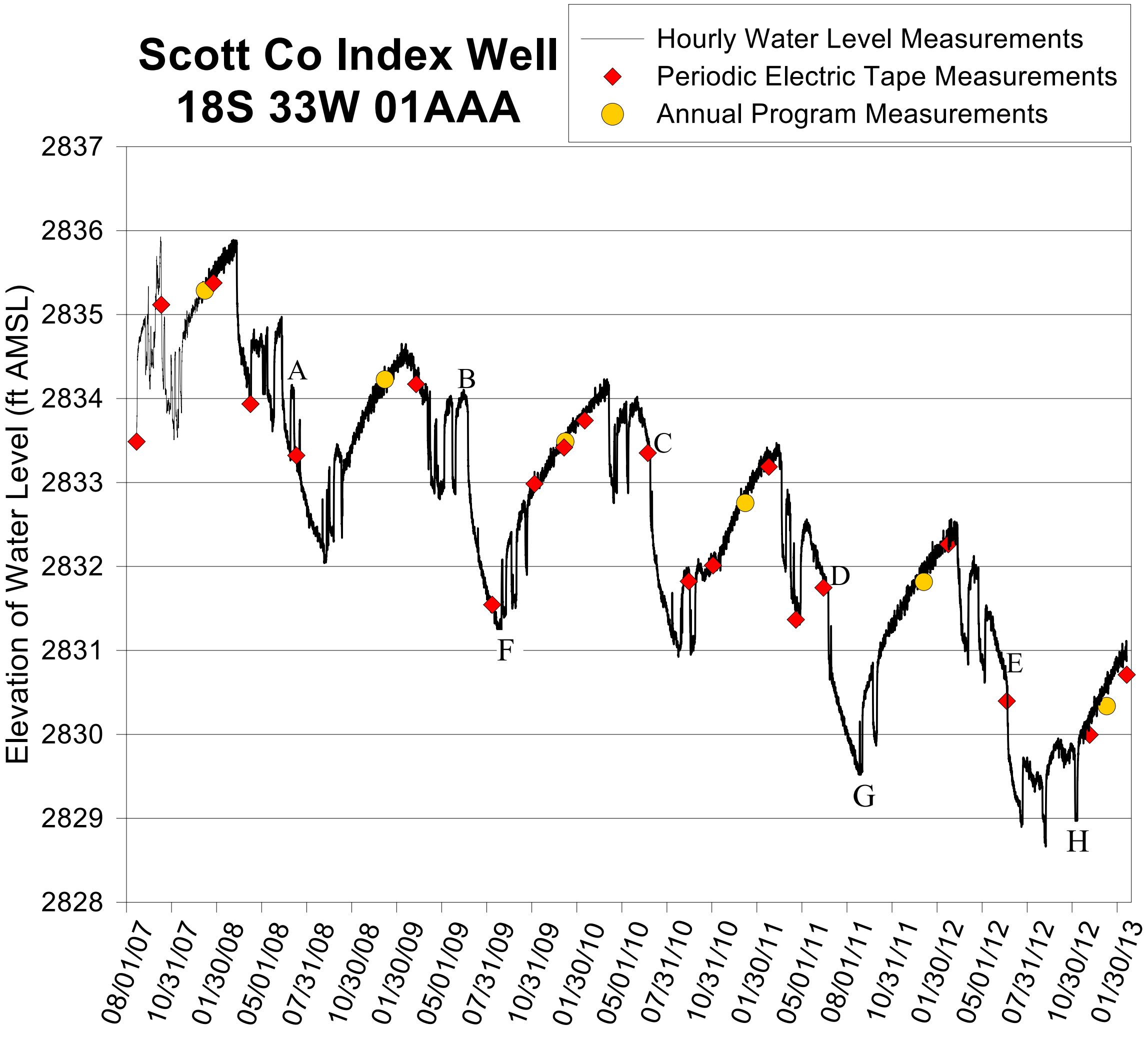


Figure 5: Scott County index well hydrograph – total data run to 2/18/13. A water-level elevation of 2829 ft corresponds to a depth to water of 138.15 ft below land surface (lsf); the top of the screen is 215 ft below lsf (elevation of 2752.15 ft) and the bottom of the aquifer is 223 ft below lsf (elevation of 2744.15 ft). The screen terminates 2 ft below the bottom of the aquifer. A–H defined in text (Section 4.2).

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

		2007	**2008**	**2009**	**2010**	**2011**	**2012**
Minimum Water-Level Elevation	Feet	<2833.4	2832.0	2831.2	2830.9	2829.5	2828.7
	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
Maximum Observed Recovery Elevation	Feet	NA	2835.9	2834.6	2834.2	2833.5	2832.6
	Date	NA	3/4/08	2/17/09	3/26/10 and 4/1/10	3/11/11	2/28/12
Apparent Recovery	Feet	NA	>2.5	2.6	3.0	2.6	3.1
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-1.3	-0.4	-0.7	-0.9
Recovery Season	Start	NA	<8/21/07	9/13/08	8/30/09	8/29/10	9/1/11
	End	NA	3/11/08	4/2/09	4/5/10	3/17/11	3/12/12
	Length (Days)	NA	>203	201.3	217.8	200.2	192.8
Pumping During Recovery Season	Days	NA	>48.2	13.7	21.0	12.8	8.7
Length of Pumping Season	Length (Days)	NA	182.3	150.0	145.7	168.1	186.42
2-mi Radius Water Use	Irrigated Acres	4132	3950	3923	3665	4078	NA
	Total Use (ac-ft)	3175.1	4059.0	2955.5	3035.9	3595.6	NA
	Irrigation Use Only (ac-ft)	3095.8	4014.3	2955.5	3017.1	3580.6	NA
	Use per Irrigated Acre (ft)	0.75	1.02	0.75	0.82	0.88	NA

3.2.2. Measurement Comparisons

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

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/7/2008	2835.29	NA	Steel tape
	2835.29[c]	-	Transducer
1/6/2009	2834.23	-1.06 (-1.24)	Steel tape
	2834.21[c]	-1.08	Transducer
	2834.95[d]	NA	Transducer
1/7/2010	2833.49	-0.74 (-0.42)	Steel tape
	2833.48[c]	-0.73	Transducer
	2833.55[e]	-1.40	Transducer
1/7/2011	2832.76	-0.73 (-0.73)	Steel tape
	2832.86[c]	-0.62	Transducer
	2832.86[e]	-0.69	Transducer
1/4/2012	2831.82	-0.94 (-0.90)	Steel tape
	2831.92[c]	-0.94	Transducer
	2831.95[e]	-0.91	Transducer
1/9/2013	2830.34	-1.48 (NA)	Steel tape
	2830.56[c]	-1.36	Transducer
	2830.61[e]	-1.34	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.

3.3. Thomas County

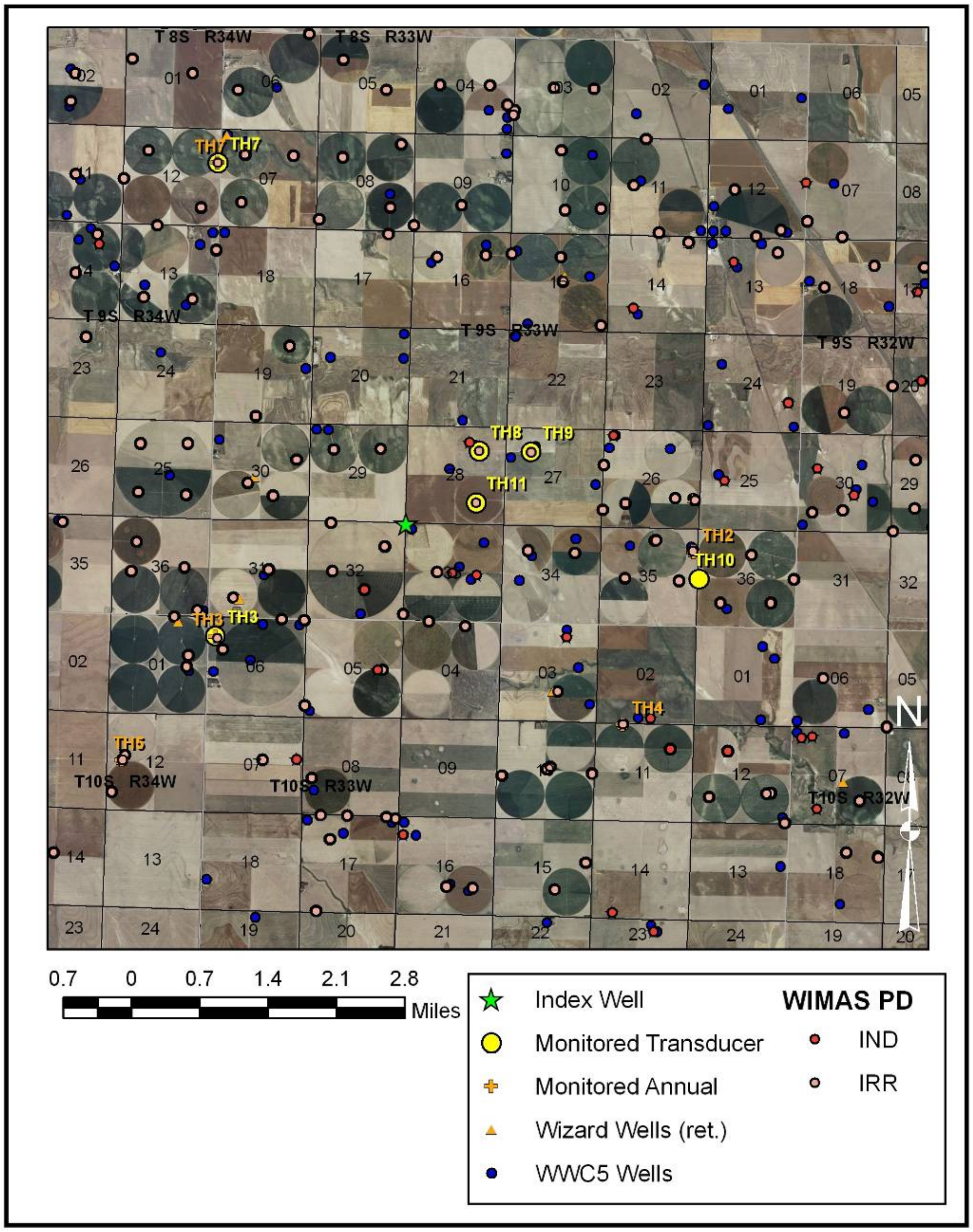


Figure 6: Thomas County site, showing the index well, nearby wells that have been equipped with transducers, surrounding annual program wells, and points of diversion in the area.

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

3.3.1. Hydrograph and General Observations

The complete hydrograph for the Thomas index well is shown in Figure 7 and its general characteristics are summarized in Table 6. The unconfined nature of the aquifer zone in which the index well is screened is illustrated by the relatively small change and rate of change in water level during each pumping and recovery season, despite 10 or more high-capacity pumping wells within a mile of the index well. Real-time viewing of the Thomas index well hydrograph is now also possible through the GMD4 website (www.gmd4.org).

The 2011–12 recovery was the second shortest observed during the monitoring period at the Thomas area, beginning on September 6, 2011, and ending on May 4, 2012. However, it was still 50 days longer than the 2010–11 recovery season. Although there were periodic short cutoffs of some wells, sustained pumping essentially continued from early May until the end of the pumping season on September 17, 2012. The 2012–13 recovery season was still ongoing at the time of this report (February 20, 2013).

Unlike the Haskell and Scott index wells, the minimum recorded water-level elevation at the Thomas index well has not declined every year. The minimum observed water-level elevation in 2012, which was the lowest recorded over the monitoring period, was 1.8 ft below that of 2011, 4.3 ft below that of 2010 (the highest recorded minimum water-level elevation during the monitoring period), and 4.2 ft, 3.3 ft, and 4.2 ft below the minimum water-level elevations in 2009, 2008, and 2007, respectively. Water-use data for 2012 will be available later in 2013. In 2011, water use within the 2-mile radius surrounding the index well was 3,299 ac-ft, the highest use year during the monitoring period. The 2011 water use was 1,043 ac-ft more than in 2010, 1,382 ac-ft more than in 2009, 474 ac-ft more than in 2008, and 430 ac-ft more than in 2007 (the next highest use year during the monitoring period). The 2011 water use was applied on only slightly more irrigated acres than previous years, so the water use per acre irrigated was the highest over the monitoring period (Table 6). The maximum observed water level in 2012 was 1.4 ft below that of 2011, 2.6 ft below that of 2010 (the highest maximum observed water level during the monitoring period), 1.6 ft below that of 2009, and 2.1 ft below that of 2008. Given that the 2012 minimum water level (recorded on September 13) was the lowest minimum recorded water-level elevation during the monitoring period, the expectation is that, in the absence of a very long recovery period, the maximum observed water level at the end of the 2012–13 recovery will be the lowest value recorded to date at the Thomas index well.

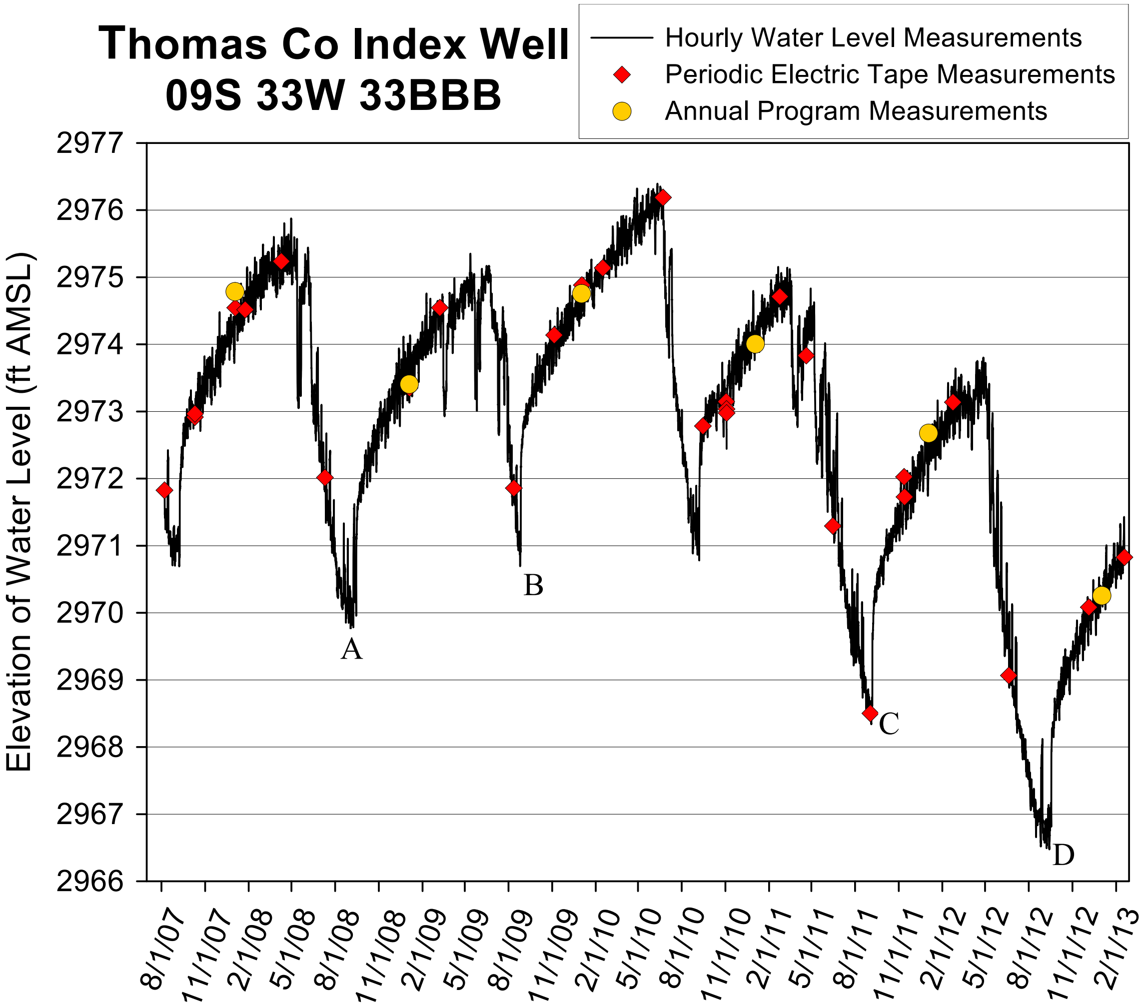


Figure 7: Thomas County index well hydrograph – total data run to 2/18/13. A water-level elevation of 2968 ft corresponds to a depth to water of 219.56 ft below land surface (lsf); the top of the screen is 274 ft below lsf (elevation of 2913.56 ft) and the bottom of the aquifer is 284 ft below lsf (elevation of 2903.56 ft). The screen terminates at the bottom of the aquifer. A–D 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
Minimum Water-Level Elevation	Feet	2970.7	2969.8	2970.7	2970.8	2968.3	2966.5
	Date	9/7/07	9/2/08	8/25/09	9/6/10	9/4/11	9/13/12
Maximum Observed Recovery Elevation	Feet	NA	2975.9	2975.4	2976.4	2975.2	2973.8
	Date	NA	4/30/08	5/12/09	6/10/10	2/20/11	4/27/12
Apparent Recovery	Feet	NA	5.2	5.6	5.7	4.4	5.5
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-0.5	+1.0	-1.2	-1.4
Recovery Season	Start	NA	9/8/07	9/8/08	8/26/09	9/6/2010	9/6/11
	End	NA	5/12/08	6/24/09	6/24/10	3/17/11	5/4/12
	Length (Days)	NA	247.2	289.5	301.4	191.4	241.3
Pumping During Recovery Season	Days	NA	5.0	17.0	2.2	18.4	14.0
Length of Pumping Season	Length (Days)	NA	118.5	63.2	74.6	173.8	135.8
2-mi Radius Water Use	Irrigated Acres	2983	3016	2958	3009	3109	NA
	Total (ac-ft)	2868.9	2825.2	1917.2	2256.1	3298.8	NA
	Use per Irrigated Acre (ft)	0.96	0.94	0.65	0.75	1.06	NA

3.3.2. Measurement Comparisons

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

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/3/2008	2974.67	NA	Steel tape
	2974.61[c]	NA	Transducer
1/4/2009	2973.29	-1.38 (-0.53)	Steel tape
	2973.18[c]	-1.43	Transducer
	2973.59[d]	NA	Transducer
1/2/2010	2974.64	+1.35 (+1.05)	Steel tape
	2974.74[c]	+1.56	Transducer
	2974.65[d]	+1.06	Transducer
1/3/2011	2973.89	-0.75 (-1.24)	Steel tape
	2974.14[c]	-0.60	Transducer
	2974.15[d]	-0.50	Transducer
1/3/2012	2972.56	-1.33 (-1.40)	Steel tape
	2972.61[c]	-1.53	Transducer
	2972.36[d]	-1.79	Transducer
1/2/2013	2970.14	-2.42 (NA)	Steel tape
	2970.26	-2.35	Transducer
	2970.31[d]	-2.05	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.

4. Interpretation of Water-Level Responses

4.1. Impact of Barometric Pressure Fluctuations on Water Levels

Significant effort has been expended over the course of this project on correcting water-level measurements recorded by pressure transducers in the index wells. Common mechanisms beyond pumping that can affect the water level in a well include fluctuations in barometric pressure and tidal forces (earth tides). In previous project reports, earth-tide effects were shown to have a negligible impact on water-level measurements, while the impact of changes in barometric pressure has been shown to be large enough to be of practical significance at one of the original index wells (Thomas County). Monitoring during 2012 found that this impact is also of practical significance at additional expansion wells in the vicinity of the Scott and Thomas index wells and at one of the new index wells along the Kansas-Oklahoma border. Given this finding and the expectation that this impact will be large wherever the depth to water is on the order of that at the Thomas County index well (> 200 ft) or greater, 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 Excel spreadsheet calculations. In previous project reports, early efforts to extract information about the hydrostratigraphy from the BRF were described. In 2012, initial work on getting more information from the BRFs began; it appears that it should be possible to get information about the nature of the hydraulic connection between the well and the formation, the viability of annular seals, and an estimate of the bulk pneumatic diffusivity of the vadose zone from the BRF. That work will be expanded in 2013.

4.2. Interpretation of Hydrographs from the Index Wells

An understanding of the primary mechanisms controlling 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 two years of this project has been directed at that issue. The major conclusions from those activities are described in the 2011 annual report (Butler et al., 2012) and the recently published paper in the journal *Groundwater* (Butler et al., 2013 – copy in Appendix B of this report). In this section, we will briefly update the insights that have been gained from interpretation of the hydrographs from the index wells.

Haskell County

The major conclusions concerning the future prospects of the HPA in the vicinity of the Haskell site were summarized in the publications described in the previous paragraph. Those conclusions remained unaltered as a result of the 2012 water-level data from the Haskell index well. The water column at 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 39 ft in height at the maximum observed drawdown for 2011. In 2012, the height of that water column at the maximum observed drawdown was approximately 36 ft. In the immediate vicinity of the irrigation wells, the water column height was likely considerably less. As the water column height continues to decrease, it is inevitable that past pumping rates will not be sustainable. It is currently unknown whether any aquifer leakage from the underlying Dakota aquifer will mitigate the rate of decline or whether the water levels in the Dakota aquifer are also declining at a similar or greater rate, meaning that upward leakage could either be minimal or downward leakage could occur. Some wells are completed in both the HPA and Dakota aquifer and could be producing relatively more water from the Dakota as the HPA becomes depleted in the area of the Haskell index well.

Scott County

The 2012 water-level data helped refine the assessment of conditions in the vicinity of the Scott index well. Figure 8, 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), and E (2012) on Figure 5. Although these data are relatively “noisy” as a result of pumps cutting on and off, a consistent picture still emerges for all five 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). After three to four days of pumping, drawdown begins to increase and an apparent period of radial flow to the pumping well (straight line on a semilog plot) lasts until 20–25 days from the onset of pumping. After that time, drawdown increases at a faster rate than would be expected for large-scale radial flow to a pumping well. This increased rate of drawdown is likely an indication of low-permeability boundaries impacting the drawdown. In this case, the increased drawdown is likely produced by a single boundary, such as one edge of the Scott-Finney depression. Note that the 2011 and 2012 drawdown data essentially overlie one another from 8 to 28 days, demonstrating the consistency of responses between years. Assessment of water-level changes at the Scott index well will continue in 2013.

The 2011 annual report presented an assessment of recovery data from one complete recovery season (2009–10) and one ongoing recovery season (2011–12). Figure 9 presents an update of the recovery assessment with the complete 2011–12 recovery season and the ongoing 2012–13 recovery (November 11 was used as the start of recovery for the 2012–13 recovery in this figure because of intermittent pumping in September and October). Water use in 2009 and 2011 differed by about 20% (durations of the 2009–10 and 2011–12 recoveries differed by about 12%); water-use data for 2012 are not yet available. Although inflow could be playing a role as at the Thomas index well, the interpretation of the coincidence of the recovery plots is still ongoing.

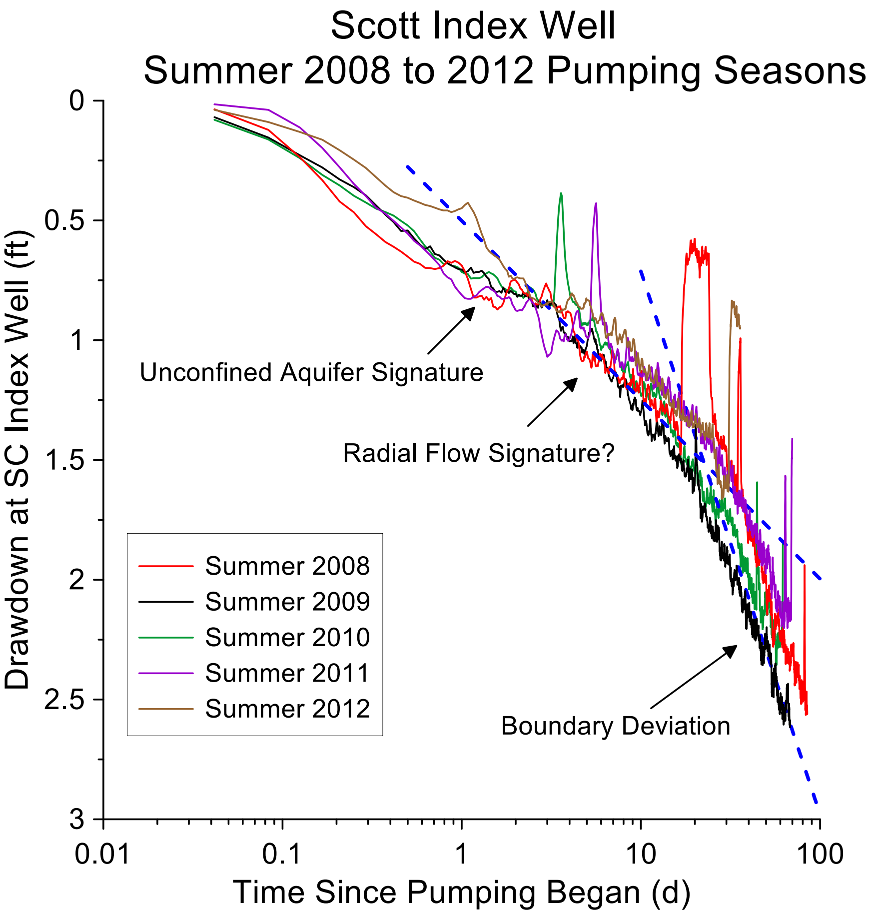


Figure 8: Drawdown in the Scott index well versus the logarithm of pumping time for pumping periods beginning at points A (2008), B (2009), C (2010), D (2011), and E (2012) on Figure 5.

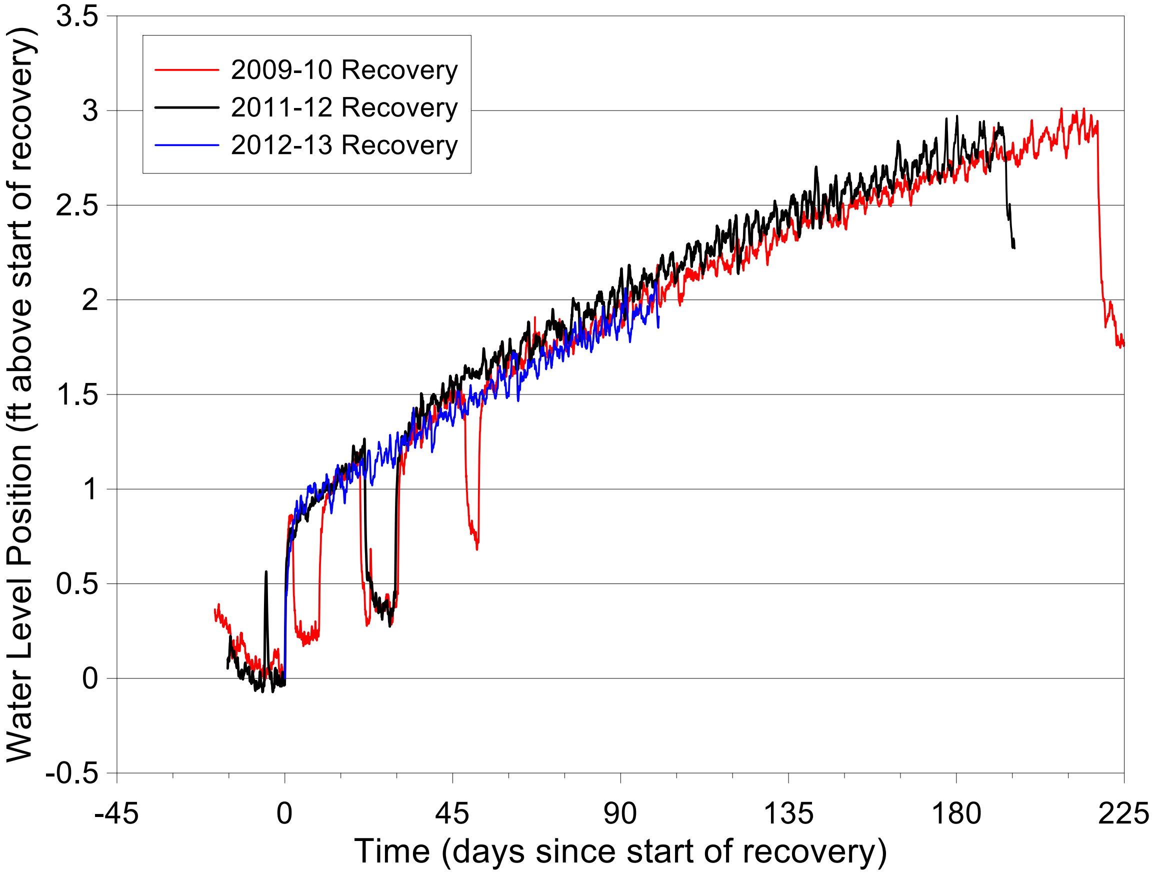


Figure 9: Water levels in the Scott index well for the 2009–10, 2011–12, and 2012–13 recovery periods. Recovery for the 2009–10, 2011–12, and 2012–13 recovery periods calculated from points F, G, and H, respectively, on Figure 5.

Thomas County

The major findings regarding the water-level data from the Thomas index well were summarized in the publications described in the first paragraph of this section. The most important finding was that there appears to be a significant amount of inflow into the unconfined aquifer at the Thomas site. Further assessments of that possibility were carried out using the 2012 data.

An assessment of two complete and one ongoing recovery seasons was presented in the 2011 annual report. Figure 10 presents an update of the recovery assessment with the results for the complete 2008–09, 2009–10, and 2011–12 recovery seasons and the still ongoing 2012–13 recovery. The 2009 and 2011 pumping seasons bound the range of conditions (water use and pumping duration) observed during the monitoring period (Table 6). Although the 2011 water use was 72% greater than that of 2009 and the irrigation season was close to 2.8 times longer, the rate of recovery was essentially the same. The agreement between the superimposed recovery plots on Figure 10 is remarkable; the rate of water-level change during the recovery periods is essentially identical. The near-coincidence of recovery rates indicates that the recovery is not a function of withdrawals during the previous pumping season; some other mechanism must be primarily responsible for the water-level changes during recovery. A similar coincidence is seen when the 2007–08 and 2010–11 recovery seasons are included, a further indication that a mechanism beyond pumping in the previous irrigation season is responsible for the rise of water levels during the recovery period.

The importance of the inflow into the HPA at the Thomas site can be demonstrated through a simple water-balance calculation using the following equation (Butler et al., 2013 – see copy in Appendix B):

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

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

For the first three complete pumping seasons monitored at the Thomas index well, water levels have been relatively stable from year to year (Figure 7). The annual withdrawals from the HPA in this vicinity thus appear to be balanced by the inflow. Given the average reported water use for the Thomas site over this period (average of 2008–10 pumping seasons is 2333 ac-ft for the area with a 2-mile radius centered on the site) and a rate of water-level change of about 3.3 ft/yr estimated from the rate of recovery between days 135 and 270 on Figure 10, the mass balance equation can be used to calculate a S_y of 0.09, which appears plausible for the sediments in the vicinity of the water table at the Thomas site. Although the inflow appears to be balancing the withdrawals over the 2008–10 pumping seasons, it will not with higher rates of pumping. The same mass balance can be performed using the 2011 water use (3299 ac-ft). In that case, an annual decline in water level of 1.3 ft is calculated for the Thomas index well, which is consistent with the measured 2011 decline in the maximum observed recovery of 1.2 ft. A return to the average water use for the decade preceding the monitoring period (3729 ac-ft) would produce an annual water-level decline exceeding 1.9 ft.

Determination of the origins of the inflow into the unconfined aquifer at the Thomas County index well and the possible inflow into the unconfined aquifer at the Scott County index well is critical for assessing the continued viability of those portions of the High Plains aquifer as a water source for irrigated agriculture. Water samples have been taken and analyzed from the index wells. Water samples have also been collected at four 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 those samples and preliminary interpretations were reported in the 2011 annual report. Further sampling and analyses will be conducted in 2013.

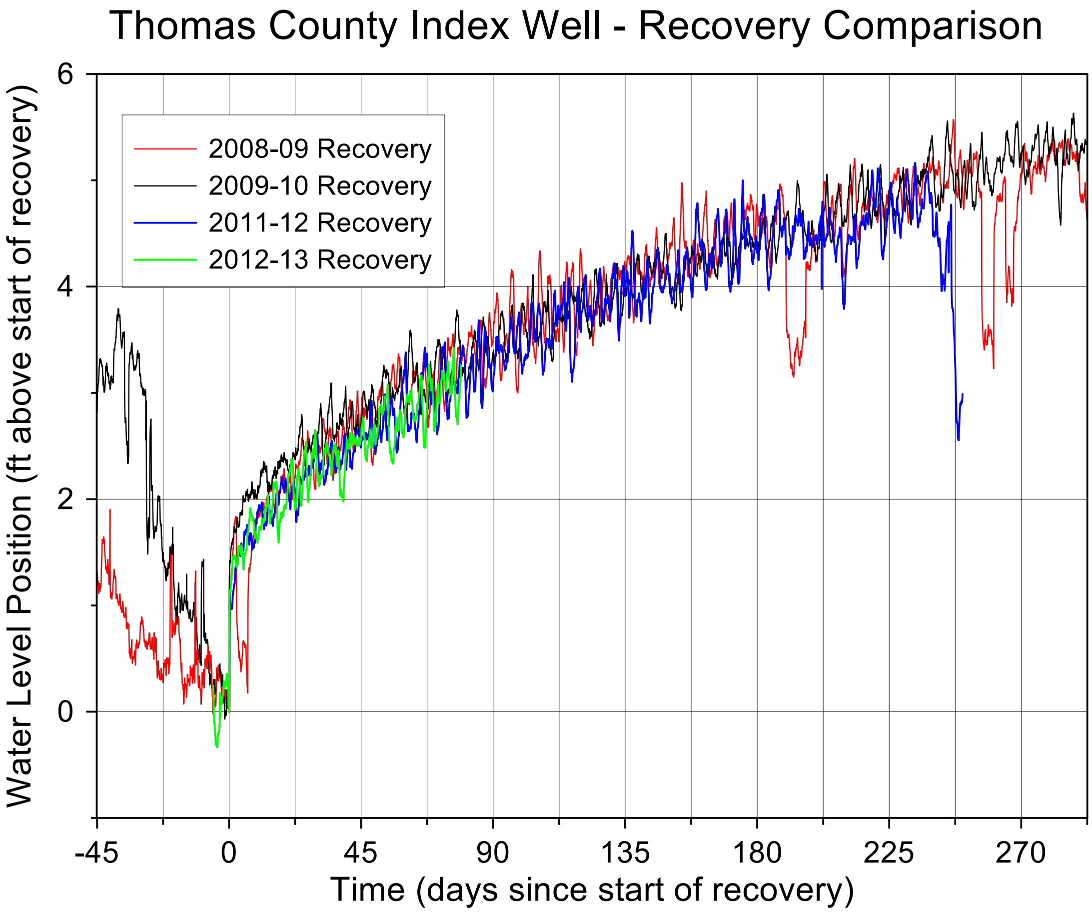


Figure 10: Water levels in the Thomas County index well for the 2008–09, 2009–10, 2011–12, and 2012–13 recovery periods. Recovery for the 2008–09, 2009–10, 2011–12, and 2012–13 recovery periods calculated from points A, B, C, and D, respectively, on Figure 7. Recovery period for 2010–11 not included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

4.3. Thomas County Expansion Project

Initially, five wells in the vicinity of the Thomas index well, including retired and active irrigation wells and a domestic well, were selected and equipped with pressure transducers provided by DWR to monitor the 2009–2010 recovery. Due to a sensor malfunction and the desire to enhance data coverage, two KGS sensors were installed in the fall of 2010 to supplement a malfunctioning sensor at well TH3 and add a new well (TH11) into the network. Table 8 provides a summary of sensor installation dates and other significant events. 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 – through the 2011–12 recovery). Thus, only three of the expansion wells are currently operating in a near-continuous fashion. Hydrographs from the index well and these three currently operating expansion wells are given in Figure 11. These "expansion" wells and a newly added annual well were surveyed in early 2012 to provide elevations of the land surface as well as casing "stick-up" at each well site. A replacement for well TH3, which has been plugged, is currently being sought. Data from the closest expansion wells (TH9 and TH11) are briefly examined here.

Table 8: Installation date and other notes for Thomas County expansion wells.

Well		Sensor	Installation Date	Notes
TH3	Retired Irrigation	DWR KGS	8/12/09 9/13/10	9/13/10 - KGS sensor added because of malfunctioning DWR sensor. 11/22/11 - Both sensors pulled at request of the land owner. Well has been plugged.
TH7	Irrigation	DWR	9/30/09 – 4/18/10 11/23/10 – 4/6/11 11/4/11 – 2/23/12	Active irrigation well, sensor installed and removed each year by KGS and GMD 4 at land owner's request. Sensor not installed for the 2012–13 recovery.
TH8	Retired Irrigation	DWR	11/5/09	Sensor malfunctioned 12/4/09 – has not been replaced – several feet of oil appear to be on top of water surface.
TH9	Retired Irrigation	DWR	11/5/09	Sensor removed 11/11 to 11/14/09 for well cap installation; operator error, data gap from 11/23/10 to 2/23/11 and 12/5/12 to 2/18/13. Otherwise operating normally.
TH10	Domestic	DWR	8/12/09	Unexplained break in data 6/22/10–9/15/10, otherwise operating normally.
TH11	Retired Irrigation	KGS	11/3/10	Sensor fitting failed sometime after 11/11/11 download, sensor pulled for repairs and replaced on 6/20/12. Appears to be operating normally.

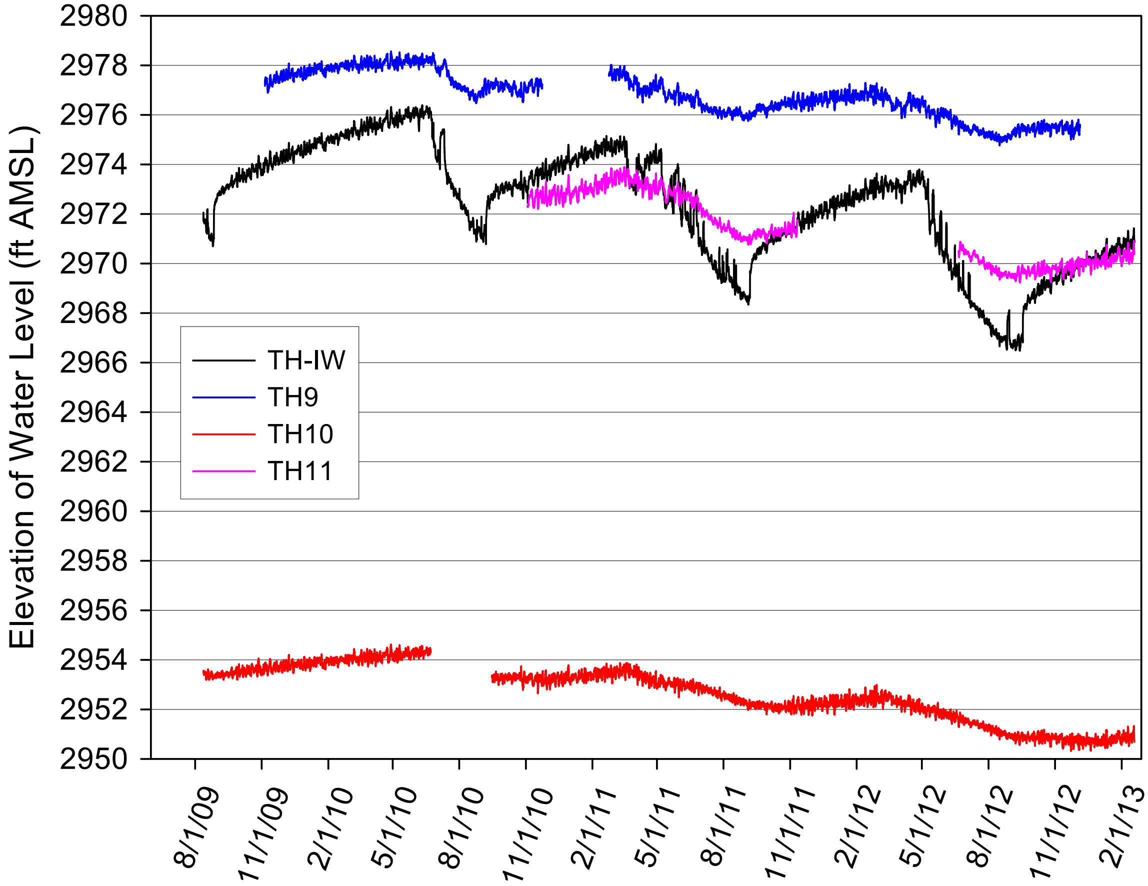


Figure 11: Hydrograph comparison from the Thomas index well and currently active Thomas expansion wells. The general water-level trend indicates west-to-east groundwater flow.

The hydrograph at well TH9 appears to be responding to many of the same pumping events as the Thomas index well (Figure 12). The responses are more subdued and smoothed (indicating a greater distance to the pumping wells) in the TH9 hydrograph but are still clearly apparent. Although the records for the 2010–11 and 2012–13 recovery periods are incomplete due to programming errors, the water levels appear to be nearing recovery prior to the start of the next pumping season. Although there is a more than two month gap (December 5, 2012 – February 18, 2013) in the 2012–13 hydrograph, manual water-level measurements on the start and end days of that gap differed by only 0.07 ft, indicating that water levels appear to have stabilized in the vicinity of well TH9. This stabilization may mean that the water levels in that vicinity have fallen into a compartmentalized interval similar to that in the upper unconfined interval at the Haskell site (see discussion in 2011 annual report and article in Appendix B). The interpretation of the TH9 hydrograph will be explored further in 2013.

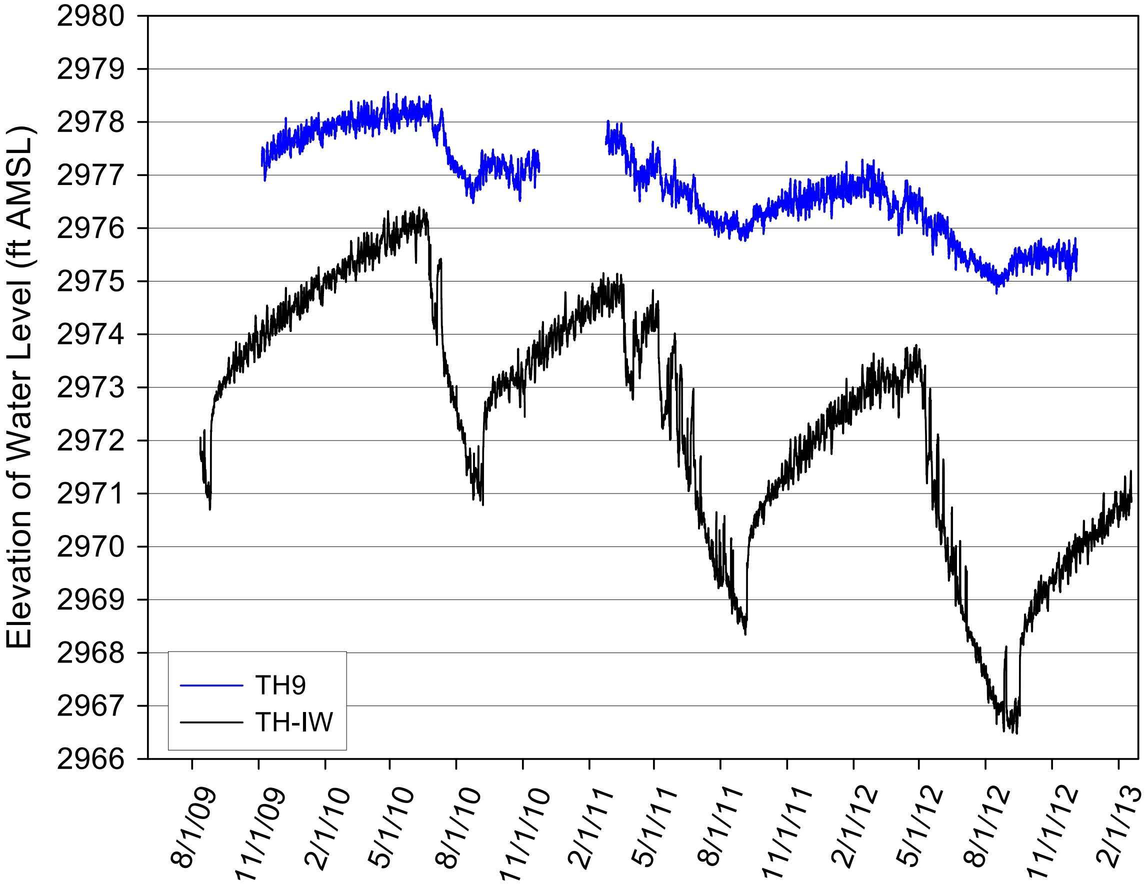


Figure 12: Hydrograph comparison of Thomas index well and expansion well TH9. TH9 is located approximately 1.5 miles NE of the index well (0.75 miles north, 1.25 miles east).

The hydrograph at well TH11 also appears to be responding to many of the same pumping events as the Thomas index well (Figure 13), although the responses are more subdued and smoothed. The lengthy gap during the 2011–12 recovery and the early portions of the 2012 pumping season (November 11, 2011 – June 20, 2012) makes it difficult to draw many conclusions from the TH11 hydrograph.

Overall, the incomplete data from the 2010–2012 period provide an initial view of what can be determined with more complete and extensive monitoring records. As data are downloaded from the remainder of the 2012–13 recovery and a replacement well for well TH3 is identified, the relationship between the index well and expansion wells should become clearer. This relationship will be explored further in 2013.

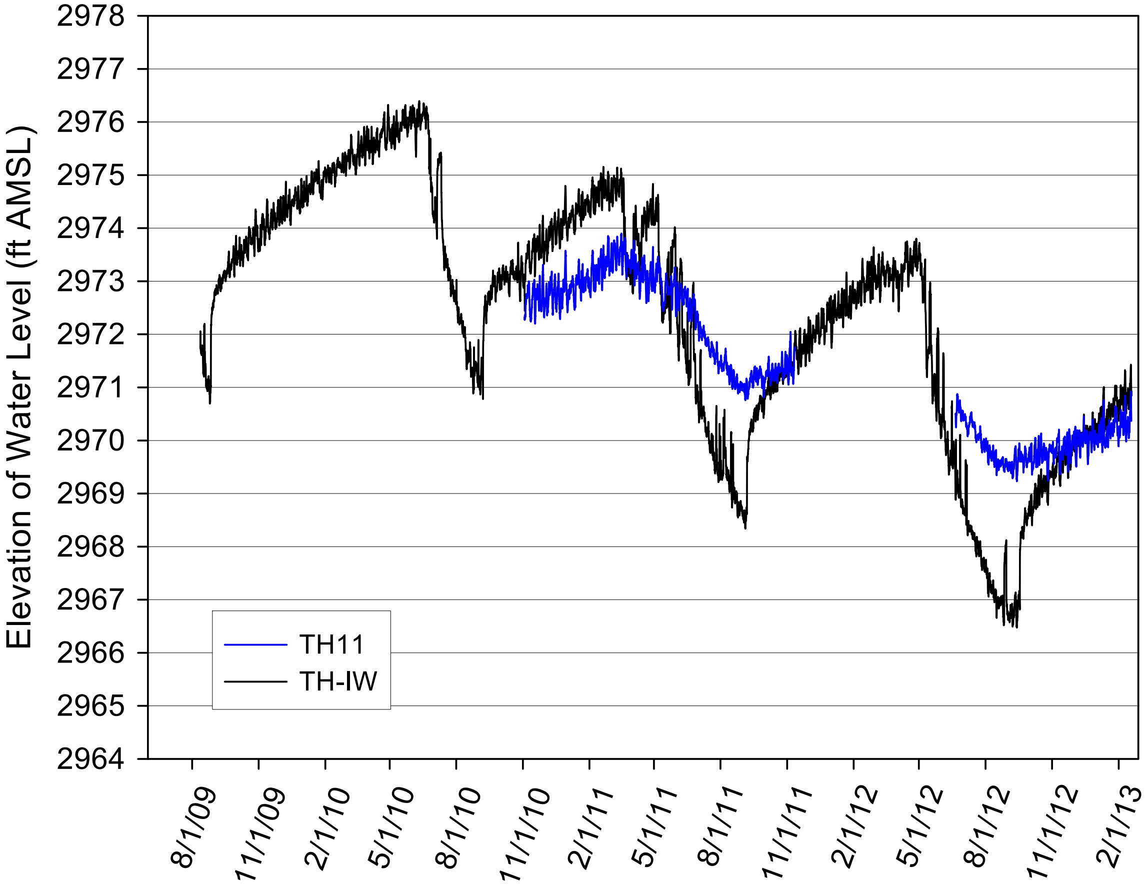


Figure 13: Hydrograph comparison of Thomas index well and expansion well TH11. TH11 is located approximately 0.70 miles ENE of the index well (0.25 miles north, 0.75 miles east).

4.4. GMD1 Expansion Project

Late in 2011, arrangements were made with landowners and GMD1 to install KGS pressure transducers in two old USGS recording wells in the area of the Scott index well (see Figure 4b); the sensors were installed on February 22, 2012. One of the new locations is 6.5 miles south of the Scott index well (henceforth, well SC-8) and the other is 22 miles to the west in Wichita County near Leoti (henceforth, well WH-1). The water columns are short in both SC-8 and WH-1, 16 feet and 10 feet, respectively. Downloaded data from these wells are shared with GMD1 and the landowners. The initial water-level data obtained from these wells are briefly described here.

Well SC-8 – This well is located just east of US 83 approximately 7.5 miles south of the Scott index well (Figure 14a; well construction information not available). The well is located just north of an old drainage channel (the landowner said that the old USGS recorder used to show a hydraulic connection with the channel). Although the field in which the well is located is not currently irrigated, a new well was under construction in the autumn of 2012. The fields adjacent to the site on the west appear to be irrigated.

The approximately one year of initial monitoring data shows a record (Figure 14b) 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 (see discussion in 2011 annual report and discussion regarding Figure 5 in Appendix B of this report). The relatively large (greater than 0.5 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).

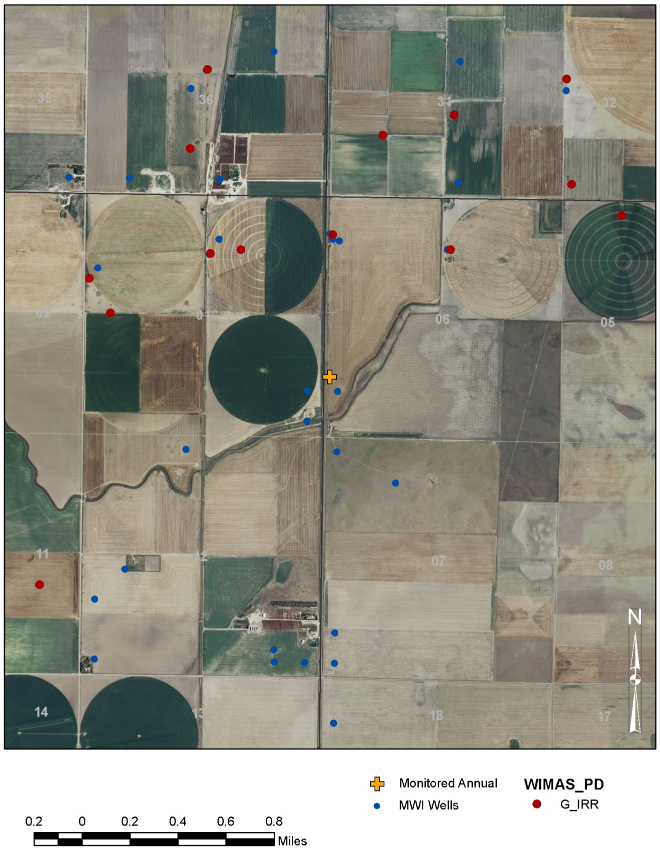


Figure 14a: Aerial view of well SC-8 site (orange cross).

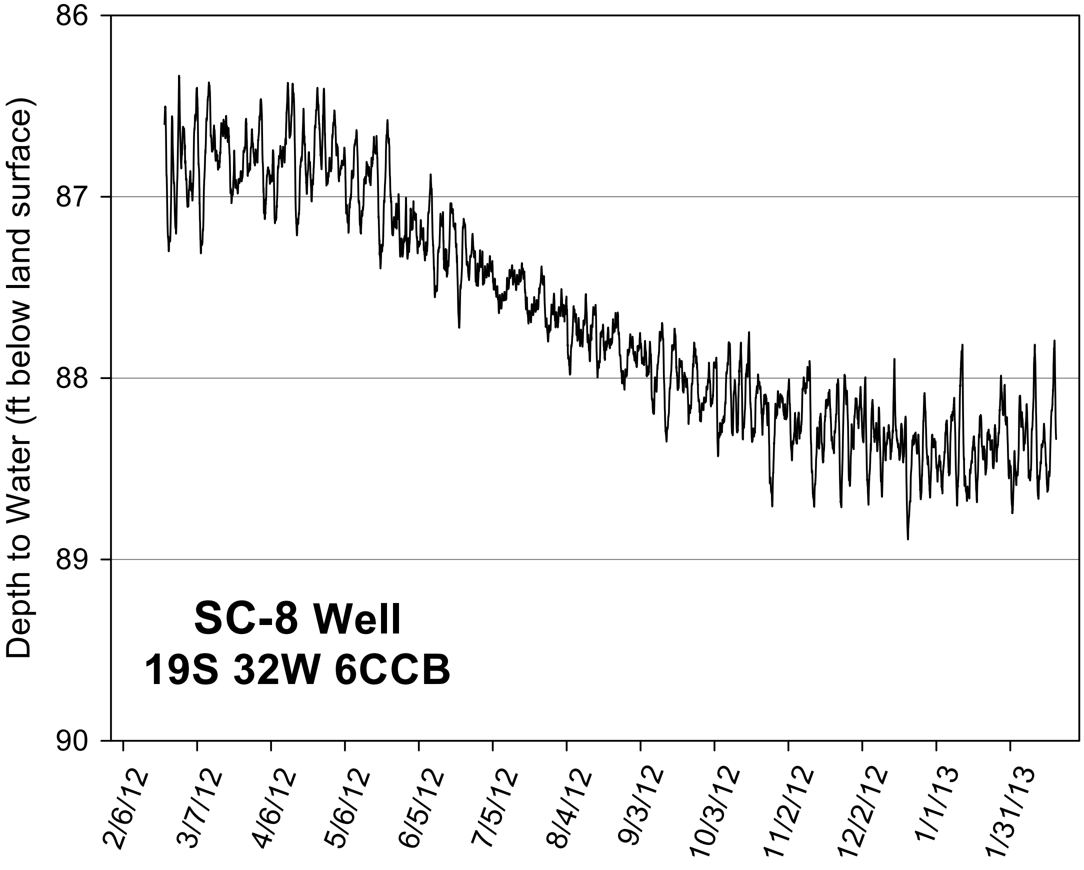


Figure 14b: Initial data set from well SC-8.

Well WH-1 – This well is located in Wichita County approximately 4 miles north of KS 96 and 2.5 miles east of the center of Leoti (Figure 15a; well construction information not available) in an area of relatively high groundwater use. The hydrograph shows much more of a pumping influence from nearby wells than that of well SC-8 (Figure 15b), but the water level appears to be nearing the bottom of the well (estimated bottom depth is 181.5 ft below the top of the casing); the estimated depth to bedrock is 210 ft. The water level in the aquifer is expected to drop below the bottom of the well during the 2013 pumping season. We will work with GMD1 to identify a replacement well in this area in 2013.

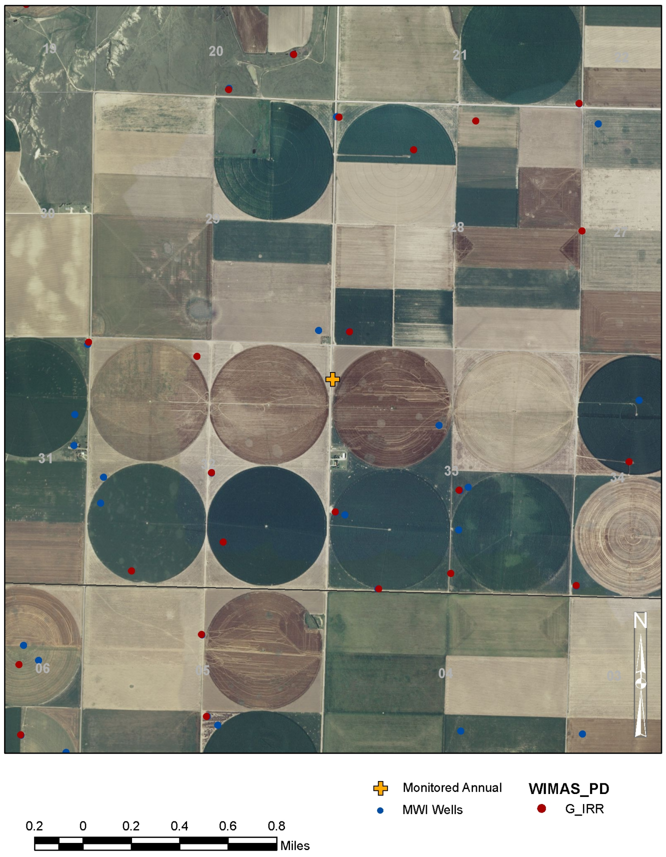


Figure 15a: Aerial view of well WH-1 site (orange cross).

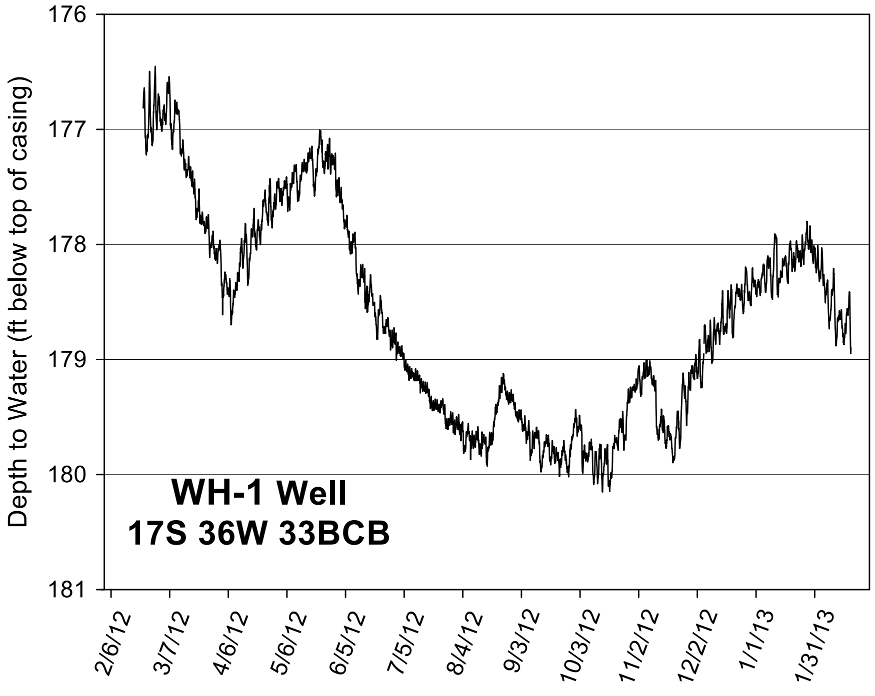


Figure 15b – Initial data set from well WH-1.

4.5. *Border Wells—GMD3 Expansion Project*

In the spring of 2012, we identified wells of opportunity in four well nests that were originally installed by the USGS (NAWQA program) in 1999 just north of the Oklahoma border. These wells are no longer used by the USGS, so they agreed to allow us to use the wells for both annual water-level measurements and continuous measurements. The well nests are located in Morton, Stevens, and Seward counties (filled red circles on Figure 1). These new monitoring locations will provide important 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 that we 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), 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). The Morton County site is located near Rolla and 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). The Stevens County site is near Hugoton and 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, has been instrumented (henceforth, Hugoton 495). Two sites are in Seward County. The site just south of Liberal includes four wells in the HPA; the second deepest well, screened at 426–436 ft, has been instrumented (henceforth, Liberal 436). The site near the Cimarron River includes three wells in the HPA and one in the Permian bedrock; the middle well in the HPA, screened at 200–210 ft, has been instrumented (henceforth, Cimarron 210). In 2013, we plan on adding a barometer at the Cimarron site and we may install transducers in additional wells if equipment is available. The USGS is considering the possibility of installing telemetry access at some of these wells. All four of these wells have been added to the annual water-level measurement network and were measured in January 2013 as part of the annual program.

On February 19, 2013, data from all four wells were downloaded. In the following paragraphs, the sites and the initial set of water-level data are briefly described.

Rolla Site, Well Rolla 366 – This is the deeper of a pair of wells that are located at this site on the edge of the Cimarron National Grasslands (Figure 16a; well construction information provided in Appendix A). Throughout the more than two months of initial monitoring (Figure 16b), the well was recovering from the previous irrigation season (note the irrigated fields in Figure 16a). The relatively large (up to 0.5 ft) amplitude fluctuations superimposed on the recovering 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. This interpretation was confirmed through an analysis using the BRF software developed earlier in this program (Bohling et al., 2011).

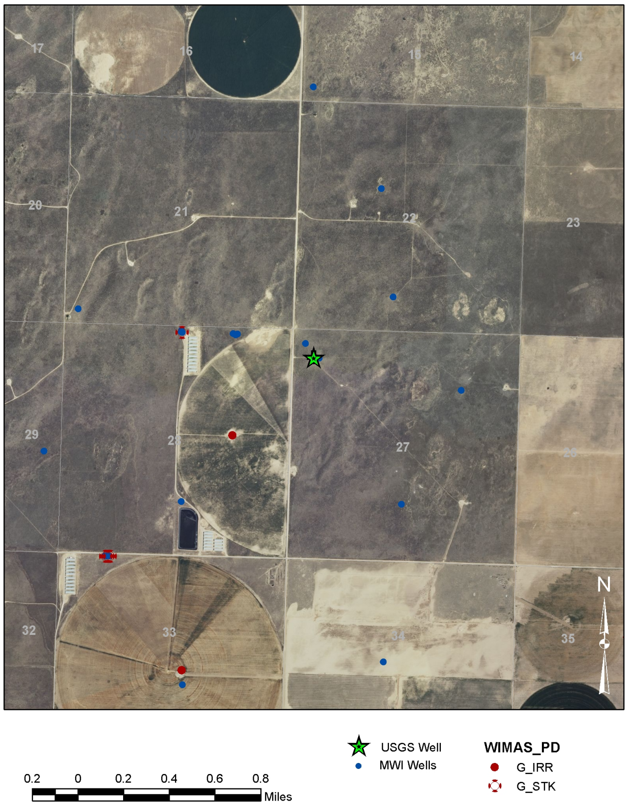


Figure 16a: Aerial view of Rolla site (green star).

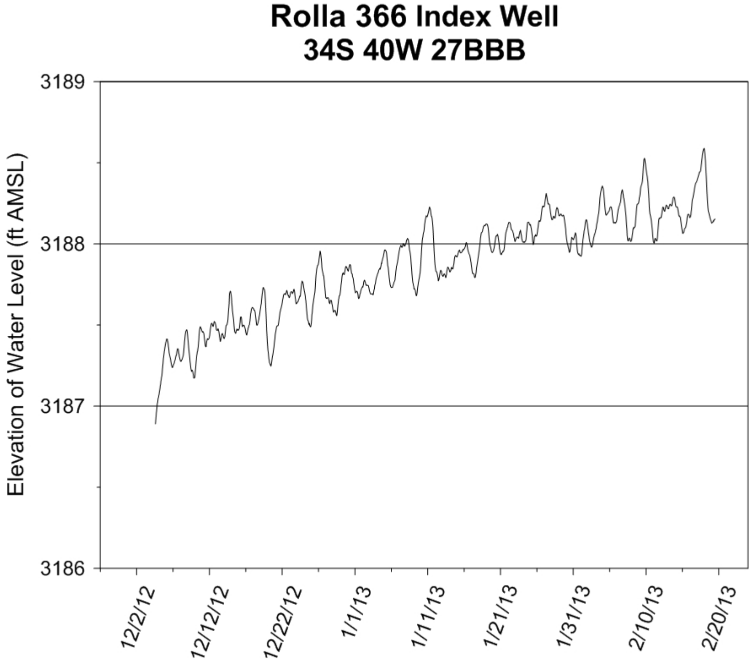


Figure 16b: Initial data set from well Rolla 366 (an elevation of 3188 ft corresponds to a depth to water [from land surface] of 186 ft).

Hugoton Site, Well Hugoton 495 – This is one of four wells at this site south of Hugoton in an area of relatively high groundwater use (Figure 17a; well construction information provided in Appendix A). The irrigation wells in the vicinity were pumping on December 4 when the sensor was installed; this pumping activity was undoubtedly driven by the same factors that resulted in similar pumping in the vicinity of the Haskell index well (Figure 3). The pumping ended on December 8 and recovery was still ongoing at the download for this report (February 19, 2013). The rapid rise in water level following cessation of pumping and the close to 40 ft of recovery over the monitoring period (Figure 17b) is similar to the behavior observed at the Haskell index well and indicates that the interval in which the well is screened acts as a confined aquifer. This interpretation was confirmed through an analysis using the BRF software developed earlier in this program (Bohling et al., 2011).

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 a figure in McMahon (2001) and the elevation of the ground surface was corrected to the value determined from a digital elevation model for the area. Figure 17c compares the estimated 1999–2000 data with data from the initial monitoring period. After the 1999 pumping season, the water levels recovered to an elevation of approximately 2970 ft. The recent monitoring data indicate that water levels in early 2013 are recovering to near 2930, a loss of about 40 ft in 13 years (>3 ft/yr).

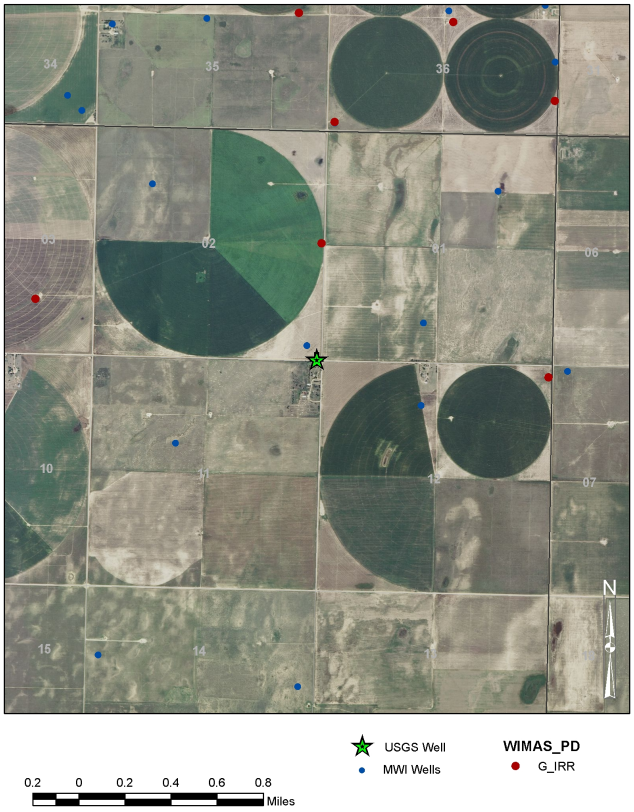


Figure 17a: Aerial view of Hugoton site (green star).

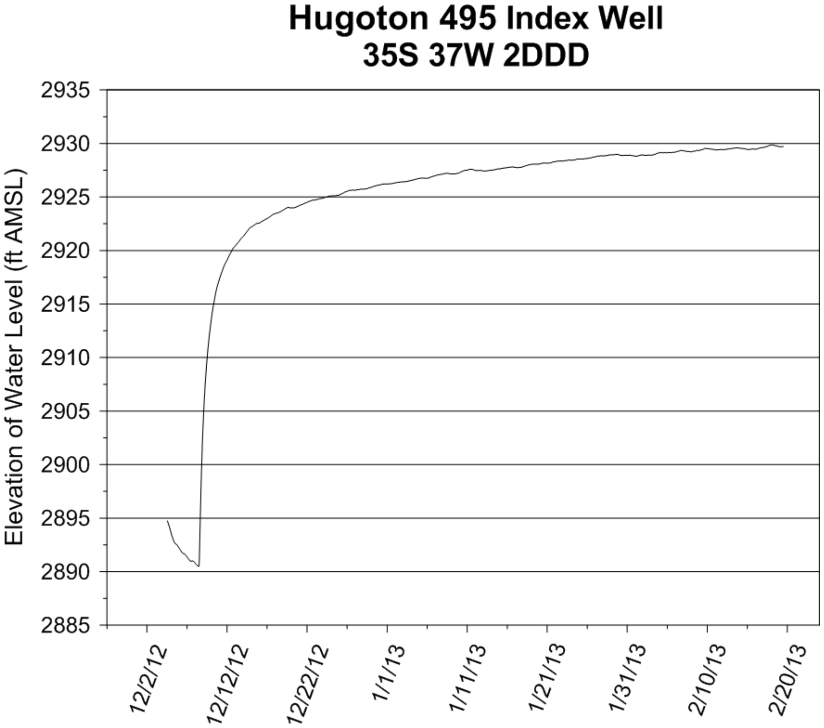


Figure 17b: Initial data set from well Hugoton 495 (an elevation of 2930 ft corresponds to a depth to water [from land surface] of 170 ft).

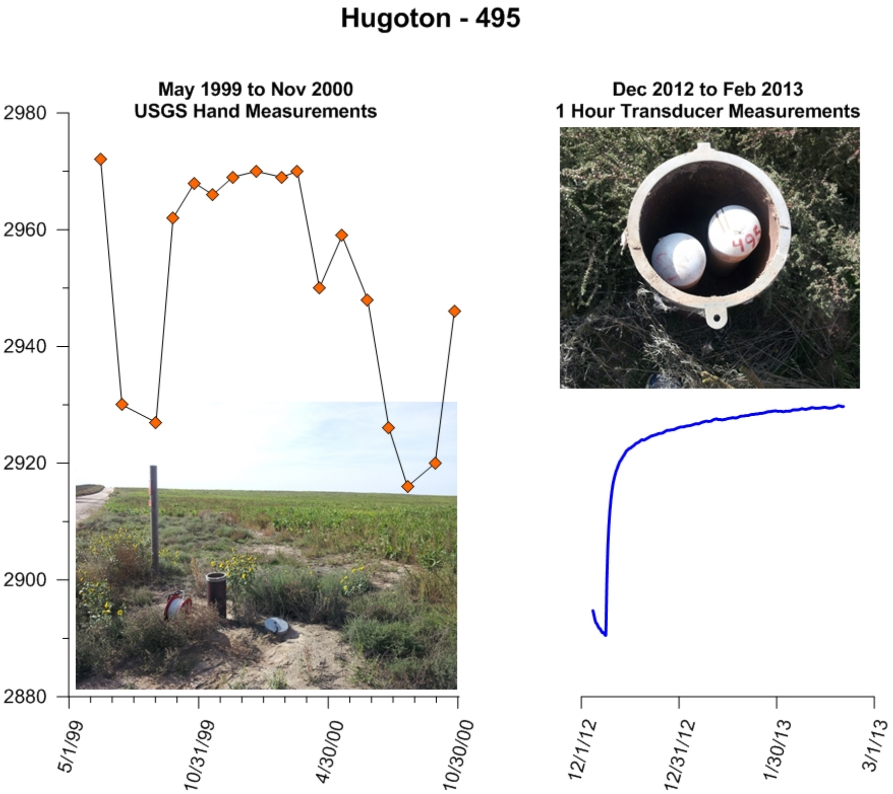


Figure 17c: Comparison of 1999–2000 manual water level measurements and the late 2012 to early 2013 continuous measurements from well Hugoton 495 with site photos.

Liberal Site, Well Liberal 436 – This is one of four wells at this site southeast of Liberal (Figure 18a; well construction information provided in Appendix A). The fields in the immediate vicinity of the site appear to be dryland farmed. Throughout the more than two months of initial monitoring (Figure 18b), the well was slowly recovering. The relatively small (less than 0.2 ft) amplitude fluctuations superimposed on the recovering water levels are an indication that the interval in which the well is screened is likely behaving as a confined aquifer. This interpretation was confirmed through an analysis using the BRF software developed earlier in this program (Bohling et al., 2011).

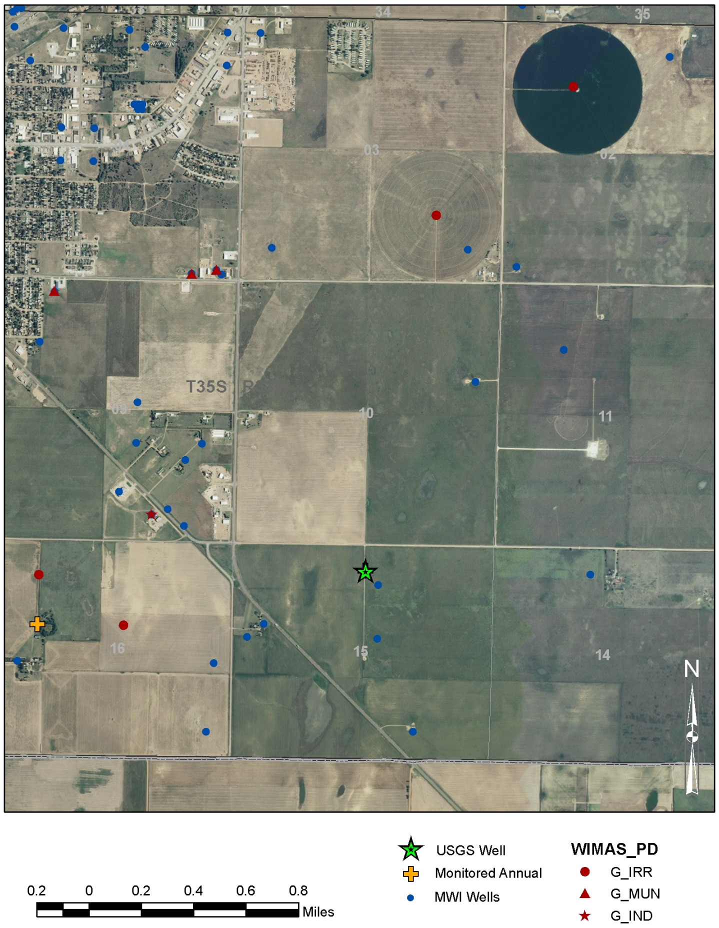


Figure 18a: Aerial view of Liberal site (green star).

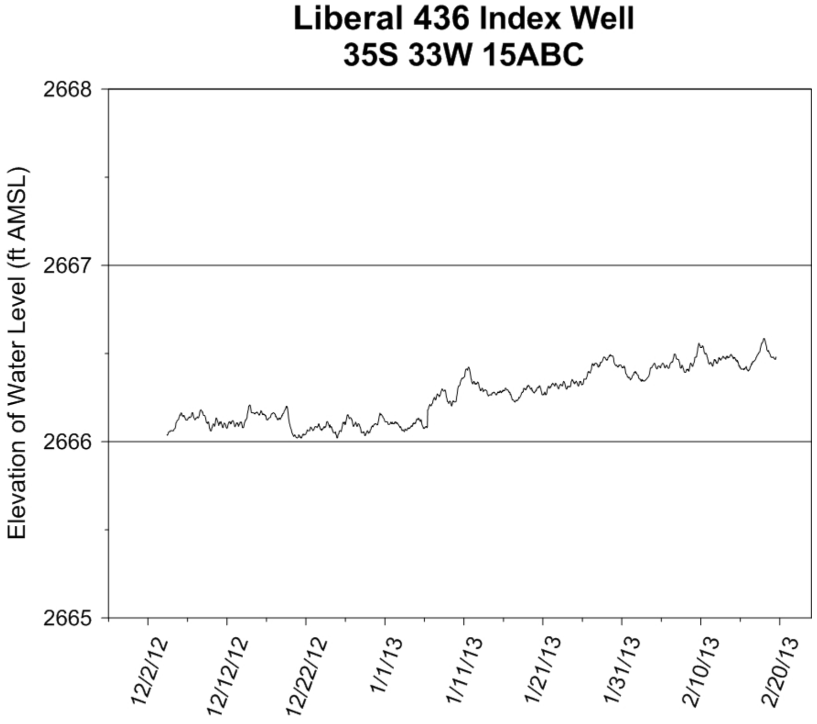


Figure 18b: Initial data set from well Liberal 436 (an elevation of 2666 ft corresponds to a depth to water [from land surface] of 155 ft).

Cimarron Site, Well Cimarron 210 – This is one of four wells at this site east of Liberal (Figure 19a; well construction information provided in Appendix A). As with the Liberal 436 well, the Cimarron 210 well recovered only a small amount during the more than two months of initial monitoring (Figure 19b). There are two quarter-section center pivot units in the fields adjacent to the site location. One of these wells may be responsible for the 0.25-ft drawdown associated with a January 27–29 pumping event. The relatively small (less than 0.2 ft) amplitude fluctuations superimposed on the recovering water levels are an indication that the interval in which the well is screened is likely behaving as a confined aquifer. However, an analysis using the BRF software developed earlier in this program (Bohling et al., 2011) found that the interval in which the well is screened is behaving as an unconfined aquifer.

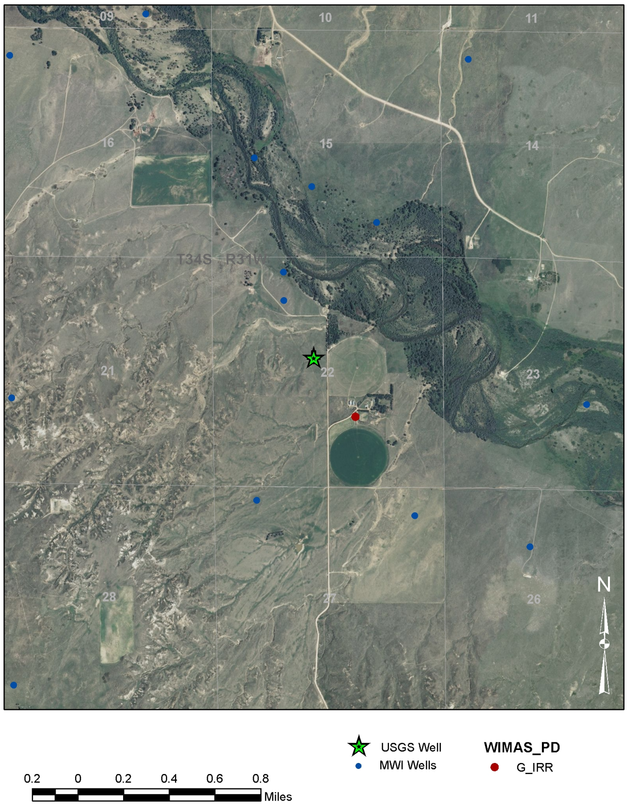


Figure 19a: Aerial view of Cimarron site (green star).

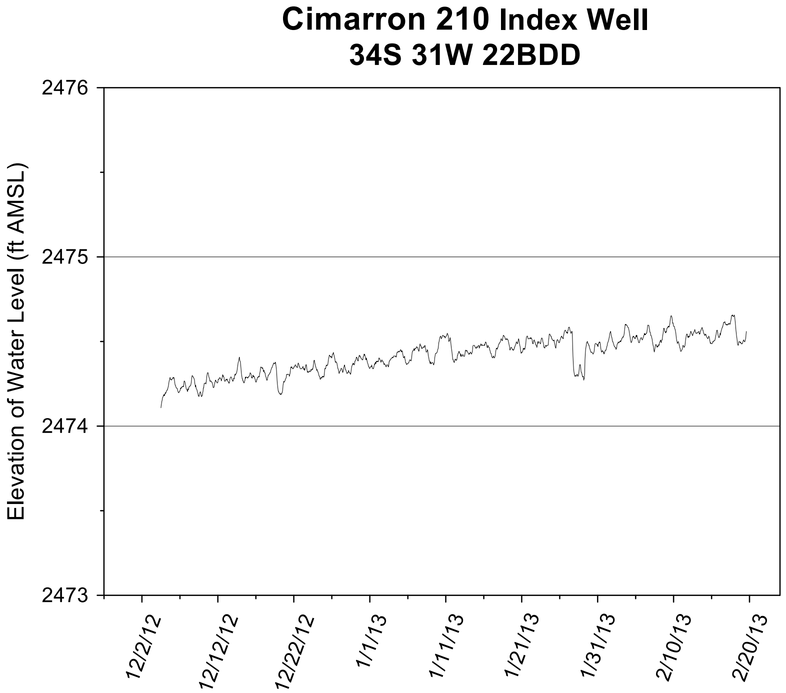


Figure 19b: Initial data set from well Cimarron 210 (an elevation of 2474 ft corresponds to a depth to water [from land surface] of 55 ft).

4.6. Sheridan-6 Subunit Wells

We are collaborating with GMD4 on the interpretation of the water-level data from the monitoring wells in the Sheridan-6 LEMA area. In 2012, we helped diagnose the source of anomalous fluctuations in the initial water-level data obtained from these monitoring wells. In 2013, we anticipate collaborating with GMD4 on the interpretation of the acquired data.

5. Relationship Between Water-Level Changes and Drought 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. Estimation of the degree of water-level change at both local and GMD scales based on such factors as amount of pumping and changes in climatic conditions, especially droughts, would be valuable for management purposes.

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 and the additional water needed for crop growth above that provided by precipitation. In addition to the amount, the timing of precipitation relative to crop stage is also important. If the number of irrigation wells and the average mix of crops remain relatively constant over a span of a decade, then the main factor controlling the annual pumping is the meteorological condition for that year.

5.2. Climatic Indices

Climatic indices provide a measure of how precipitation-related weather conditions deviate from historic norms, both in the direction of droughts and wet periods. Commonly used climatic indices for which data are readily available are the Palmer Drought Severity Index (PDSI), the Crop Moisture Index (CMI) (and related Palmer Z Index), and the Standardized Precipitation Index (SPI) (Hayes, National Drought Mitigation Center; Heim, 2002; Logan et al., 2010; National Climatic Data Center). The PDSI is a monthly index calculated using precipitation, soil moisture, potential evapotranspiration, and other factors important to plant growth (Palmer, 1965). The Palmer Z index is also a monthly index involving procedures related to those used to determine the PDSI, but it was developed to evaluate short-term moisture conditions in crop-producing areas; the PDSI, in comparison, was developed to monitor long-term wet and dry spells. The CMI is a weekly index based on an approach similar to the Palmer Z index computation (Palmer, 1968). The SPI was developed to quantify precipitation deficits and surpluses for a variety of time scales of relevance for water resources (McKee et al., 1993). The SPI values are normalized by long-term records for different climatic divisions.

5.3. Annual Winter Water-Level Measurements

Annual winter groundwater levels have been measured in a network of irrigation and other well types in western Kansas for many decades. Prior to 1997, the USGS and DWR measured the water levels. Starting in 1997, the KGS took over the cooperative measurements made by the USGS, with DWR continuing their measurements. The KGS then developed additional procedures for measurement acquisition and transfer of the data to a relational database (WIZARD). The KGS, at first in cooperation with the USGS and later solely, has historically reported and analyzed the data starting from the year 1996 (to reflect the difference between the winter 1996 and 1997 measurements).

Since 1996, the number of water-right permitted wells (mainly irrigation wells) in the three western GMDs has remained nearly constant. The large increase in the number of points of diversion (wells) occurred during the 1950s through the early 1980s; the increase from 1996 to 2012 was less than a couple percent of the current total. For example, the accumulated numbers of points of diversion in Thomas, Scott, and Haskell counties in 2013 were 1,112, 1,340, and 1,597, respectively. The numbers of points of diversion that were added after 1996 were 40, 25, and 0 for these three counties, respectively. Thus, for the period 1996–2012, the main driver for water-level changes in the HPA in western Kansas was the amount of pumping from each well.

5.3.1. Water-Level Change in the Groundwater Management Districts

The mean annual year-to-year changes in winter water-levels during 1996–2012 for the three western GMDs are displayed in Figure 20. 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 (GMD 4 to 1 to 3).

5.3.2. Water-Level Change in the Index Wells

Winter water levels have been measured by steel tape in the index wells since their installation in addition to the continuous recording of water levels by transducers in the wells (see Tables 3, 5, and 7). Figure 21 shows the annual year-to-year water-level changes for both the tape and transducer values for 2008–2012 (values unadjusted for barometric pressure), along with the mean water-level changes for the GMDs during these same years. The annual changes in the Scott County well have been within a relatively narrow range (between -0.6 and -1.5 ft; a total absolute range of about 0.9 ft), whereas the changes have been appreciably larger at the Thomas County well (between +1.6 and -2.5 ft; a total absolute range of about 4.1 ft), and even greater at the Haskell County well (between -4.0 and -10.1 ft; a total absolute range of about 6.1 ft).

The range in the annual water-level declines for the Scott County index well is only a little smaller than that for the mean annual water-level change for GMD 1 during 2008–2012. In contrast, the ranges in the annual water-level changes for the Thomas and Haskell index wells are substantially greater than the mean water-level changes for GMD 4 and 3, respectively. Although the patterns in the annual water-level changes for the three index wells are generally dissimilar, the increase and decrease patterns for the Thomas and Haskell index wells are somewhat similar to those for the GMD in which they are located.

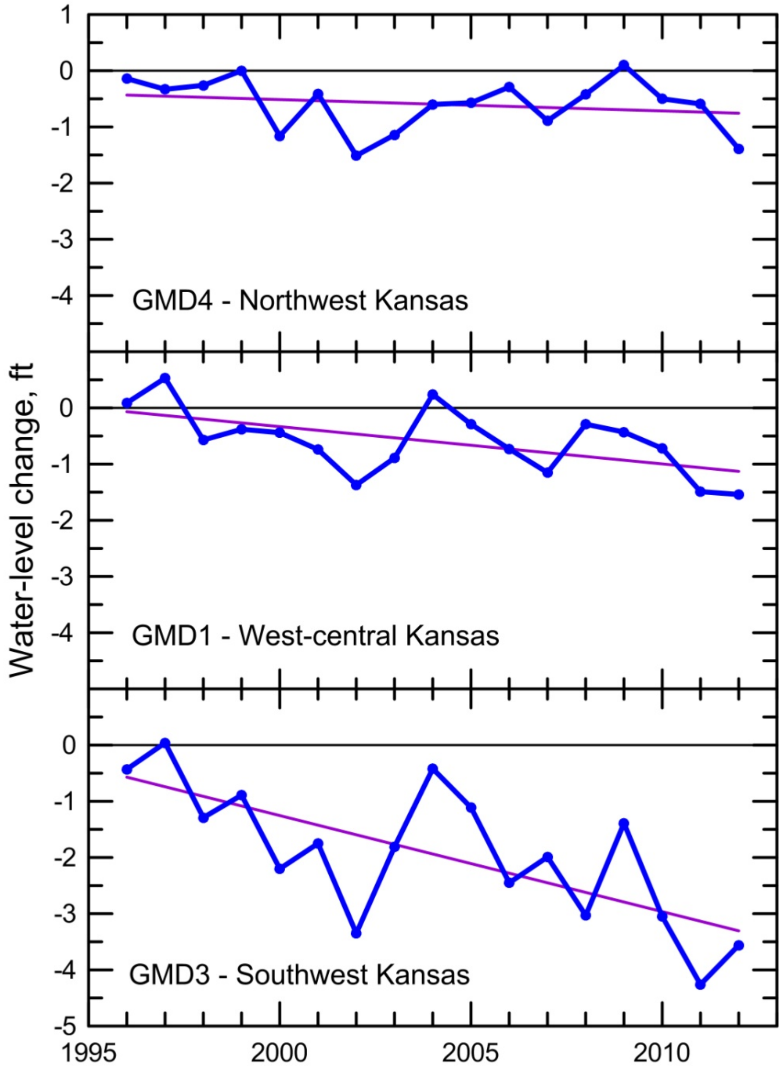


Figure 20: Mean annual water-level change in the HPA in the three GMDs in western Kansas during 1996–2012. The blue lines and points represent the mean annual water-level change and the purple line is the linear regression for the data. The zero line is the division between rises and declines.

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

5.4.1. 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. Plots of mean annual drought indices for climatic divisions 1, 4, and 7 versus the mean annual change in winter water levels for GMDs 4, 1, and 3, respectively, during 1996–2012 were prepared and the correlation coefficients (coefficient of determination, R^2) computed. The correlations with the water-level changes were greater for the mean annual Palmer Z index and the 12-month SPI for December (Figures 22 and 23) than for the mean annual PDSI (Table 9). Overall, the 12-month SPI for December gave the best correlations for the three GMDs, although the differences with the Palmer Z index for GMDs 3 and 4 were very small. The correlations for the GMD1 water-level change and climatic indices (Figures 22b and 23b) were not nearly as good as for GMDs 3 and 4 (Figures 22 and 23, a and c), no matter which climatic index was considered.

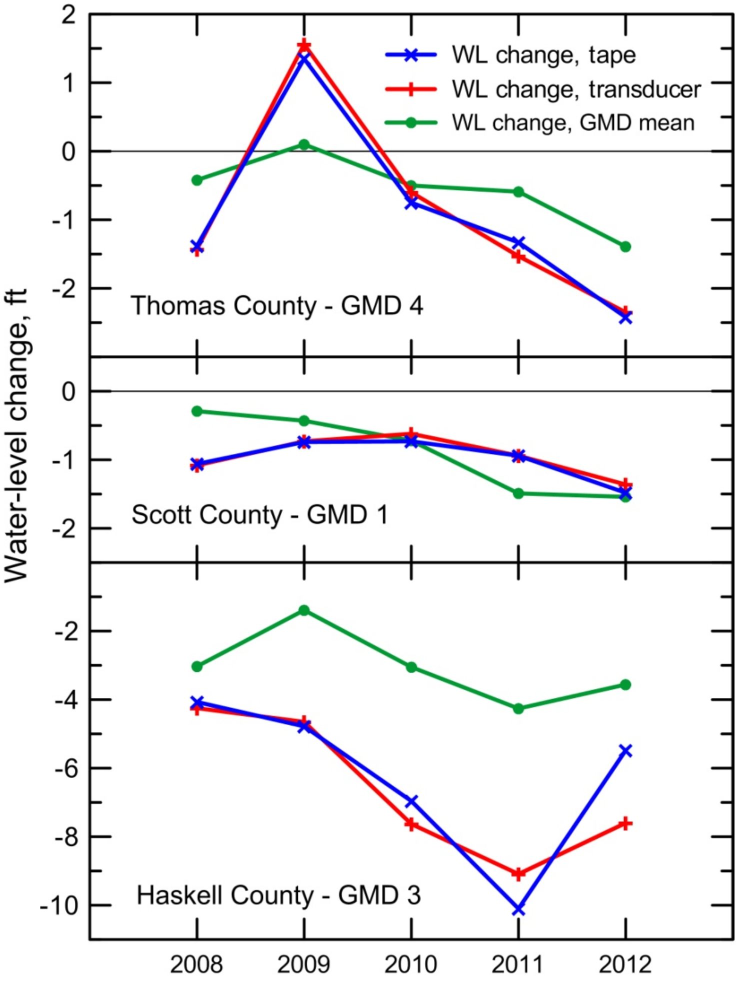


Figure 21: Annual winter water-level changes in the three index wells in the HPA and the mean annual changes in the three GMDs in western Kansas in which they are located. The zero line is the division between rises and declines.

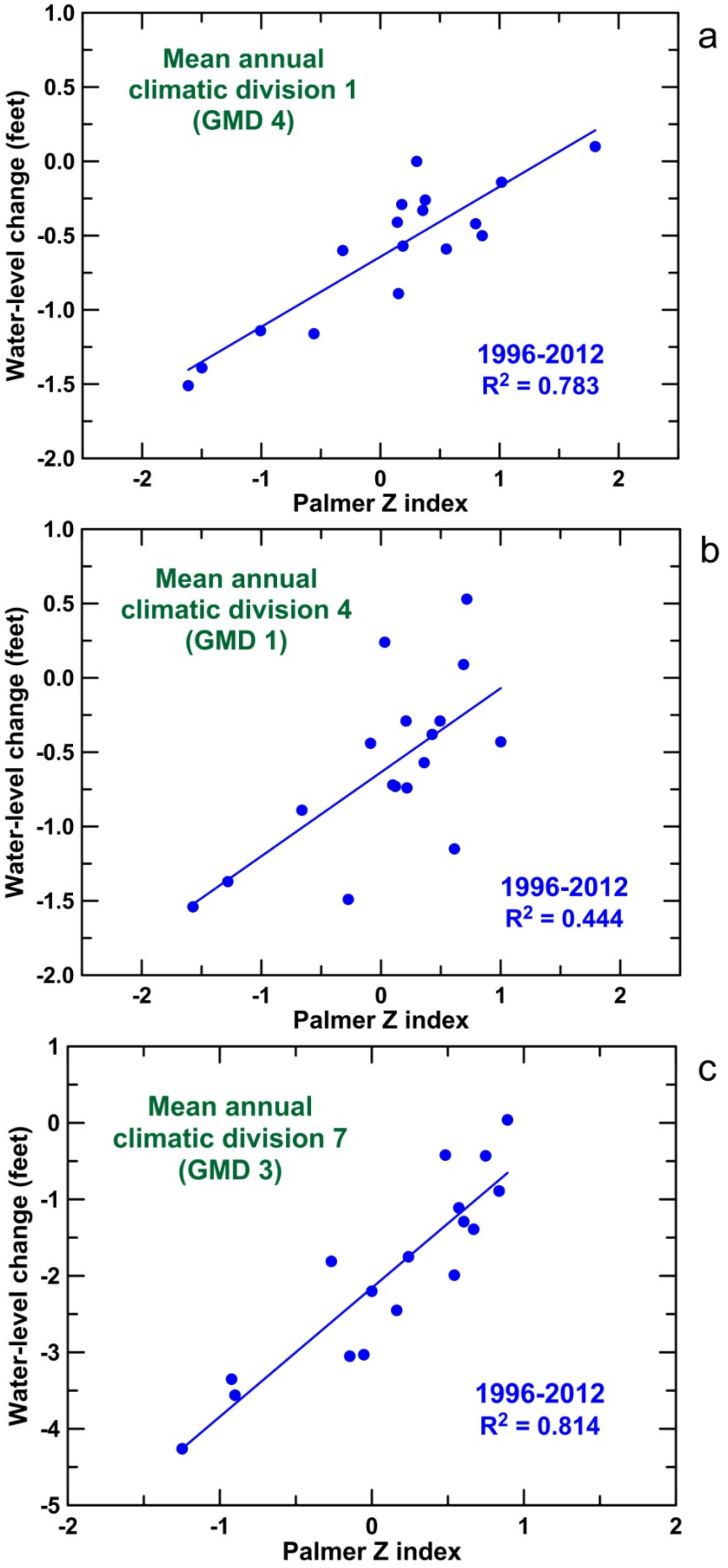


Figure 22: Correlation of mean annual winter water-level change during 1996–2012 for the three western GMDs in the HPA with the mean annual Palmer Z index for the appropriate climatic division.

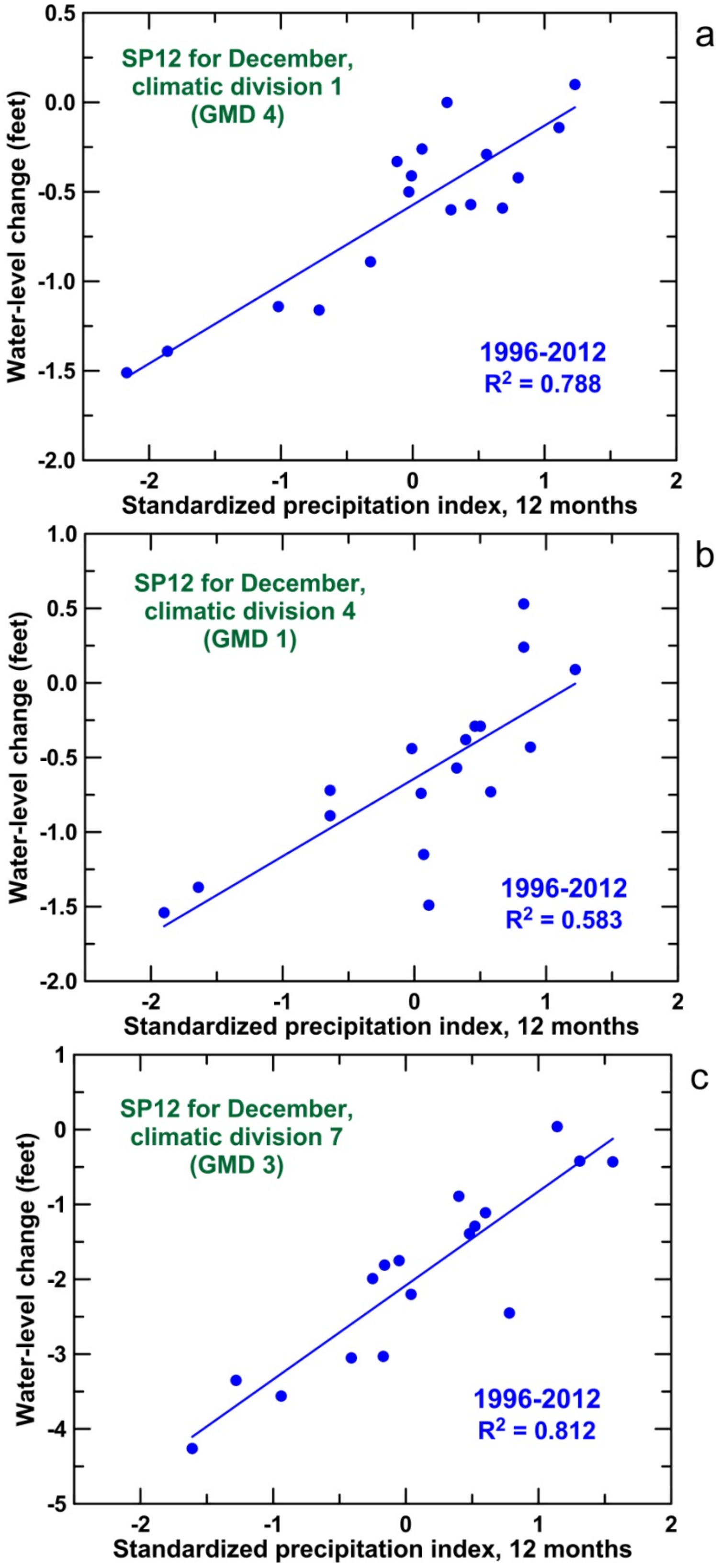


Figure 23: Correlation of mean annual winter water-level change during 1996–2012 for the three western GMDs in the HPA with the 12-month SPI for the appropriate climatic division.

Table 9: Coefficients of determination (R^2) for the correlation of mean annual winter water-level changes for GMDs 4, 1, and 3 with the mean annual climatic indices for climatic divisions 1, 4, and 7 during 1996–2012.

	GMD and Climatic Division		
Climatic index	GMD4 ΔWL – Div. 1	GMD1 ΔWL – Div. 4	GMD3 ΔWL – Div. 7
PDSI	0.479^{**}	0.212^{*}	0.651^{***}
Palmer Z	0.783^{***}	0.444^{**}	0.814^{***}
SPI-12, December	0.788^{***}	0.583^{***}	0.812^{***}

* Significant at P = 0.05
** Significant at P= 0.01
*** Significant at P = 0.001

Irrigation pumping is expected to be tied more significantly to growing season conditions than mean annual conditions. Mean climatic indices for different months or monthly periods were computed for the PDSI and Palmer Z index and used, along with the reported 6- and 9-month SPI values for different months, for determining whether better correlations with the mean annual water-level changes for the three GMDs exist. The results indicated that correlations with the mean of different month spans for the PDSI substantially improved over those with the mean annual PDSI for all three GMDs (Table 10). All of the correlations are statistically highly significant. Although the optimum correlation of the water-level change with PDSI is about the same as that for the Palmer Z index and SPI for GMD3, the optimum PDSI correlations are not as good as for the other two indices for GMDs 1 and 4. As with the annual drought indices, the optimum correlations were not nearly as good for GMD1 as for GMDs 3 and 4. Plots for the optimum correlations of mean annual water-level changes with the Palmer Z index and SPI, which overall give the highest R^2 values, are displayed in Figures 24 and 25.

Table 10: Optimum coefficients of determination (R^2) for the correlation of mean annual water-level changes for GMDs 4, 1, and 3 with climatic indices for climatic divisions 1, 4, and 7 during 1996–2012. All of the R^2 values are significant at the P = 0.001 level except for that for the PDSI division 4 versus GMD1 water-level change, which is significant at the P = 0.01 level.

Climatic index	GMD and Climatic Division	R^2
PDSI, August	GMD4 ΔWL – Div. 1	0.739
Palmer Z, mean Jun.–Sep.	GMD4 ΔWL – Div. 1	0.822
SPI, 12-month, December	GMD4 ΔWL – Div. 1	0.788
PDSI, mean Aug.–Nov.	GMD1 ΔWL – Div. 4	0.463
Palmer Z, mean Jun.–Nov.	GMD1 ΔWL – Div. 4	0.656
SPI, 9-month, October	GMD1 ΔWL – Div. 4	0.654
PDSI, mean Jun.–Dec.	GMD3 ΔWL – Div. 7	0.833
Palmer Z, mean Apr.–Nov.	GMD3 ΔWL – Div. 7	0.830
SPI, 9-month, October	GMD3 ΔWL – Div. 7	0.828

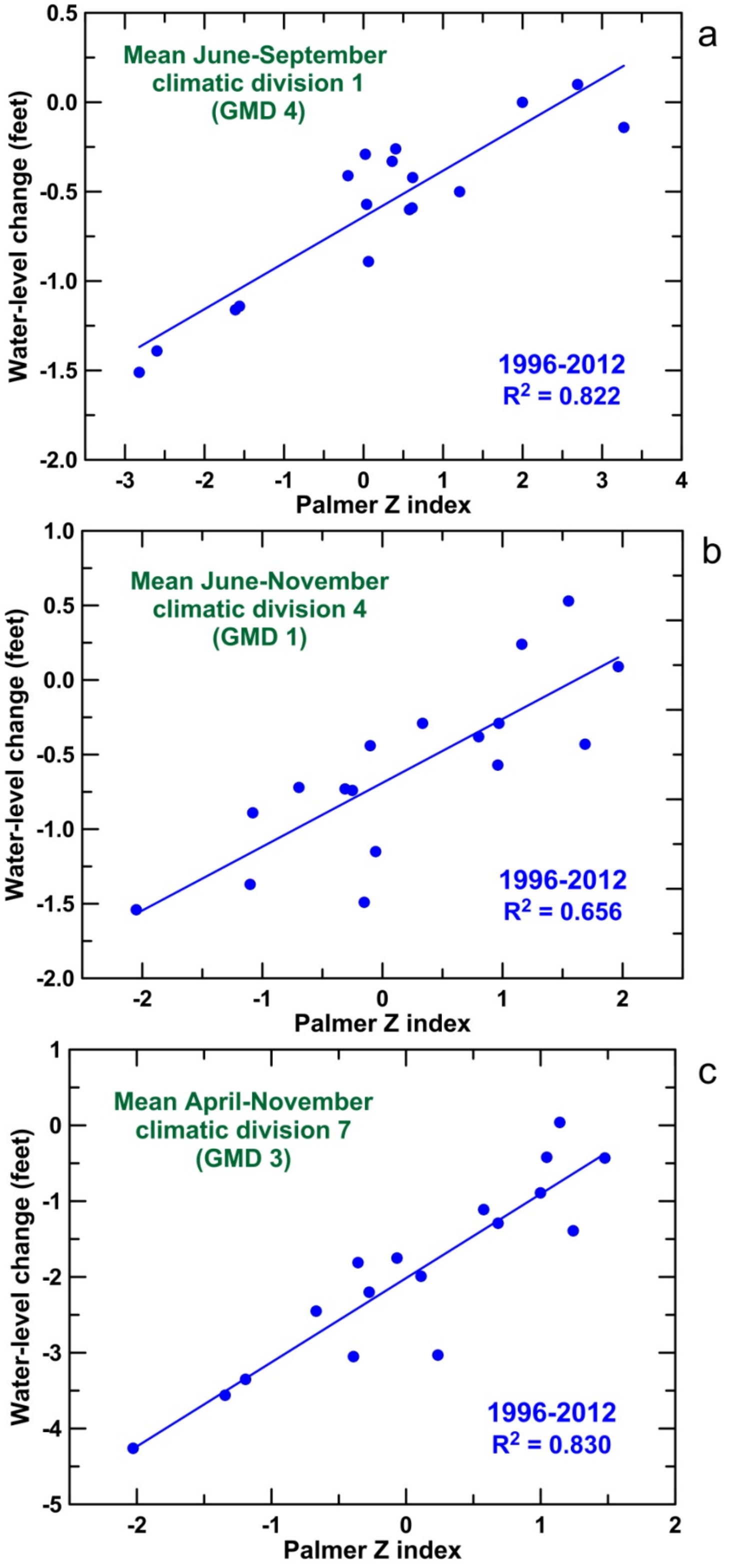


Figure 24: Correlation of mean annual winter water-level change during 1996–2012 in the three western GMDs in the HPA with the period of Palmer Z index values giving the greatest correlation. Period for Palmer Z index changes among plots.

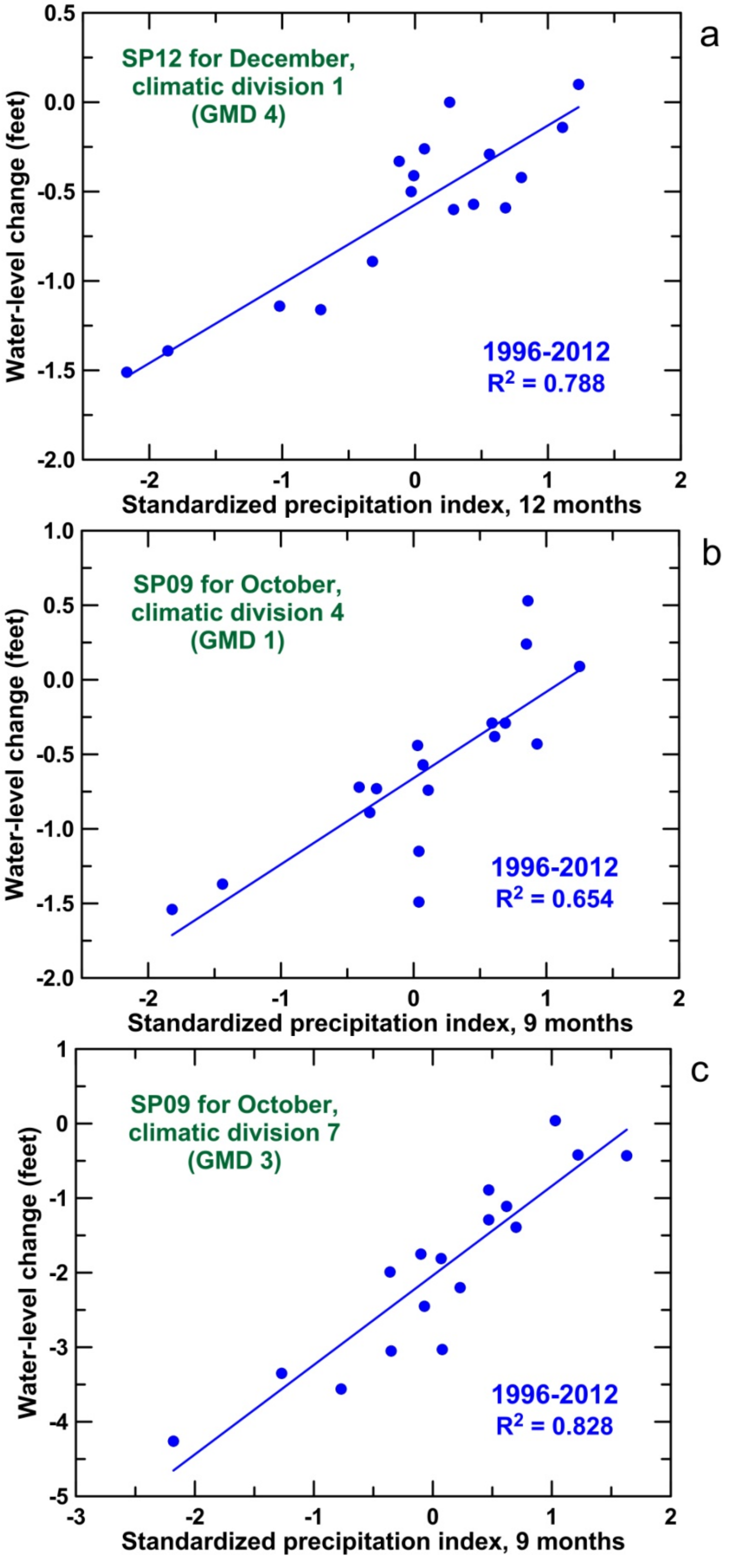


Figure 25: Correlation of mean annual winter water-level change during 1996–2012 in the three western GMDs in the HPA with the period of SPI values giving the greatest correlation. SPI period changes between plot for GMD1 and plots for GMDs 3 and 4.

5.4.2. Correlations for the Index Wells

The particular periods for the Palmer Z index and the SPI that give the optimum R^2 in the climatic index and water-level change correlations were used to assess the relationship of the climatic indices with the annual water-level changes for the tape and transducer measurements (uncorrected for atmospheric pressure) at the three index wells. Plots of the climatic indices versus water-level changes are given in Figures 26–28 and the R^2 values are listed in Table 11. The correlations are significant at the $P = 0.05$ level for the relationship between the annual water-level change at the Thomas County well (both tape and transducer measurements) and the mean Palmer Z index for June to September. For the mean annual water-level change at the Haskell County well, the correlations are significant at the $P = 0.05$ level for the relationship between the transducer measurement and the mean Palmer Z index for April–November, and both the tape and transducer measurements and the 9-month SPI for October. None of the correlations for the Scott County index well are statistically significant.

Table 11: Coefficients of determination (R^2) for the correlation of mean annual water-level changes at the three index wells with climatic indices for climatic divisions 1, 4, and 7 during 2008–2012. The periods for the climatic indices are those that give optimum R^2 for the correlations with the mean annual water-level changes for GMDs 1, 3, and 4.

Climatic index	Index well, WL Measurement Type, and Climatic Division	R^2
Palmer Z, mean Jun.–Sep.	Thomas County, tape – Div. 1	0.80^*
Palmer Z, mean Jun.–Sep.	Thomas County, transducer – Div. 1	0.75^*
SPI, 12-month, December	Thomas County, tape – Div. 1	0.52
SPI, 12-month, December.	Thomas County, transducer – Div. 1	0.44
Palmer Z, mean Jun.–Nov.	Scott County, tape – Div. 4	0.43
Palmer Z, mean Jun.–Nov.	Scott County, transducer – Div. 4	0.25
SPI, 9-month, October	Scott County, tape – Div. 4	0.53
SPI, 9-month, October	Scott County, transducer – Div. 4	0.33
Palmer Z, mean Apr.–Nov.	Haskell County, tape – Div. 7	$0.58^\#$
Palmer Z, mean Apr.–Nov.	Haskell County, transducer – Div. 7	0.80^*
SPI, 9-month, October	Haskell County, tape – Div. 7	0.79^*
SPI, 9-month, October	Haskell County, transducer – Div. 7	0.78^*

$^\#$ Significant at $P = 0.1$

* Significant at $P = 0.05$

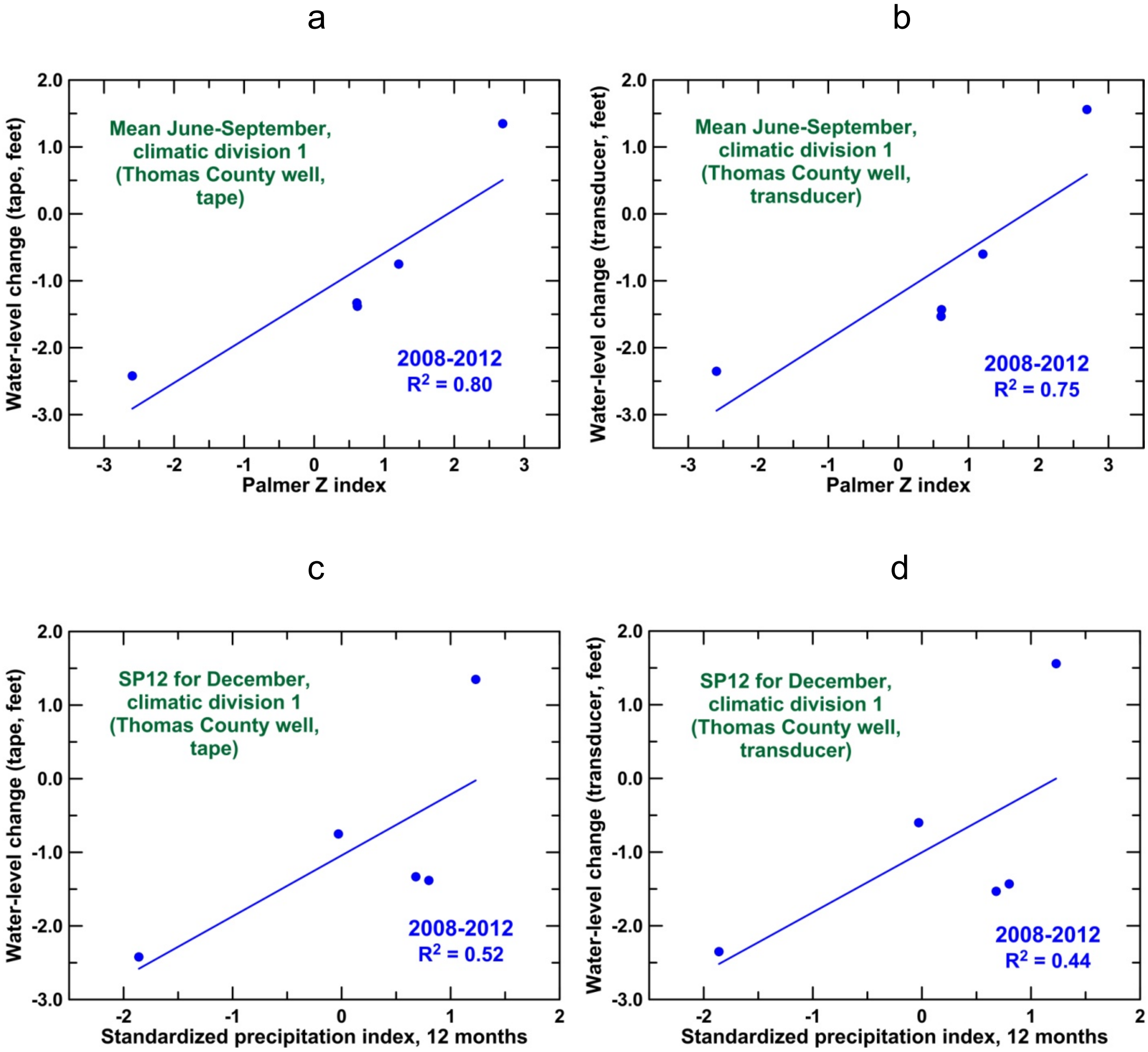


Figure 26: Correlation of winter water-level change during 2008–2012 at the Thomas County index well with the periods of Palmer Z index (a and b) and SPI (c and d) that give the greatest R^2 for climatic division 1.

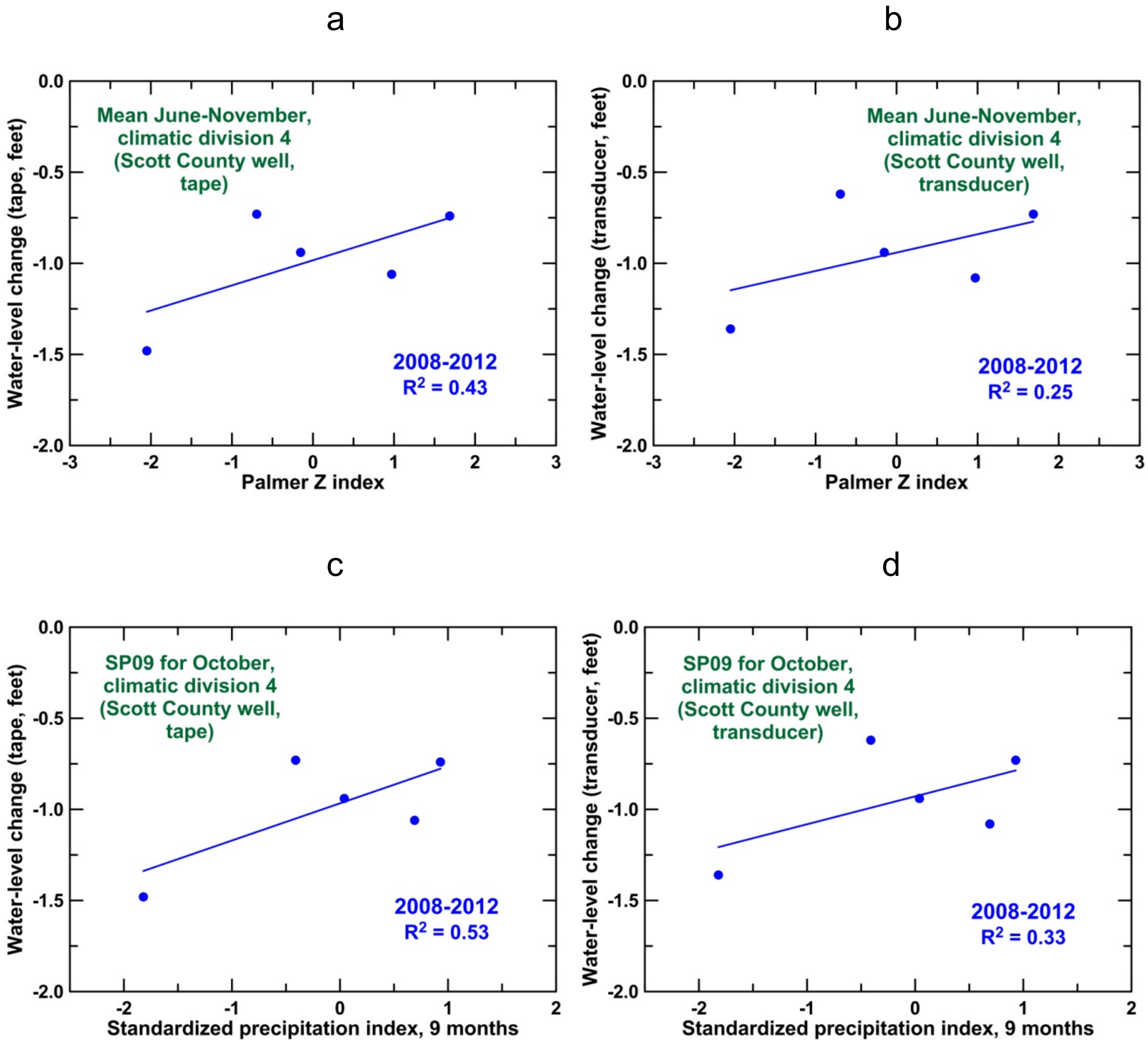


Figure 27: Correlation of winter water-level change during 2008–2012 at the Scott County index well with the periods of Palmer Z index (a and b) and SPI (c and d) that give the greatest R^2 for climatic division 4.

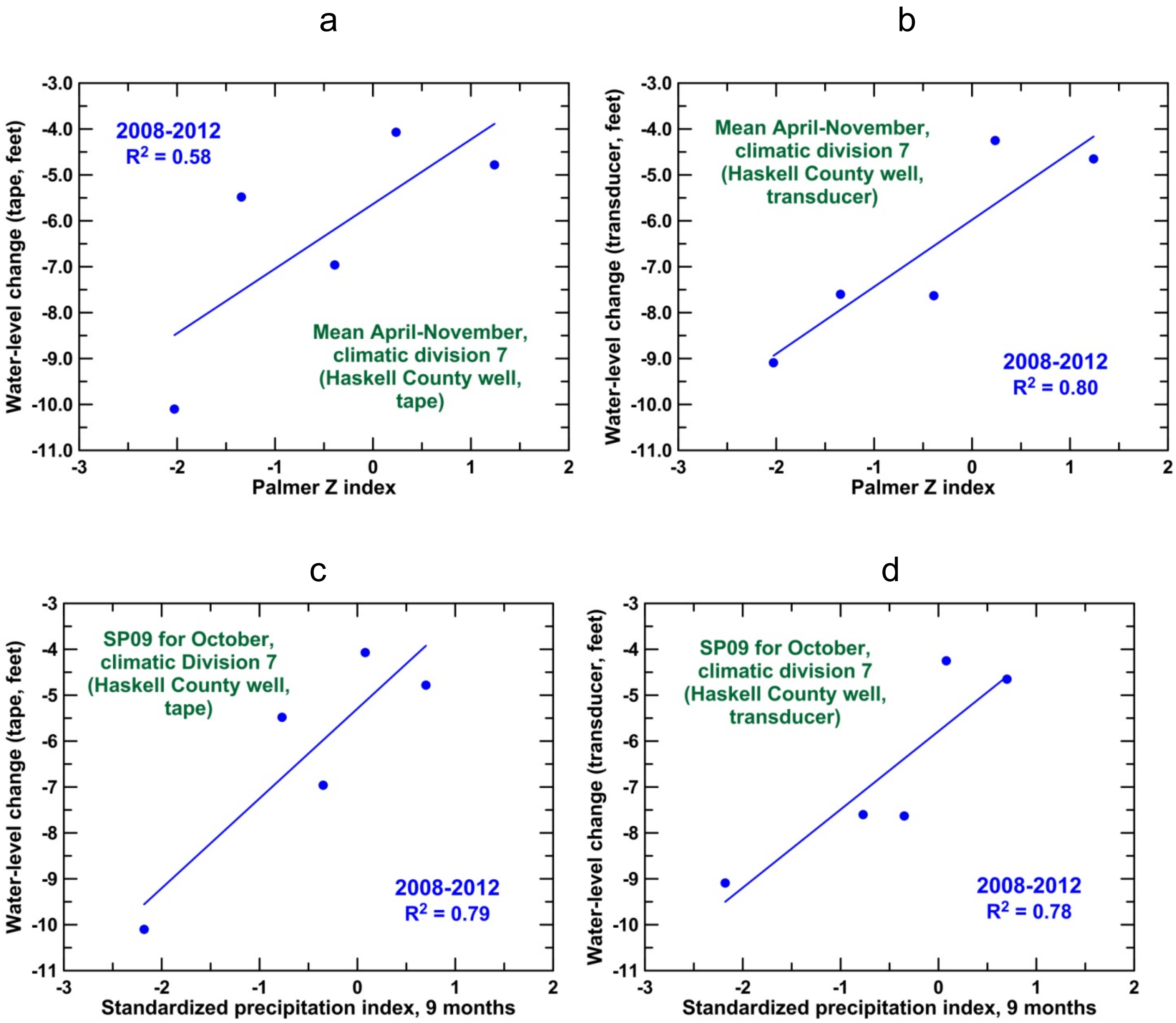


Figure 28: Correlation of winter water-level change during 2008–2012 at the Haskell County index well with the periods of Palmer Z index (a and b) and SPI (c and d) that give the greatest R^2 for climatic division 7.

As a whole, the relative nature of the water-level changes and their relationships with climatic indices are similar for the index wells and the GMD-wide area in which they are located. The correlations for both GMD 1 and the Scott County index well are appreciably smaller than for the other two GMDs and index wells. This suggests that mechanisms other than just climatic variations are important in controlling irrigation pumping and water-level declines in GMD 1. One possible mechanism is the limitation in the amount of groundwater that can be pumped from the aquifer because the saturated thickness in a substantial part of GMD1 is no longer adequate for sustaining pumping at typical rates needed for irrigation. In contrast, most of the variations in the annual water-level changes at both the district-wide and index well scale in GMDs 3 and 4 can be explained by selected climatic indices. Thus, even though the hydrogeology at each index well may differ from that at many of the irrigation wells in the districts in which they are located, some characteristics of the annual water-level variations at the index wells and their relationship to climatic indices appear to be similar to the district-wide characteristics, indicating that the index wells do indeed act, in some respects, as representative (index) wells for their GMDs.

5.5. Prediction of Annual Water-Level Change for Continued Drought

The summers of 2011 and 2012 were particularly dry in western Kansas. It is unknown whether these drought conditions will continue into the future. The 1930s and 1950s include the longest and most severe years of recorded drought in Kansas based on weather records that extend back to 1895. Figures 29 and 30 compare the Palmer Z and SPI climatic indices, respectively, for 2009–2012 with those for 1950–1958, using the periods of the indices that give the maximum correlation with the mean annual water-level changes for GMDs 1, 3, and 4 for 1996–2012 (Table 10). Tables 12 and 13 list the climatic descriptions for the 1950s drought, which extended from 1952 to 1956, based on the climatic indices and periods used for Figures 29 and 30. The last year of the 1950s drought period (1956) contained the most severe drought conditions. In general, the SPI drought characterization was more severe than that for the Palmer Z index for the 1950s drought based on the periods that give the optimum correlations with annual water-level changes in the GMDs during 1996–2012.

Table 12: Drought conditions during the 1950s for climatic divisions of western Kansas based on the periods of the Palmer Z index that give the highest correlations with mean annual water-level changes in GMDs 1, 3, and 4 during 1996–2012.

	GMD and climatic index period		
Year	GMD 4, mean Jun.–Sep.	GMD 1, mean Jun.–Nov.	GMD 3, mean Apr.–Nov.
1952	Moderate drought	Moderate drought	Moderate drought
1953	Transition from no to moderate drought	Normal range	Normal range
1954	Severe drought	Moderate drought	Moderate drought
1955	Severe drought	Moderate drought	Normal range
1956	Extreme drought	Severe drought	Severe drought

Table 13: Drought conditions during the 1950s for climatic divisions of western Kansas based on the periods of the SPI that give the highest correlations with mean annual water-level changes in GMDs 1, 3, and 4 during 1996–2012.

	GMD and climatic index period		
Year	GMD 4, 12-month for Dec.	GMD 1, 9-month for Oct.	GMD 3, 9-month for Oct.
1952	Severely dry	Severely dry	Severely dry
1953	Near normal	Moderately dry	Moderately dry
1954	Severely dry	Moderately dry	Moderately dry
1955	Severely dry	Near normal	Near normal
1956	Extremely dry	Extremely dry	Extremely dry

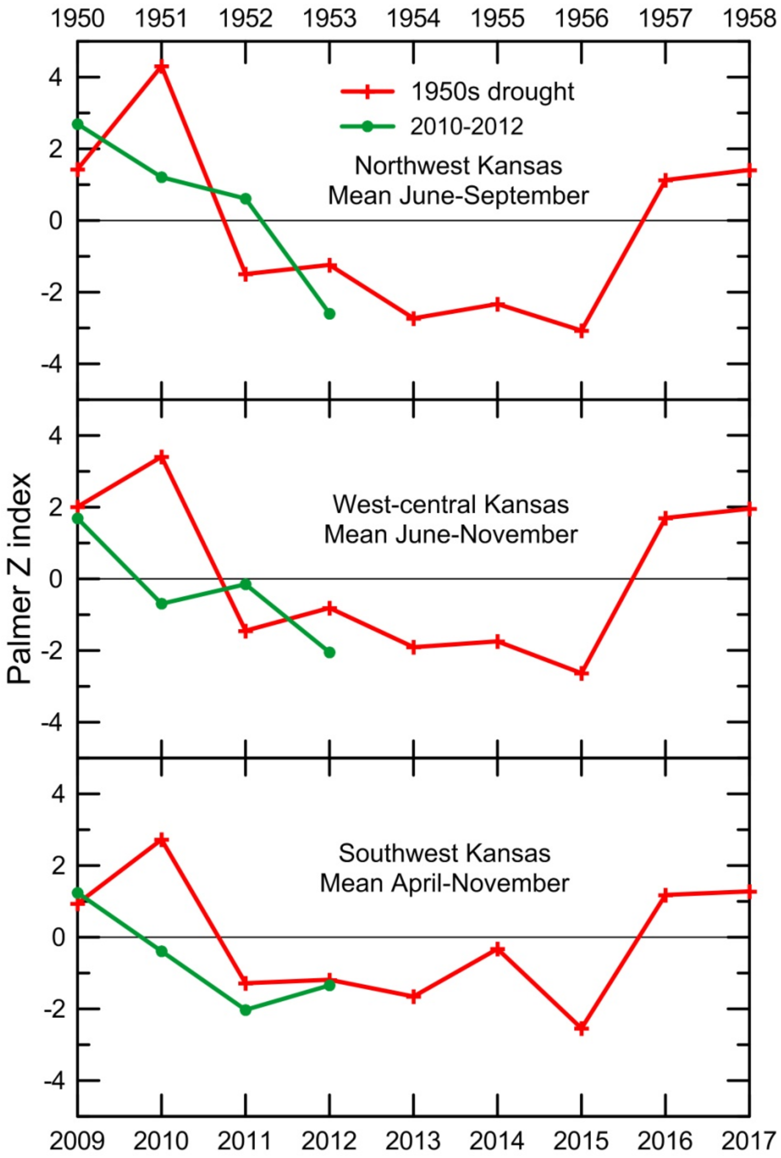


Figure 29: Comparison of Palmer Z index values for 2009–2012 with those for 1950–1958, using the periods of the index that give the maximum correlation with the mean annual winter water-level changes for GMDs 1, 3, and 4 for 1996–2012 (Table 10).

The values for the Palmer Z index and SPI used to create the 1950s drought index values in Figures 29 and 30 could be used to predict mean annual water-level declines for each of the three western GMDs and also for the index wells based on the regression equations for the climatic index and water-level decline plots. If such a procedure were applied to a drought that extended beyond 2012 to mimic the 1954–1956 portion of the 1950s drought, total water-level declines of 4.0 ft, 4.8 ft, and 11.1 ft would occur for 2013–2015 for GMD 4, GMD 1, and GMD3, respectively, based on the Palmer Z index. For the SPI values, the total water-level declines would be 4.2 ft, 4.9 ft, and 10.6 ft for GMD 4, GMD 1, and GMD3, respectively. The assumption of 1956 conditions for 2015 alone would give annual water-level declines of 1.4 ft, 1.8 ft, and 4.8 ft based on the Palmer Z index, and declines of 1.6 ft, 2.3 ft, and 5.0 ft based on the SPI for GMD 4, GMD 1, and GMD3, respectively. These inferred declines would be about the same experienced during 2012 in GMD4 (the maximum observed during 1996–2012), and would be greater than observed for any year during 1996–2012 for GMDs 1 and 3.

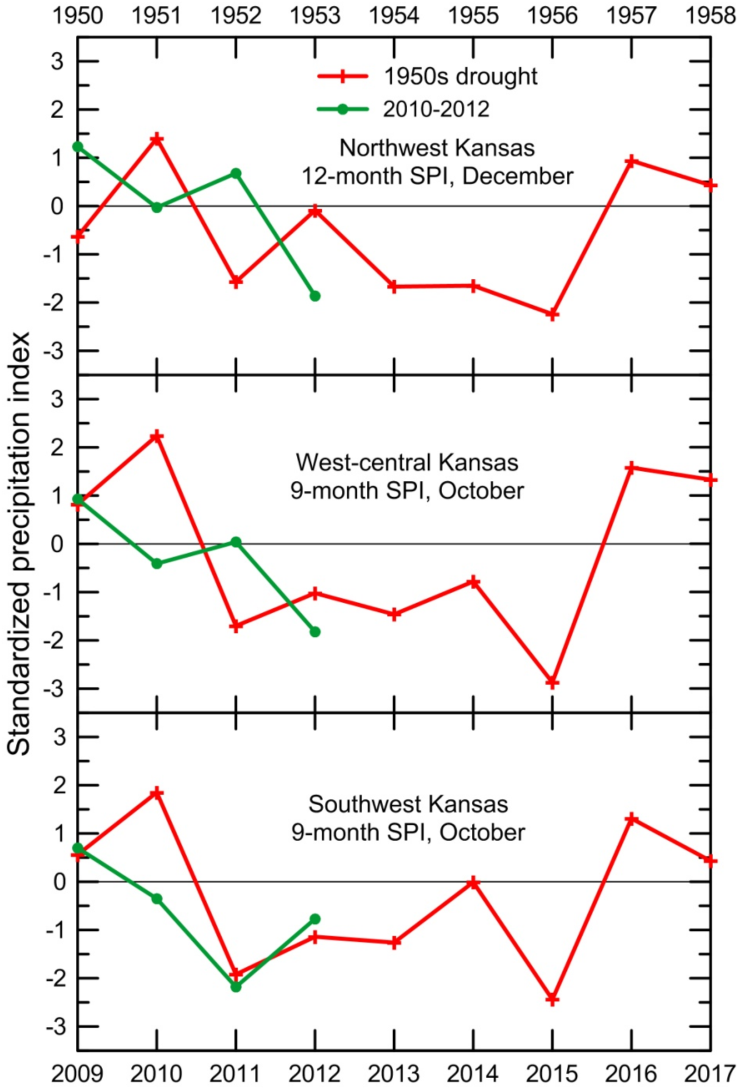


Figure 30: Comparison of SPI values for 2009–2012 with those for 1950–1958, using the periods of the index that give the maximum correlation with the mean annual winter water-level changes for GMDs 1, 3, and 4 for 1996–2012 (Table 10).

Similarly, if the regression equations with the highest R^2 for the association of the annual water-level changes at the index wells with climatic indices (Table 11) were used to estimate water-level changes, the total declines for continued drought during 2013–2015 that mimicked 1954–1956 would be approximately 9.0 ft, 3.9 ft, and 24.6 ft for the Thomas, Scott, and Haskell counties index wells, respectively. The assumption of 1956 conditions for 2015 alone would give water-level declines of 3.2 ft, 1.6 ft, and 9.7 ft for the Thomas, Scott, and Haskell counties index wells, respectively. Although the water-level declines inferred for 1954–1956 conditions would represent substantial decreases in the saturated thickness at the Thomas and Scott counties locations, the aquifer thickness would still be great enough to allow irrigation pumping. However, if climatic conditions during 2013–2015 are similar to those during 1954-1956, the total estimated decline at the Haskell County site would be so great that expected pumping rates would be substantially smaller than sustained in the past.

6. Impact of Barometric Pressure Fluctuations on Annual Water-Level Measurements

As noted in previous reports (Butler et al., 2012; Buddemeier et al., 2010), the index well records demonstrate that barometric pressure variations can have a significant impact on water levels in certain settings within the HPA. This will be particularly true for wells screened in unconfined intervals with a deep water table, as is the case for the Thomas County index well. The barometric efficiency of this well is close to 1, meaning that the barometrically induced water-level fluctuations are comparable in magnitude to the temporal variations in barometric pressure, variations that can be on the order of a foot when expressed in terms of an equivalent height of water. Consequently, barometrically induced water-level fluctuations in a well could have a significant impact on the assessment of aquifer declines, since the barometrically induced fluctuations could be comparable in magnitude to water-level changes due to the actual loss or gain of water in the aquifer over a year. This section examines the expected effect of barometric pressure variations on the assessment of water-level changes between the 2012 and 2013 annual measurement campaigns, using a barometric response function computed for the Thomas County index well as representative of a worst-case scenario. Wells screened in unconfined intervals with shallower water tables (e.g., the Scott County index well) or in confined intervals (e.g., the Haskell County index well) are expected to exhibit smaller barometric responses.

6.1. Assessment of Spatial Variations in Barometric Pressure

Two pieces of information are required to compute the expected water-level responses to barometric pressure variations at a well: 1) a barometric pressure record representative of conditions at the well location and 2) a barometric response function describing the relationship between the water level in the well at a particular time and the sequence of barometric pressure values over some preceding time frame (Butler et al., 2011). The first requirement leads to consideration of spatial variation in barometric pressures, since one needs to know how close a weather station should be to a well in order for its barometric pressure record to be representative of conditions at the well location or, alternatively, to assess the spatial density of weather stations required to accurately interpolate barometric pressures to the well location. The following discussion will show that, as long as time frames of a few days or more are considered, the barometric pressure record is essentially the same over the entire Kansas High Plains aquifer region, meaning that barometric pressure data from a single location or a few widely spaced locations can be considered reasonably representative of the entire region.

Buddemeier et al. (2010) show that the barometric pressure readings at transducers inside the well casings of the three index wells agree extremely well when expressed as deviations from their respective mean values (see Figure 3.2 in that report). Here we examine barometric pressure records from more widely separated weather stations, essentially encompassing the Kansas High Plains region, and reach essentially the same conclusion.

Figure 31 shows the locations of 235 weather stations in the Kansas High Plains region whose data can be obtained by querying the Weather Underground web site, www.wunderground.com. These data include barometric pressure measurements, generally given in inches of mercury.

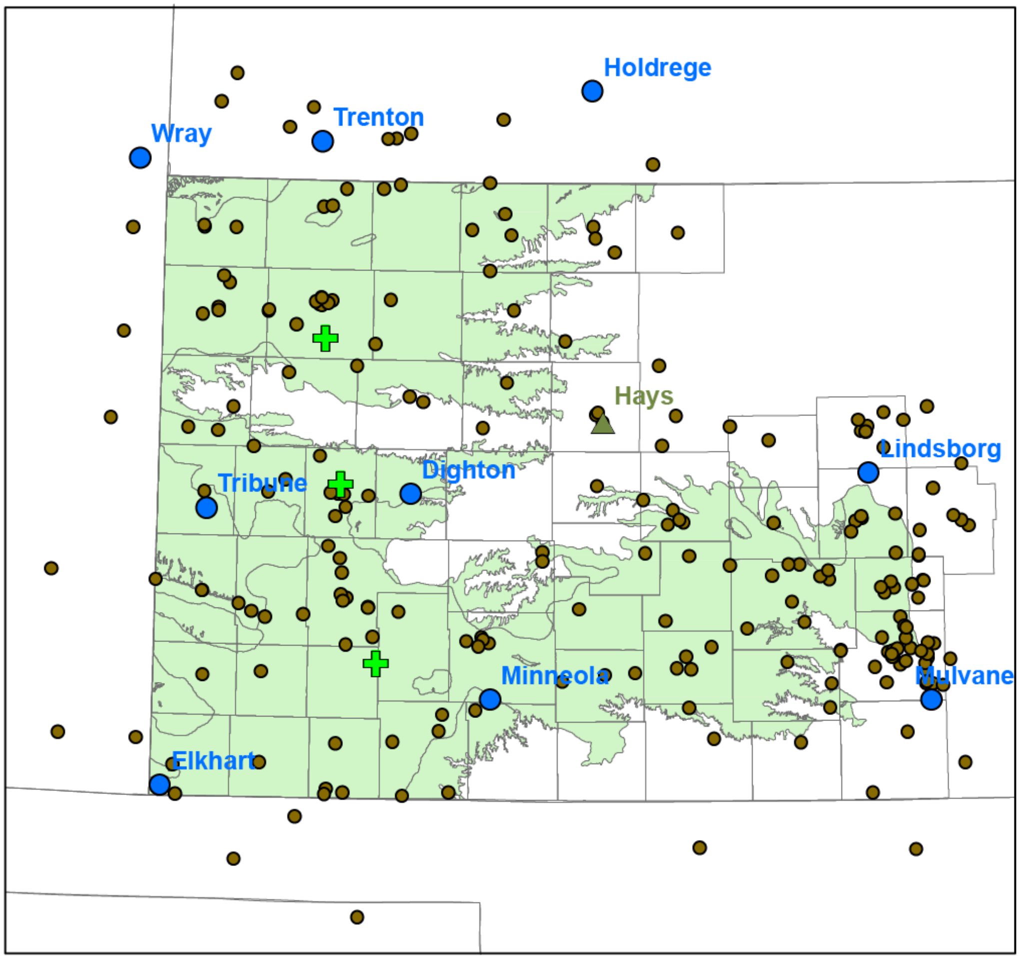


Figure 31: Locations of 235 Kansas High Plains region weather stations whose data can be obtained through the Weather Underground web site. Blue circles highlight locations of nine stations examined in Figure 32, the triangle represents the Hays airport weather station, and crosses represent the three original KGS index wells.

We identified a large number of weather stations in the High Plains region, including the 235 shown in Figure 31, in anticipation of needing to interpolate between stations to accurately represent the barometric pressure variations at any given location. However, in order to assess the need for this interpolation step, we first compared the barometric pressure records from the nine widely-spaced weather stations represented by the blue circles in Figure 31. Figure 32 shows the barometric pressure records from these nine stations for the first full week of January 2013, after removing the mean pressure for each station over that week.

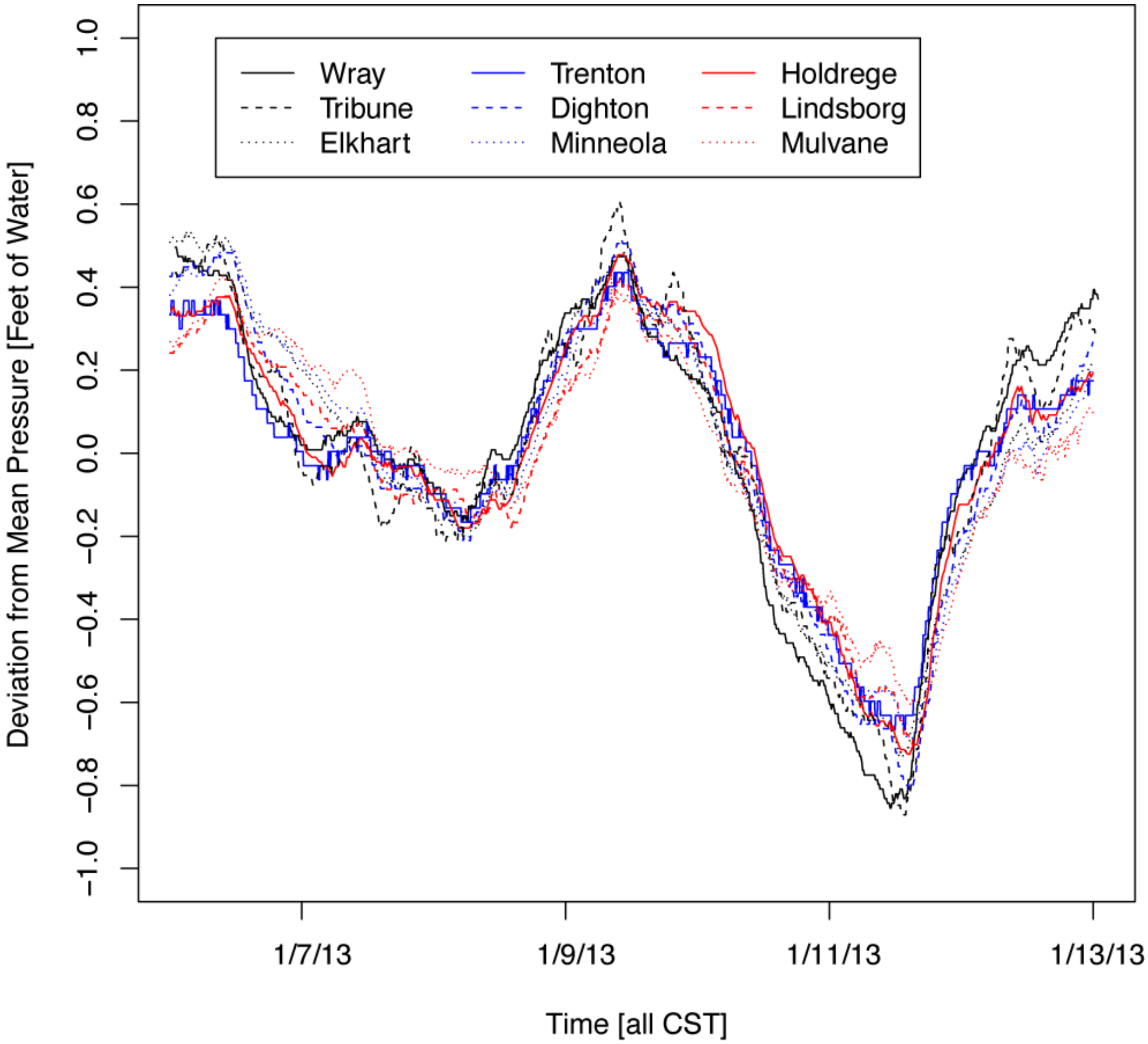


Figure 32: Deviations of barometric pressure, in equivalent feet of water, from station mean for the week from January 6 to January 12, 2013 (tick marks at midnight) for nine widely separated stations represented by the blue circles in Figure 31.

Although these records do not agree as closely as those for the index well barometric records shown in Figure 3.2 of Buddemeier et al. (2010), they agree closely enough that they would be essentially interchangeable for the purpose of estimating the expected range of water-level responses to barometric pressure fluctuations over this time period.

Note that the barometrically induced water-level fluctuations (deviations from mean) over a given time period depend only on the fluctuations in barometric pressure about its mean value, as shown in Figure 32, and not on the mean barometric pressure. Comparisons of mean-removed barometric pressure records from these nine stations for different time periods yielded comparable results, indicating that spatial variations in barometric pressure over the Kansas High Plains region will not have a significant influence on the assessment of the expected impact of barometric pressure variations on water-level measurements, as long as we are considering time frames of a few days or more.

Consequently, at least for the sake of this preliminary assessment, we decided to identify a single weather station to serve as the source of barometric pressure information. The goal was to find a weather station that has a consistent and reasonably detailed record going back to at least 1996, the first year of the current annual measurement program. The Hays airport weather station (KHYS) meets these criteria, with an essentially continuous barometric pressure record since before 1996. The measurement interval was 60 minutes in 1996 but has been 20 minutes from 1997 to the present. Figure 33 shows that the mean-removed Hays record agrees closely with the three index well records for the month of January 2011, and the same is true for other intervals examined. Consequently, we selected the Hays airport station (triangle in Figure 31) as the barometric pressure data source for the current assessment.

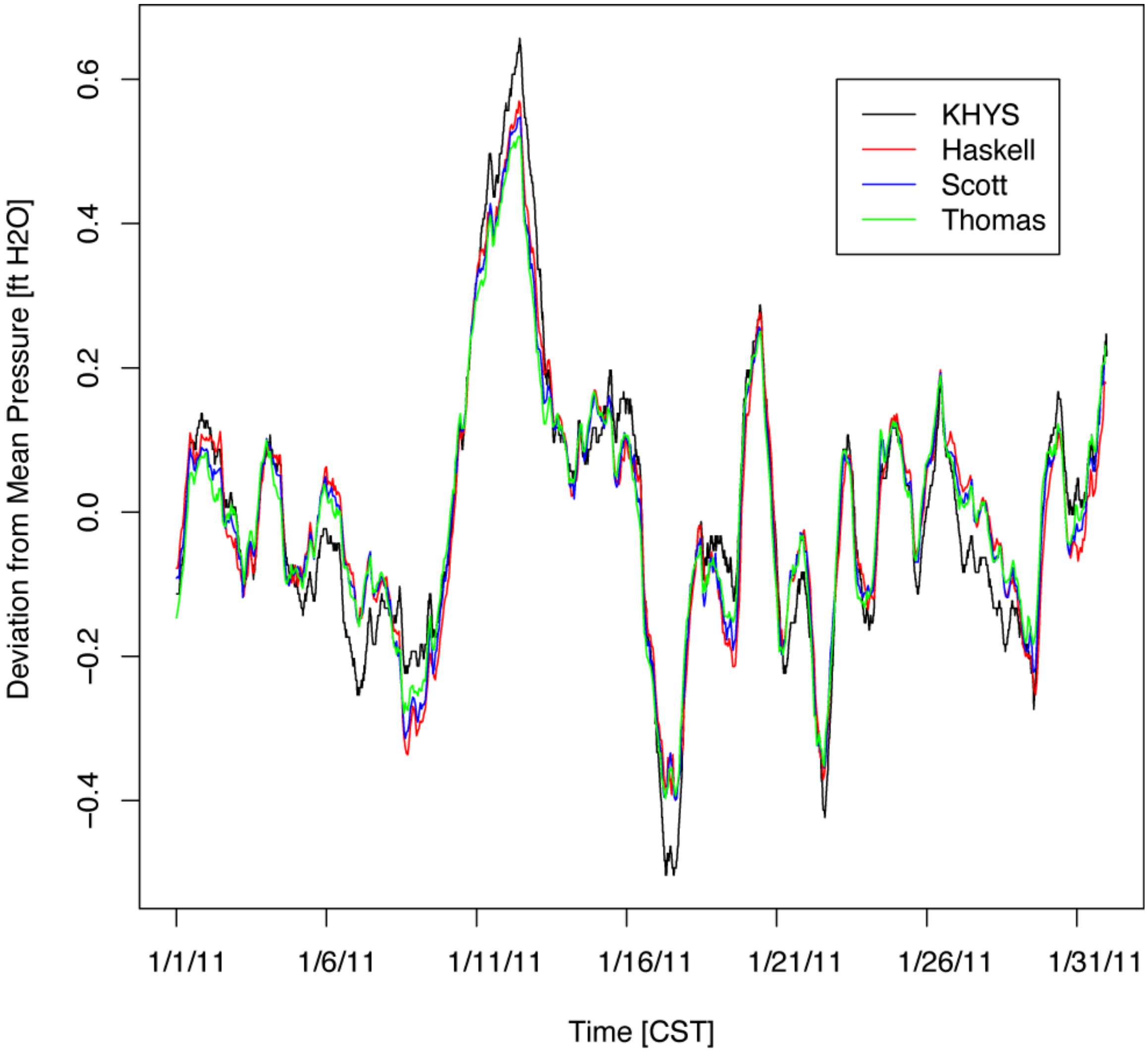


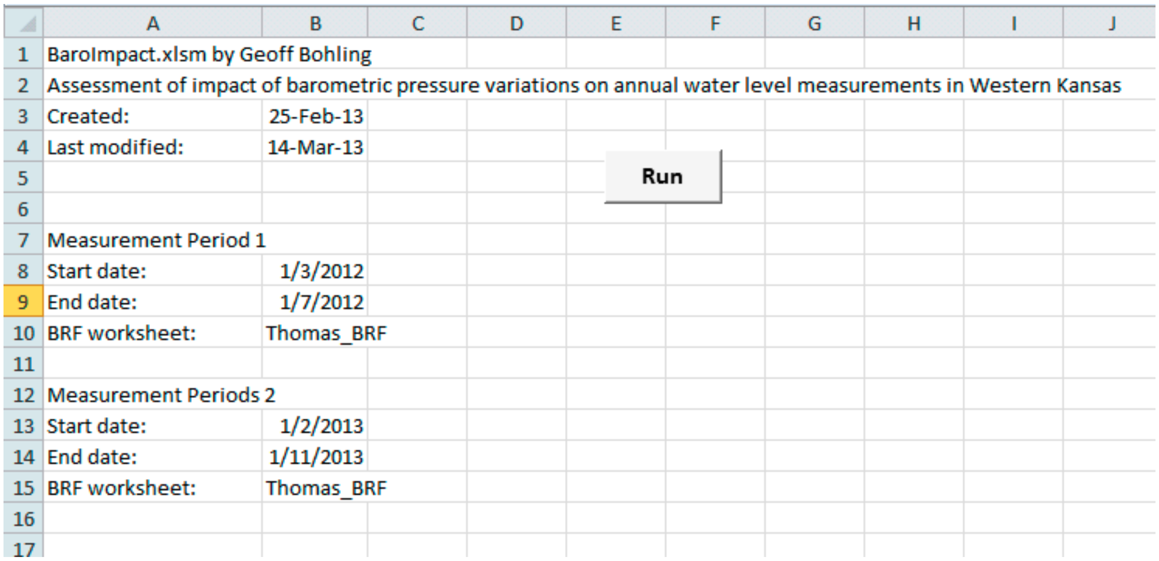
Figure 33: Comparison of Hays airport weather station (KHYS) barometric pressure record to those from the three index wells.

We would expect spatial variation in the barometric response function to have a significant impact on barometrically induced water-level responses. However, this variation is very difficult to quantify in any rigorous fashion due to the heterogeneity of the aquifer, the dependence of a well's barometric response on the location of the screen relative to the local hydrostratigraphy, and the temporal variation in barometric response characteristics due to changes in water-table height (or vadose zone thickness) over time. We anticipate that a current project aimed at improved aquifer characterization based on drillers' logs (see section 8.3) will provide information regarding spatial variations in barometric response characteristics due to aquifer heterogeneity, but it is doubtful that all the factors affecting barometric response could be assessed for every well in the annual measurement network. As mentioned above, we use the barometric response function for the Thomas County index well here, taking the deep, unconfined conditions at this well as a worst-case scenario with regard to barometric influence.

6.2. *Estimation of Barometric Impact on 2012 to 2013 Water-Level Changes*

We are working on developing an Excel workbook for the estimation of barometrically induced water-level fluctuations, which we expect to release as a KGS open-file report sometime in 2013. Here we use a preliminary version of this workbook to estimate the possible influence of barometric pressure variations on the assessment of water-level changes between the 2012 and 2013 annual HPA measurement campaigns. Although the entire measurement time range considered in the annual water-level assessment spans from late December into February, the majority of annual water-level measurements are obtained over a period of approximately one week early in January. Consequently, the majority of the annual decline values are obtained from differences of water levels measured at some point during the two measurement "weeks". The premise behind the code in the workbook is that the barometrically induced water-level fluctuations over a specified time period translate into barometrically induced uncertainty in the water-level measurement at a particular well as a consequence of the essentially random timing of the measurement within the time interval. The uncertainty in the resulting water-level change estimates is then assessed by computing all possible pairwise differences of barometrically induced water-level fluctuations between the two periods (comparing each time in one period to all times in the other period).

The workbook allows the user to specify two different time periods, e.g., the periods over which annual water-level measurements were obtained in two different years, and a barometric response function (BRF) associated with each period. The user enters this information on a simple "control" worksheet (Figure 34).

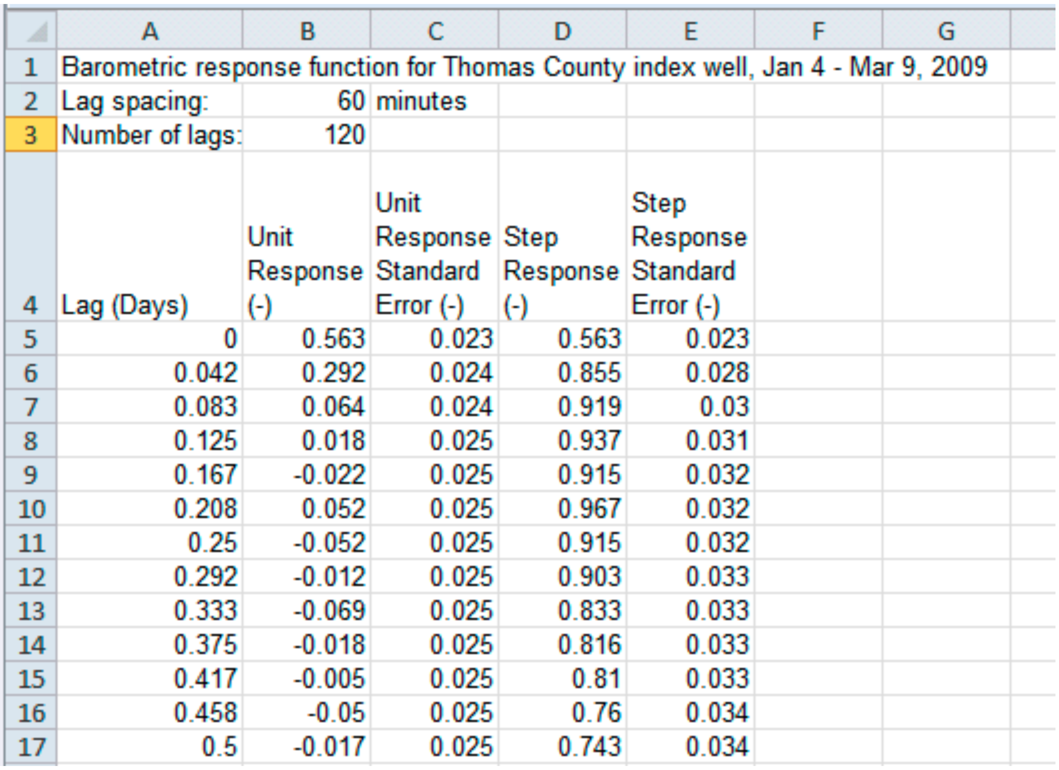


	A	B
1	BaroImpact.xlsm by Geoff Bohling	
2	Assessment of impact of barometric pressure variations on annual water level measurements in Western Kansas	
3	Created:	25-Feb-13
4	Last modified:	14-Mar-13
5		
6		
7	Measurement Period 1	
8	Start date:	1/3/2012
9	End date:	1/7/2012
10	BRF worksheet:	Thomas_BRF
11		
12	Measurement Periods 2	
13	Start date:	1/2/2013
14	End date:	1/11/2013
15	BRF worksheet:	Thomas_BRF
16		
17		

Figure 34: Control worksheet in Excel workbook for assessment of barometric impact on water-level measurements.

In 2012, the majority of the water level measurements (964 of 1,496) were obtained during the five-day period from January 3 to January 7 (inclusive). In 2013, the majority (985 of 1,401) were obtained during the ten-day period from January 2 to January 11.

The user specifies the BRF for each period by adding a worksheet containing the BRF coefficients to the workbook and entering the name of that worksheet in cell B10 (first period) or cell B15 (second period) on the control worksheet. In many cases it would be reasonable to use the same BRF for both periods, as we are here, but we allow the option of using two different BRFs to accommodate possible changes in the BRF due, in particular, to declining water levels over time. For this example, for both time periods, we are using a BRF computed for winter 2009 data from the Thomas County index well (Figure 35).



	A	B	C	D	E	F	G
1	Barometric response function for Thomas County index well, Jan 4 - Mar 9, 2009						
2	Lag spacing:	60	minutes				
3	Number of lags:	120					
4	Lag (Days)	Unit Response (-)	Unit Response Standard Error (-)	Step Response (-)	Step Response Standard Error (-)		
5	0	0.563	0.023	0.563	0.023		
6	0.042	0.292	0.024	0.855	0.028		
7	0.083	0.064	0.024	0.919	0.03		
8	0.125	0.018	0.025	0.937	0.031		
9	0.167	-0.022	0.025	0.915	0.032		
10	0.208	0.052	0.025	0.967	0.032		
11	0.25	-0.052	0.025	0.915	0.032		
12	0.292	-0.012	0.025	0.903	0.033		
13	0.333	-0.069	0.025	0.833	0.033		
14	0.375	-0.018	0.025	0.816	0.033		
15	0.417	-0.005	0.025	0.81	0.033		
16	0.458	-0.05	0.025	0.76	0.034		
17	0.5	-0.017	0.025	0.743	0.034		

Figure 35: Example barometric response function (BRF) worksheet.

The critical pieces of information in this BRF worksheet are the BRF lag spacing (cell B2), which should be given in minutes, the number of lags (cell B3), and then the list of unit response coefficients in column B, starting in row 5. These are the only cells that the workbook code actually reads; anything else on the worksheet is for the user's information only. The number of coefficients should be equal to the number of specified lags plus one (121 in this case). Also, the coefficients should be dimensionless, meaning they apply to barometric pressures and water levels measured in the same units. The BRF itself could be computed using the KGS BRF software (Bohling et al., 2011), although the header information has been substantially reduced here compared to that produced by the KGS BRF code.

Clicking the Run button on the control sheet launches Visual Basic code that computes the expected barometric impact on water-level measurements during each period specified and the resulting uncertainty in water-level change between the two periods. The code first obtains the Hays airport barometric pressure records for each time period by querying the Weather Underground web site. In fact, the code obtains barometric pressures for a somewhat longer period, moving the start date back (earlier) by the duration of the barometric response function (120 hours, or five days, in this case), since *nlag* prior barometric pressure values are needed to compute the water-level response at the beginning of the requested time period (where *nlag* is the number of lags in the BRF). The code then interpolates the measured pressures to a regular sequence of times at the same spacing as the BRF lags, in order to be able to apply the BRF to the pressure sequence. Because the readings from the Hays airport are at regular 20-minute intervals and the BRF lag spacing is 60 minutes, the interpolation in this case really amounts to sampling every third measurement. The code also converts the barometric pressure readings from inches of mercury to equivalent feet of water (multiplying by 1.135). The final manipulation of the barometric pressures is removal of the mean value from the interpolated record, since only the fluctuations about this mean are of consequence to the fluctuations of the water levels about their mean.

The interpolated, mean-removed barometric pressure sequence for each period is then convolved with the barometric response function to obtain the barometrically induced water-level fluctuations for that period. The mean of the water-level fluctuations will generally be near zero, since they are computed from a zero-mean pressure record, but not exactly zero. The code removes the mean from each water-level sequence, since it is the fluctuations about a presumed mean or static level for the period that we consider to represent the barometrically induced uncertainty in the measurement. The mean-removed barometric pressure and water-level response records are written to a separate worksheet for each period. Figures 36 and 37 show the results for the 2012 and 2013 measurement periods in this example.

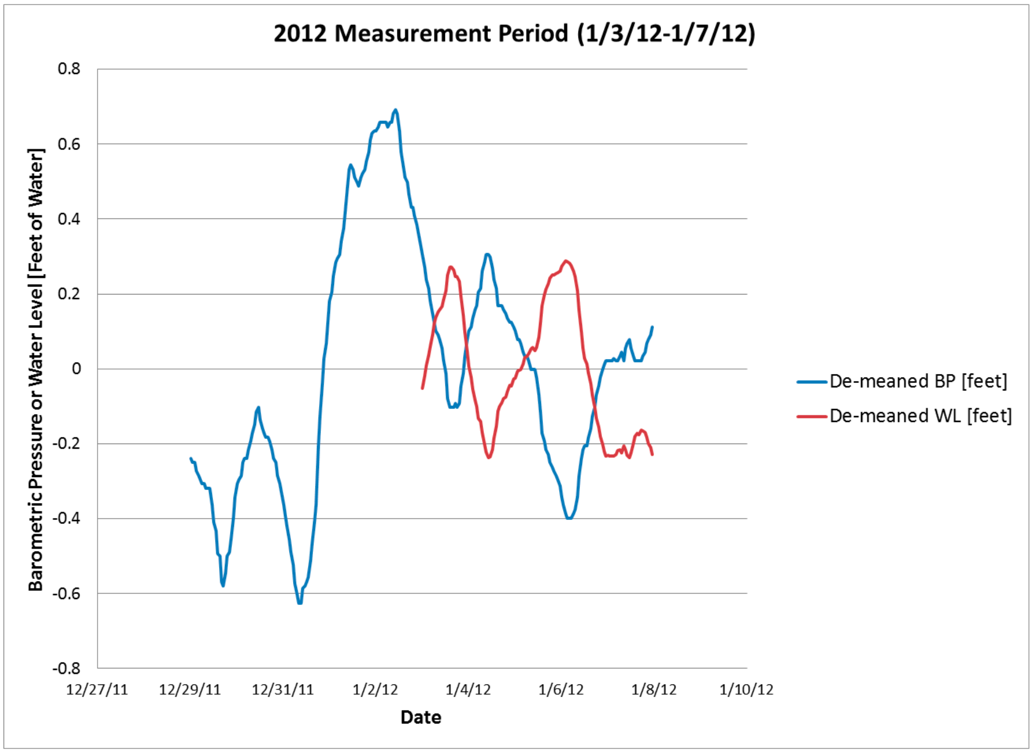


Figure 36: Barometric pressure fluctuations (blue) and corresponding water-level responses (red) for the 2012 measurement period.

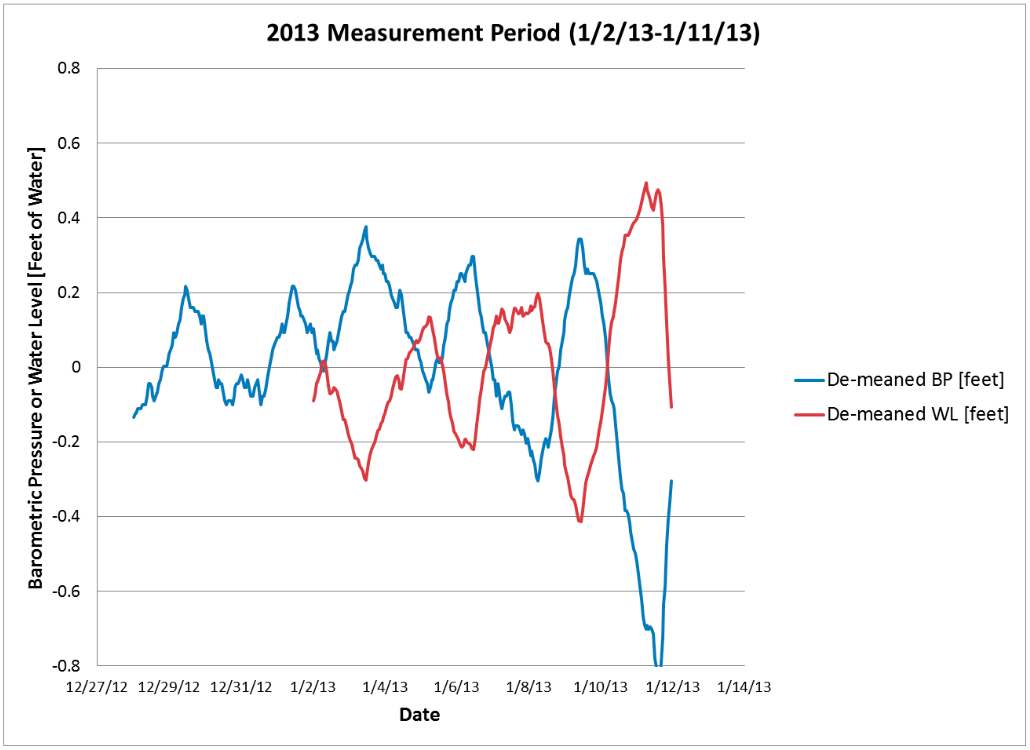


Figure 37: Barometric pressure fluctuations (blue) and corresponding water-level responses (red) for the 2013 measurement period.

In this example, a drop in barometric pressure early in the first measurement period leads to an increase in the water level, peaking at about 0.3 feet on the afternoon of January 3, 2012. In contrast, an increase in barometric pressure early in the second measurement period leads to a water-level decrease, with a minimum value of about -0.3 feet on the morning of January 3, 2013. Thus, if the two annual measurements at a particular well were taken at these two times, barometric pressure effects would contribute an apparent decline of 0.6 feet to the hypothetical water-level decline that one would estimate based on comparing water levels averaged over the two measurement periods (that is, factoring out barometrically induced fluctuations about the mean over each period).

To provide a systematic assessment of the consequent uncertainty in the water-level change estimates, the code produces a spreadsheet containing all possible pairwise differences of barometrically induced water-level responses for the two periods, with a surface chart illustrating these differences and summary statistics. The chart for this example is shown in Figure 38.

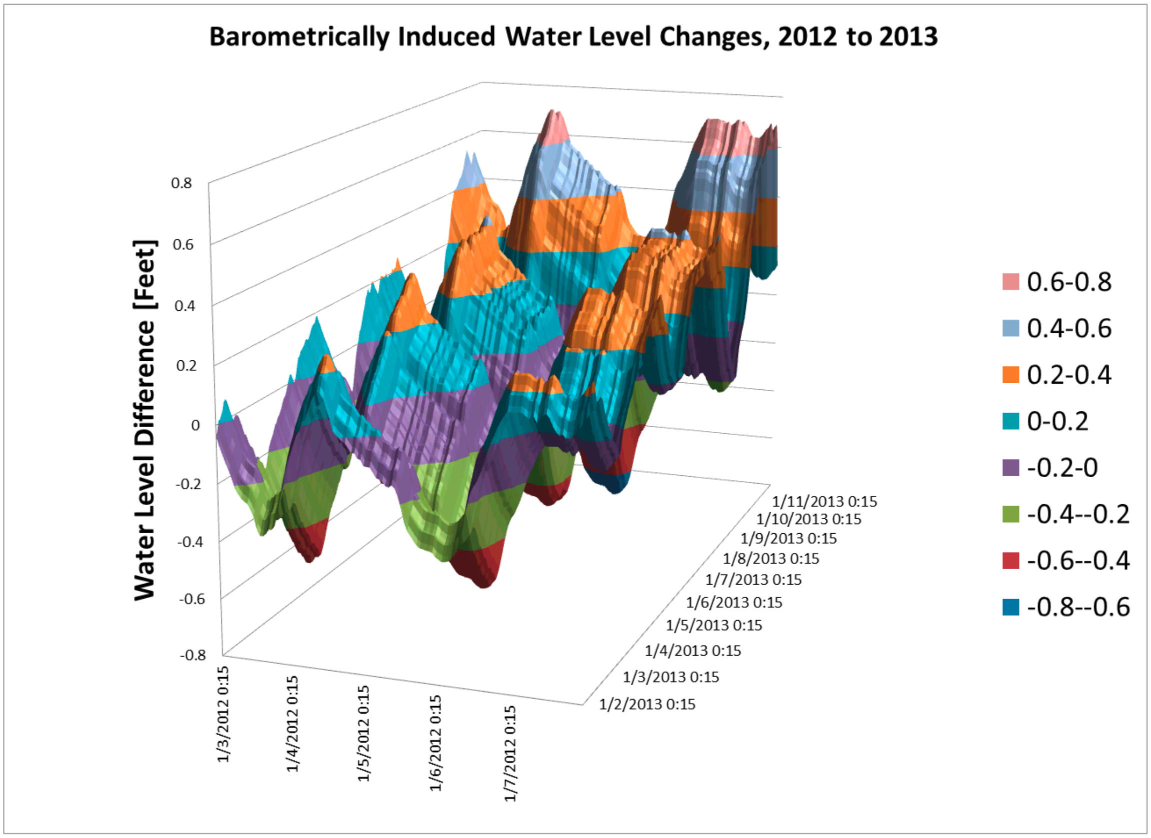


Figure 38: Surface chart illustrating all possible pairwise differences of barometrically induced water-level fluctuations for two measurement periods. Time sequence associated with 2012 measurement period (January 3– 7, 2012) runs left to right across the front and sequence associated with 2013 measurement period (January 2–11, 2013) runs front to back along the right.

The barometrically induced water-level decline of approximately 0.6 ft mentioned above appears as the negative peak near the left front corner of the surface shown in Figure 38. Similarly, other possible combinations of measurement times between the two periods lead to the range of differences illustrated in the chart. The summary statistics written to the spreadsheet show that these differences range from -0.70 ft (a water-level decline) to 0.73 ft (a water-level increase), with a standard deviation of 0.28 ft. The distribution of differences (Figure 39) is sufficiently close to normal that the standard deviation provides a reasonable descriptor of the data distribution. The mean of the differences is zero by design, since differences are taken between two zero-mean series (and the mean of differences between two series equals the difference of the means).

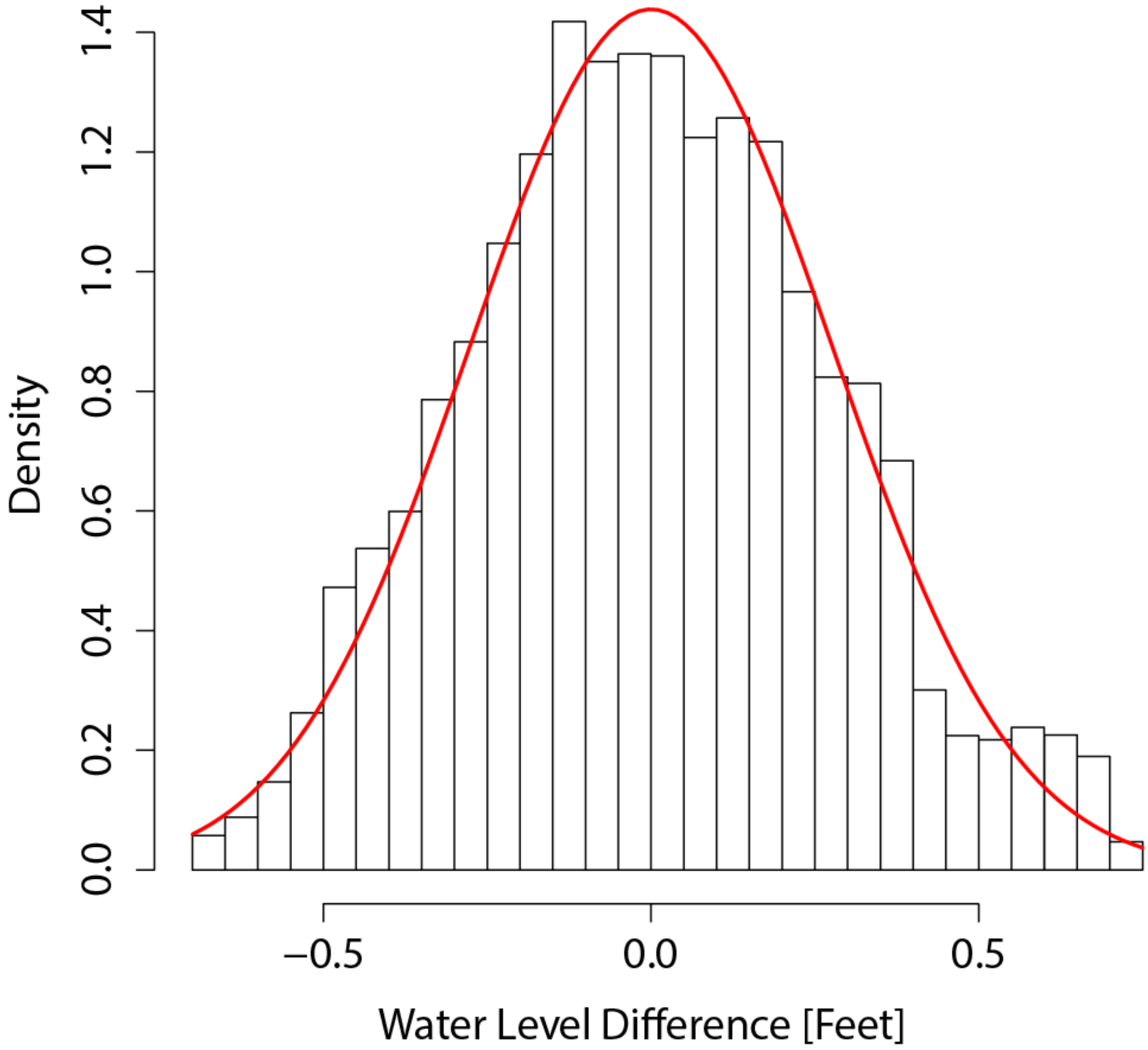


Figure 39: Histogram of barometrically induced water-level fluctuations (expressed as density function), with normal density function (red line) with same mean (0) and standard deviation (0.28 feet) as data.

The workbook provides an easy means to assess barometric impacts considering different time periods and different barometric response functions. In this example, expanding each of the two periods to the entire month of January results in barometrically induced water-level differences between the two years ranging from a decline of 1.0 ft to an increase of 1.2 ft, with a standard deviation of 0.31 ft. (Excel cannot produce the surface chart in this case, because the lengths of the data records exceed the number of "series" allowed in a chart, but the difference matrix could be exported from Excel and displayed using other software.) It would also be relatively simple to give the user the option of obtaining the barometric pressure data from different weather stations, but, as discussed above, it seems unlikely that this would have a significant impact on the results.

It is important to keep in mind that barometric variation represents only one source of uncertainty in the assessment of annual changes in water level. It should be the dominant source of uncertainty if the two measurement periods considered were periods in which the average water level represented fully recovered, static conditions. However, as noted in other reports, recovery from irrigation pumping continues throughout the winter in many portions of the aquifer. Variations in the timing of each year's measurement campaign relative to the end of the irrigation season (or, more accurately, vice-versa) can also be a significant source of uncertainty in the annual changes in water level. For example, the earliest end of the irrigation season at the Thomas County index well during the monitoring period was August 26 (2008) and the latest was September 17 (2012). Assuming that this 22 day difference occurred in successive years on which the annual water-level measurements were taken on January 8 (135 days after August 26), the Thomas County recovery data (Figure 10) indicate that water levels should rise about 0.25-0.30 ft over the additional 22 days for the earlier end to the irrigation season. Thus, in some years, the timing of the measurement relative to the end of the irrigation season can introduce uncertainty on the order of that produced by fluctuations in barometric pressure.

The workbook will be further refined in 2013. If a user wants to assess differences for water-level measurements taken over a specific day or two (e.g., measurements taken by the KGS team during the annual measurement program), representative stations within each GMD may be more appropriate than the Hays station. In addition, the approach used in this initial version of the workbook uses the short-term mean over the period designated by the user (plus the additional period needed for the BRF calculation). Use of a short-term mean could reduce the estimated impact of barometric pressure fluctuations, so a longer-term mean (e.g., one month) centered on the user-designated period might be more appropriate.

7. Kansas High Plains Aquifer Atlas

In 2012, the KGS developed the digital Kansas High Plains Aquifer Atlas (Fross et al., 2012). This atlas, which is available through the KGS web site (http://www.kgs.ku.edu/HighPlains/ HPA_Atlas/index.html), was created to serve as a gateway to data on the HPA in Kansas. One section of the atlas is focused on the index well program. The complete data series from all three of the original index wells and the latest project report can now be accessed through the atlas. The atlas will be updated as new data become available.

8. Spin-offs and Related Research

In 2012, complementary research furthered the work of the project.

8.1. Haskell County NSF Project

In the summer of 2010, the KGS was awarded a $381,000 grant from the National Science Foundation (NSF) to study the subsurface stratigraphic framework, sedimentary facies, and chronostratigraphy of the Ogallala Formation and overlying units. 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, so the borehole had not been completed at the time of this report.

8.2. Department of Energy Grant

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

8.3. 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. Fluid will be collected from sediment core samples, and physical, chemical, and isotopic determinations will be made on the fluid to provide additional insights into recharge in the area of the index well. Sampling will begin at a location one mile south of the Thomas index well in the latter half of March of 2013.

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

The KGS was awarded a two-year $30,000 grant to investigate approaches to better use the information in drillers' logs. The objectives of this project, which follows on the survey's earlier PST+ project, are to 1) develop software and protocols to increase the 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. Considerable progress has already been made on the first two project objectives. In the fall of 2012, a Graduate Research Assistant funded by the project transcribed logs for 250 wells in the vicinity of the Thomas County index well and mapped the verbatim log descriptions into a set of 72 standardized lithologies. The standardized lithologies (sediment types in most cases) were then mapped into five categories representing expected hydraulic conductivity ranges, and the proposed geostatistical procedures were used to develop a three-dimensional representation of lithological variation in the area (Figure 40).

Subsequent steps will involve refinement of the three-dimensional lithology model through application of the cross-validation process and other quality-control procedures followed by development of a three-dimensional flow model employing hydrogeological parameters derived from the lithology model. The flow model will be used to simulate the water-level responses in the index well (and the nearby expansion wells) to pumping in surrounding wells, providing a means to test the utility of the drillers' log information and effectiveness of the proposed procedures in the development of quantitative hydrogeologic models of the High Plains aquifer. Thus, the index well project will provide the basis for assessing the results of the drillers' log project and the drillers' log project should provide significant insight regarding the detailed aquifer dynamics reflected in the index well responses, along with providing a means to transfer this insight to other, less intensively monitored portions of the aquifer.

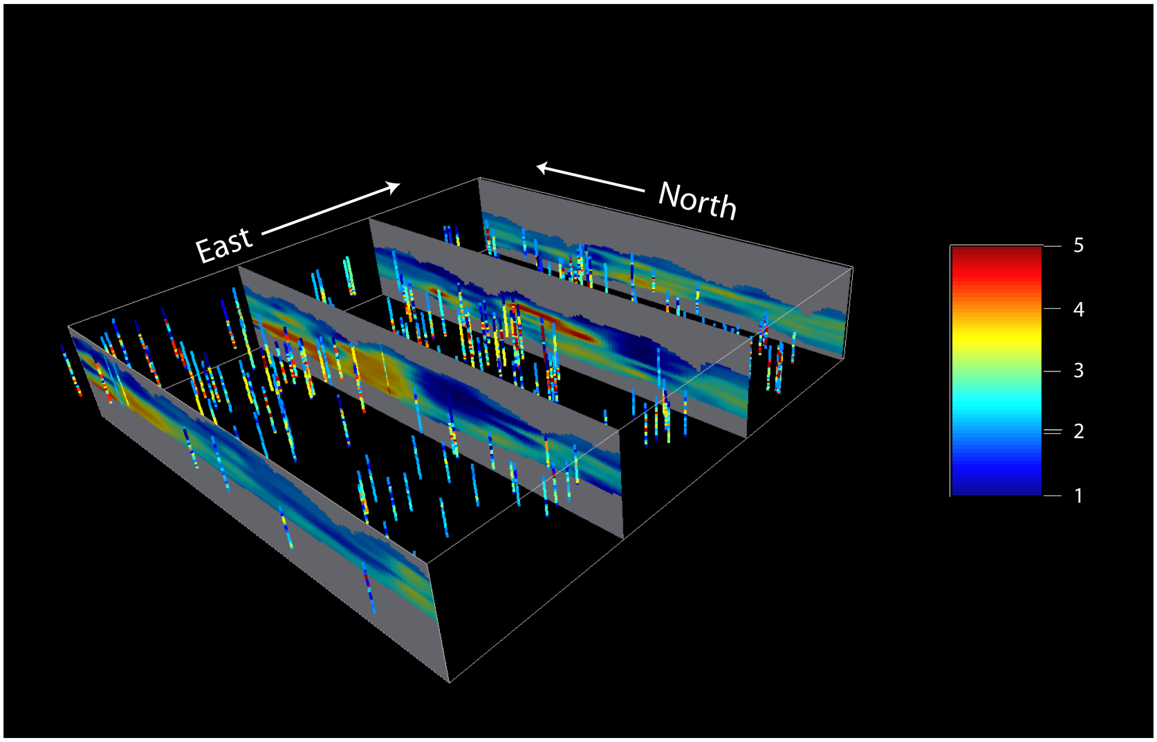


Figure 40: Average hydraulic conductivity category (1 for lowest permeability materials to 5 for highest permeability) in 250 wells in the vicinity of the Thomas County index well and in slices of a three-dimensional model. The model volume is approximately 15 miles on a side, centered on the index well, and 490 feet thick. The gray areas are above land surface or below bedrock.

9. Summary of 2012 Accomplishments and Plans for 2013

9.1. 2012 Accomplishments

- Continued collection and processing of data. Telemetered data from the original three index wells have continued to be served on the web, and downloads have been used for analysis and presentation. Data collection and analysis from the Thomas expansion wells have continued.
- Addition of new wells into the network in the vicinity of the Scott site in GMD1 (two wells) and along the Kansas-Oklahoma border in GMD3 (four wells); interpretation of the initial hydrographs from these wells.
- Continued detailed analysis of hydrographs at all three index well sites; developed approximate water balance for Thomas site.
- Continued comparison of transducer data with the results of the annual water-level network.
- Web publication of journal article on interpretation of water-level changes at the Haskell and Thomas sites (print publication in March 2013).
- An analysis of climatic indices and their relationship to annual water-level changes measured at the index well and across the western three GMDs.

- Initial development of a computer tool for readily identifying susceptibility of water-level change estimates from the annual water-level measurement program to barometric pressure effects.
- Integration of program data into the digital Kansas High Plains Aquifer Atlas.
- Presentations on the index well program given to the KWO, DWR, GMD personnel and the 2012 Kansas Field Conference, among others.

9.2. Planned Activities, 2013

- Recovery and pumping assessment for 2012 and 2013 periods.
- Continue detailed analysis of hydrographs from all three index well sites, expansion wells, and any other data sets that we can find.
- Continue to monitor and analyze water levels at the two additional wells in the vicinity of the Scott County index well; seek replacement well for well WH-1
- Continue to monitor and analyze water levels at the four new index wells along the Kansas-Oklahoma border in GMD3; monitor additional wells at one or more of these sites, if possible.
- 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 the Scott and Haskell index wells.
- Continue progression towards improving end-user capabilities for broader implementation of the index well program.
- Revise and complete computer tool for readily identifying susceptibility of water-level change estimates from the annual water-level measurement program to barometric pressure effects.
- Cooperate with GMD4 on interpretation of monitoring data from the Sheridan-6 index wells.
- Assess contribution of Dakota aquifer to pumping withdrawals in the vicinity of the Haskell County index well, including determination of the number of wells completed in both the HPA and the Dakota aquifer, available water-level data for these wells, and assessment of the direction of possible leakage.
- Continue assessment of relationship between climatic indices and annual water-level changes in the three western GMDs.
- Integrate information from drillers' logs in the vicinity of the Thomas County index well into interpretation of water-level responses in that area

9.3. Outstanding Issues

Major unresolved issues include the following:

- The source and areal extent of the inflow, which is not induced by pumping activity, in the vicinity of the Thomas County index well.
- Conditions in the HPA at the Scott County site; understanding is still incomplete but inflow not induced by pumping may also be occurring in that vicinity.

- Conditions in the HPA in the area of thick saturated interval along the Kansas-Oklahoma border.

10. References

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

Buddemeier, R.W., R. Stotler, J.J. Butler, Jr., W. Jin, K. Beeler, E. Reboulet, P.A. Macfarlane, S. Kreitzer, D.O. Whittemore, G. Bohling, and B.B. Wilson, 2010. High Plains Aquifer Calibration Monitoring Well Program: Third Year Progress Report: Kansas Geological Survey, Open-File Report 2010-3. Available online at http://www.kgs.ku.edu/Hydro/Publications/2010/OFR10_3/index.html.

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

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

Butler, J.J., Jr., R. Stotler, D.O. Whittemore, E. Reboulet, G.C. Bohling, and B.B, Wilson, 2012. High Plains Aquifer Calibration Monitoring Well Program: Fifth Year Progress Report: Kansas Geological Survey, Open-File Report 2012-2. Available online at http://www.kgs.ku.edu/Hydro/Publications/2012/OFR12_2/index.html.

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

Hayes, M.J., Comparison of major drought indices: National Drought Mitigation Center, Lincoln, Nebraska, http://drought.unl.edu/Planning/Monitoring/ComparisonofIndicesIntro.aspx (accessed March 2013).

Heim, R.R., Jr., 2002. A review of Twentieth-Century drought indices used in the United States: Bulletin of the American Meteorological Society, 83, 1149–1165.

Kruseman, G.P., and N.A. de Ridder, 1990. Analysis and Evaluation of Pumping Test Data – ILRI Pub. 47: Int. Inst. for Land Reclamation and Improvement, the Netherlands, 377 p.

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

McKee, T.B., N.J. Doesken, and J. Kleist, 1993. The relationship of drought frequency and duration to time scales: Preprints, 8th Conference Applied Climatology, 17–22 January, Anaheim, California, p. 179–184.

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 pp.

National Climatic Data Center, U.S. Palmer drought indices: http://www.ncdc.noaa.gov/oa/climate/research/prelim/drought/palmer.html (accessed March 2013).

Palmer, W.C., 1965. Meteorological drought: Research Paper No. 4, U.S. Weather Bureau, (NOAA Library and Information Services Division, Washington, D.C. 20852), http://www.ncdc.noaa.gov/temp-and-precip/drought/docs/palmer.pdf (accessed March 2013).

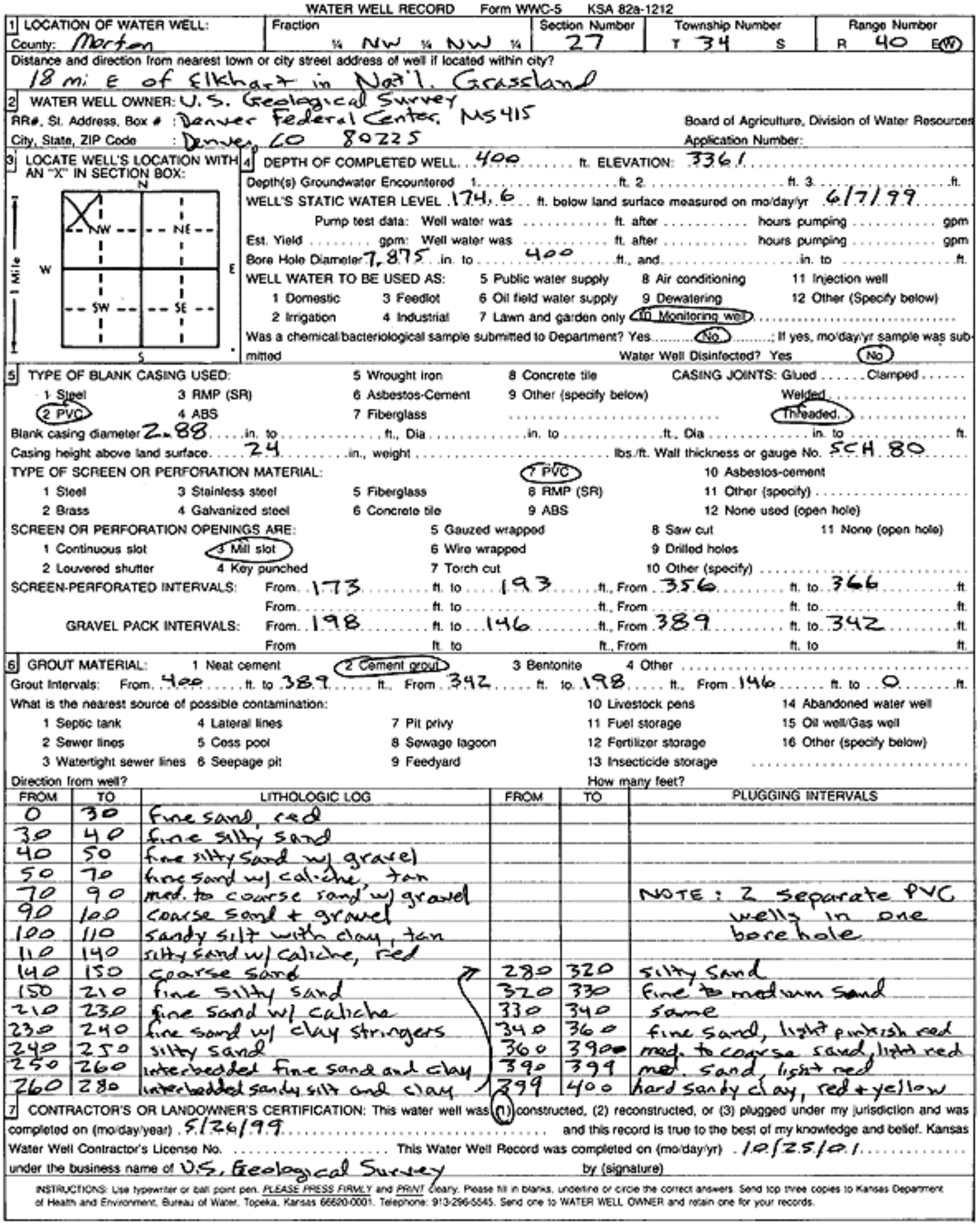
Palmer, W.C., 1968. Keeping track of crop moisture conditions, nationwide: the new Crop Moisture Index, Weatherwise, 21, 156–161.

Young, D.P., R.W. Buddemeier, D.O. Whittemore, and E. Reboulet, 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. Available online at http://www.kgs.ku.edu/Hydro/Publications/2007/OFR07_30/index.html.

Young, D.P., R.W. Buddemeier, J.J. Butler, Jr., W. Jin, D.O. Whittemore, E. Reboulet, and B.B. Wilson, 2008. High Plains Aquifer Calibration Monitoring Well Program: Year 2 Progress Report: Kansas Geological Survey, Open-File Report 2008–29. Available online at http://www.kgs.ku.edu/Hydro/Publications/2008/OFR08_29/index.html.

11. Appendix A – Border Well Construction Information

Rolla 366 – 2.5 in Sch80 casing and screen – deeper of two wells in same borehole.
Screened Interval: 356–366 ft below land surface
Gravel Pack Interval: 342–389 ft below land surface
Grout Interval: 0–146 ft, 198–342 ft, and 389–400 ft below land surface



WATER WELL RECORD Form WWC-5 KSA 82a-1212

1 LOCATION OF WATER WELL: County: Morton
Fraction ¼ NW ¼ NW ¼
Section Number 27
Township Number T 34 S
Range Number R 40 E [✓ W]
Distance and direction from nearest town or city street address of well if located within city? 18 mi E of Elkhart in Nat'l. Grassland

2 WATER WELL OWNER: U.S. Geological Survey
RR#, St. Address, Box # : Denver Federal Center, MS415
City, State, ZIP Code : Denver, CO 80225
Board of Agriculture, Division of Water Resources
Application Number:

3 LOCATE WELL'S LOCATION WITH AN "X" IN SECTION BOX:
N, W, E, S; NW (X), NE, SW, SE; 1 Mile

4 DEPTH OF COMPLETED WELL 400 ft. ELEVATION: 3361
Depth(s) Groundwater Encountered 1. ft. 2. ft. 3. ft.
WELL'S STATIC WATER LEVEL 174.6 ft. below land surface measured on mo/day/yr 6/7/99
Pump test data: Well water was ft. after hours pumping gpm
Est. Yield gpm: Well water was ft. after hours pumping gpm
Bore Hole Diameter 7.875 in. to 400 ft., and in. to ft.
WELL WATER TO BE USED AS: 1 Domestic 2 Irrigation 3 Feedlot 4 Industrial 5 Public water supply 6 Oil field water supply 7 Lawn and garden only 8 Air conditioning 9 Dewatering [✓ 10 Monitoring well] 11 Injection well 12 Other (Specify below)
Was a chemical/bacteriological sample submitted to Department? Yes [✓ No]; If yes, mo/day/yr sample was submitted
Water Well Disinfected? Yes [✓ No]

5 TYPE OF BLANK CASING USED: 1 Steel [✓ 2 PVC] 3 RMP (SR) 4 ABS 5 Wrought iron 6 Asbestos-Cement 7 Fiberglass 8 Concrete tile 9 Other (specify below)
CASING JOINTS: Glued Clamped Welded [✓ Threaded]
Blank casing diameter 2.88 in. to ft., Dia in. to ft., Dia in. to ft.
Casing height above land surface 24 in., weight lbs./ft. Wall thickness or gauge No. SCH 80
TYPE OF SCREEN OR PERFORATION MATERIAL: 1 Steel 2 Brass 3 Stainless steel 4 Galvanized steel 5 Fiberglass 6 Concrete tile [✓ 7 PVC] 8 RMP (SR) 9 ABS 10 Asbestos-cement 11 Other (specify) 12 None used (open hole)
SCREEN OR PERFORATION OPENINGS ARE: 1 Continuous slot 2 Louvered shutter [✓ 3 Mill slot] 4 Key punched 5 Gauzed wrapped 6 Wire wrapped 7 Torch cut 8 Saw cut 9 Drilled holes 10 Other (specify) 11 None (open hole)
SCREEN-PERFORATED INTERVALS: From 173 ft. to 193 ft., From 356 ft. to 366 ft.
From ft. to ft., From ft. to ft.
GRAVEL PACK INTERVALS: From 198 ft. to 146 ft., From 389 ft. to 342 ft.
From ft. to ft., From ft. to ft.

6 GROUT MATERIAL: 1 Neat cement [✓ 2 Cement grout] 3 Bentonite 4 Other
Grout Intervals: From 400 ft. to 389 ft., From 342 ft. to 198 ft., From 146 ft. to 0 ft.
What is the nearest source of possible contamination: 1 Septic tank 2 Sewer lines 3 Watertight sewer lines 4 Lateral lines 5 Cess pool 6 Seepage pit 7 Pit privy 8 Sewage lagoon 9 Feedyard 10 Livestock pens 11 Fuel storage 12 Fertilizer storage 13 Insecticide storage 14 Abandoned water well 15 Oil well/Gas well 16 Other (specify below)
Direction from well? How many feet?

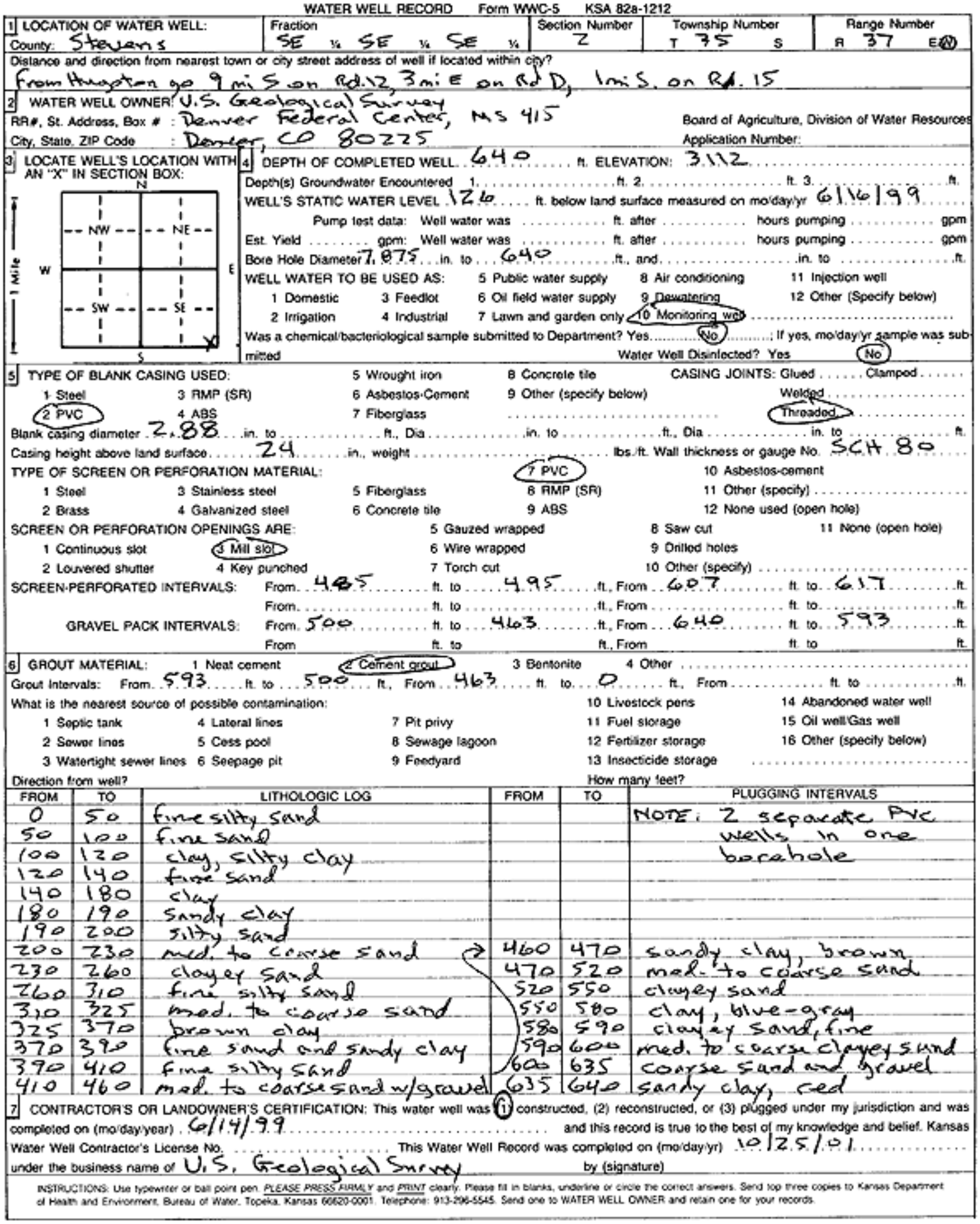
FROM	TO	LITHOLOGIC LOG	FROM	TO	PLUGGING INTERVALS
0	30	fine sand, red			
30	40	fine silty sand			
40	50	fine silty sand w/ gravel			
50	70	fine sand w/ caliche, tan			
70	90	med. to coarse sand w/ gravel			NOTE: 2 separate PVC
90	100	coarse sand + gravel			wells in one
100	110	sandy silt with clay, tan			borehole
110	140	silty sand w/ caliche, red			
140	150	coarse sand	280	320	silty sand
150	210	fine silty sand	320	330	fine to medium sand
210	230	fine sand w/ caliche	330	340	same
230	240	fine sand w/ clay stringers	340	360	fine sand, light pinkish red
240	250	silty sand	360	390	med. to coarse sand, light red
250	260	interbedded fine sand and clay	390	399	med. sand, light red
260	280	interbedded sandy silt and clay	399	400	hard sandy clay, red + yellow

7 CONTRACTOR'S OR LANDOWNER'S CERTIFICATION: This water well was [✓ (1)] constructed, (2) reconstructed, or (3) plugged under my jurisdiction and was completed on (mo/day/year) 5/26/99 and this record is true to the best of my knowledge and belief. Kansas Water Well Contractor's License No. This Water Well Record was completed on (mo/day/yr) 10/25/01 under the business name of U.S. Geological Survey by (signature)

INSTRUCTIONS: Use typewriter or ball point pen. PLEASE PRESS FIRMLY and PRINT clearly. Please fill in blanks, underline or circle the correct answers. Send top three copies to Kansas Department of Health and Environment, Bureau of Water, Topeka, Kansas 66620-0001. Telephone: 913-296-5545. Send one to WATER WELL OWNER and retain one for your records.

OFFICE USE ONLY T R E/W SEC. ¼ ¼ ¼

Hugoton 495 – 2.5 in Sch80 casing and screen – shallower of two wells in same borehole.
Screened Interval: 485–495 ft below land surface
Gravel Pack Interval: 463–500 ft below land surface
Grout Interval: 0–463 ft below land surface



WATER WELL RECORD Form WWC-5 KSA 82a-1212

1 LOCATION OF WATER WELL: County: Stevens
Fraction SE ¼ SE ¼ SE ¼
Section Number 2
Township Number T 35 S
Range Number R 37 E [✓ W]
Distance and direction from nearest town or city street address of well if located within city?
From Hugoton go 9 mi S on Rd. 12, 3 mi E on Rd D, 1 mi S. on Rd. 15

2 WATER WELL OWNER: U.S. Geological Survey
RR#, St. Address, Box # : Denver Federal Center, MS 415
City, State, ZIP Code : Denver, CO 80225
Board of Agriculture, Division of Water Resources
Application Number:

3 LOCATE WELL'S LOCATION WITH AN "X" IN SECTION BOX:
N — NW — NE — W — E — SW — SE — S — 1 Mile — X

4 DEPTH OF COMPLETED WELL 640 ft. ELEVATION: 3112
Depth(s) Groundwater Encountered 1. ft. 2. ft. 3. ft.
WELL'S STATIC WATER LEVEL 126 ft. below land surface measured on mo/day/yr 6/16/99
Pump test data: Well water was ft. after hours pumping gpm
Est. Yield gpm: Well water was ft. after hours pumping gpm
Bore Hole Diameter 7.875 in. to 640 ft., and in. to ft.
WELL WATER TO BE USED AS: 5 Public water supply 8 Air conditioning 11 Injection well
1 Domestic 3 Feedlot 6 Oil field water supply 9 Dewatering 12 Other (Specify below)
2 Irrigation 4 Industrial 7 Lawn and garden only [✓ 10 Monitoring well]
Was a chemical/bacteriological sample submitted to Department? Yes [✓ No]; If yes, mo/day/yr sample was submitted
Water Well Disinfected? Yes [✓ No]

5 TYPE OF BLANK CASING USED: 5 Wrought iron 8 Concrete tile CASING JOINTS: Glued Clamped
1 Steel 3 RMP (SR) 6 Asbestos-Cement 9 Other (specify below) Welded
[✓ 2 PVC] 4 ABS 7 Fiberglass [✓ Threaded]
Blank casing diameter 2.88 in. to ft., Dia in. to ft., Dia in. to ft.
Casing height above land surface 24 in., weight lbs./ft. Wall thickness or gauge No. SCH 80
TYPE OF SCREEN OR PERFORATION MATERIAL: [✓ 7 PVC] 10 Asbestos-cement
1 Steel 3 Stainless steel 5 Fiberglass 8 RMP (SR) 11 Other (specify)
2 Brass 4 Galvanized steel 6 Concrete tile 9 ABS 12 None used (open hole)
SCREEN OR PERFORATION OPENINGS ARE: 5 Gauzed wrapped 8 Saw cut 11 None (open hole)
1 Continuous slot [✓ 3 Mill slot] 6 Wire wrapped 9 Drilled holes
2 Louvered shutter 4 Key punched 7 Torch cut 10 Other (specify)
SCREEN-PERFORATED INTERVALS: From 485 ft. to 495 ft., From 607 ft. to 617 ft.
From ft. to ft., From ft. to ft.
GRAVEL PACK INTERVALS: From 500 ft. to 463 ft., From 640 ft. to 593 ft.
From ft. to ft., From ft. to ft.

6 GROUT MATERIAL: 1 Neat cement [✓ 2 Cement grout] 3 Bentonite 4 Other
Grout Intervals: From 593 ft. to 500 ft., From 463 ft. to 0 ft., From ft. to ft.
What is the nearest source of possible contamination:
1 Septic tank 4 Lateral lines 7 Pit privy 10 Livestock pens 14 Abandoned water well
2 Sewer lines 5 Cess pool 8 Sewage lagoon 11 Fuel storage 15 Oil well/Gas well
3 Watertight sewer lines 6 Seepage pit 9 Feedyard 12 Fertilizer storage 16 Other (specify below)
13 Insecticide storage
Direction from well?
How many feet?

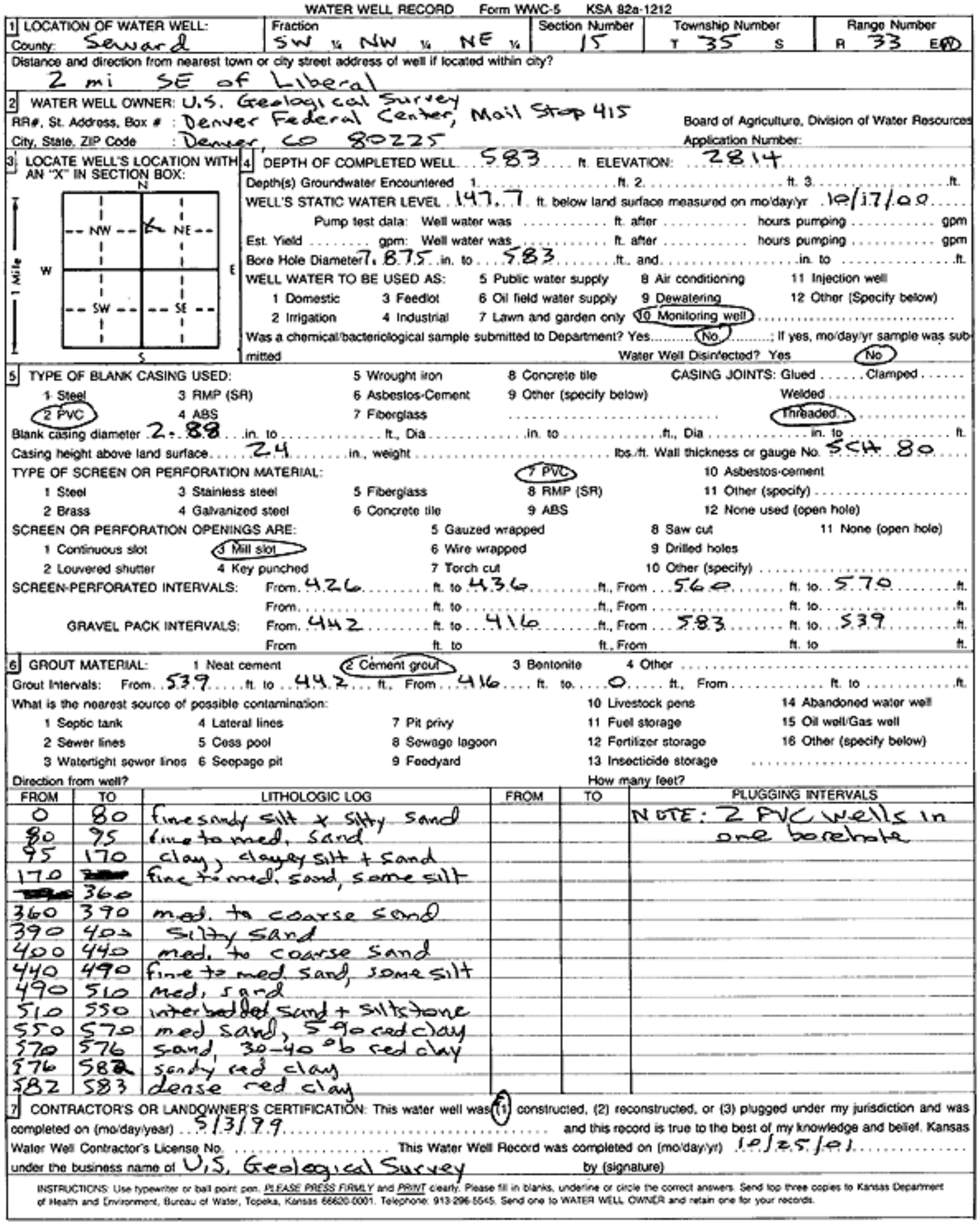
FROM	TO	LITHOLOGIC LOG	FROM	TO	PLUGGING INTERVALS
0	50	fine silty sand			NOTE: 2 separate PVC
50	100	fine sand			wells in one
100	120	clay, silty clay			borehole
120	140	fine sand			
140	180	clay			
180	190	sandy clay			
190	200	silty sand			
200	230	med. to coarse sand	460	470	sandy clay, brown
230	260	clayey sand	470	520	med. to coarse sand
260	310	fine silty sand	520	550	clayey sand
310	325	med. to coarse sand	550	580	clay, blue-gray
325	370	brown clay	580	590	clayey sand, fine
370	390	fine sand and sandy clay	590	600	med. to coarse clayey sand
390	410	fine silty sand	600	635	coarse sand and gravel
410	460	med. to coarse sand w/gravel	635	640	sandy clay, red

7 CONTRACTOR'S OR LANDOWNER'S CERTIFICATION: This water well was [✓ (1) constructed], (2) reconstructed, or (3) plugged under my jurisdiction and was completed on (mo/day/year) 6/14/99 and this record is true to the best of my knowledge and belief. Kansas Water Well Contractor's License No. This Water Well Record was completed on (mo/day/yr) 10/25/01 under the business name of U.S. Geological Survey by (signature)

INSTRUCTIONS: Use typewriter or ball point pen. *PLEASE PRESS FIRMLY* and *PRINT* clearly. Please fill in blanks, underline or circle the correct answers. Send top three copies to Kansas Department of Health and Environment, Bureau of Water, Topeka, Kansas 66620-0001. Telephone: 913-296-5545. Send one to WATER WELL OWNER and retain one for your records.

OFFICE USE ONLY T R E/W SEC. ¼ ¼ ¼

Liberal 436 – 2.5 in Sch80 casing and screen – shallower of two wells in same borehole.
Screened Interval: 426–436 ft below land surface
Gravel Pack Interval: 416–442 ft below land surface
Grout Interval: 0–416 ft below land surface



WATER WELL RECORD Form WWC-5 KSA 82a-1212

1 LOCATION OF WATER WELL: County: Seward
Fraction: SW ¼ NW ¼ NE ¼
Section Number: 15
Township Number: T 35 S
Range Number: R 33 E[✓ W]
Distance and direction from nearest town or city street address of well if located within city?
2 mi SE of Liberal

2 WATER WELL OWNER: U.S. Geological Survey
RR#, St. Address, Box # : Denver Federal Center, Mail Stop 415
City, State, ZIP Code : Denver, CO 80225
Board of Agriculture, Division of Water Resources
Application Number:

3 LOCATE WELL'S LOCATION WITH AN "X" IN SECTION BOX:
N, W, E, S, 1 Mile, NW, NE, SW, SE
X

4 DEPTH OF COMPLETED WELL 583 ft. ELEVATION: 2814
Depth(s) Groundwater Encountered 1. .... ft. 2. .... ft. 3. .... ft.
WELL'S STATIC WATER LEVEL 147.7 ft. below land surface measured on mo/day/yr 10/17/00
Pump test data: Well water was .... ft. after .... hours pumping .... gpm
Est. Yield .... gpm: Well water was .... ft. after .... hours pumping .... gpm
Bore Hole Diameter 7.875 in. to 583 ft., and .... in. to .... ft.
WELL WATER TO BE USED AS: 1 Domestic 2 Irrigation 3 Feedlot 4 Industrial 5 Public water supply 6 Oil field water supply 7 Lawn and garden only 8 Air conditioning 9 Dewatering [✓ 10 Monitoring well] 11 Injection well 12 Other (Specify below)
Was a chemical/bacteriological sample submitted to Department? Yes .... [✓ No] ....; If yes, mo/day/yr sample was submitted
Water Well Disinfected? Yes [✓ No]

5 TYPE OF BLANK CASING USED: 1 Steel [✓ 2 PVC] 3 RMP (SR) 4 ABS 5 Wrought iron 6 Asbestos-Cement 7 Fiberglass 8 Concrete tile 9 Other (specify below)
CASING JOINTS: Glued .... Clamped .... Welded .... [✓ Threaded]
Blank casing diameter 2.88 in. to .... ft., Dia .... in. to .... ft., Dia .... in. to .... ft.
Casing height above land surface 24 in., weight .... lbs./ft. Wall thickness or gauge No. SCH 80
TYPE OF SCREEN OR PERFORATION MATERIAL: 1 Steel 2 Brass 3 Stainless steel 4 Galvanized steel 5 Fiberglass 6 Concrete tile [✓ 7 PVC] 8 RMP (SR) 9 ABS 10 Asbestos-cement 11 Other (specify) .... 12 None used (open hole)
SCREEN OR PERFORATION OPENINGS ARE: 1 Continuous slot 2 Louvered shutter [✓ 3 Mill slot] 4 Key punched 5 Gauzed wrapped 6 Wire wrapped 7 Torch cut 8 Saw cut 9 Drilled holes 10 Other (specify) .... 11 None (open hole)
SCREEN-PERFORATED INTERVALS: From 426 ft. to 436 ft., From 560 ft. to 570 ft.
From .... ft. to .... ft., From .... ft. to .... ft.
GRAVEL PACK INTERVALS: From 442 ft. to 416 ft., From 583 ft. to 539 ft.
From ft. to ft., From ft. to ft.

6 GROUT MATERIAL: 1 Neat cement [✓ 2 Cement grout] 3 Bentonite 4 Other ....
Grout Intervals: From 539 ft. to 442 ft., From 416 ft. to 0 ft., From .... ft. to .... ft.
What is the nearest source of possible contamination: 1 Septic tank 2 Sewer lines 3 Watertight sewer lines 4 Lateral lines 5 Cess pool 6 Seepage pit 7 Pit privy 8 Sewage lagoon 9 Feedyard 10 Livestock pens 11 Fuel storage 12 Fertilizer storage 13 Insecticide storage 14 Abandoned water well 15 Oil well/Gas well 16 Other (specify below)
Direction from well? How many feet?

FROM	TO	LITHOLOGIC LOG	FROM	TO	PLUGGING INTERVALS
0	80	fine sandy silt + silty sand			NOTE: 2 PVC wells in one borehole
80	95	fine to med. sand			
95	170	clay, clayey silt + sand			
170	[illegible]	fine to med. sand, some silt			
[illegible]	360				
360	390	med. to coarse sand			
390	400	silty sand			
400	440	med. to coarse sand			
440	490	fine to med. sand, some silt			
490	510	med. sand			
510	550	interbedded sand + siltstone			
550	570	med sand, 5% red clay			
570	576	sand, 30-40 % red clay			
576	582	sandy red clay			
582	583	dense red clay			

7 CONTRACTOR'S OR LANDOWNER'S CERTIFICATION: This water well was [✓ (1)] constructed, (2) reconstructed, or (3) plugged under my jurisdiction and was completed on (mo/day/year) 5/3/99 and this record is true to the best of my knowledge and belief. Kansas Water Well Contractor's License No. .... This Water Well Record was completed on (mo/day/yr) 10/25/01 under the business name of U.S. Geological Survey by (signature)

INSTRUCTIONS: Use typewriter or ball point pen. *PLEASE PRESS FIRMLY* and *PRINT* clearly. Please fill in blanks, underline or circle the correct answers. Send top three copies to Kansas Department of Health and Environment, Bureau of Water, Topeka, Kansas 66620-0001. Telephone: 913-296-5545. Send one to WATER WELL OWNER and retain one for your records.

OFFICE USE ONLY
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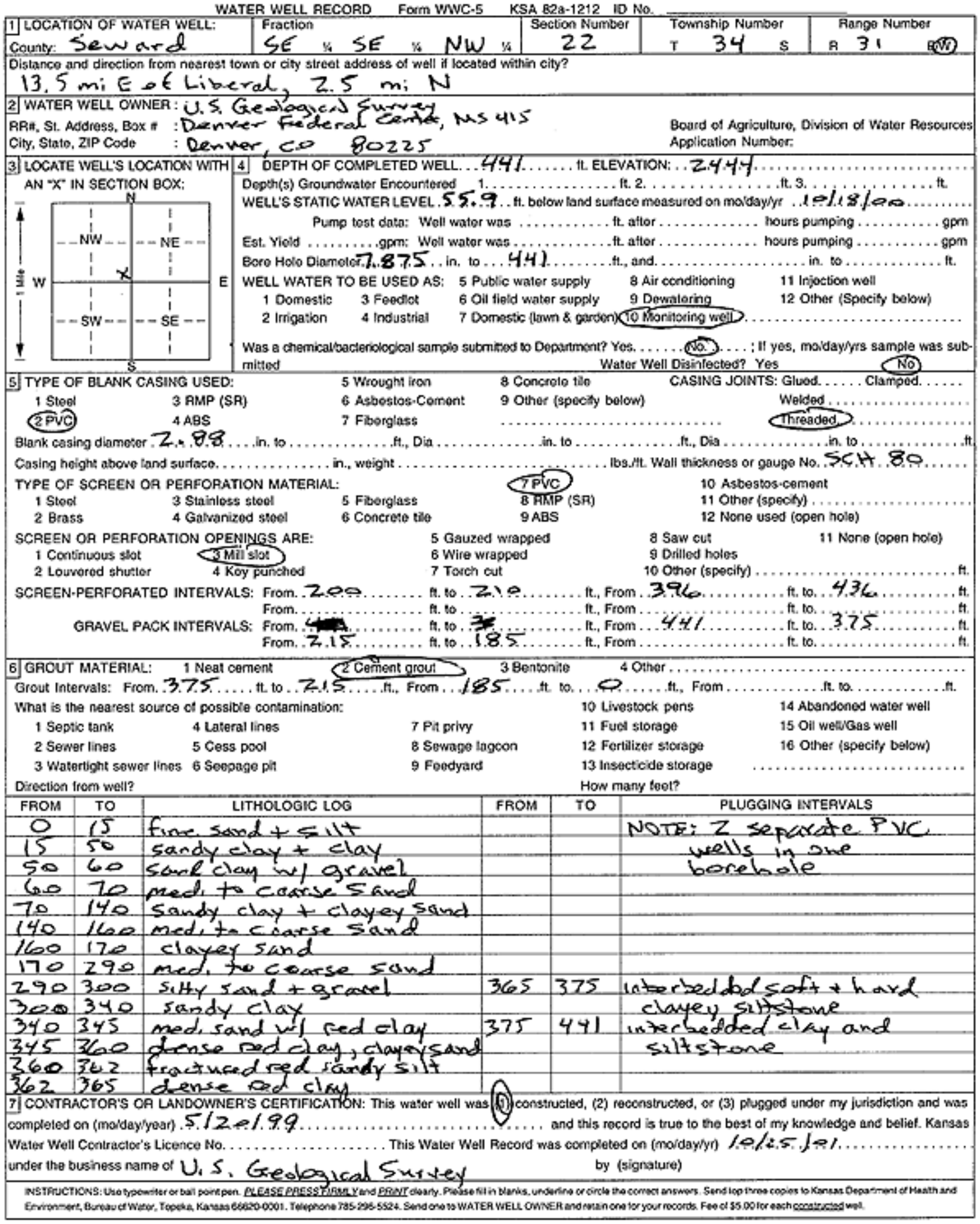
Cimarron 210 – 2.5 in Sch80 casing and screen – shallower of two wells in same borehole.

Screened Interval: 200–210 ft below land surface
Gravel Pack Interval: 185–215 ft below land surface
Grout Interval: 0–185 ft below land surface



WATER WELL RECORD Form WWC-5 KSA 82a-1212 ID No.

1 LOCATION OF WATER WELL:
County: Seward
Fraction: SE ¼ SE ¼ NW ¼
Section Number: 22
Township Number: T 34 S
Range Number: R 31 [✓ W]

Distance and direction from nearest town or city street address of well if located within city?
13.5 mi E of Liberal, 2.5 mi N

2 WATER WELL OWNER: U.S. Geological Survey
RR#, St. Address, Box #: Denver Federal Center, MS 415
City, State, ZIP Code: Denver, CO 80225
Board of Agriculture, Division of Water Resources
Application Number:

3 LOCATE WELL'S LOCATION WITH AN "X" IN SECTION BOX:

4 DEPTH OF COMPLETED WELL 441 ft. ELEVATION: 2444
Depth(s) Groundwater Encountered 1. ft. 2. ft. 3. ft.
WELL'S STATIC WATER LEVEL 55.9 ft. below land surface measured on mo/day/yr 10/18/00
Pump test data: Well water was ft. after hours pumping gpm
Est. Yield gpm: Well water was ft. after hours pumping gpm
Bore Hole Diameter 7.875 in. to 441 ft., and in. to ft.
WELL WATER TO BE USED AS: 1 Domestic 2 Irrigation 3 Feedlot 4 Industrial 5 Public water supply 6 Oil field water supply 7 Domestic (lawn & garden) 8 Air conditioning 9 Dewatering [✓ 10 Monitoring well] 11 Injection well 12 Other (Specify below)
Was a chemical/bacteriological sample submitted to Department? Yes [✓ No]; If yes, mo/day/yrs sample was submitted
Water Well Disinfected? Yes [✓ No]

5 TYPE OF BLANK CASING USED: 1 Steel [✓ 2 PVC] 3 RMP (SR) 4 ABS 5 Wrought iron 6 Asbestos-Cement 7 Fiberglass 8 Concrete tile 9 Other (specify below)
CASING JOINTS: Glued Clamped Welded [✓ Threaded]
Blank casing diameter 2.88 in. to ft., Dia in. to ft., Dia in. to ft.
Casing height above land surface in., weight lbs./ft. Wall thickness or gauge No. SCH 80
TYPE OF SCREEN OR PERFORATION MATERIAL: 1 Steel 2 Brass 3 Stainless steel 4 Galvanized steel 5 Fiberglass 6 Concrete tile [✓ 7 PVC] 8 RMP (SR) 9 ABS 10 Asbestos-cement 11 Other (specify) 12 None used (open hole)
SCREEN OR PERFORATION OPENINGS ARE: 1 Continuous slot 2 Louvered shutter [✓ 3 Mill slot] 4 Key punched 5 Gauzed wrapped 6 Wire wrapped 7 Torch cut 8 Saw cut 9 Drilled holes 10 Other (specify) ft. 11 None (open hole)
SCREEN-PERFORATED INTERVALS: From 200 ft. to 210 ft., From 396 ft. to 436 ft.
From ft. to ft., From ft. to ft.
GRAVEL PACK INTERVALS: From [illegible] ft. to [illegible] ft., From 441 ft. to 375 ft.
From 215 ft. to 185 ft., From ft. to ft.

6 GROUT MATERIAL: 1 Neat cement [✓ 2 Cement grout] 3 Bentonite 4 Other
Grout Intervals: From 375 ft. to 215 ft., From 185 ft. to 0 ft., From ft. to ft.
What is the nearest source of possible contamination: 1 Septic tank 2 Sewer lines 3 Watertight sewer lines 4 Lateral lines 5 Cess pool 6 Seepage pit 7 Pit privy 8 Sewage lagoon 9 Feedyard 10 Livestock pens 11 Fuel storage 12 Fertilizer storage 13 Insecticide storage 14 Abandoned water well 15 Oil well/Gas well 16 Other (specify below)
Direction from well? How many feet?

FROM	TO	LITHOLOGIC LOG	FROM	TO	PLUGGING INTERVALS
0	15	fine sand + silt			NOTE: 2 separate PVC
15	50	sandy clay + clay			wells in one
50	60	sand clay w/ gravel			borehole
60	70	med. to coarse sand			
70	140	sandy clay + clayey sand			
140	160	med. to coarse sand			
160	170	clayey sand			
170	290	med. to coarse sand			
290	300	silty sand + gravel	365	375	interbedded soft + hard
300	340	sandy clay			clayey siltstone
340	345	med. sand w/ red clay	375	441	interbedded clay and
345	360	dense red clay, clayey sand			siltstone
360	362	fractured red sandy silt			
362	365	dense red clay			

7 CONTRACTOR'S OR LANDOWNER'S CERTIFICATION: This water well was [✓ (1)] constructed, (2) reconstructed, or (3) plugged under my jurisdiction and was completed on (mo/day/year) 5/20/99 and this record is true to the best of my knowledge and belief. Kansas Water Well Contractor's Licence No. This Water Well Record was completed on (mo/day/yr) 10/25/01 under the business name of U.S. Geological Survey by (signature)

INSTRUCTIONS: Use typewriter or ball point pen. *PLEASE PRESS FIRMLY* and *PRINT* clearly. Please fill in blanks, underline or circle the correct answers. Send top three copies to Kansas Department of Health and Environment, Bureau of Water, Topeka, Kansas 66620-0001. Telephone 785-296-5524. Send one to WATER WELL OWNER and retain one for your records. Fee of $5.00 for each constructed well.

12. APPENDIX B: Interpretation of Water-Level changes in the High Plains Aquifer in Western Kansas

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ABSTRACT

Water-level changes in wells provide a direct measure of the impact of groundwater development at a scale of relevance for management activities. Important information about aquifer dynamics and an aquifer's future is thus often embedded in hydrographs from continuously monitored wells. Interpretation of those hydrographs using methods developed for pumping-test analyses can provide insights that are difficult to obtain via other means. These insights are demonstrated at two sites in the High Plains aquifer in western Kansas. One site has thin unconfined and confined intervals separated by a thick aquitard. Pumping-induced responses in the unconfined interval indicate a closed (surrounded by units of relatively low permeability) system that is vulnerable to rapid depletion with continued development. Responses in the confined interval indicate that withdrawals are largely supported by leakage. Given the potential for rapid depletion of the unconfined interval, the probable source of that leakage, it is likely that large-scale irrigation withdrawals will not be sustainable in the confined interval beyond a decade. A second site has a relatively thick unconfined aquifer with responses that again indicate a closed system. However, unlike the first site, previously unrecognized vertical inflow can be discerned in data from the recovery periods. In years of relatively low withdrawals, this inflow can produce year-on-year increases in water levels, an unexpected occurrence in western Kansas. The prevalence of bounded-aquifer responses at both sites has important ramifications for modeling studies; transmissivity values from pumping tests, for example, must be used cautiously in regional models of such systems.

INTRODUCTION

The High Plains region of the United States hosts some of the most productive irrigated agricultural land in the world owing to the vast Ogallala-High Plains aquifer complex (henceforth, High Plains aquifer [HPA]) that it overlies (Figure 1a). This extensively utilized aquifer provides irrigation and, to a much lesser extent, drinking and industrial water supplies that account for about 23% of all groundwater withdrawals in the United States (Maupin and Barber 2005). Much of the aquifer system, however, is on a fundamentally unsustainable path. Large pumping-induced declines in water levels have called into question the viability of the aquifer as a continuing resource for irrigated agriculture, a linchpin of the region's economy (Dennehy et al. 2002, Waksom et al. 2006, Sophocleous 2010). The future is further clouded by the prospect of climate change; sizable portions of the High Plains region are characterized by relatively steep lateral gradients in climatic variables, indicating the potential vulnerability of the region to the impacts of a changing climate (Rosenberg et al. 1999, 2003; Brunsell et al. 2010; Logan et al. 2010).

Many local, state, and federal agencies have expended significant resources to acquire information about the HPA. As a result, we have a good regional-level understanding of many important aspects of the system (e.g., Dennehy et al. 2002, Buchanan et al. 2009, McGuire 2011, Fross et al. 2012). However, our understanding of how the aquifer responds to groundwater development on the scale of relevance for management activities (several tens to a few hundreds of km^2, henceforth, local scale) is far from complete. Although drillers' logs, various geophysical techniques, and periodic manual water-level measurements provide useful information for water-resources managers, they cannot reliably characterize how the aquifer responds to pumping activity on the local scale. The most direct measure of the impact of local groundwater development is the transient water-level response to pumping. Thus, important information about the effect of nearby development activities and the future viability of that portion of the aquifer is often embedded in hydrographs from continuously monitored wells. Interpretation of those hydrographs can enhance understanding of aquifer behavior and provide insights of considerable practical value.

Hydrographs from continuously monitored wells in the HPA in western Kansas reveal the wide range of behaviors that can occur in this aquifer (Figures 2 and 3). Commonly observed hydrograph characteristics include a modest degree of irrigation-season drawdown and the stabilization of water levels prior to the next irrigation season (Figure 2), significant (tens of meters) drawdown and water levels that continue to recover (incomplete recovery) until the start of the next irrigation season (Figure 3a), and a modest degree of drawdown, incomplete recovery, and an inconsistent pattern (decreases and increases) in year-on-year changes in water level (Figure 3b). The range of characteristics shown in such hydrographs provides important information about the mechanisms that control drawdown, the significance of recharge, the conceptualization of the aquifer that is appropriate for modeling studies, and, most critically, what the future may hold for the HPA in the vicinity of the monitored wells.

The purpose of this paper is to demonstrate the value of insights that can be gleaned from examination of hydrographs from continuously recording monitoring wells. Although a great deal of time, money, and effort is directed at obtaining such hydrographs, much less attention is given to their interpretation. The basic issue we address here is that of how to better use water-level data from continuously monitored wells to obtain information of relevance for local management activities. Our primary focus is on water-level changes produced by the extended period of pumping during the irrigation season; those changes provide an integrated aquifer response to development activities and can reveal the impacts of local characteristics that are difficult to assess otherwise. Water-level changes following the cessation of pumping are also considered, as much useful information can be obtained from this recovery period. Commonly observed water-level fluctuations produced by variations in barometric pressure (e.g., Figures 2 and 3b) and other mechanisms can provide useful information about hydrostratigraphy and well construction (e.g., Spane 2002; Butler et al. 2011), but are not the focus here.

PUMPING-INDUCED CHANGES IN WATER LEVEL

Water-level changes in wells can be produced by a wide variety of mechanisms. However, in aquifers undergoing development, the largest changes are invariably produced by pumping activity (e.g., Figures 2 and 3). Interpretation of those changes can provide critical insights into the long-term prospects for the aquifer in that vicinity. In the following sections, we demonstrate the nature of the insights that can be gained from hydrographs at two sites in the HPA in western Kansas. The aquifer at these sites consists of a heterogeneous sequence of sand and gravel interspersed with clay and silt deposited primarily during the Tertiary Period by streams that carried sediments eastward from the Rocky Mountains. Some horizons within the HPA sediments are cemented by calcium carbonate to form caliche beds (Gutentag et al. 1984).

The Haskell (HS) Site

The HS site (37.66 N latitude, 100.66 W longitude) is located in Haskell County in southwestern Kansas (Figure 1a) in an area of high irrigation-well density (see Stotler et al. [2011] for aerial photos) and groundwater use (average annual use for 2007-10 over a 32.5 km^2 circular area centered on the Haskell index well [well HS-IW in Figure 1b] was 10.76x10^6 m^3 [equates to an areal average water depth of 0.33 m]). The site has a semiarid climate with an average annual precipitation of 0.52 m and an average annual reference evapotranspiration (rate of evapotranspiration expected for grass of uniform height, actively growing, well-watered, and completely shading the ground; rate estimated from the Kansas State University network of meteorological stations) of 2.07 m (KSRE 2012, Fross et al. 2012); the area is flat with no significant surface runoff. The HPA hydrostratigraphy in the vicinity of the site consists of an unconfined sand and gravel interval, which is steadily diminishing in saturated thickness, overlying a thick clay aquitard that overlies a thin confined sand and gravel interval on top of bedrock (Figure 1b). The bedrock is the Dakota Formation, which consists of shales with scattered sandstone lenses in this area. The sandstone lenses are tapped for fresh-water supplies, although to a much lesser extent than the overlying HPA. Wells in the HPA in this area are primarily screened in the unconfined interval, the confined interval, or both. However, even when the well is only screened in the confined interval, the gravel pack extends to near land surface in virtually all wells other than well HS-IW. As would be expected, the pumping-induced responses observed in wells at the HS site vary dramatically between wells screened in the unconfined interval and those screened in the deeper confined interval.

Wells in Unconfined Interval

Hydrographs (Figure 2) from a pumping well (HS-20, see Figure 1b) and a nearby observation well (HS-8), both of which are screened only in the unconfined interval, illustrate characteristics that are common to hydrographs from many of the wells screened only in that interval at the HS site. First, despite the numerous irrigation wells in the unconfined interval in the vicinity of this well pair, every change in water level at HS-8 is associated with pumping at HS-20; no other pumping well appears to be affecting the water level at HS-8. Second, although well HS-20 is pumped nearly continuously for the 70-day irrigation season, water levels in the two wells recover in just over two weeks, a small fraction of the duration of pumping. Third, after the short recovery period, no further changes in water level occur at either well beyond small-amplitude fluctuations produced primarily by variations in barometric pressure.

These three characteristics are indicative of pure groundwater mining, i.e. all water pumped at HS-20 is being removed from storage in the sands and gravels in the vicinity of the well pair; lateral flow from more distant regions and vertical inflow are insignificant over the time frame of seasonal irrigation pumping. The first two characteristics indicate that the permeable materials in which the wells are screened pinch out or are truncated by units of relatively low permeability in all directions, i.e. these materials function as a small closed-system (compartmentalized) aquifer. The very short, relative to the pumping period, duration of recovery, despite the continuing drawdown throughout the pumping period, is particularly diagnostic in this regard, as the time to recovery in an unbounded aquifer is typically a few multiples of the duration of pumping. Finally, the stabilization of water levels after the short recovery period indicates that vertical inflow is essentially negligible.

The limited lateral extent of the sands and gravels, which is not unexpected in the fluvial depositional setting characteristic of the HPA, can be explored in more detail using pumping-test interpretation methods (e.g., Streltsova 1988, Kruseman and de Ridder 1990). The near-continuous pumping at HS-20 over the irrigation season can be viewed as a long-term pumping test, enabling water-level changes during this period to be interpreted as pumping-induced drawdown. Figure 4a is a plot of the drawdown at HS-8 versus the logarithm of the time since pumping began at HS-20 (for this analysis, pumping is assumed to start at time A on Figure 2 and end at time B). In an aquifer of infinite lateral extent, drawdown, after a relatively short period of pumping, will fall on a straight line in this plotting format, an indication of large-scale radial flow to the pumping well. In this case, however, the semilog linear relationship only persists through the first four to five days of pumping. After that time, drawdown increases at a more rapid rate, an indication that the cone of depression has reached the boundary of the aquifer in one or more directions. The increasing rate of deviation from the straight line is an indication that at least two no-flow boundaries have been reached, as a single linear boundary would produce a straight line with twice the slope of the first (Kruseman and de Ridder 1990).

Previous work has found that if an aquifer is surrounded by units that act as no-flow boundaries over the time frame of the pumping period (i.e. a bounded (compartmentalized) aquifer), a plot of drawdown versus time will be a straight line after the cone of depression has reached the boundary of the aquifer in all directions (Streltsova 1988). The drawdown at HS-8 falls on such a straight line after about 15 days of pumping (Figure 4b), an indication that the sands and gravels are acting as a closed system. Thus, the conclusions derived from a detailed examination of water-level changes during the irrigation season are consistent with those obtained from the general hydrograph characteristics discussed earlier. Note that the rapid recovery illustrated in the hydrograph of Figure 2 is a result of this linear-in-time relationship (Figure 4b). Water-level changes during the recovery period can be modeled by the superposition of a pumping well and an imaginary recharge well (Kruseman and de Ridder 1990). In this case, the absolute magnitude of the rate of water-level change in both wells will be equal once the recharge cone has reached the aquifer boundaries in all directions, producing the rapid stabilization of water levels. In an unbounded aquifer, however, drawdown is logarithmic in time, leading to an asymptotic approach to recovery over a much longer time period.

The lateral extent of the sands and gravels can be estimated from the slope ($\Delta s/\Delta t$, where s is drawdown and t is time since pumping began) of the straight line on Figure 4b using a general relationship that has its origins in an analytical solution presented by Muskat (1937) for drawdown in a circular, laterally bounded aquifer (Streltsova 1988):

$$\frac{\Delta s}{\Delta t} = \frac{Q}{S_y A_s}$$

(1)

where Q is the pumping rate [L^3/T], S_y is the specific yield of the unconfined aquifer [-], and A_s is the aquifer area [L^2].

Equation (1) can be rearranged to solve for A_s. Given the slope and pumping rate in the Figure 4 caption and a specific yield estimate of 0.22 determined from a Cooper-Jacob analysis (Kruseman and de Ridder 1990) of the HS-8 drawdown, an area of

1.09×10^6 m^2 is calculated for the bounded aquifer (for an ideal circular aquifer, this results in a radius of 589 m). Although the configuration of the sands and gravels is unknown, the key finding is that these materials are limited in lateral extent.

The area of the aquifer can also be estimated from the hydrograph of Figure 2 using a mass balance expression:

$$WU = S_y A_s \Delta s_{is} \tag{2}$$

where WU and Δs_{is} are the total water use [L^3] and the water-level change [L] over the irrigation season, respectively. Using the reported 2007 WU for well HS-20 of 2.73×10^5 m^3, the Δs_{is} of 1.246 m calculated from Figure 2 (difference between water levels [24-hr averages] on April 15 and November 15), and the same S_y as before (0.22), an aquifer area of 1.00×10^6 m^2 is calculated, which is in excellent agreement (within 9%) of that found with equation (1).

Virtually all of the wells screened only in the unconfined interval at the HS site display some variant of closed-system behavior. However, hydrographs from observation wells will differ in form depending on the position of the well relative to the pumping well and the aquifer boundaries. If the observation well is relatively close to the pumping well (closer than point A on Figure 5), water levels will rise up to the final water-table position upon cessation of pumping, similar to well HS-8 in Figure 2. If the observation well is relatively far from the pumping well (further than point A on Figure 5), water levels will continue to fall until the final water-table position is reached. In some of the wells in the unconfined interval, small water-level changes highly correlated with pumping in the confined interval are superimposed on the much larger closed-system response. These additional changes appear to be produced primarily by flow down wells that are screened in both intervals or by flow down gravel packs of wells screened only in the confined interval.

The compartmentalized nature of the unconfined sands and gravels, which is not unexpected given the depositional setting and the downward hydrostratigraphic transition from a sequence dominated by sand and gravel (channel deposits) to one dominated by clay and silt (interchannel floodplain deposits), has important implications for their continued viability as a water source for irrigated agriculture. The amount of water that ultimately can be withdrawn from these materials is essentially determined by the volume of water stored in them; the rate of lateral or vertical inflow is too small for those mechanisms to be major contributors on the time frame of a few to several years. Given the screened interval (771-795 m elevation) and the average yearly decline (about 1.2 m/yr) at well HS-20, and assuming the pump intake is at the base of the screened interval, the current rate of pumping will be unsustainable within a decade, if not sooner. Reductions in pumping at HS-20, however, would extend the "lifespan" of the resource by the percentage of those reductions because of the absence of other wells pumping from these sands and gravels, i.e. the "common pool" in this case has only one member (pumping well HS-20). Although management activities can significantly and predictably alter decline rates in such closed systems, the small degree of lateral and vertical inflow is the ultimate limitation on the long-term sustainability of the resource.

Wells in Confined Interval

The multi-year hydrograph from an observation well (Haskell index well [HS-IW]) screened only in the confined interval (Figure 3a) illustrates the large drawdown and incomplete recovery that are characteristics of hydrographs from many of the wells screened only in this interval. Not one of the monitored wells screened only in the confined interval exhibits the very short recovery period seen in wells in the overlying unconfined aquifer.

Conditions in the confined interval can be explored in more detail using pumping-test interpretation methods. An examination of hydrographs from wells at the HS site reveals that the water-level drop at A on Figure 3a appears to be produced by a relatively short (5.3 d) period of pumping at a single well in the confined interval (well HS-1, the closest pumping well [distance of 752 m, Figure 1b] to well HS-IW). Thus, water-level changes at HS-IW during this period can be viewed as drawdown resulting from a multi-day pumping test. This drawdown (not shown) exhibits a short (0.5 d) radial-flow period after which the rate of change decreases below that expected for radial flow (opposite direction from deviation of Figure 4a), an indication of pumping-induced inflow to the aquifer. The source of this inflow is most likely downward flow of water from the overlying units, but upward flow from the underlying bedrock could also be contributing. Although the pumping period ends before water levels stabilize, Van der Kamp (1989) developed a method for calculation of the drawdown that would have occurred if the pumping had continued (i.e. the method “extends” the period of pumping-induced drawdown). Figure 6 is a plot of drawdown at HS-IW versus time since pumping began at well HS-1 that includes the values calculated with the Van der Kamp drawdown extension. In this case, it appears that drawdown would have stabilized with continued pumping. Thus, the entire amount pumped from well HS-1 would have eventually been supplied by pumping-induced inflow (leakage) to the confined interval.

This leakage-dominated response to pumping at a single well is consistent with the hydrograph of Figure 3a. Although pumping at well HS-1 produces only 4 m of drawdown at HS-IW, much more drawdown occurs during the irrigation season because of well interference, i.e. cones of depression from multiple pumping wells interact with one another to increase drawdown to more than 35 m. The interference-enhanced drawdown continues to increase until it is large enough to induce sufficient leakage to significantly slow the rate of decline and, in certain years (2009 and 2010), appears to nearly balance pumping withdrawals in the latter portion of the irrigation season. This pumping-induced leakage is also undoubtedly responsible for the relative stability of the minimum observed water level in the first two-thirds of the monitoring period (Figure 3a). None of the hydrographs from wells screened in the confined interval exhibit the closed-system behavior observed in the overlying unconfined interval.

The leaky-aquifer response of the confined sands and gravels has important implications for the continued viability of these materials as a water source for irrigated agriculture. Pumping withdrawals from this interval appear to be heavily dependent on downward leakage from the overlying units. However, as indicated in the previous section, the unconfined aquifer will be largely dewatered in a relatively few years; at that point, the leakage will be drawn from water stored in the aquitard and, possibly, from the underlying shales and scattered sandstones. It is unclear whether those units can yield water at a sufficient rate to meet irrigation-season demands. Thus, it is likely that drawdown will continue to increase until the pumping wells have an insufficient saturated thickness of permeable sediments to meet demands. The severity of the situation is demonstrated by the height of the water column at well HS-IW. Although this well is screened at the bottom of the aquifer and is over 750 m from the closest pumping well, the water column was less than 12 m in height at the peak of irrigation pumping for 2011. In the immediate vicinity of the pumping wells, the column height must have been considerably less. Given that pumping from the confined interval will undoubtedly increase as shallower wells in the depleted unconfined sands and gravels are deepened, it is likely that large-scale irrigation withdrawals will not be sustainable beyond the current decade in the vicinity of the HS site, except, possibly, in those wells that are also completed in the scattered sandstones of the underlying Dakota Formation. Despite the relatively large drawdown in both the unconfined and confined aquifers at the HS site, there has been little change in annual irrigation withdrawals; average water use for the decade preceding the monitoring period ($11.16\text{x}10^6$ m^3) is just slightly (<4%) greater than that of the monitoring period.

The Thomas (TH) Site

The TH site (39.23 N latitude, 101.02 W longitude) is located in Thomas County in northwestern Kansas (Figure 1a) in an area of moderate well density (see Stotler et al. [2011] for aerial photos) and groundwater use (average annual use for 2007-10 over 32.5 km^2 circular area centered on the Thomas index well [well TH-IW in Figure 1b] was $3.05\text{x}10^6$ m^3 [areal average water depth of 0.09 m]). The site is semiarid in climate with an average annual precipitation of 0.51 m and an average annual reference evapotranspiration of 1.93 m (KSRE 2012, Fross et al. 2012); the area is flat with no significant surface runoff. The HPA hydrostratigraphy in the vicinity of the site consists of an interbedded mix of coarse gravels through clays on top of primarily shale (Pierre

Formation) bedrock (Figure 1b); there are no fresh-water aquifers below the HPA in this vicinity. Water-level responses to pumping and changes in barometric pressure indicate that the saturated unconsolidated interval at the TH site acts as an unconfined aquifer.

The multi-year hydrograph (Figure 3b) from an observation well (Thomas index well [TH-IW]) screened at the bottom of the unconsolidated interval illustrates characteristics that appear to be common to many wells in this portion of the HPA (Stotler et al. 2011). First, the maximum drawdown is modest (1.2-1.8 m at this well) as a result of the unconfined nature of the aquifer. Second, a thick "noise" band is evident as a result of water-level responses to fluctuations in barometric pressure (deep water-table response [Weeks 1979]). Third, although the recovery period is very long (e.g., ended in late June in both 2009 and 2010), there is no indication that the water levels are nearing stabilization at the onset of pumping for the next irrigation season. Fourth, unlike any of the monitored wells at the HS site, a year-on-year increase (2009 to 2010) in the maximum observed water level occurred during the monitoring period. These last two characteristics are particularly noteworthy and strongly hint at the possibility of a source of inflow to the HPA at this site.

The TH-IW hydrograph indicates that an isolated pumping event occurred in March of 2009 (point A on Figure 3b). An expanded view of water levels in late winter to spring 2009 reveals a relatively short (6.8 d) pumping period superimposed on a near-linear recovery trend (Figure 7). In contrast to expectations for an unbounded aquifer, water levels do not return to the trend line during the recovery period. One explanation for the failure to return to the trend line is that the aquifer is laterally bounded on all sides by units of relatively low permeability (i.e. a closed system). This explanation is supported by removing the linear trend from the water-level data; the resulting plot (not shown) bears a striking similarity to the HS-8 hydrograph (Figure 2).

Conditions in the unconfined aquifer can be explored further by considering the 2010 irrigation season (the year with the most continuous pumping) as a long-term pumping test beginning at point B on Figure 3b. A plot of drawdown at well TH-IW versus the time since pumping began (Figure 8) shows that drawdown falls on a straight line for over 35 days, a clear indication of a compartmentalized (closed-system) aquifer. Thus, the conclusions derived from an examination of a single pumping event (Figure 7) are consistent with those obtained from the assessment of the entire pumping season (Figure 8). Note that after 45 days of pumping, drawdown becomes more variable as a result of pumps cutting on and off. Even in this period, however, water levels that are offset from, but nearly parallel to, the drawdown trend are observed prior to the cessation of widespread irrigation pumping (point R marks the end of widespread pumping and the beginning of the seasonal recovery).

Water-level responses that exhibit closed-system behavior (linear responses at moderate to large times of pumping) can be, in certain situations, the product of human activity (i.e. nearby pumping) rather than the result of the juxtaposition of units of vastly differing permeability. Although the turning on and off of multiple pumping wells can be observed in the hydrograph from well TH-IW (Figure 3b), the consistency of the water-level response to a single short-term pumping event (Figure 7), which was likely produced by pumping at a single well, and to the entire irrigation season (Figure 8), which is produced by pumping at multiple wells, indicates that the sand and gravel units in which the TH-IW well is screened are likely laterally bounded by units of relatively low permeability. However, unlike the unconfined interval at the HS site, the “common pool” in this case appears to have multiple members (pumping wells).

Given that the aquifer acts as a closed system at the TH site over the time frame of pumping periods, one would expect a very rapid recovery, as in the unconfined interval at the HS site (Figure 2). However, in contrast to those conditions, water levels at well TH-IW continue to rise until the onset of pumping for the next irrigation season (Figure 3b). Thus, there is a marked inconsistency between the water-level changes during the pumping period, which indicate a bounded-aquifer response with no lateral flow from more distant regions, and those during the recovery period, which indicate an inflow to the aquifer. The most likely explanation for this apparent inconsistency is that there is a relatively steady vertical inflow throughout the year to the unconfined aquifer at the TH site.

A closer look at the water-level data from well TH-IW can shed some light on mechanisms controlling responses during the recovery period. We have found that a useful approach for assessing such mechanisms is to superimpose recovery data from multiple years; this is done by setting both the time and water-level elevation at the start of each recovery period to zero (Figure 9). The two recovery periods used in Figure 9 were chosen because of the large differences in the preceding irrigation seasons; the 2008 irrigation season was nearly twice as long (with almost 50% more pumping) as the 2009 season (Stotler et al. 2011) because of the greater precipitation in 2009. The agreement between the superimposed recovery plots is clear; the rates of water-level change during the two periods are essentially identical. The near-coincidence of recovery rates indicates that the recovery is not a function of withdrawals or precipitation during the previous irrigation season; some other mechanism beyond pumping-induced flow or recharge of recent precipitation must be the primary control on recovery. A similar agreement is seen when the 2007-08 and 2010-11 periods are included, a further indication that a mechanism beyond pumping or precipitation in the previous irrigation season is responsible for the rise of water levels during the recovery period. Given the near-coincidence of recovery rates from different years, the increase in the maximum observed water level from 2009 to 2010 (Figure 3b) is simply a result of the relatively high water-level elevation at the end of the 2009 irrigation season and the subsequent lengthy period of recovery (298 days). If the 2007-08 recovery, which began at essentially the same water-level elevation, had extended to 298 days instead of ending 50 days earlier, a similar maximum water level would have been attained. Likewise, if the 2010-11 recovery had been the same length as that of 2009-10, a maximum water level close to that of the 2009-10 recovery would have been attained.

At least two mechanisms can be invoked to explain the near-coincidence of recovery rates. One possibility is downward flow that originated as irrigation return flow or irrigation-enhanced recharge. The water-level change during recovery is not consistent with previous recharge studies in western Kansas (e.g., Sophocleous 2005), but that could be a result of the time needed for the recharge associated with irrigation to traverse the thick (60+ m) vadose zone, i.e. previous studies were completed prior to the time at which the full impact of irrigation activities could be detected. In this case, the consistency in recovery rates between years could be a product of homogenization of year-to-year variations in surface inflow during the lengthy passage through the vadose zone (e.g., Sophocleous 2005). A second possibility is inflow produced by the drainage of overlying low-permeability units induced by a falling water table. This drainage could combine with irrigation return flow to produce consistent recovery rates over the monitoring period. The possibility of upward vertical flow of older water due to pumping-induced head changes in the HPA is less likely because of the low permeability of the underlying shale. Ongoing studies of the hydrogeochemistry of the HPA in the vicinity of the TH site should help identify which mechanisms are the major contributors to the inflow.

The importance of the inflow into the HPA at the TH site can be demonstrated through a simple water-balance calculation. Over the monitoring period at the TH site, water levels have been relatively stable from year to year (Figure 3b). The annual withdrawals from the HPA in this vicinity thus appear to be balanced by the inflow. Given the average reported water use for the TH site over this period ($3.05 \text{ x}10^6 \text{ m}^3$ for the 32.5 km^2 area centered on the site) and a rate of water-level change of about 1.0 m/yr estimated from the rate of recovery between days 135 and 270 on Figure 9, equation (2) can be used to calculate a S_y of 0.09, which appears plausible for the sediments in the vicinity of the water table at the TH site (Figure 1b). Although the inflow appears to be balancing the withdrawals over the period of Figure 3b, a return to the average water use for the decade preceding the monitoring period ($4.60\text{x}10^6 \text{ m}^3$) would produce an annual water-level decline exceeding 0.5 m. Note that the estimated inflow rate of 0.09 m/yr (rate of water-level change multiplied by S_y) is many times the estimated annual recharge rate for the HPA in western Kansas (e.g., Sophocleous 2005) and near the maximum recharge rate reported by Scanlon et al. (2010) for HPA areas under cultivation in Texas with coarse-textured soils and relatively shallow depths to water.

The inflow observed at the TH site during the recovery period does not appear to be isolated to that immediate area. The similarity between the hydrograph from TH-IW and those from short monitoring periods at additional wells in northwest Kansas (Stotler et al. 2011, unpublished data) indicates that inflow from a yet-to-be-identified source, which is not influenced by annual irrigation pumping or precipitation, appears to be widespread over portions of northwest Kansas. The identification of that source is critical for reliable assessment of the future of the HPA in those areas.

DISCUSSION AND CONCLUSIONS

This work demonstrates the practical value of the insights that can be gained from the interpretation of hydrographs from continuously recorded monitoring wells. Although the focus here is on hydrographs from two sites in the High Plains aquifer of western Kansas, the general approach is applicable at any site. Assessment of water-level changes during both pumping and recovery periods can provide important insights into factors such as the mechanisms controlling aquifer behavior, the significance and source of recharge, and the long-term prospects for the aquifer in the vicinity of the monitored wells.

The HPA is a critical economic resource for western Kansas and the adjoining multi-state region. Interpretation of the hydrographs from the Haskell site in southwestern Kansas indicates that the aquifer will have great difficulty in meeting irrigation-season demand in the vicinity of that site beyond this decade. Conditions at the Thomas site in northwestern Kansas appear less dire. Although water levels have been drawn down over 20 m since the onset of large-scale irrigation pumping, assessment of hydrographs from the Thomas site and other wells in the general area indicate a previously unrecognized vertical inflow to the aquifer in that vicinity. Identification of the source of that inflow is critical for determining the long-term prospects of the High Plains aquifer in that portion of northwestern Kansas.

A common assumption invoked for modeling of regional aquifers, such as the HPA, is that transmissivity estimates from pumping tests are representative of conditions over much larger volumes of the aquifer than those directly affected by the tests themselves. However, the water-level data considered here indicate that portions of the aquifer in the vicinity of both sites appear to consist of transmissive “pods” that are separated by much less permeable sediments. In regional-scale models of such settings, transmissivity values determined from pumping tests (e.g., from the slope of the straight line on Figure 4a) must be used cautiously because they do not reflect the less transmissive intervals (between the “pods”) that may well be the primary control on regional-scale flow in such systems. Thus, a strong emphasis on honoring transmissivity estimates from pumping tests may not be appropriate for modeling investigations of portions of the HPA in western Kansas and other regional aquifer systems. In the absence of hydrographs from continuously monitored wells, modeled annual or seasonal head changes much smaller than observed changes may be one indication of such a “patchy” aquifer system.

A key element of the approach described here is the application of pumping-test interpretation methods to hydrographs from continuously monitored wells. In aquifers experiencing a strong seasonal pattern of extraction driven by irrigation demands, such as the HPA, the water-level response to the extended pumping period can be interpreted as pumping-induced drawdown. This allows us to draw upon the large body of work in the well-hydraulics literature; this previous work has proven particularly useful for identifying aquifer boundaries that will have a critical control on long-term well yields. Such boundaries are often difficult, if not impossible, to identify from the results of the typical short-term pumping test (Butler 2009).

Continuous monitoring of water levels has significant advantages over periodic manual measurements. Periodic measurements can provide information on long-term temporal trends in water levels and serve as the basis for important synoptic regional-level assessments of an aquifer. However, as shown here, we should be getting more from our monitoring networks. Thus, selected wells in networks used for periodic measurements should be instrumented for continuous monitoring so that the aquifer response to development activities can be more reliably evaluated. The resulting insights into important practical issues, such as where the extracted water is coming from and what the future might hold for the aquifer in that vicinity, will be difficult to obtain via other means.

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REFERENCES

Bohling, G.C., and B.B. Wilson. 2011. Statistical and geostatistical analysis of the Kansas High Plains water table elevations, 2011 measurement campaign. *Kansas Geological Survey Open-File Rept. 2011-16*.

Bohling, G.C., W. Jin, and J.J. Butler, Jr. 2011. Kansas Geological Survey Barometric Response

Function software user's guide. *Kansas Geological Survey Open-File Report 2011-10* http://www.kgs.ku.edu/HighPlains/OHP/index_program/brf.html (accessed July 29, 2012).

Brunsell, N.A., A.R. Jones, T.L. Jackson, and J.J. Feddema. 2010. Seasonal trends in air temperature and precipitation in IPCC AR4 GCM output for Kansas, USA: Evaluation and implications. *International Journal of Climatology* 30, no. 8: 1178-1193, doi: 10.1002/joc.1958.

Buchanan, R.C., R.R. Buddemeier, and B.B. Wilson. 2009. The High Plains Aquifer. *Kansas Geological Survey Public Information Circular 18* http://www.kgs.ku.edu/Publications/ pic18/index.html (accessed July 29, 2012).

Buddemeier, R.W., R. Stotler, J.J. Butler, Jr., W. Jin, K. Beeler, E. Reboulet, P.A. Macfarlane, S. Kreitzer, D.O. Whittemore, G. Bohling, and B.B, Wilson. 2010. High

Plains aquifer calibration monitoring well program: Third year progress report. *Kansas Geological Survey Open-File Rept. 2010-3* http://www.kgs.ku.edu/Hydro/Publications/2010/OFR10_3/ofr2010_3.pdf (accessed July 29, 2012).

Butler, J.J., Jr. 2009. Pumping tests for aquifer evaluation – Time for a change? *Ground Water* 47, no. 5: 615-617.

Butler, J.J., Jr., W. Jin, G.A. Mohammed, and E.C. Reboulet. 2011. New insights from well responses to fluctuations in barometric pressure. *Ground Water* 49, no. 4: 525-533.

Dennehy, K.F., D.W. Litke, and P.B. McMahon. 2002. The High Plains aquifer, USA: Groundwater development and sustainability. In: K.M. Hiscock, M.O. Rivett, R.M Davison (eds) Sustainable groundwater development. *Geological Society of London Special Publication 193*: 99-119.

Fross, D., M. Sophocleous, B.B. Wilson, and J.J. Butler, Jr. 2012. *Kansas High Plains Aquifer Atlas*, Kansas Geological Survey http://www.kgs.ku.edu/HighPlains/OHP/index.shtml (accessed July 30, 2012).

Gutentag, E.D., F.J. Heimes, N.C. Krothe, R.R. Luckey, and J.B. Weeks. 1984. Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New

Mexico, Oklahoma, South Dakota, Texas, and Wyoming. *U.S. Geological Survey, Professional Paper 1400-B*, 63 p.

Kruseman, G. P., and N. A. de Ridder. 1990. *Analysis and Evaluation of Pumping Test Data – ILRI Pub. 47*. The Netherlands: International Institute for Land Reclamation and Improvement.

KSRE. 2012. *Weather Data Library*. Kansas State University Research and Extension http://www.ksre.ksu.edu/wdl (accessed July 27, 2012).

Logan, K.E., N.A. Brunsell, A.R. Jones, and J.J. Feddema. 2010. Assessing spatiotemporal variability of drought in the US central plains. *Journal of Arid Environments* 74, no. 2: 247-255, doi: 10.1016/j.jaridenv.2009.08.008.

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

McGuire, V.L. 2011. Water-level changes in the High Plains aquifer, predevelopment to 2009, 2007-08, and 2008-09, and change in water in storage, predevelopment to 2009. *U.S. Geological Survey Scientific Investigations Report 2011-5089*.

Miller, R.D., R.C. Buchanan, and L. Brosius. 1998. Measuring water levels in Kansas. *Kansas Geological Survey Public Information Circular 12* http://www.kgs.ku.edu/Publications/pic12/ pic12_1.htm (accessed July 29, 2012).

Muskat, M. 1937. *The Flow of Homogeneous Fluids Through Porous Media*. New York: McGraw Hill.

Rosenberg, N.J., D.J. Epstein, D. Wang, L. Vail, R. Srinivasan, and J.G. Arnold. 1999. Possible impacts of global warming on the hydrology of the Ogallala aquifer region. *Climatic Change* **42**: 677-692.

Rosenberg, N.J., R.A. Brown, R.C. Izaurralde, and A.M. Thomson. 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.

Scanlon, B.R., R C. Reedy, and J.B. Gates. 2010. Effects of irrigated agroecosystems: (1) Quantity of soil water and groundwater quantity in the Southern High Plains, Texas. *Water Resour. Res.* 46, W09537, doi:10.1029/2009WR008427.

Sophocleous, M. 2005. Groundwater recharge and sustainability in the High Plains aquifer in Kansas, USA. *Hydrogeology Journal* 13, no. 2: 351-365.

Sophocleous, M. 2010. Review: groundwater management practices, challenges and innovations in the High Plains aquifer USA – lessons and recommended actions. *Hydrogeology Journal* 18: 559-575.

Spane, F.A. 2002. Considering barometric pressure in ground-water flow investigations. *Water Resour. Res.* 38, no. 6: 10.1029/2001WR000701.

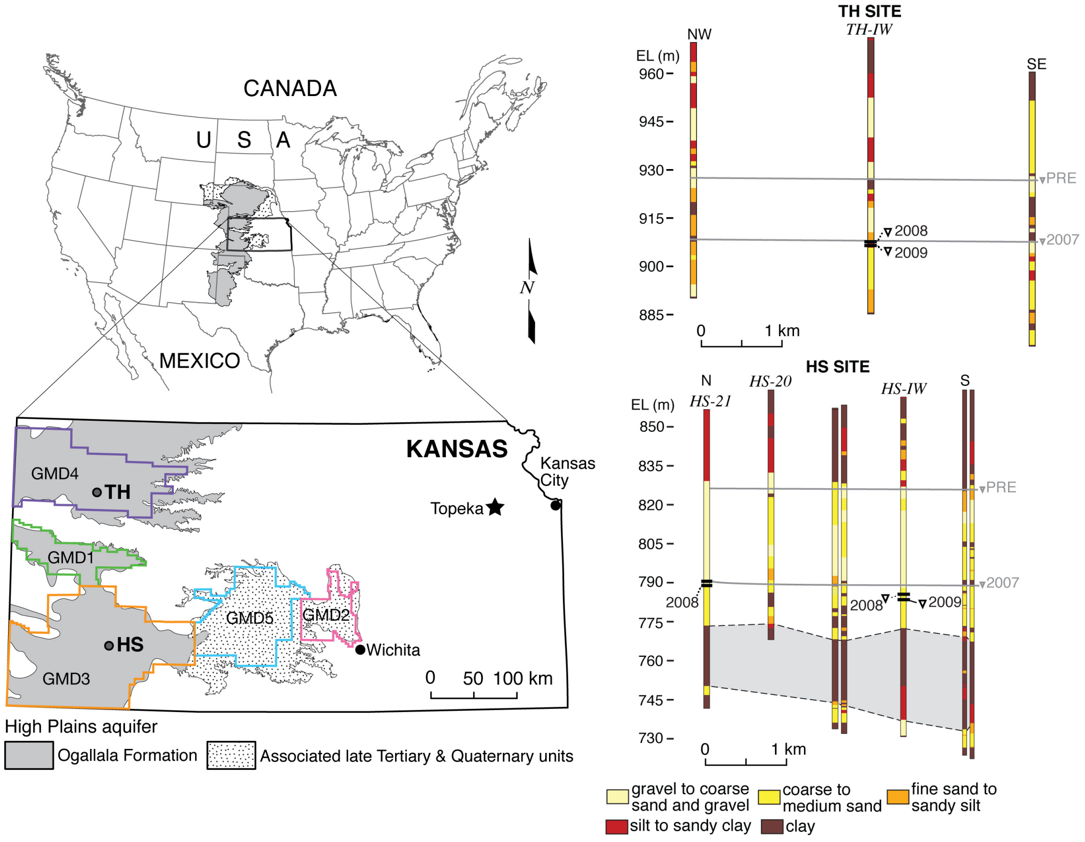
Stotler, R., J.J. Butler, Jr., R.W. Buddemeier, G.C. Bohling, S. Comba, W. Jin, E. Reboulet, D.O. Whittemore, and B.B. Wilson. 2011. High Plains aquifer calibration monitoring well program: Fourth year progress report. *Kansas Geological Survey Open-File Rept. 2011-4* http://www.kgs. ku.edu/Hydro/Publications/2011/OFR11_4/KGS-OFR-2011-4.pdf (accessed July 29, 2012).

Streltsova, T.D. 1988. *Well Testing in Heterogeneous Formations*. New York: Wiley.

Van der Kamp, G. 1989. Calculation of constant-rate drawdowns from stepped-rate pumping tests. *Ground Water* 27, no. 2: 175-183.

Waksom, R., J. Pritchett, and J. Schneekloth. 2006. Outlook on the High Plains aquifer: What's in store for irrigated agriculture? *Great Plains Soil Fertility Conference, Proceedings*, Denver, CO, March 2006, pp 122-128.

Weeks, E.P. 1979. Barometric fluctuations in wells tapping deep unconfined aquifers. *Water Resour. Res.* 15, no. 5: 1167-1176



a) b)

Figure 1 – a) Location map for the High Plains aquifer (HPA) in the United States and Kansas (inset). The HPA consists of the Ogallala Formation (Ogallala aquifer) and associated late Tertiary and Quaternary units. Kansas inset also shows the portions of the HPA in Kansas that are overlain by groundwater management districts (GMDs), TH and HS indicate the locations of the two field sites discussed here (after Sophocleous 2010); b) Sediment characteristics from drillers' logs (not to scale) at the two field sites (elevation above mean sea level abbreviated by EL). Other than HS-20, these logs terminate at or near the bottom of the HPA. Shaded interval between logs at HS site is the aquitard unit discussed in text. "PRE" denotes the water level prior to onset of large-scale irrigation pumping; individual years denote the water levels manually measured in January of that year as part of the annual water-level measurement program in Kansas (Miller et al. 1998, Bohling and Wilson 2011). The PRE and 2007 water levels at the TH site are interpolated values from nearby annual measurement wells; the PRE and 2007 water levels at the HS site are based on a single well (HS-21) because of the fewer annual measurement wells in that vicinity. The 2008 and 2009 values are based on measurements at the indicated well. Well HS-1 is just east of the two middle logs in the HS site cross-section.

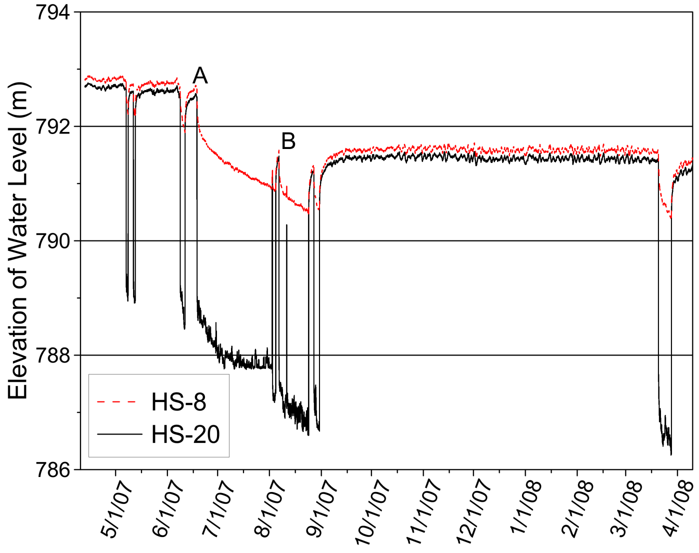
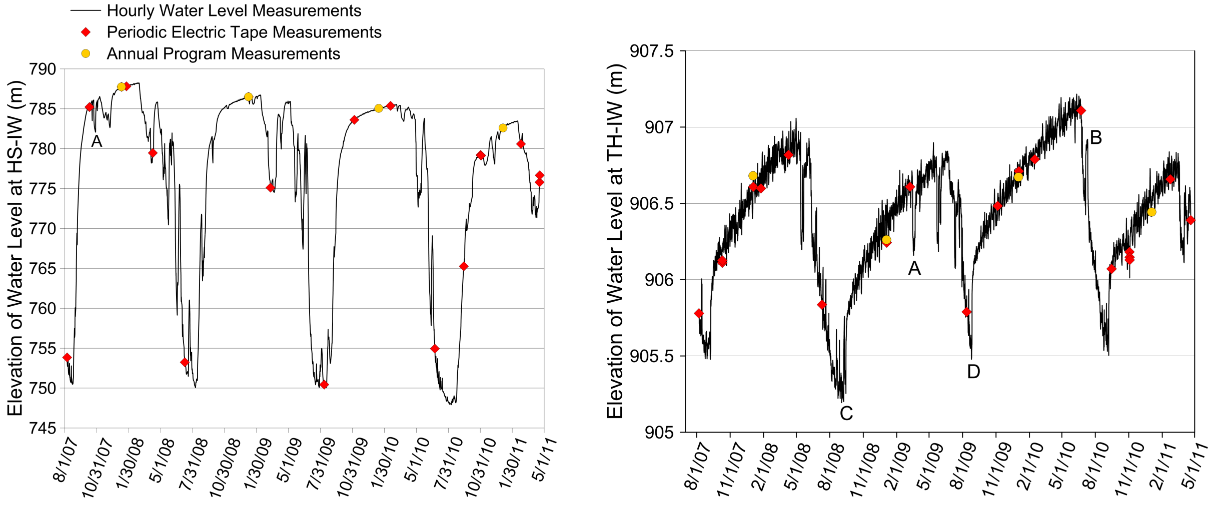
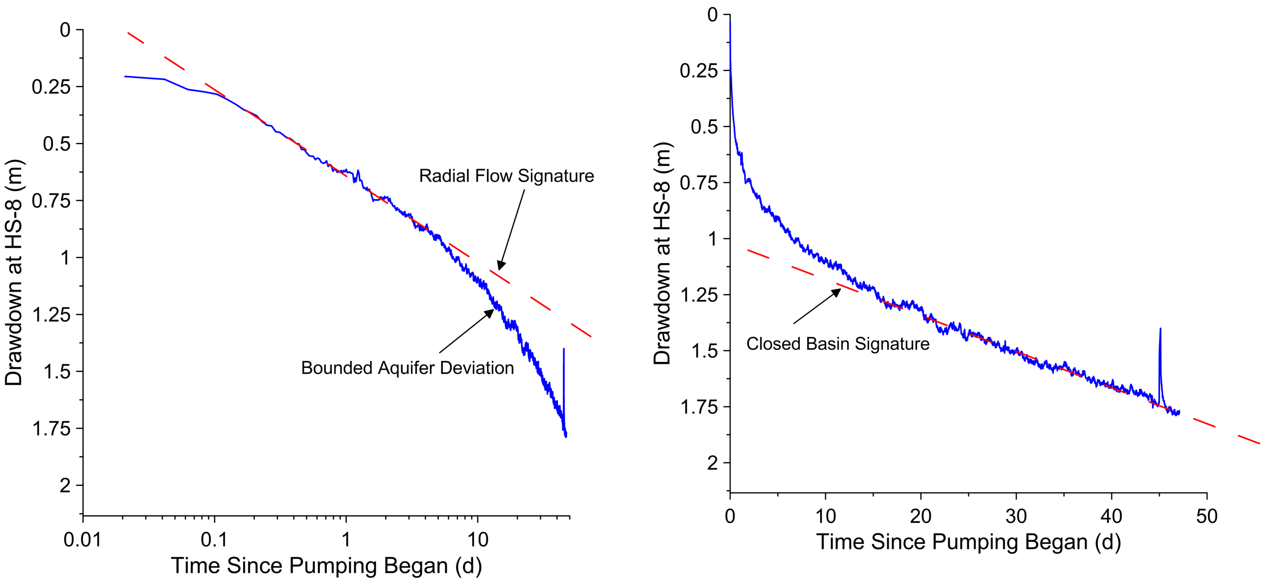


Figure 2 – Elevation of water level in wells HS-20 (pumping well, see Figure 1b) and HS-8 (observation well) from spring 2007 to spring 2008 (distance between wells is 20.1 m; measurements obtained using transducer at fixed elevation in water column; a water-level elevation of 792 m corresponds to a depth to water of 70.2 m). Near-parallel fluctuations in water levels in the spring of 2007 (prior to period of extended pumping) and during the fall and winter of 2007-08 are primarily produced by variations in barometric pressure. High-frequency fluctuations in water levels at HS-20 during periods of pumping are produced by pump noise and small variations in pumping rate amplified by nonlinear well losses; apparent stabilization in water levels in well HS-20 in mid-summer is due to water level falling past transducer, transducer repositioned later in summer (data from Buddemeier et al. [2010]). Water-level elevations, which are essentially equal in the two wells under non-pumping conditions, are offset slightly for illustrative purposes; A and B defined in text.



a) b)

Figure 3 – Elevation of water level versus time (measurements obtained using transducer at fixed elevation in water column; data from Stotler et al. [2011] and E. Reboulet [unpublished data]): a) Haskell index well (HS-IW in Figure 1b; a water-level elevation of 785 m corresponds to a depth to water of 80.0 m; A defined in text; well drilled in summer 2007); b) Thomas index well (TH-IW in Figure 1b; a water-level elevation of 907 m corresponds to a depth to water of 64.5 m; A-D defined in text; the hydrograph "band" is produced by water-level fluctuations in response to variations in barometric pressure; well drilled in summer 2007). Legend for both plots is given above Figure 3a.



a)

b)

Figure 4 – Response at well HS-8 to pumping at well HS-20 during summer 2007 pumping season: a) Drawdown versus logarithm of time since pumping began; b) Drawdown versus time since pumping began (pumping assumed to start at point A on Figure 2; pumping rate was approximately 0.045 m^3/s; data not corrected for fluctuations in barometric pressure; slope of dashed line in b) is 0.0162 m/d; distance between wells is 20.1 m).

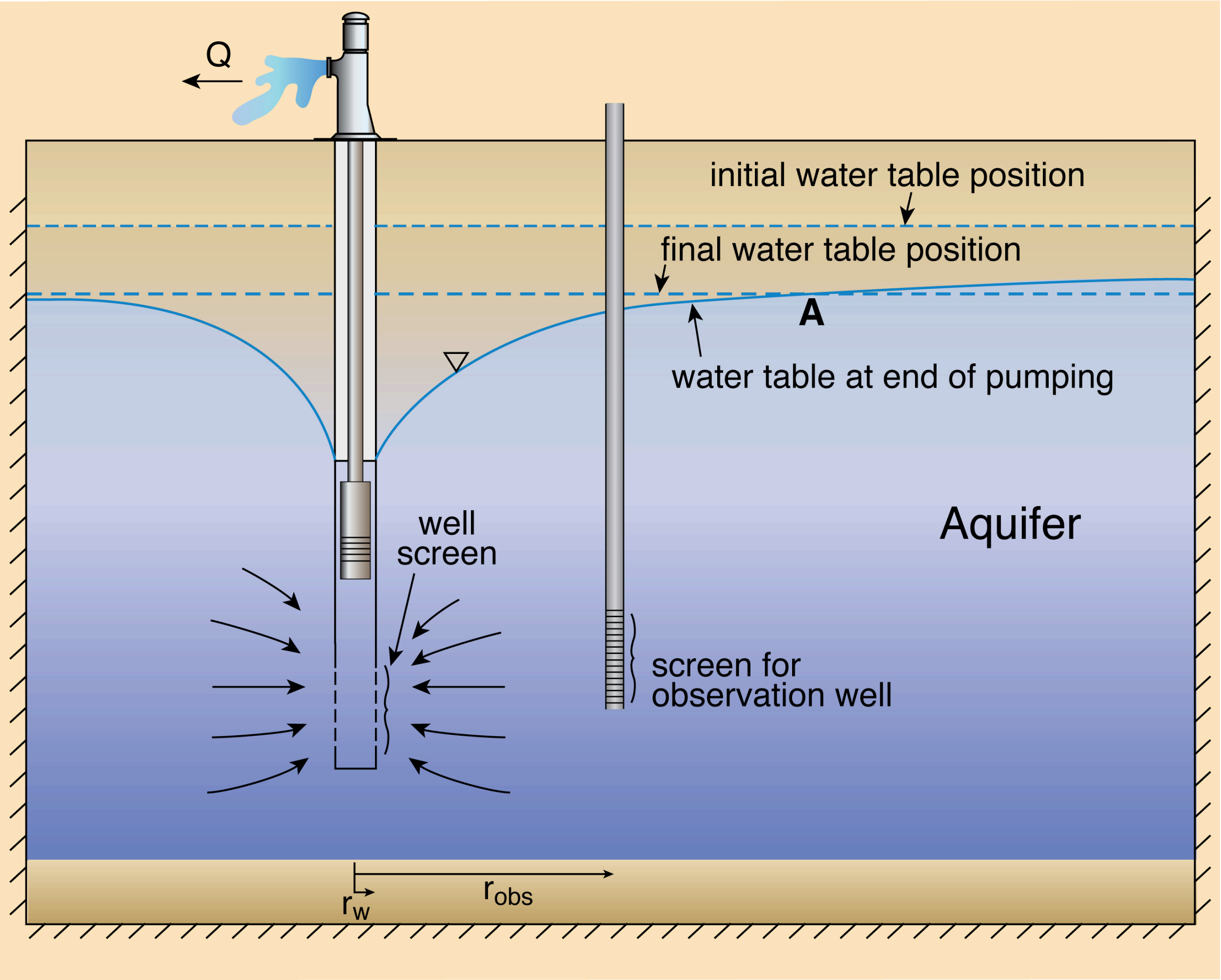


Figure 5 – Cross-sectional view of a hypothetical closed-system (compartmentalized) aquifer with an observation well at a distance of r_{obs} from the pumping well (not to scale; final water-table position refers to position at end of recovery period; A marks the location at which the water table at the end of pumping crosses the final water-table position).

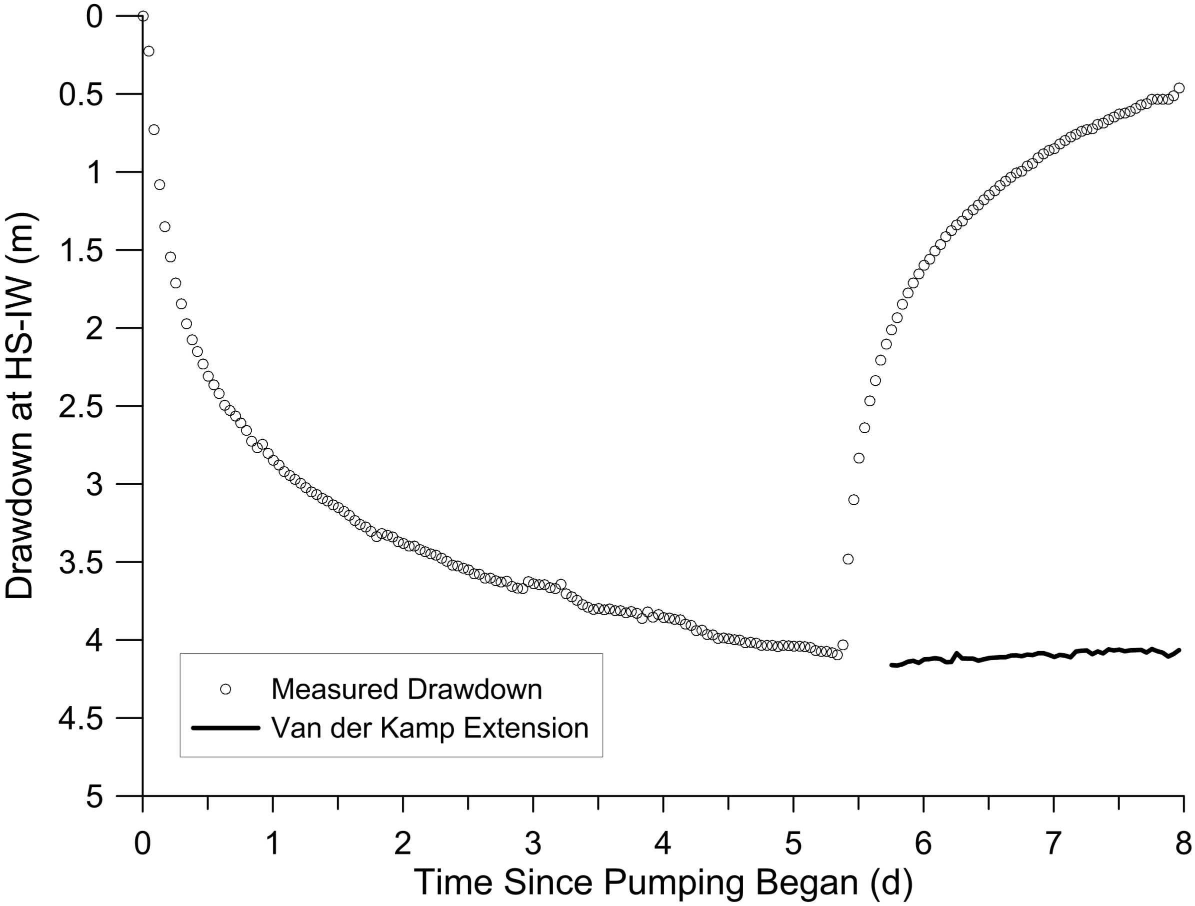


Figure 6 - Drawdown at Haskell index well (HS-IW) versus time since pumping began at well HS-1 (see Figure 1b caption) for pumping period in the fall of 2007 (pumping assumed to start at point A on Figure 3a; data corrected for background upward head trend (0.01 m/d) but not for fluctuations in barometric pressure; gap between extended drawdown and the cessation of pumping due to the frequency (hourly) of drawdown measurements producing uncertainty about the exact time at which pumping commenced and ceased; distance between wells is 752 m).

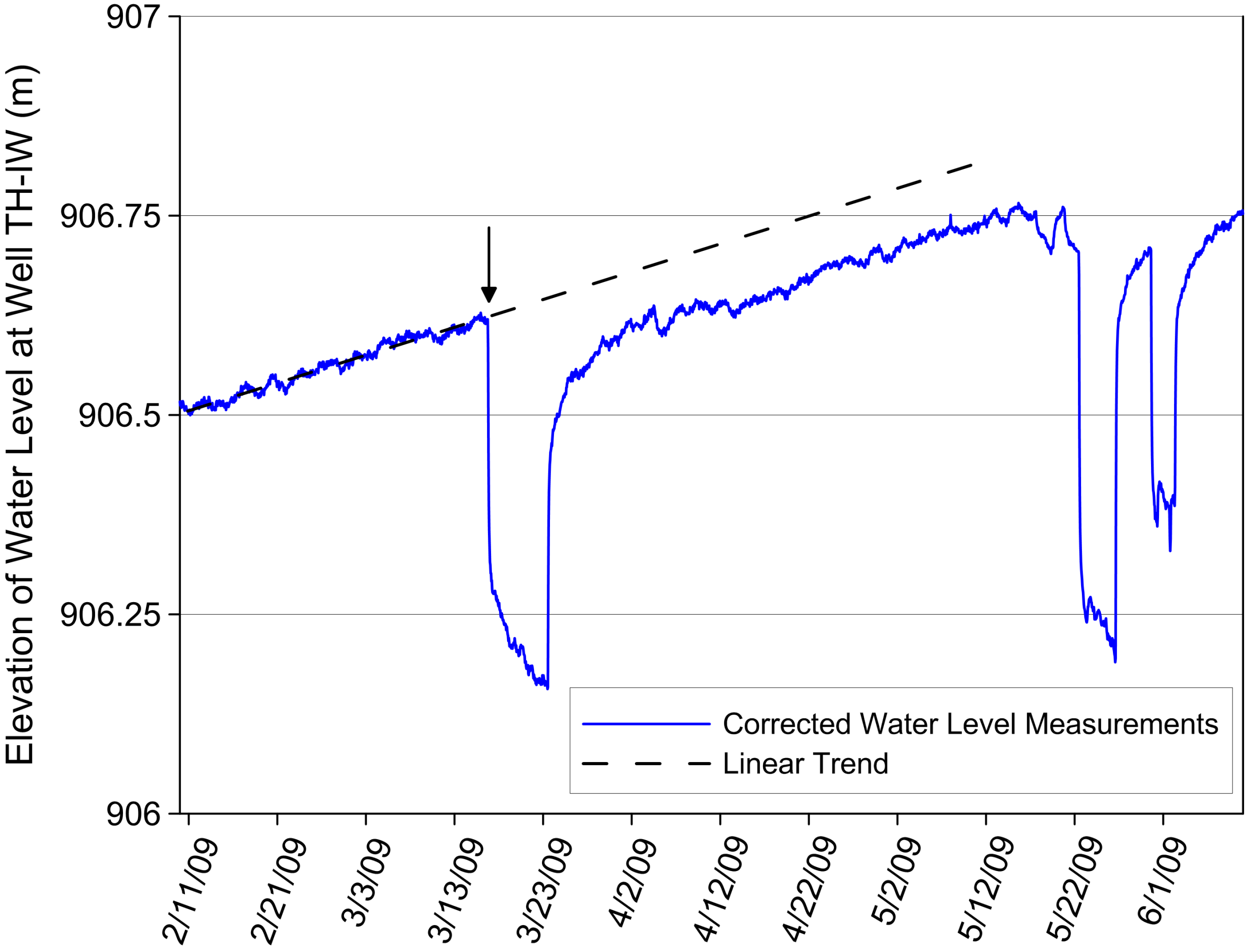


Figure 7 - Elevation of water level at Thomas index well (TH-IW) for late winter to late spring of 2009 (data from Stotler et al. [2011]; water levels corrected for fluctuations in barometric pressure using spreadsheet of Bohling et al. [2011]; arrow indicates start of the 6.8-d pumping period).

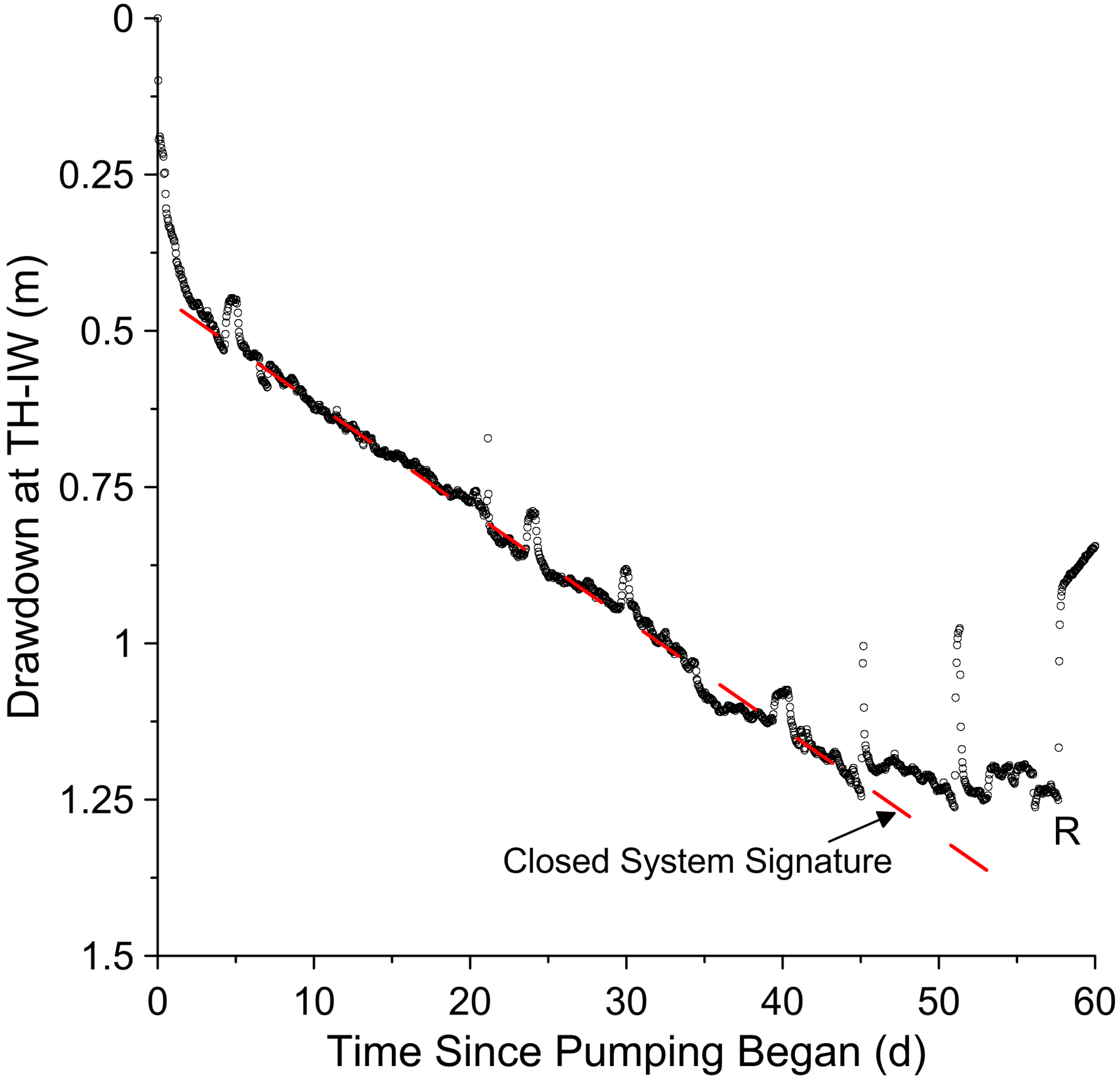


Figure 8 - Drawdown at Thomas index well (TH-IW) versus time since pumping began for summer 2010 pumping season (pumping assumed to start at point B on Figure 3b; data corrected for fluctuations in barometric pressure using spreadsheet of Bohling et al. [2011]; R defined in text).

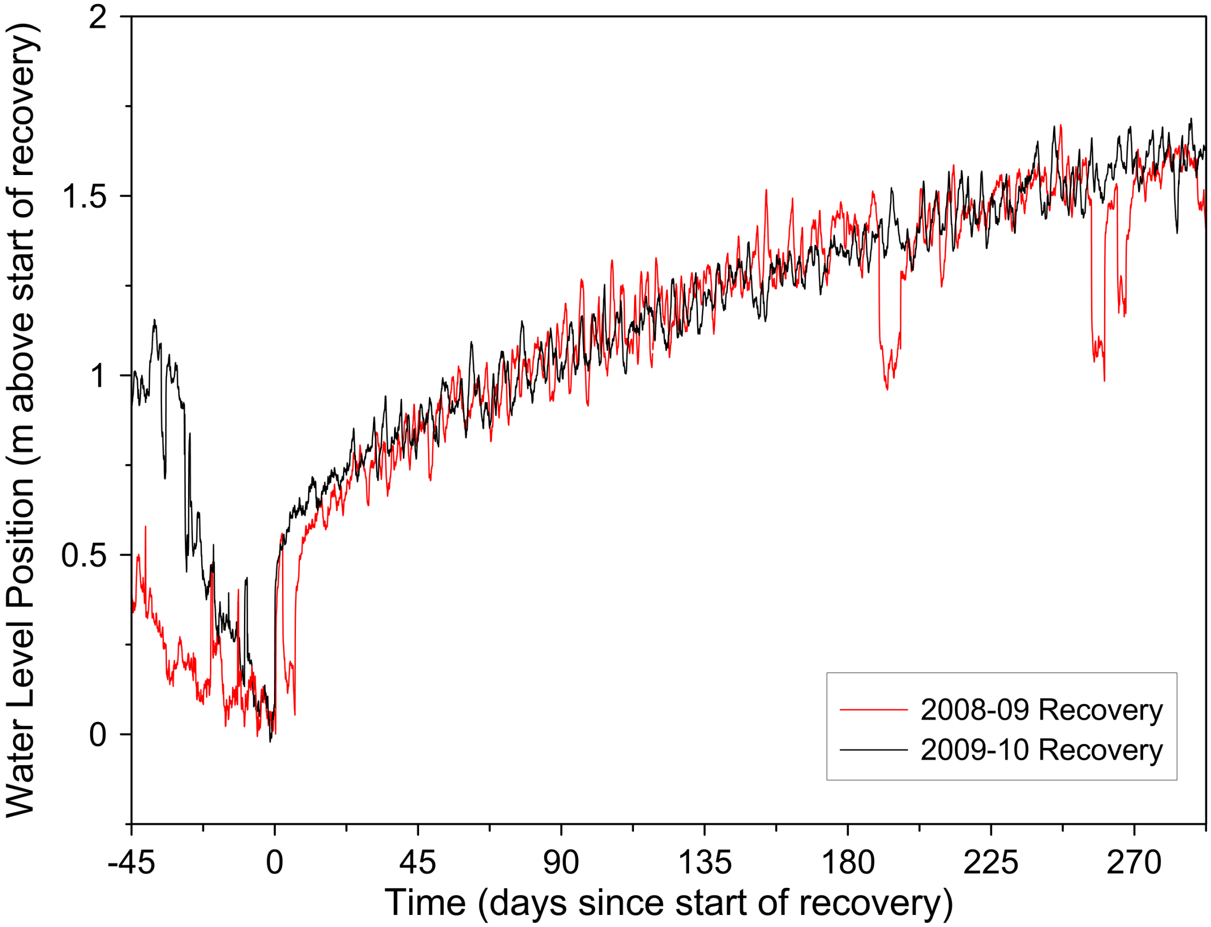


Figure 9 – Water-level change since start of recovery in well TH-IW versus time of recovery for the 2008-09 and 2009-10 recovery periods (2008-09 and 2009-10 recoveries start at points C and D, respectively, on Figure 3b; the time and water-level elevation at the start of recovery were set to zero for each period; durations of 2008 and 2009 pumping seasons were 118 d and 63 d, respectively; data not corrected for fluctuations in barometric pressure).