Kansas Geological Survey

High Plains Aquifer Calibration Monitoring Well Program: Fifth Year Progress Report

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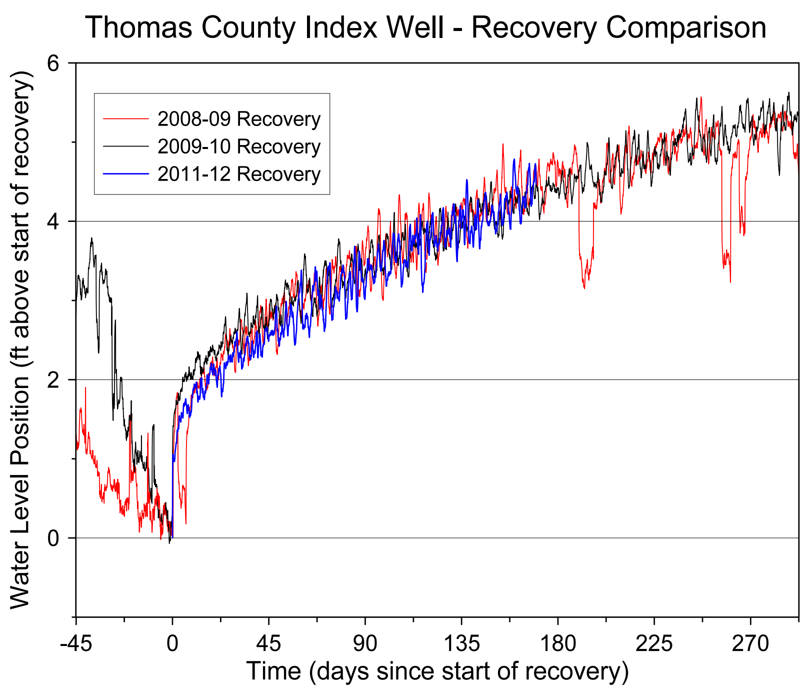

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Executive Summary

The index well program is directed at developing improved approaches for measuring and interpreting hydrologic responses at the local (section to township) scale in the High Plains aquifer (HPA) in western Kansas. The study is supported by the Kansas Water Office (KWO) with Water Plan funding as a result of KWO's interest in and responsibility for long-term planning of ground-water 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 measure of the impact of management strategies. At the time of this report, monitoring data (hourly frequency) from four full recovery and pumping seasons and one ongoing recovery season have been obtained at the three index wells; additional water-level data have been obtained from wells in the vicinity of two of the index well sites.

This report provides (a) an update of the hydrographs for the three index wells; (b) interpretation of hydrographs from the index wells and the wells in the expanded monitoring areas in the vicinity of two of the index wells; (c) a discussion of the expanded monitoring that has resulted from the findings of the index well program; (d) a discussion of the sampling and geochemical analysis of water from the three index wells and from four irrigation wells near one of the index wells; and (e) the final version of the KGS barometric correction spreadsheet program, which calculates the barometric response function for a given well and corrects the measured water levels for the impact of barometric pressure changes. A particular emphasis of this report is on the important new insights that have been obtained from the interpretation of hydrographs from the index wells and from wells in the expanded monitoring areas in the vicinity of two of the index wells.

The major findings of the project are as follows:

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

2) The data from the index wells provide the critical context needed for improved interpretation of the results of the annual measurement program.

3) Hydrographs from the index wells and associated monitoring wells can be analyzed using methods developed for the interpretation of pumping tests to obtain insights into the primary mechanisms controlling the changes in water level in those

portions of the HPA. An understanding of these mechanisms is critical for reliable assessment of what the future holds for the HPA in western Kansas.

4) A detailed examination of the hydrographs from the Haskell County index well and DWR-monitored wells in that vicinity reveals that, despite the relatively thick saturated interval, it is likely that large-scale irrigation withdrawals will not be sustainable beyond the current decade in the vicinity of the Haskell site, except, possibly, in those wells that are also completed in the discontinuous sandstones of the underlying Dakota Formation.

5) A detailed examination of the hydrographs from the Thomas County index well and nearby wells monitored with the assistance of DWR and GMD4 reveals that a significant amount of water flows into the HPA in that vicinity. This inflow, which is revealed by the near-coincidence of recovery rates between years, is independent of conditions in the previous pumping season (e.g., duration, withdrawals, and precipitation). Determination of the origins of this inflow at the Thomas County index well is critical for assessing the continued viability of that portion of the HPA as a water source for irrigated agriculture.

6) Hydrograph patterns observed at the Thomas County index well were also discerned in shorter-term hydrographs from two wells in Sheridan and northwestern Thomas counties, indicating that such inflow is likely also occurring in those areas.

7) A detailed examination of the hydrograph from the Scott County index well reveals that inflow independent of conditions in the previous pumping season is also affecting water levels during recovery periods at that well. Further data, however, are needed before more conclusive statements can be made.

The focus of project activities in 2012 will be on the continuation of the detailed analyses of hydrographs from the project wells, expansion of the monitoring in the vicinity of the Scott County index well, 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, and an assessment of the contribution of the Dakota aquifer to pumping withdrawals in the vicinity of the Haskell County index well.

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1. Introduction and Background

The calibration monitoring (index) 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 ground-water 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 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 measure 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 sub-unit 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 year five of the study, monitoring data (hourly frequency) from four 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 (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 the 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; and (6) 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.

This report will provide (a) an update of the hydrographs for the three index wells; (b) interpretation of hydrographs from the index wells and the wells in the expanded monitoring areas in the vicinity of two of the index wells; (c) a discussion of the expanded monitoring that has resulted from the findings of the index well program; (d) a discussion of the sampling and geochemical analysis of water from the three index wells and from four irrigation wells near one of the index wells; and (e) the final version of the KGS barometric correction spreadsheet program, which calculates the barometric response function for a given well and corrects the measured water levels for the impact of barometric pressure changes. A particular emphasis of this report will be on the important new insights that have been obtained from the interpretation of hydrographs from the index wells and from wells in the expanded monitoring areas in the vicinity of two of the index wells.

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 are instrumented by DWR that 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 currently ongoing in four of these additional wells, although only for the recovery period at one of the 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 the sixth year of this program, with the assistance of GMD1, two additional "wells of opportunity" were added in the

vicinity of the Scott County index well. Each of these wells is equipped with a transducer. 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 an impairment complaint (since withdrawn) was filed. It appears that a two-aquifer system exists: an unconfined upper aquifer zone and a thin but productive confined aquifer zone on top of bedrock with a thick clay layer separating the two. The project well was installed to sample only the lower confined aquifer zone near the site of the impairment complaint; DWR has installed transducers in a number of nearby wells screened in one or both aquifer zones and these wells are being utilized 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.

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. Since 50-100 ft of saturated thickness is required to sustain high-volume irrigation pumping under most aquifer and water-use conditions (Hecox et al., 2002) and both areas have shown long-term declines in water level, 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 also 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 water-level responses at both the Scott and Thomas sites indicate unconfined (water-table) aquifer conditions.

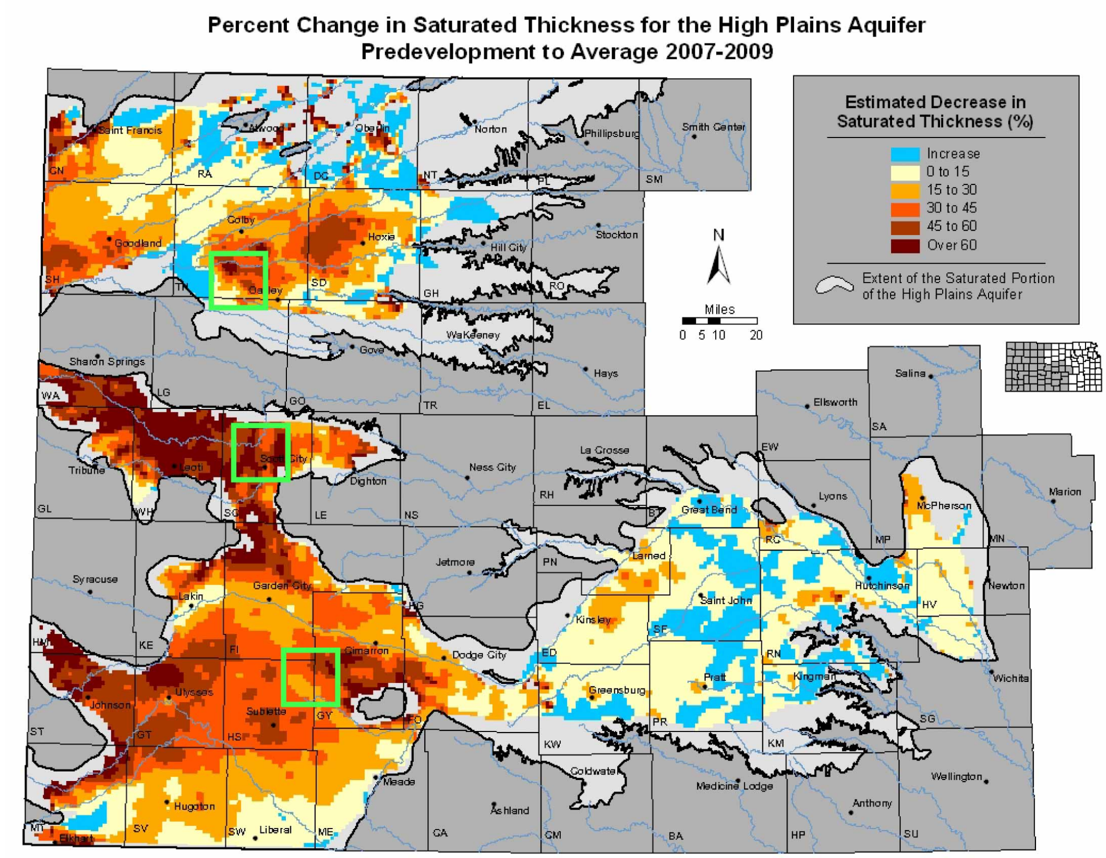

Figure 1: The Kansas portion of the High Plains aquifer, with aquifer and county boundaries shown. Each colored pixel represents one section (1 mi^2), coded to show the degree of ground-water depletion from the beginning of large-scale development to the average of conditions in 2007-2009. The three green boxes surround the index well study sites.

Table 1: Characteristics of the index well sites

Site	2012 WL elev. (ft)[a]	2012 Saturated thickness (ft)	Bedrock depth (estimated ft below lsf)	Screened interval (ft below lsf)	2010 Water Use (AF)		
					1-mi circle	2-mi circle	5-mi circle
Haskell	2559.6	154.6	433	420-430	2006	8973	50396
Scott	2834.1	90.1	223	215-225	910	3036	15982
Thomas	2972.1	69.1	284	274-284	918	2256	11118

[a]2012 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html)

3. Overview of Index Well Sites and Monitoring Data

This section provides a brief overview of the hydrographs from all three sites. With over four and a third 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, coupled with additional work in the fifth year of 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.

3.1. *Haskell County*

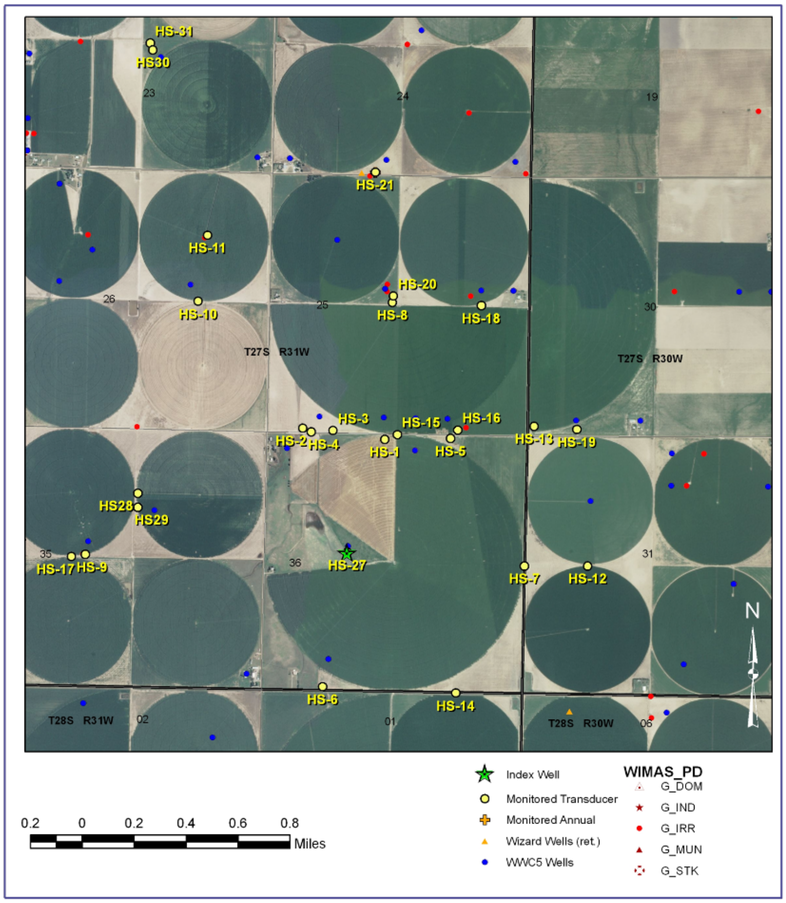

Figure 2: Haskell County site, showing the index well, adjacent monitoring wells, and points of diversion within the area of concentrated DWR studies. Most of the marked wells are equipped with transducers.

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 2010-11 recovery started on August 24th, the date of last pumping for 2010 that had a major impact on the index well, and ended on February 15th when nearby pumping began. However, very few periods during this time were completely free of the influence of pumping. The longest period of undisturbed recovery was between December 24, 2010, and February 15, 2011. A pumping event of approximately one day in duration has occurred approximately one month after the end of the pumping season in every year since monitoring began. Also, similar to previous years, the pumping season started earlier in the area of the Haskell site compared with the Scott and Thomas sites, with a break during 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 or the moderate rain that occurred in the area on April 15 and 27, 2011 (daily radar precipitation images of the National Weather Service, http://water.weather.gov/precip/). The 2011-12 recovery season began on August 29, 2011, and was still ongoing at the time of this report.

Each year, the minimum recorded water-level elevation declined from the previous year. The lowest water level observed by far was in 2011; the minimum 2011 water-level elevation was 7.9 ft lower than in 2010, 14.8-14.9 ft lower than in 2008 or 2009, and 16.2 ft lower than in 2007. Water-use data for 2011 will be available later in 2012. In 2010, water use within the 2-mile radius surrounding the index well was 959 ac-ft less than in 2008, the highest use year during the monitoring period, and 209 and 252 ac-ft more than during 2007 and 2009, respectively. The 2010 water use, however, was applied on fewer irrigated acres than previous years, resulting in higher water use per acre irrigated (Table 2). In 2009 and 2010, the index well recorded year-to-year declines in the maximum recovered water level of 5.0 and 3.9 ft, respectively. In 2011, the decline was 6.8 ft. Given the much lower water-level minimum recorded in 2011, the expectation is that the decline in the maximum recovered water level in 2012 will exceed the 2011 decline.

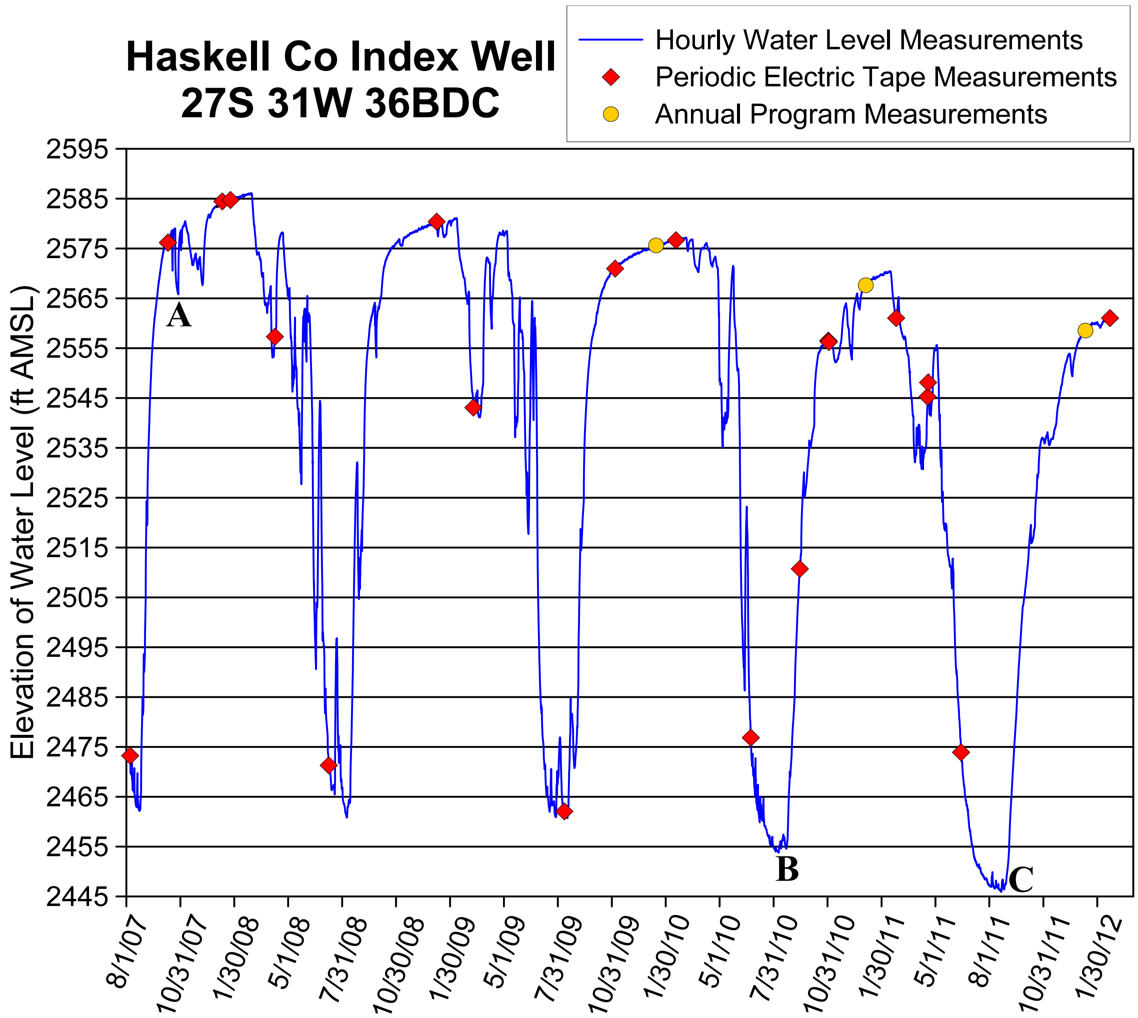

Figure 3: Haskell County index well hydrograph – total data run to 2/21/12. A water-level elevation of 2445 ft corresponds to a depth to water of 392.85 ft below land surface (lsf); the top of the screen is 420 ft below lsf and the bottom of the aquifer is 433 ft below lsf.

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

		2007	2008	2009	2010	2011
Minimum Water-Level Elevation	Feet	2462.1	2460.8	2460.7	2453.8	2445.9
	Date	8/23/07	8/8/08	8/16/09	8/9/10	8/21/11
Maximum Observed Recovery Elevation	Feet	NA	2586.1	2581.1	2577.2	2570.4
	Date	NA	2/28/08	2/9/09	3/5/10	2/13/11
Apparent Recovery	Feet	NA	124.0	120.3	116.5	116.6
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-5.0	-3.9	-6.8
Recovery Season	Start	NA	8/24/07	8/13/08	8/18/09	8/24/10
	End	NA	2/28/08	2/10/09	3/6/10	2/15/11
	Length (# Days)	NA	189.2	181.0	200.2	174.9
Pumping During Recovery Season	# Days	NA	41.5	20.00	5.2	25.8[a]
Length of Pumping Season	Length (# Days)	NA	166.1	188.5	171.0	193.7
2-mi Radius Water Use	Irrigated Acres	6475	7755	6259	6114	NA
	Total Use (ac-ft)	8764.01	9931.71	8720.45	8972.70	NA
	Use per Irrigated Acre (ft)	1.35	1.28	1.39	1.47	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 Co.

Date	WL elev (ft)	Indicated Annual WL Decline (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
	2574.51[d]	5.59	Transducer
1/4/2011	2568.67	6.96 (6.8)	Steel tape
	2567.91[c]	7.63	Transducer
	2567.94[d]	6.57	Transducer
1/11/2012	2558.57	10.1 (NA)	Steel tape
	2558.82[c]	9.09	Transducer
	2558.75[d]	9.19	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.

3.2. Scott County

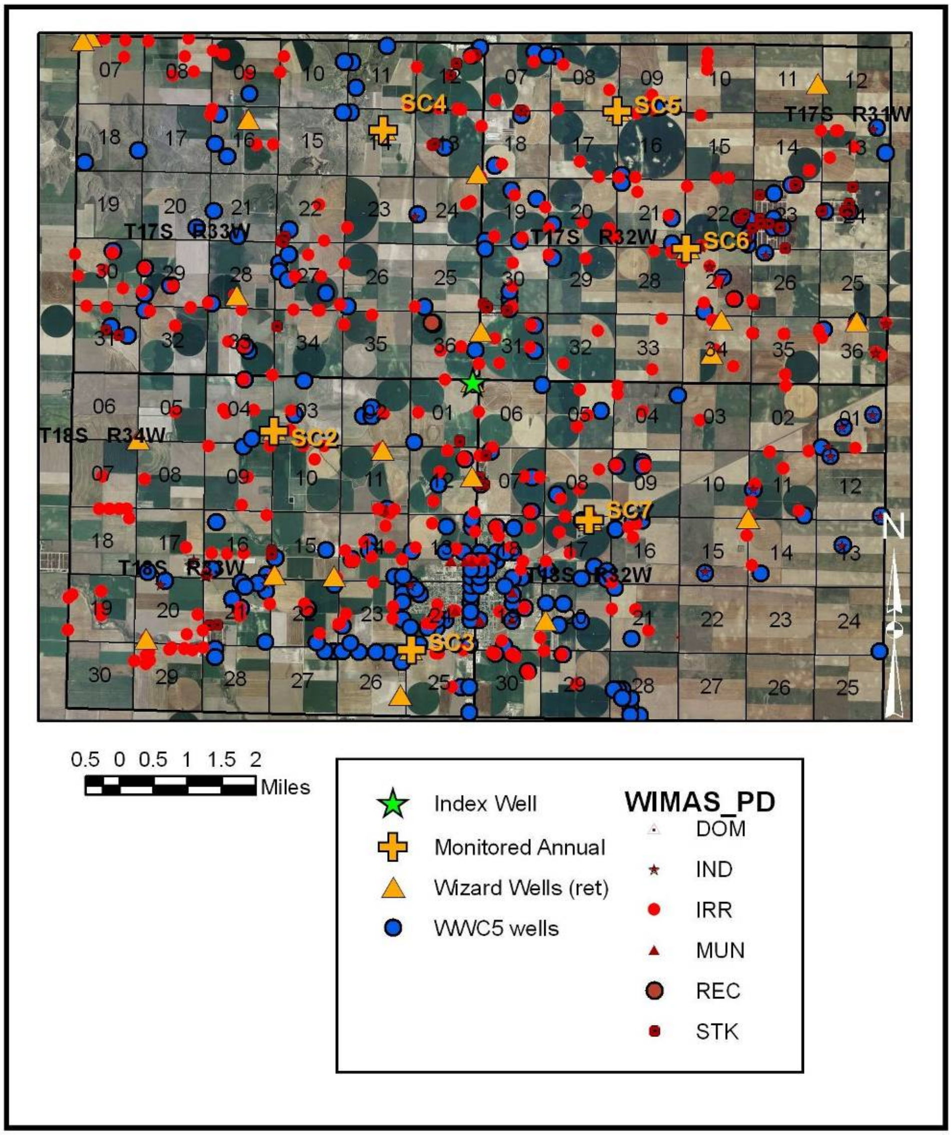

Figure 4: Scott County site, showing the index well, other monitored wells, and adjacent points of diversion.

Figure 4 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.

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 2010-11 recovery started at the end of August, with approximately 10 days of pumping in mid-September. This pumping period was followed by a quick recovery of almost a foot, followed by almost one month of negligible water-level change, before a nearly linear recovery commenced in mid-November. Pumping started in mid-March, with a couple of brief breaks in April and early May. Moderate rain on April 15, substantial precipitation during April 26-27, and moderate rain on May 12, 2011, may be related to these breaks. After a sudden drop of over 0.75 ft within 24 hours on June 24-25, a relatively steady rate of drawdown was maintained until the end of the pumping season on September 1, 2011. The 2011-12 recovery season was still ongoing at the time of this report.

Each year, the minimum recorded water-level elevation declined from the previous year. The lowest water level observed by far was in 2011; the minimum 2011 water-level elevation was 1.4 ft lower than in 2010, 1.7 ft lower than in 2009, and 2.5 ft lower than in 2008. Water-use data for 2011 will be available later in 2012. Water use within the 2-mile radius surrounding the index well was highest during 2008, and approximately 1000 ac-ft less during 2007, 2009, and 2010. The year-to-year declines in the maximum recovered water level were 1.3 ft, 0.4 ft, and 0.7 ft between the 2007-08 and 2008-09, the 2008-09 and 2009-10, and the 2009-10 and 2010-11 recovery seasons, respectively. The expectation, based on the decline in the minimum recorded water-level elevation in 2011, is that the decline in the maximum recovered water level between the 2010-11 and 2011-12 recovery seasons will exceed these previous declines.

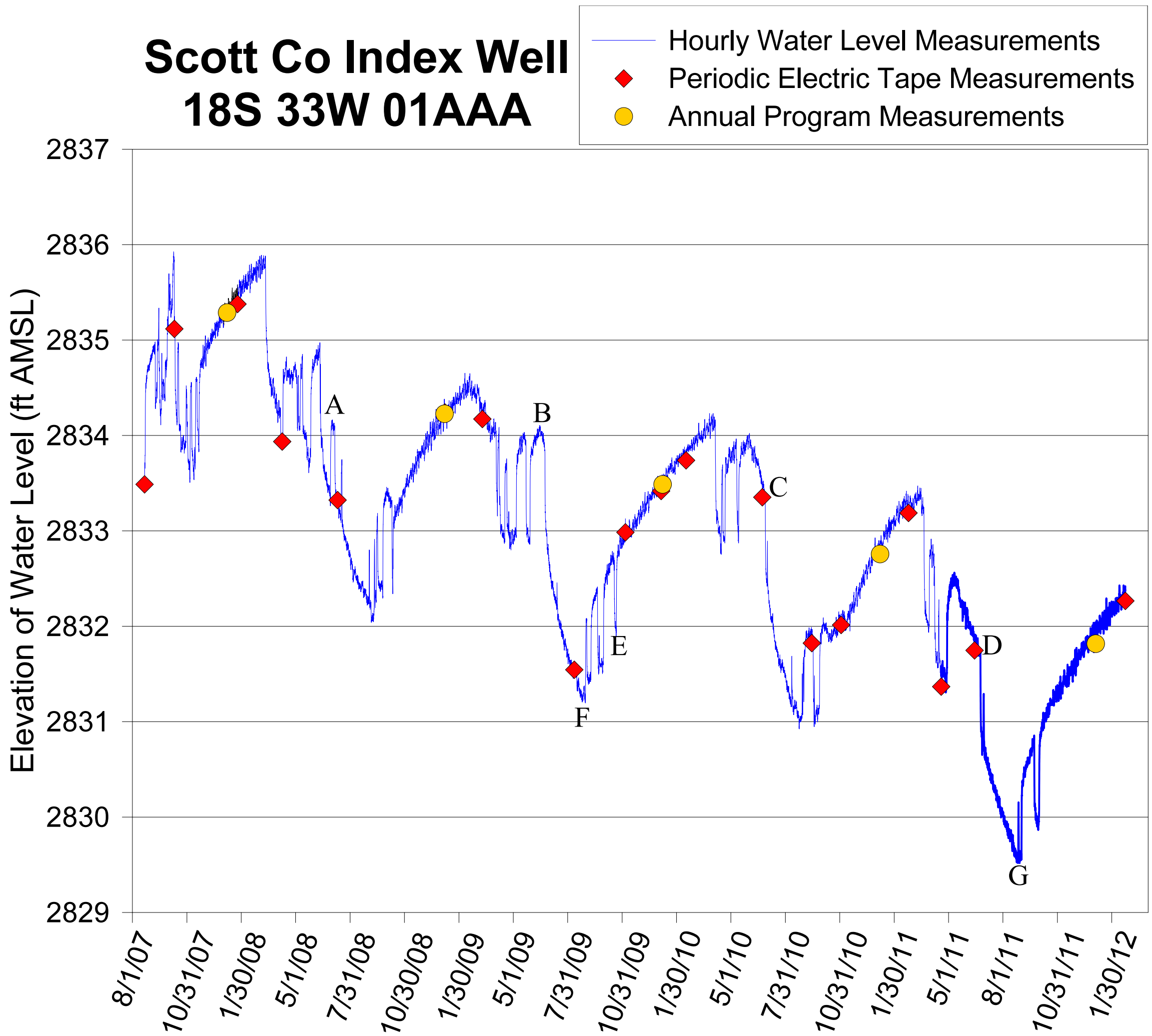

Figure 5: Scott County index well hydrograph – total data run to 2/22/12. A water-level elevation of 2829 ft corresponds to a depth to water of 138.15 ft below land surface (lsf); the top of the screen is 215 ft below lsf and the bottom of the aquifer is 223 ft below lsf.

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

		2007	2008	2009	2010	2011
Minimum Water-Level Elevation	Feet	<2833.4	2832.0	2831.2	2830.9	2829.5
	Date	8/21/07	9/5/08	8/30/09	8/24/10 and 9/18/10	8/26/11 and 8/29/11
Maximum Observed Recovery Elevation	Feet	NA	2835.9	2834.6	2834.2	2833.5
	Date	NA	3/4/08	2/17/09	3/26/10 and 4/1/10	3/11/11
Apparent Recovery	Feet	NA	>2.5	2.6	3.0	2.6
Apparent Water-Level Change from Previous Year	Feet	NA	NA	-1.3	-0.4	-0.7
Recovery Season	Start	NA	<8/21/07	9/13/08	8/30/09	8/29/10
	End	NA	3/11/08	4/2/09	4/5/10	3/17/11
	Length (# Days)	NA	>203	201.3	217.8	200.2
Pumping During Recovery Season	# Days	NA	>48.2	13.7	21.0	12.8
Length of Pumping Season	Length (# Days)	NA	182.3	150.0	145.7	168.1
2-mi Radius Water Use	Irrigated Acres	4132	3950	3923	3665	NA
	Total Use (ac-ft)	3175.09	4059.02	2955.48	3035.89	NA
	Irrigation Use Only (ac-ft)	3095.78	4014.33	2955.48	3017.08	NA
	Irrigation Use per Irrigated Acre (ft)	0.75	1.02	0.75	0.82	NA

3.2.2. Measurement Comparisons

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

Date	WL elev (ft)	Indicated Annual WL Decline (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 (NA)	Steel tape
	2831.92[c]	0.94	Transducer
	2831.95[e]	0.91	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*

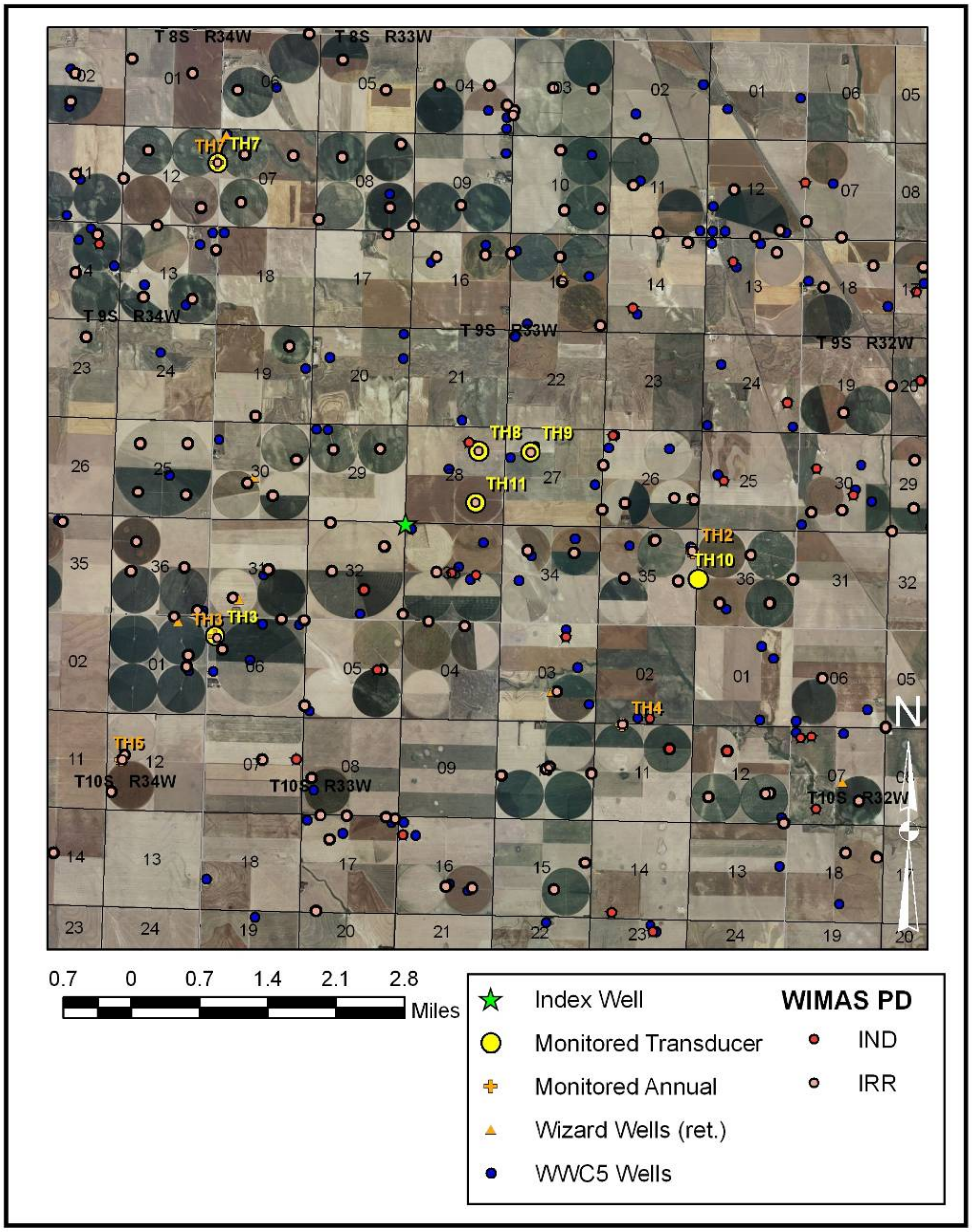

Figure 6: Thomas County site, showing the index well, nearby wells that have been equipped with transducers, surrounding annual program wells, and points of diversion in the area.

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 2010-2011 recovery was the shortest observed to date in the Thomas area, beginning on September 6, 2010, and ending on March 17, 2011. Although pumping started in mid-March, there was a general pause through the month of April, with intermittent pumping through May. The pauses and intermittent interruptions in pumping are likely related to the moderate to substantial rain received on April 15 and 25-27, and May 19 and 24-25, 2011. Sustained pumping commenced in early June and continued until the end of the pumping season on September 4, 2011. The 2011-12 recovery season was ongoing at the time of this report.

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 2011, which was the lowest recorded over the monitoring period, was 2.7 ft below that of 2010. However, the 2010 level was the highest recorded minimum water-level elevation during the monitoring period (0.62 ft, 1.33 ft, and 0.26 ft above the minimum water-level elevations in 2007, 2008, and 2009, respectively). Water-use data for 2011 will be available later in 2012. Water use within the 2-mile radius surrounding the index well was similar during 2007 and 2008, and 800-1000 ac-ft less during 2009 and 2010. The maximum observed water level in 2011 was over a foot below that of 2010, primarily because of the additional three months of recovery in 2010, but essentially the same as that in 2009 and only 0.42 ft below that of 2008. Thus, the change in maximum observed water level was quite modest between the spring of 2008 and the spring of 2011, particularly if one considers that the recovery period was over 50 days longer in 2008. In 2011, the lowest water level was recorded on September 4, and was nearly 1.4 ft lower than the previous minimum recorded water-level elevation. Thus, the expectation is that, in the absence of a relatively long recovery period, the maximum observed water level at the end of the 2011-12 recovery will be the lowest value recorded to date at the Thomas index well.

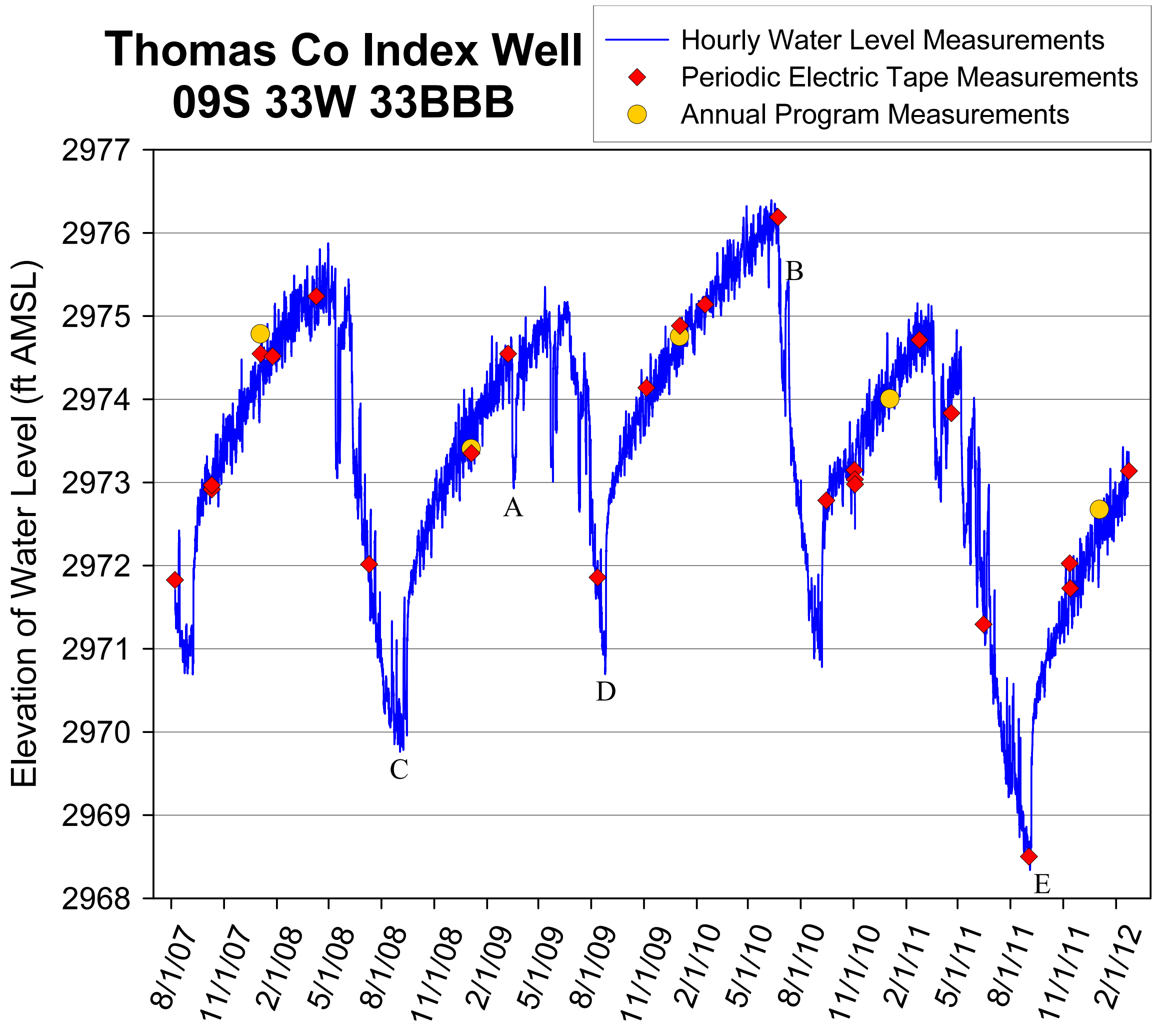

Figure 7: Thomas County index well hydrograph – total data run to 2/23/12. A water-level elevation of 2968 ft corresponds to a depth to water of 219.56 ft below land surface (lsf); the top of the screen is 274 ft below lsf and the bottom of the aquifer is 284 ft below lsf.

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

		2007	2008	2009	2010	2011
Minimum Drawdown Elevation	Feet	2970.7	2969.8	2970.7	2970.8	2968.3
	Date	9/7/07	9/2/08	8/25/09	9/6/10	9/4/11
Maximum Observed Recovery Elevation	Feet	NA	2975.9	2975.4	2976.4	2975.2
	Date	NA	4/30/08	5/12/09	6/10/10	2/20/11
Apparent Recovery	Feet	NA	5.2	5.6	5.7	4.4
Apparent Water-Level Change from Previous Year	Feet	NA	NA	-0.5	+1.0	-1.2

Recovery Season	Start	NA	9/8/07	9/8/08	8/26/09	9/6/2010
	End	NA	5/12/08	6/24/09	6/24/10	3/17/11
	Length (# Days)	NA	247.2	289.5	301.38	191.4
Pumping During Recovery Season	# Days	NA	5.0	17.0	2.2	18.4
Length of Pumping Season	Length (# Days)	NA	118.5	63.2	74.6	173.8
2-mi Water Use	Irrigated Acres	2983	3016	2958	3009	NA
	Total (ac-ft)	2868.87	2825.21	1917.17	2256.13	NA
	per Irrigated Acre (ft)	0.96	0.94	0.65	0.75	NA

3.3.2. Measurement Comparisons

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

Date	WL elev (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 (NA)	Steel tape
	2972.61[c]	-1.53	Transducer
	2972.36[d]	-1.79	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 decline in the maximum recovered water level measured by the index well transducer.
[c] average of values over time interval 0800-1600, not corrected for barometric pressure.
[d] average of values over time interval 0800-1600, corrected for barometric pressure using KGS barometric correction program.

4. Interpretation of Water-Level Responses

4.1. Barometric Correction of Water-Level Response

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 reports, earth-tide effects were shown to have a negligible impact on water-level measurements, while the impact of changes in barometric pressures is large enough to be of practical significance at one of the index wells (Thomas County). Given this finding and the potential impact of barometric pressure fluctuations on the measurements from the annual water-level program, the KGS developed an Excel spreadsheet to remove the effect of barometric-pressure fluctuations from water-level measurements (henceforth, water-level correction). This spreadsheet was revised in the first half of 2011 as a result of the experience of KGS staff working with datasets from the index wells and associated wells of opportunity. A KGS Open-File Report (Bohling et al., 2011) describing the spreadsheet was published in 2011 and is attached to this report as Appendix A.

4.2. Interpretation of Hydrographs from the Index Wells and Associated Wells of Opportunity

An understanding of the primary mechanisms controlling the changes in water level in 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 major component of the activities for the fifth year of this project has been directed at that issue. In this section, we will briefly describe the insights that have been gained from interpretation of the hydrographs from the index wells and nearby wells of opportunity.

<u>Haskell County</u>
Figure 8 is a N-S lithologic cross section of the unconsolidated sequence in the HPA at the Haskell site. The hydrostratigraphy of the site consists of unconfined and confined aquifer intervals separated by a thick clay (aquitard) unit. Wells in the vicinity of the Haskell site are primarily screened in the unconfined interval, the confined interval, or both. However, some of these wells are also screened across sandstone units within the underlying Dakota aquifer. Even when the well is only screened in the lower confined interval of the HPA, the gravel pack extends to near land surface in virtually all wells other than the index well.

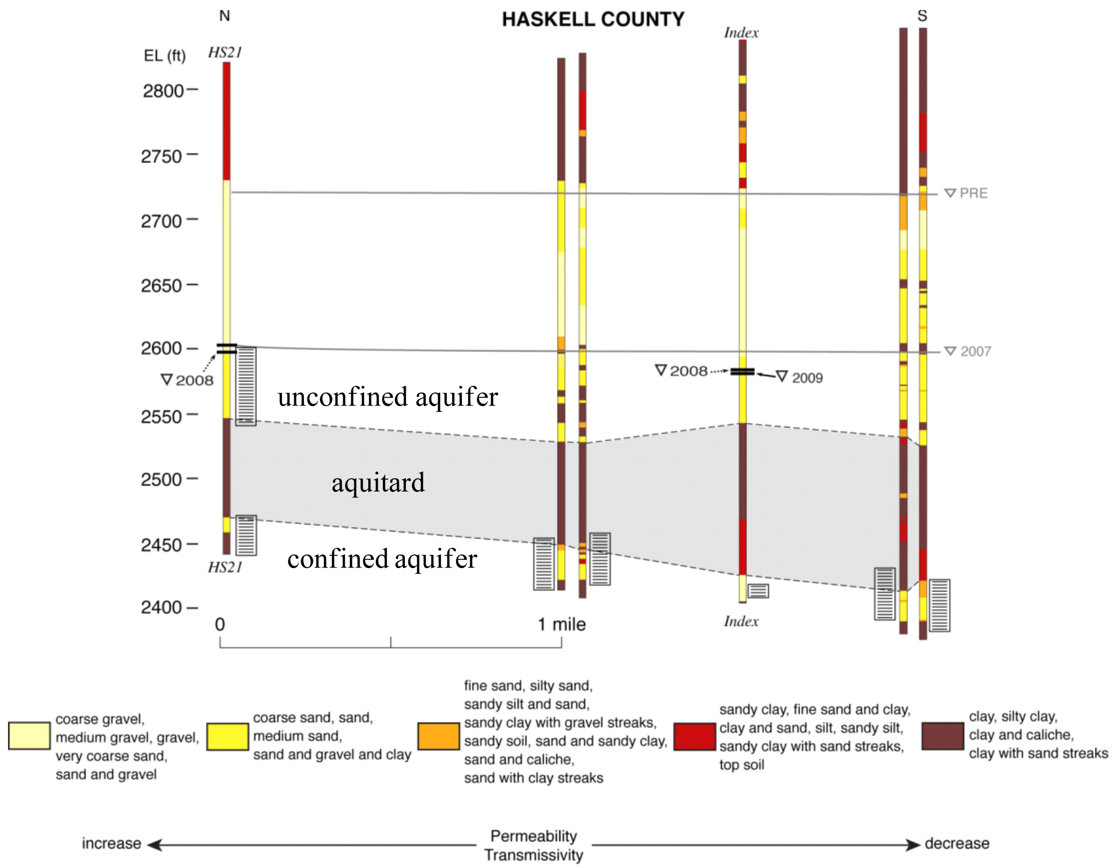

Figure 8: Lithologic cross section for the HPA at the Haskell site. In N-S orientation, the displayed wells are HS-21, HS-2, HS-4, index well, irrigation well near HS-6 (C S2 SW sec. 36, T. 27 S., R. 31 W.), and HS-6. The 2007 level represents the measured January 2007 water level in annual well HS-21.

Wells in unconfined interval

Figure 2 is an aerial view of the Haskell County site with the DWR-monitored wells (henceforth, DWR wells) marked by yellow circles. The majority of the DWR wells are screened in the unconfined interval of Figure 8. Figure 9 displays 2007-08 hydrographs from two such wells: an irrigation well (HS-20) and a nearby (separation distance of 66 ft) observation well (HS-8) located approximately 1 mile north of the index well. Three noteworthy characteristics of these hydrographs are common to many wells screened in the unconfined interval. First, despite the numerous irrigation wells 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, the two wells recover in just over two weeks, a small fraction of the duration of pumping at HS-20. Third, after the short recovery period, no further changes in water level occur at either well beyond small-amplitude fluctuations produced by variations in barometric pressure. These three characteristics are indicative of pure ground-water mining, i.e. all water pumped at HS-20 is being removed from storage in the sands in the vicinity of the well pair; there is no significant lateral flow from more distant regions. Thus, the sands in which the two wells are screened pinch out or are truncated by units of low permeability (e.g., clays and silts) in all directions, i.e. these sands function as a small closed-basin (bathtub or 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. Moreover, the stabilization of water levels after the short recovery period indicates that negligible inflow occurs as either vertical recharge from above or upward seepage from below.

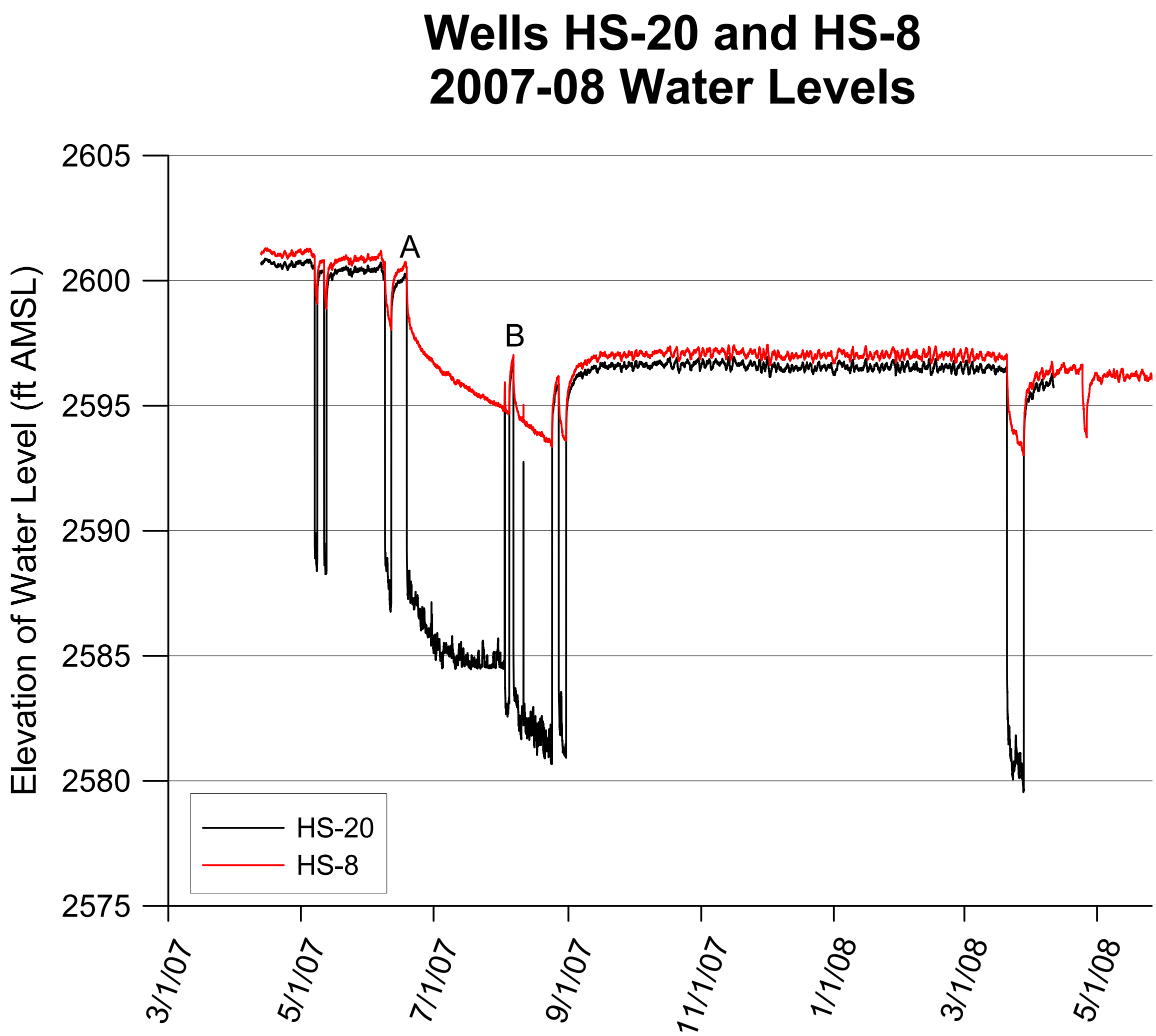

Figure 9: Water levels at wells HS-8 and HS-20 from early spring 2007 to late spring 2008. The flattening of the HS-20 hydrograph for a portion of the 2007 pumping season is probably due to the water level moving past the transducer; the sensor appears to have been repositioned later in the summer. Note that monitoring at HS-20 was interrupted in April 2008 for unknown reasons. Well locations are shown on Figure 2.

The limited lateral extent of the sands in which wells HS-8 and HS-20 are screened can be explored in more detail using traditional 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 at HS-8 during this period to be interpreted as pumping-induced drawdown. Figure 10a is a plot of the drawdown at HS-8 versus the logarithm of the time since pumping began (for this analysis, pumping is assumed to start at time A on Figure 9 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 drawdown falls on the straight line only through the first four to five days. After that time, the 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 shown on Figure 10a is an indication that at least two boundaries have been reached. The nature of the aquifer boundaries can be explored further by plotting drawdown versus the time since pumping began (and not the logarithm of that quantity). As shown in Figure 10b, drawdown after about 15 days falls on a straight line when plotted in this format, an indication that the cone of depression has reached the boundary of the aquifer in all directions, i.e. the sands are acting as a closed-basin (bathtub or compartmentalized) aquifer. Thus, the conclusions derived from a detailed examination of a single pumping period are consistent with those obtained from the longer-term hydrograph. Note that the rapid recovery illustrated in the hydrograph of Figure 9 is a result of the linear-in-time relationship of Figure 10b. Water-level changes during the recovery period can be modeled by the superposition of a pumping well and an imaginary injection (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 (Kruseman and de Ridder 1990).

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 of Figure 10b using a general relationship that has its origins in an analytical solution presented by Muskat (1937) for drawdown in a circular closed-basin aquifer (Streltsova 1988):

$$\Delta s/\Delta t = Q/(S_y A_s) \qquad (1)$$

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 from the Figure 10b caption, a pumping rate of 713 gpm, and a specific yield estimate of 0.2 determined from the Cooper-Jacob analysis of the drawdown in Figure 10a, an area of $12.9\text{x}10^6$ ft^2 is calculated for the bounded aquifer (for an ideal circular aquifer, this results in a radius of

2,025 ft). 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 9 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 221 ac-ft (9.63×10^6 ft^3), the Δs_{is} of 4.09 ft calculated from Figure 9 (difference between water levels [24-hr averages] on April 15 and November 15), and the same S_y as before (0.2), an aquifer area of 11.7×10^6 ft^2 is calculated, which is in excellent agreement (within 9%) of that found with equation (1).

Virtually all the DWR wells screened in the unconfined interval in the vicinity of the Haskell index well display some form of closed-basin 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, water levels will rise up to the final water-table position upon cessation of pumping, similar to well HS-8 in Figure 9. If the observation well is relatively far from the pumping well, water levels will continue to fall until the final water-table position is reached (e.g., well HS-10 in Appendix A of third-year report (Buddemeier et al., 2010)). In some of the wells in the unconfined interval, water-level changes highly correlated with pumping in the confined interval are superimposed on the closed-basin response (e.g., well HS-15 in Appendix A of third-year report (Buddemeier et al. 2010)). In those cases, the responses appear to be produced by flow down the gravel pack of a well screened in the lower confined interval or by pumping-induced vertical leakage through the aquitard. In all of these cases, the sands in the unconfined interval appear to be of limited lateral extent.

The closed-basin (compartmentalized) nature of the sands in the unconfined interval has important implications for the continued viability of those sands 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. Thus, for example, given the screened interval (2529-2609 ft) and the average yearly decline (about 4 ft/yr) at well HS-20, and assuming the pump is at the base of the screened interval, the current rate of pumping will be unsustainable within six to seven years, if not sooner. Reductions in pumping at HS-20 would extend the "lifespan" of the aquifer because of the closed-basin nature of the sands, i.e. the "common pool" in this case has only one member. Although management activities can significantly and predictably alter decline rates in such systems, the small degree of lateral and vertical inflow is the ultimate limitation on the long-term sustainability of the resource.

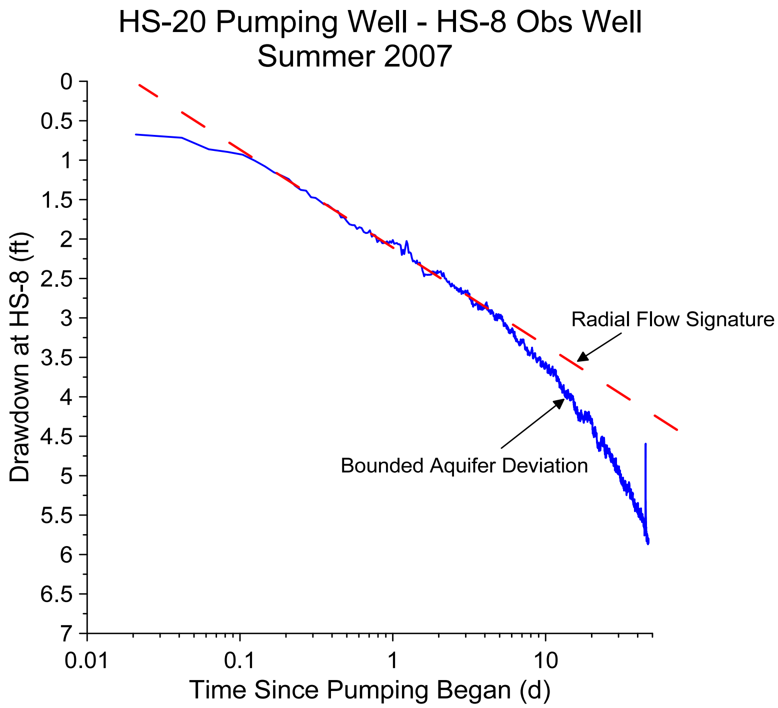

Figure 10a: Drawdown versus the logarithm of time since pumping began for the summer 2007 irrigation season; drawdown and pumping time are from point A on Figure 9. Note that the transmissivity and specific yield of the aquifer in the vicinity of the well pair can be estimated from the slope and x-intercept, respectively, of the dashed straight line.

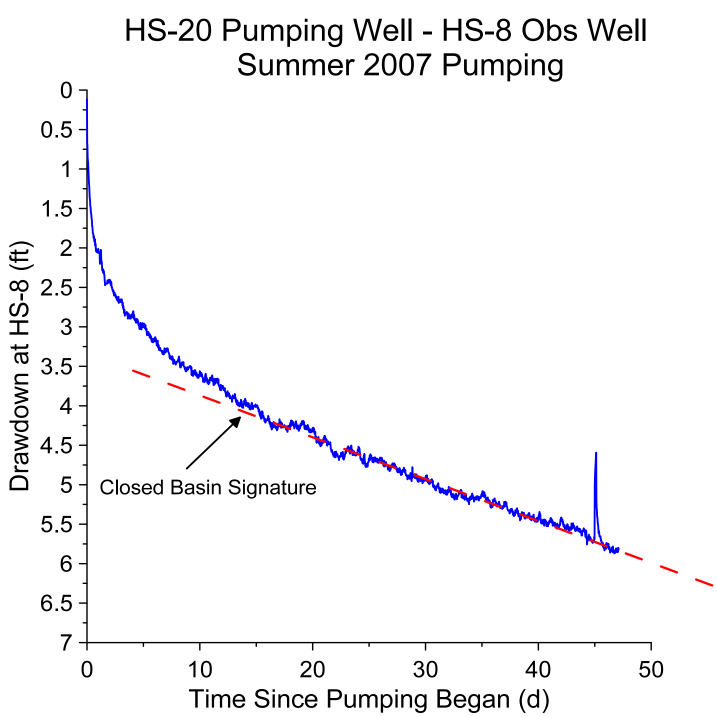

Figure 10b: Drawdown versus the time since pumping began for the summer 2007 irrigation season; drawdown and pumping time are from point A on Figure 9; slope is approximately 0.053 ft/d.

Wells in confined interval

Increasingly over time, more wells are being drilled into the thin, but productive, confined sand interval at the Haskell site. During 2001-2011, eleven irrigation wells were completed within the 9-square-mile area surrounding the index well in either the confined interval (six wells), the unconfined and confined intervals (one well), or both intervals and sandstones of the underlying Dakota aquifer (four wells). Five of these 11 wells were constructed during 2006-2011. Figure 8 shows a N-S line of wells, including the index well, that are screened in the lower confined interval. The sands in this interval appear to be more laterally continuous than sands in the unconfined interval, as hydrographs from wells HS-1, HS-2, HS-4, HS-7, and HS-18 are similar in form to that of the index well, and well HS-6 has a muted form of the same pattern (see Figure 2 for well locations). However, well HS-21, which is at the northern end of the cross section of Figure 8, shows no response to pumping in the confined interval, despite the more than 120 ft of drawdown produced by pumping in that interval, indicating that the lower sand at HS-21 is not in hydraulic communication with the interval to the south over the time frame of the monitoring period. The muted response at well HS-6 (8 ft of drawdown versus 120+ ft at the other wells) indicates that the sand interval in which it is screened is in only very limited hydraulic communication with the heavily pumped interval to the north.

Figure 3 is the hydrograph from the index well for the entire monitoring period. This hydrograph displays three noteworthy characteristics common to hydrographs from wells screened in this interval. First, the pumping-induced drawdown exceeds 120 ft every year during the monitoring period. Second, water levels are still recovering from the previous irrigation season when pumping begins for the next irrigation season. Third, the decline in the maximum observed water level was considerably greater than the decline in the minimum observed water level early in the monitoring period (decline in minimum observed water level was 1.4 ft from August 2007 to August 2009 while the decline in the maximum recovered water levels for these years was 8.9 ft). These characteristics are an indication of a high degree of well interference coupled with vertical leakage induced by the large drawdown. Note that not one of the monitored wells screened only in this interval exhibits the very short recovery period seen in wells in the overlying unconfined aquifer. However, well HS-21, which is screened in both intervals, does have a very short recovery period (e.g., Figure 3.4 in Young et al. (2008)), a further demonstration that the lower sand at HS-21 is isolated from the heavily pumped intervals to the south.

As with the sands in the unconfined interval, conditions in the confined interval can be explored in detail using traditional pumping-test interpretation methods and a more recent extension of those methods. A close examination of hydrographs from wells screened in this interval reveals that the water-level drop at A on Figure 3 is 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 2,467 ft] to the Haskell index well). Thus, water-level changes at the index well during this period can be viewed as drawdown resulting from a short-term pumping test. Figure 11a is a plot of pumping-induced drawdown versus the logarithm of the time since pumping began for this pumping event. As with Figure 10a, a period exists during which drawdown falls on a straight line, an indication of large-scale radial flow to the pumping well. However, in contrast to the response in the unconfined sands, the rate of drawdown at larger times decreases below that expected for radial flow, an indication of inflow of water to the aquifer. The source of that inflow is most likely from the overlying aquitard and unconfined sands, but upward flow from the underlying Dakota formation could also be contributing. The increasing rate of deviation from the straight line is an indication that the water level is beginning to stabilize as a result of that inflow. However, pumping ceased before further stabilization could occur. Van der Kamp (1989) developed a method for calculating the drawdown that would have occurred during the period in which water levels are recovering if pumping had not stopped. That approach was used here to calculate the drawdown that would have been observed if well HS-1 had continued pumping. Figure 11b is a plot of drawdown versus time that shows the drawdown calculated using the Van der Kamp extension. This extension, which is based on a theoretically sound manipulation of the observed drawdown, demonstrates that the drawdown would have stabilized if well HS-1 had continued to pump. Note that the upward trend in the extended drawdown is a product of the background upward trend in water levels shown in Figure 3. Based on the Van der Kamp extension, it appears that with continued pumping at well HS-1, the entire pumped amount would have shortly been supplied by pumping-induced inflow (leakage) into the aquifer.

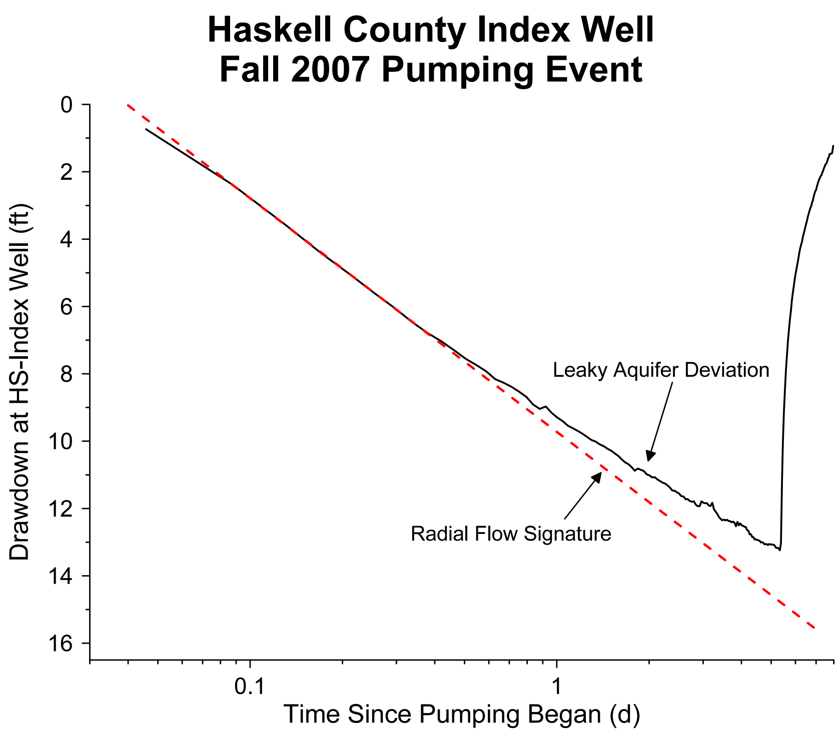

Figure 11a: Drawdown in the Haskell County index well versus the logarithm of time since pumping began for the pumping event at A on Figure 3.

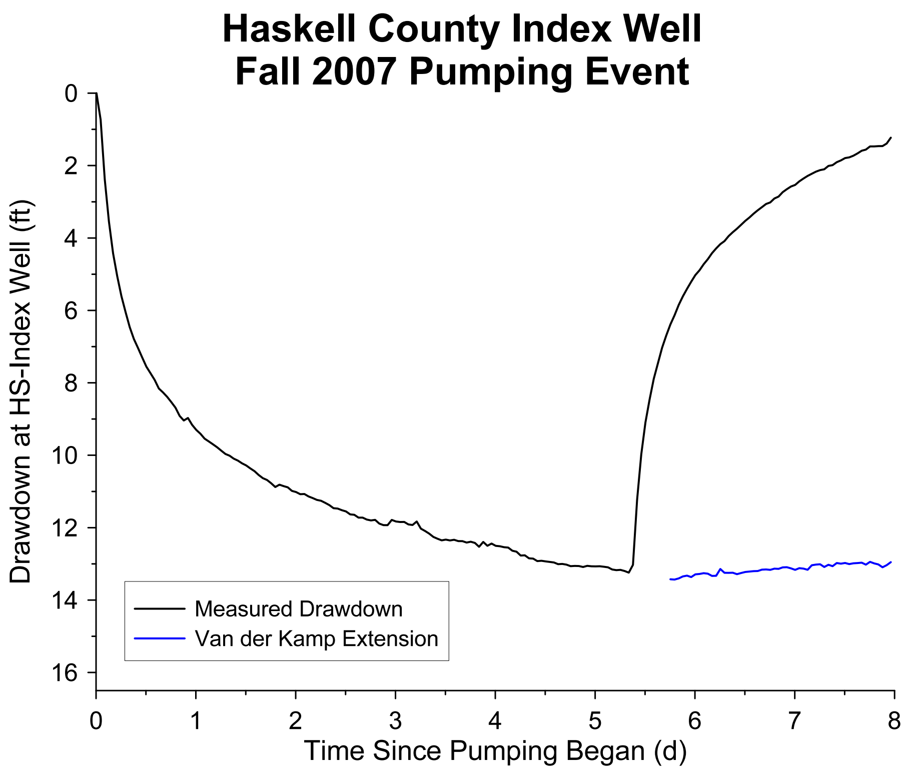

Figure 11b: Drawdown in the Haskell County index well versus the time since pumping began for the pumping event at A on Figure 3; Van der Kamp extension is an estimate of the drawdown that would have occurred if pumping had continued.

This leakage-dominated response to pumping at a single well is consistent with the hydrograph of Figure 3. Although pumping at HS-1 produced only 13 ft of drawdown at the index well, 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 120 ft. This 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 the pumping withdrawals in the latter portion of the irrigation season. This pumping-induced leakage is undoubtedly primarily responsible for the slower rate of decline for the minimum observed water level than for the maximum observed water level in the first half of the monitoring period. It is possible that the similarity in these rates in the latter half of the monitoring period is an indication of dewatering of portions of the unconfined sands that had previously provided leakage to the confined interval.

The leaky aquifer response of the sands in the confined interval has important implications for the continued viability of those sands as a water source for irrigated agriculture. Pumping withdrawals from this interval appear to be heavily dependent on downward leakage from the overlying aquitard and unconfined sands. However, in a relatively few years, the unconfined sand interval will be largely dewatered; at that point, the leakage will be drawn from water stored in the aquitard and, possibly, from the underlying Dakota 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 irrigation demands. For example, the water column at the index well, which is screened at the bottom of the aquifer and is over 2,450 ft from the closest pumping well, was only 39 ft in height at the maximum observed drawdown for 2011. In the immediate vicinity of the irrigation wells, the saturated thickness was likely considerably less. Given that pumping from the confined interval will undoubtedly increase as shallower wells are replaced by deeper wells, it is likely that the large-scale irrigation withdrawals will not be sustainable beyond the current decade in the vicinity of the Haskell site, except, possibly, in those wells that are also completed in the discontinuous sandstones of the underlying Dakota Formation.

Scott County

Figure 12 is a NNW-SSE lithologic cross section of the unconsolidated sequence at the Scott site. The hydrostratigraphy of the site consists of an interbedded mix of coarse gravels through clays. Although the upper half of the unconsolidated sequence is made up of relatively fine sediments, changes in water levels in the Scott County index well, whether in response to pumping or fluctuations in barometric pressure, indicate that the sands in which the well is screened are unconfined. Given that the well is screened at the bottom of the unconsolidated saturated interval, we can assume that the entire interval behaves as an unconfined aquifer.

Figure 5 is the hydrograph of the index well for the entire monitoring period. Four characteristics are worth noting: 1) the maximum drawdown is only 3-4 ft/yr as result of the unconfined nature of the aquifer and the distance to the closest high-capacity well; 2) there is no indication in either the pumping or recovery periods that the sands are acting as a closed-basin aquifer or that there is a significant component of vertical leakage induced by pumping; 3) water levels are still recovering from the previous irrigation season when pumping begins for the following year and there is no indication that the water levels are nearing stabilization at the onset of pumping; and 4) the maximum and minimum observed water levels decrease in a similar manner. Given these characteristics, the unconfined aquifer at the Scott County site appears to be more laterally extensive than the unconfined sands at the Haskell site with no signs of pumping-induced vertical inflow to the system as in the confined interval at the Haskell site.

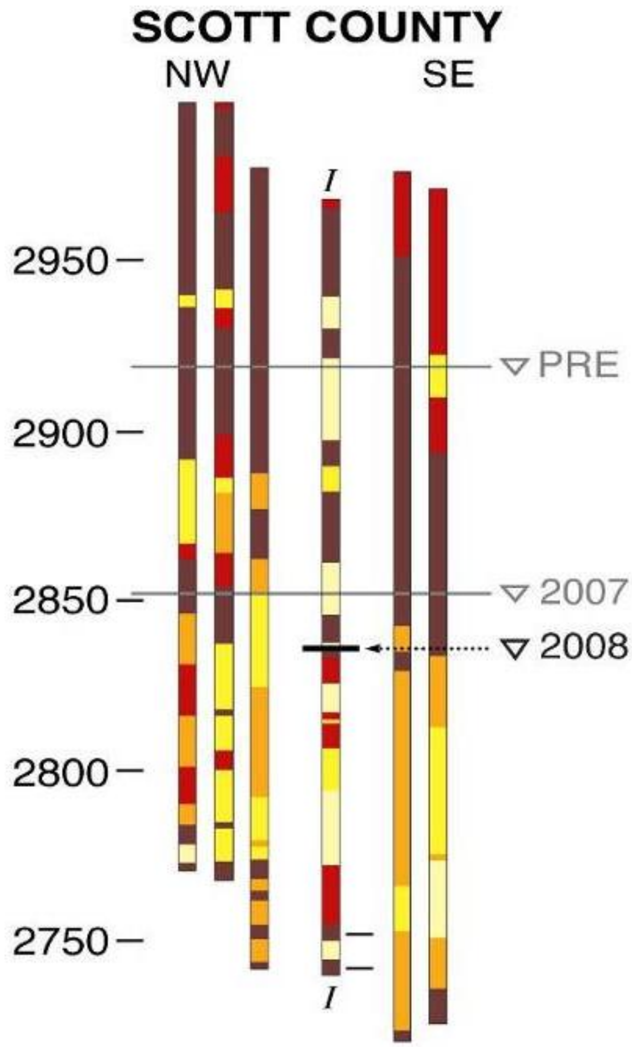

Figure 12: Lithologic cross section for the Scott County site. The 2007 level represents the measured January 2007 water level in a nearby annual well. See Figure 8 for legend.

Conditions in the unconfined aquifer at the Scott County site can be explored in more detail using traditional methods for interpretation of pumping tests. As with the unconfined interval at the Haskell site, the irrigation season can be viewed as a long-term pumping test. Although the analysis is ongoing, some initial results have been obtained. Figure 13 is a plot of drawdown versus the logarithm of time since pumping began for pumping periods beginning at A (2008), B (2009), C (2010), and D (2011) on Figure 5. These data are relatively "noisy" as a result of pumps cutting on and off, but a consistent picture still emerges for all four pumping seasons. An apparent period of radial flow to the pumping well lasts until nearly 20 days from the onset of pumping. After that time, however, drawdown increases at a faster rate than would be expected for large-scale radial flow to the pumping well. This is an indication of low-permeability boundaries impacting the drawdown. Unlike the unconfined sands at Haskell County, the rate of deviation from the radial flow line does not appear to continually increase, so there is no indication of a closed-basin response at the Scott index well. The deviation may be produced by the edges of the Scott-Finney depression but little more can be said at this point. Assessment of water-level changes at the Scott index well will continue in the sixth year of this project. Additional discussion of water-level changes during the recovery period is provided in the following section.

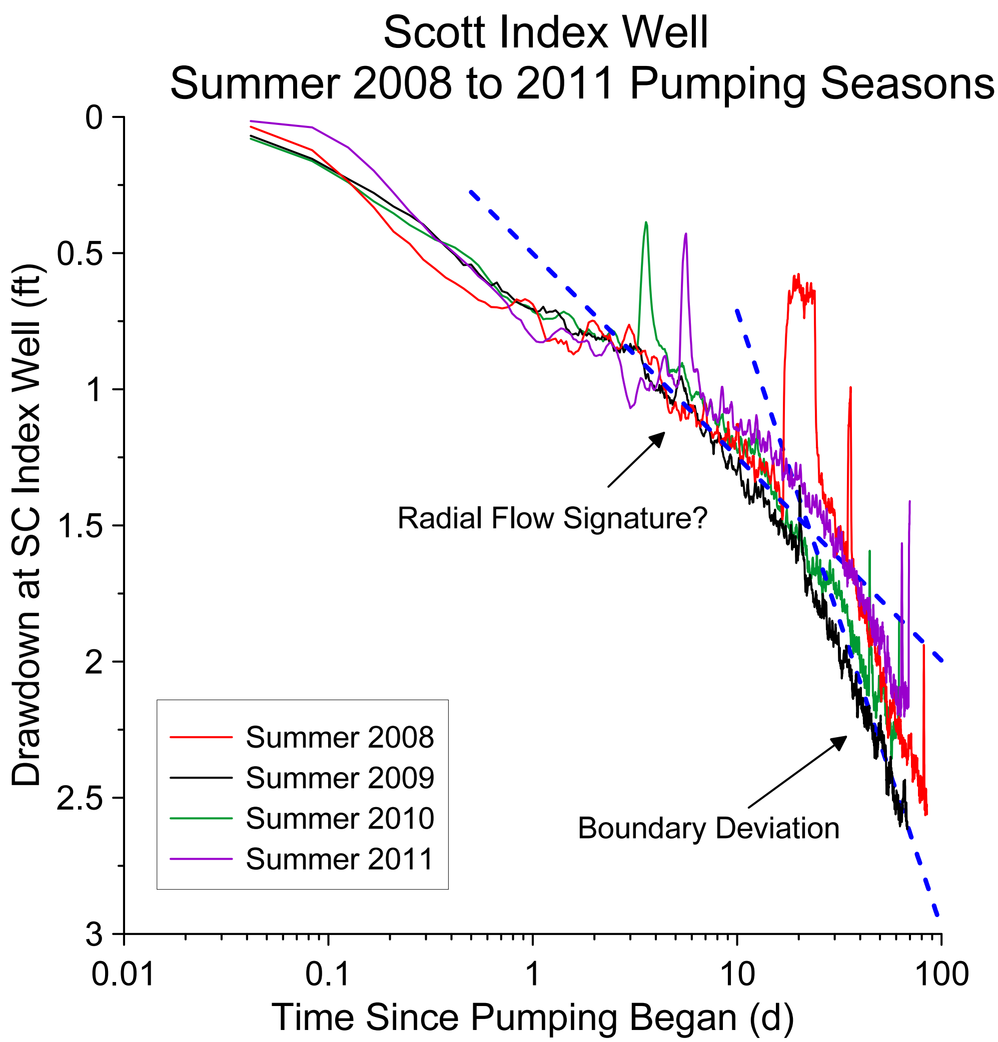

Figure 13: Drawdown in the Scott County index well versus the logarithm of time since pumping began for pumping seasons beginning at points A (2008), B (2009), C (2010), and D (2011) on Figure 5.

Thomas County

Figure 14 is a NW-SE lithologic cross section of the unconsolidated sequence at the Thomas site. The hydrostratigraphy of the site consists of an interbedded mix of coarse gravels through clays. As with the Scott County well, changes in water levels in the Thomas County index well, whether in response to pumping or fluctuations in barometric pressure, indicate that the sands in which the well is screened are unconfined. Given that the well is screened at the bottom of the unconsolidated saturated interval, we can again assume that this interval acts as an unconfined aquifer.

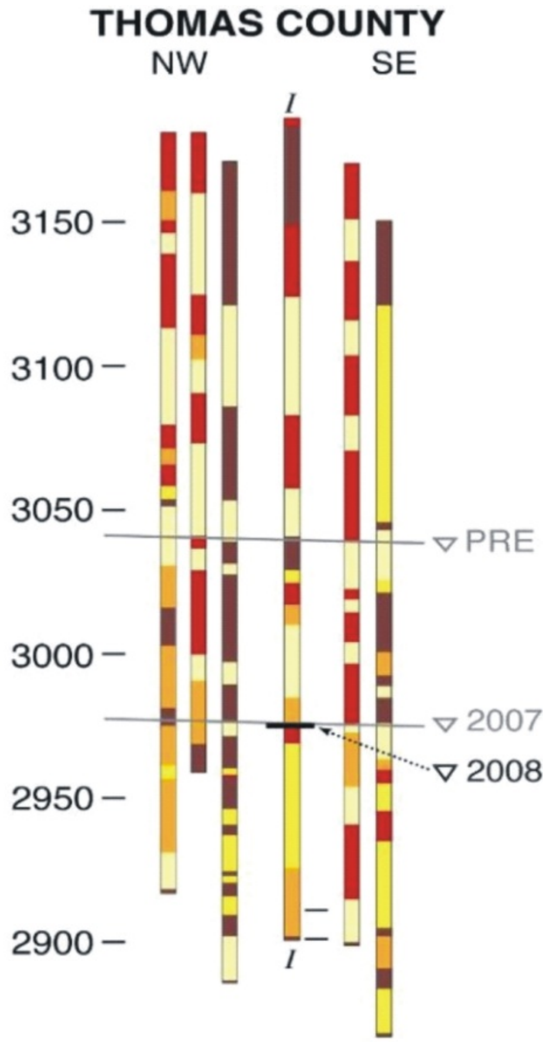

Figure 14: Lithologic cross section for the Thomas County site. The 2007 level represents the measured January 2007 water level in a nearby annual well. See Figure 8 for legend.

Figure 7 is the hydrograph of the index well for the entire monitoring period. Six characteristics are worth noting: 1) the maximum drawdown during the pumping season is only 4-7 ft/yr as result of the unconfined nature of the aquifer and the distance to the closest high-capacity well; 2) there is a thick “noise” band in the water-level data that is a product of water-level responses to fluctuations in barometric pressure; 3) the recovery period is much longer (e.g., ended in late June in both 2009 and 2010) than at the Scott (ended early April both years) or Haskell (ended early February (2009) and early March (2010)) sites; 4) water levels are still recovering from the previous irrigation season when pumping begins for the following year and there is no indication that the water levels are nearing stabilization at the onset of pumping; 5) other than in 2011, both the minimum and maximum observed water levels have fluctuated over a range that is less than 1.5 ft since the summer of 2007; and 6) most noteworthy, unlike the Scott index well or any of the monitored wells at the Haskell site, an increase in the maximum observed water level (between 2009 and 2010) occurred during the monitoring period. The last three characteristics indicate that there is likely an additional source of inflow into the unconfined sands at the Thomas County index well.

As at the other two sites, conditions in the aquifer at the Thomas County site can be explored in more detail using traditional methods for interpretation of pumping tests. From the Thomas County hydrograph, it appears that an isolated pumping event occurred at the point marked A on Figure 7 in the spring of 2009. An expanded view of water levels in the late winter to spring period in 2009, after correction for fluctuations in barometric pressure (see Appendix A), is given in Figure 15. A pumping period beginning at A and ending at B is superimposed on a near-linear recovery trend. Water levels, however, do not return to the trend line during the recovery period. A return to the trend line is expected in the case of large-scale lateral flow to a pumping well and was observed for a similar isolated pumping event in the Scott County index well hydrograph (E on Figure 5). One explanation for the failure to return to the trend line is that the aquifer is behaving as if it is laterally bounded on all sides by low-permeability units, i.e. it is acting as a closed-basin aquifer. This explanation is supported by viewing the drawdown after the linear trend has been removed. The resulting plot (Figure 16) shows a striking similarity to the well HS-8 hydrograph in Figure 9.

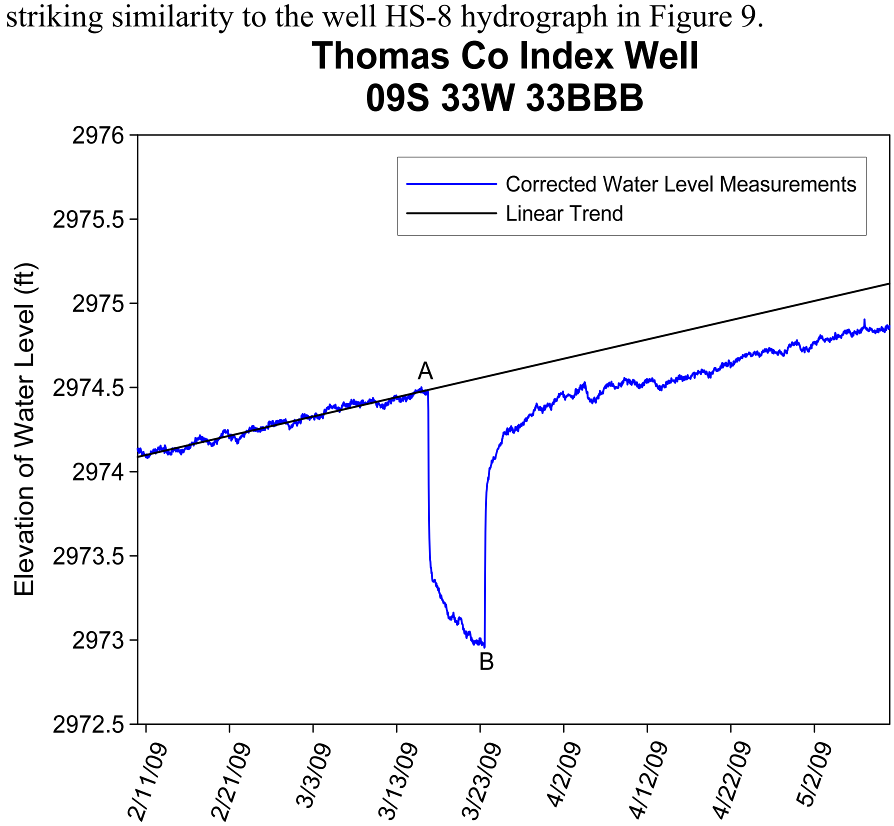

Figure 15: Water levels in the Thomas County index well for later winter and spring of 2009.

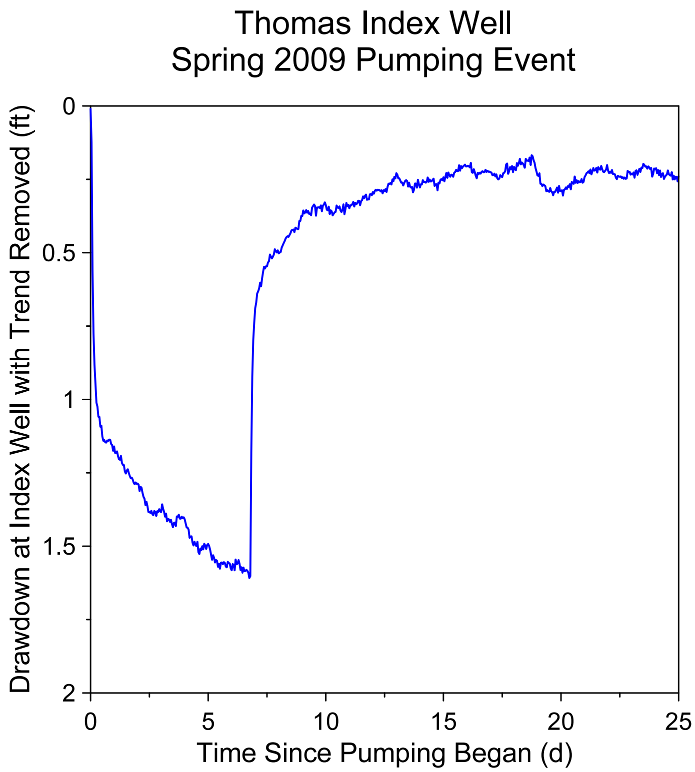

Figure 16: Drawdown in the Thomas County index well after removal of linear trend versus the time since pumping began for the pumping event from points A to B on Figure 15.

Conditions in the unconfined aquifer can be further explored by considering the 2010 irrigation season (the least noisy of the irrigation seasons) as a long-term pumping test beginning at point B on Figure 7. A plot of drawdown versus the time since pumping began (Figure 17) shows that drawdown falls on a straight line when plotted in this format for over 35 days, an indication that the cone of depression has reached the boundary of the aquifer in all directions, i.e. the sands are acting as a closed-basin (bathtub or compartmentalized) aquifer. Thus, the conclusions derived from an examination of a single pumping event are consistent with those obtained from the entire pumping season. Note that after 45 days of pumping, drawdown becomes more variable as a result of pumps cutting on and off. However, even in this period, water levels offset from but nearly parallel to the drawdown trend are observed prior to the cessation of widespread irrigation pumping (point R on plot marks the end of widespread pumping and the beginning of the recovery period).

Water-level responses that exhibit closed-basin 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 the Thomas index well (Figure 7), the consistency of the water-level response to a single short-term pumping event (Figure 15), which was likely produced by pumping at a single well, and to the entire irrigation season (Figure 17), which is produced by pumping at multiple wells, indicates that the sand and gravel units in which the Thomas index well is screened are likely laterally bounded by units of relatively low permeability. However, unlike the unconfined interval at the Haskell site, the "common pool" in this case appears to have multiple members (pumping wells).

Consideration of a single pumping event or the entire irrigation season reveals that the aquifer acts as a closed-basin system. Thus, during the recovery period, one would expect a very rapid recovery, similar to that observed in the unconfined interval at the Haskell site (e.g., Figure 9). However, in contrast to conditions in the unconfined interval at the Haskell site, water levels continue to rise until the onset of pumping for the subsequent irrigation season. The inflow producing this rise is not a result of lateral flow from more distant regions because the aquifer acts as a closed-basin system on the time scale of a recovery period. Thus, there appears to be a significant amount of vertical inflow into the unconfined aquifer at the Thomas County site.

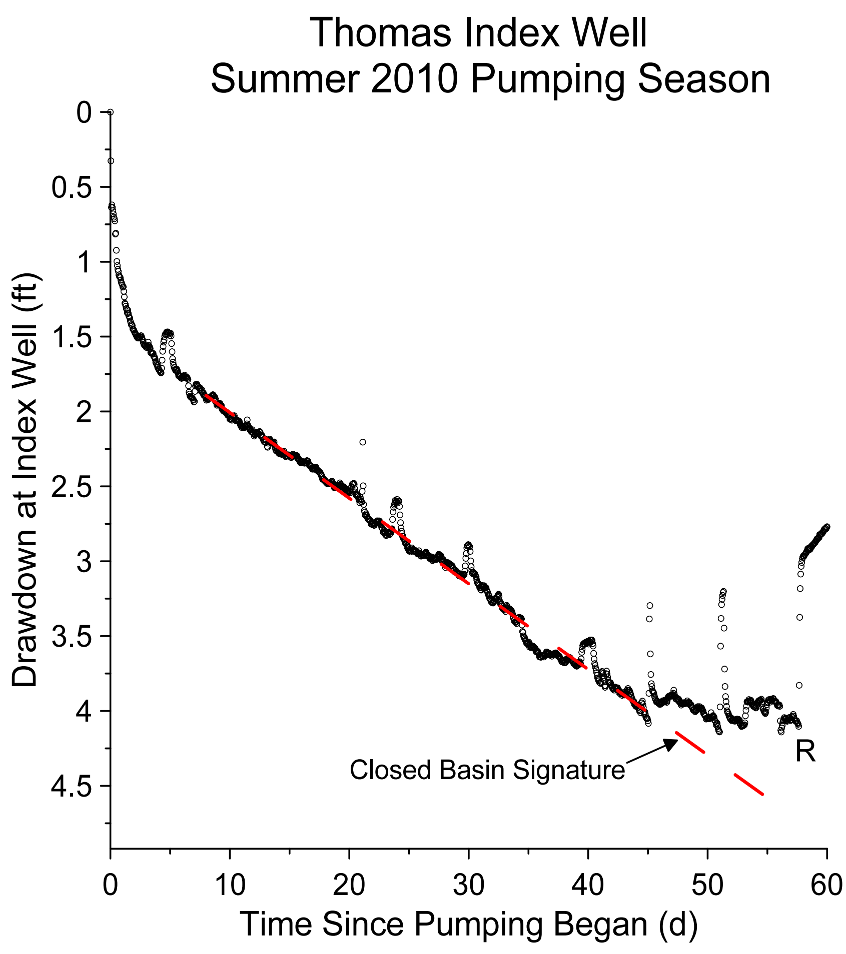

Figure 17: Drawdown in the Thomas County index well versus the time since pumping began for the summer 2010 pumping period beginning at point B on Figure 7; R marks the beginning of the recovery period (cessation of widespread pumping for 2010).

The possibility of vertical inflow can be explored further by examining the recovery data. One useful approach for assessing behavior during the recovery period, which was developed for this project, is to superimpose recovery data from different years. This is done by setting the time and water-level elevation at the start of the recovery period to zero for each year. Figure 18 shows the results for the complete 2008-09 and 2009-10 recovery seasons and the still ongoing 2011-12 recovery. The 2008-09 and 2009-10 recovery seasons were chosen because the 2008 irrigation season was nearly twice as long (with almost 50% more pumping) than the 2009 irrigation season (Table 6). Although the 2011 water use is yet to be determined, the 2011 pumping period was over 50 days longer than that in 2008 and large water-level declines were observed during the 2011 pumping season (Figure 7). Thus, the 2011 water use is most likely greater than that of 2008. The agreement between the superimposed recovery plots is remarkable; the rate of water-level change during the three 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. Given the similar recovery rates between years, the increase in the maximum observed water level in the 2009-10 period is therefore just a product of the relatively high minimum water-level elevation for the 2009 irrigation season and the following lengthy period of recovery (298 days). If the 2007-08 recovery 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 period had been the same length as the 2009-10 period, a maximum water level close to that of the 2009-10 period would have been attained.

A similar recovery assessment can be performed for the Scott and Haskell index wells. Figure 18b presents two recovery seasons from the Scott well. The 2009-10 and the ongoing 2011-12 recovery seasons were chosen because 1) the much larger water use expected for the 2011 pumping season, and 2) the data for these two recovery seasons are less affected by pumping interferences. Although there was no indication of pumping-induced inflow from the hydrograph of Figure 5, the coincidence of recovery plots again points to the possibility of inflow similar to that at the Thomas site (i.e. not induced by pumping). Further conclusions can be drawn once the 2011 water-use data are available.

Figure 18c presents two recovery seasons from the Haskell well. The 2010-11 and the ongoing 2011-12 recovery seasons were chosen because 1) the much larger water use expected for the 2011 pumping season, and 2) the data for these two recovery seasons are less affected by pumping interferences. The lack of coincidence of recovery plots indicates that inflow similar to that at the Thomas site (i.e. not induced by pumping) is insignificant at the Haskell site. The recovery during the 2010-11 recovery is much more rapid than the 2011-12 recovery because of the shorter 2010 pumping season. As the water levels during the 2010-11 recovery begin to approach recovery, the rate of change greatly decreases and the 2011-12 recovery water levels "catch up."

Determination of the origins of the vertical 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 are given in Section 5 of this report.

The vertical inflow observed at the Thomas County index well does not appear to be isolated to that immediate area. Figure 19 shows the interpolated change in water level (based on the annual measurement program) in the HPA between 2009 and 2010. The blue region in most of Thomas County indicates that water levels rose between 2009 and 2010. In a pure ground-water mining situation, such water-level increases would only be observed if there was a large difference in the duration of the previous pumping season and the duration of recovery prior to annual measurements in successive years. In this case, the duration of the pumping season for 2008 was nearly twice that of 2009. The 2009-10 recovery period began 13 days earlier than the 2008-09 recovery (8/26/09 vs. 9/8/08) and the 2010 annual measurement was taken two days earlier than the 2009 annual measurement (1/2/2010 vs. 1/4/2009). Thus, the 2009-10 recovery was 11 days longer than the 2008-09 recovery at the time of the annual water-level measurements (the total duration of recovery was within one week of four months in both cases). It is possible that the general rise in water level across Thomas County in Figure 19 is simply a product of the large difference in durations of the previous pumping seasons. However, the hydrograph from the Thomas County index well indicates otherwise, a demonstration of the value of the index wells for interpretation of the results of the annual water-level measurement program. Note that given the depth to water (>210 ft at the Thomas County index well) and that the same maximum water level as in 2009 would have been observed at the Thomas index well in 2008 and 2011 if the recovery periods had been longer, vertical infiltration of 2009 precipitation is not responsible for the rise in water level across Thomas County in Figure 19. Although 2009 was a wet year in the GMD4 region, the reported water usage in 2009 (1917 af) was still 68% of that in 2008 (2825 af). Further investigation of the amount and source of the vertical inflow will be pursued in the sixth year of this project.

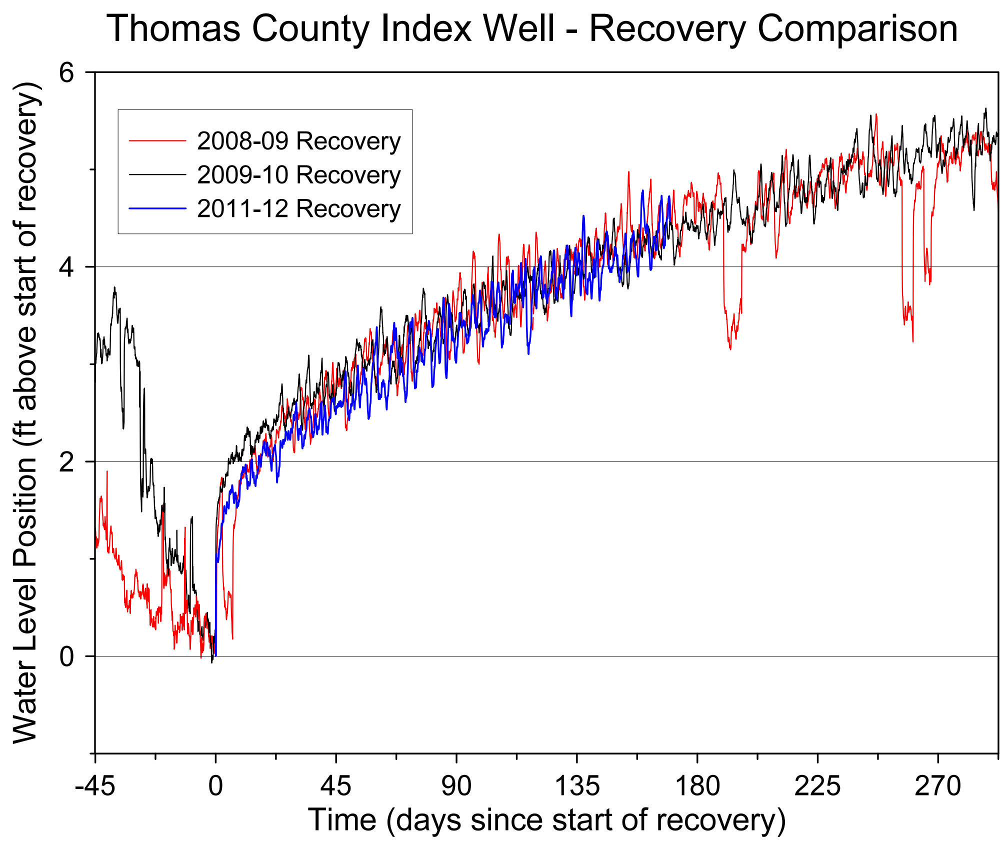

Figure 18a: Water levels in the Thomas County index well for the 2008-09, 2009-10, and 2011-12 recovery periods; recovery for the 2008-09, 2009-10, and 2011-12 recovery periods calculated from points C, D and E, respectively, on Figure 7.

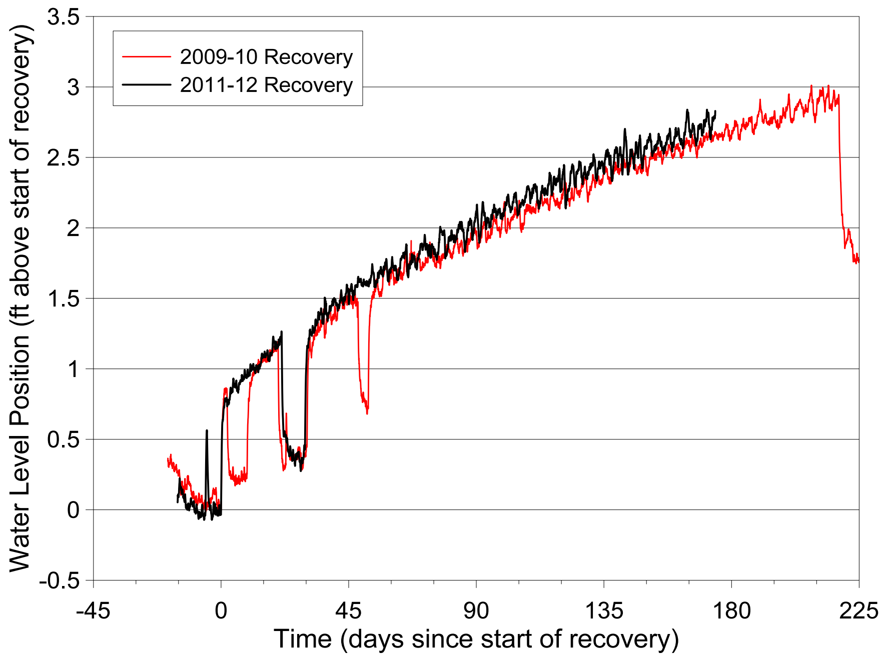

Figure 18b: Water levels in the Scott County index well for the 2009-10 and 2011-12 recovery periods; recovery for the 2009-10 and 2011-12 recovery periods calculated from points F and G, respectively, on Figure 5.

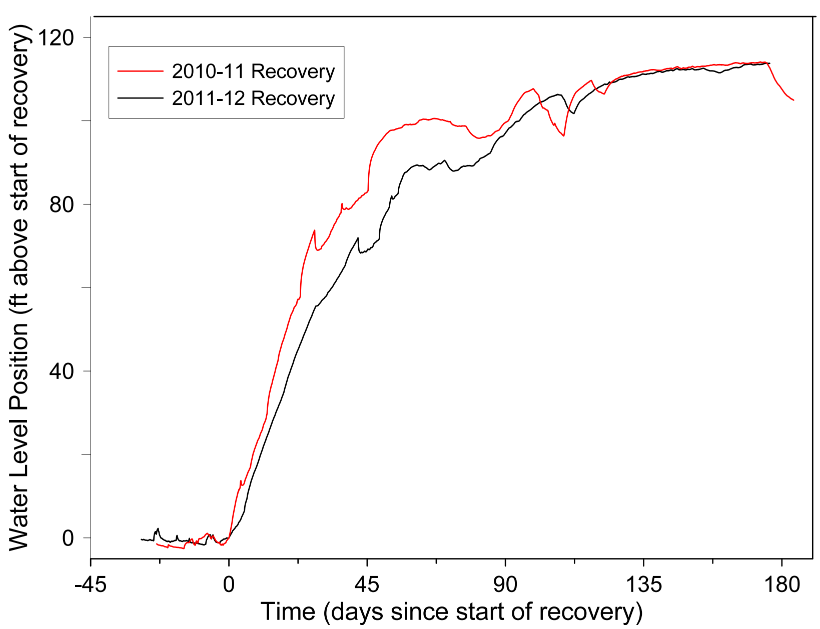

Figure 18c: Water levels in the Haskell County index well for the 2010-11 and 2011-12 recovery periods; recovery for the 2010-11 and 2011-12 recovery periods calculated from points B and C, respectively, on Figure 3.

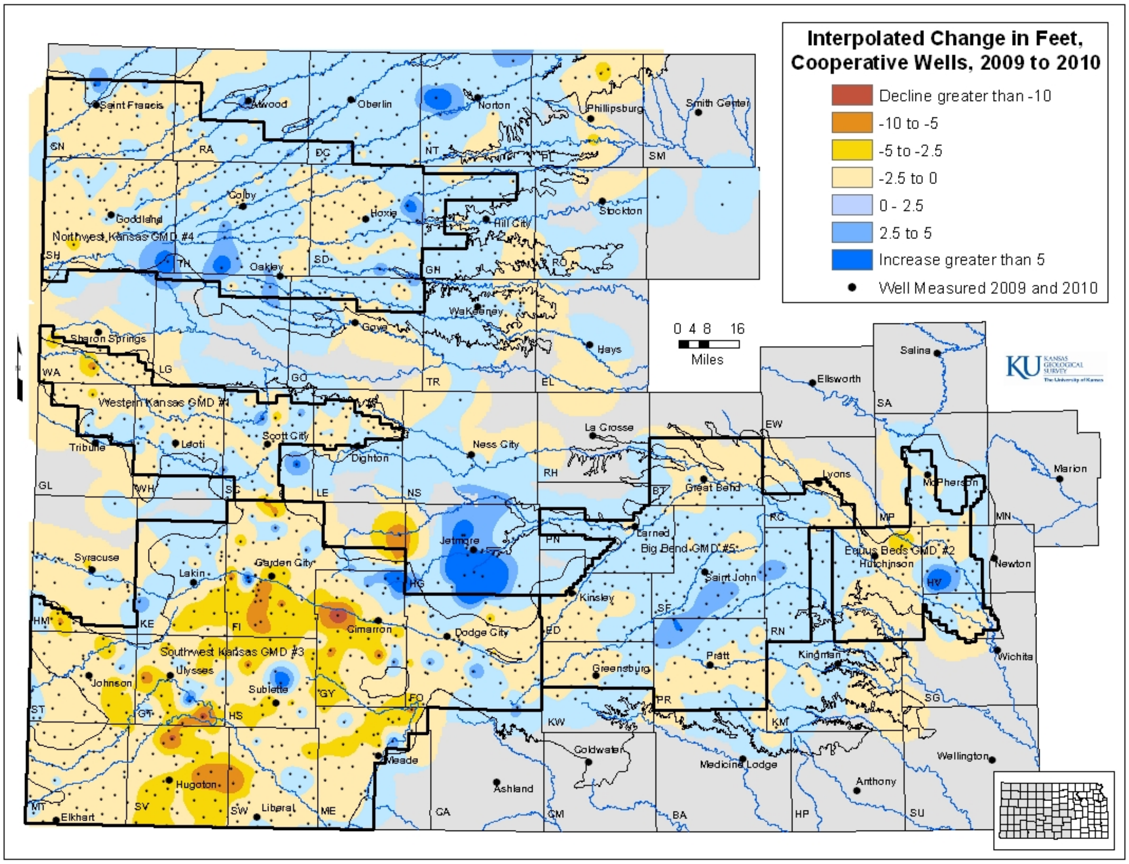

Figure 19: Interpolated change in water level for 2009-10 using data from the annual water-level measurement program.

4.3. Thomas County Expansion Project

Initially, five wells, including retired and active irrigation wells and a domestic well, were selected and instrumented 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. A summary of sensor installation dates and other significant events is provided in Table 8. Hydrographs from the index well and the five monitored wells that functioned in 2010 are given in Figure 20. 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. Although full recovery information was not available for either TH3 or TH7, water levels in both are clearly higher than levels in the index well. Water levels in wells TH9, TH10, and TH11 are close to the levels in the index well. This is expected given the water-table map constructed as part of the Thomas County water budget project indicated an overall west-to-east ground-water flow field (Stotler et al., 2011). At the time of this report, sensors are operating in wells TH7 (to be removed prior to the start of the irrigation season), TH9, and TH10. A replacement for well TH3, which has been plugged, is currently being sought. The malfunctioning sensor in well TH11 will be replaced shortly.

Table 8: Installation date and other notes for Thomas Co. 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 -	Active irrigation well, sensor installed and removed each year by KGS and GMD 4 at land owner's request.
TH8	Retired Irrigation	DWR	11/5/09	Sensor malfunctioned 12/4/09 – yet to be replaced.
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.
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.

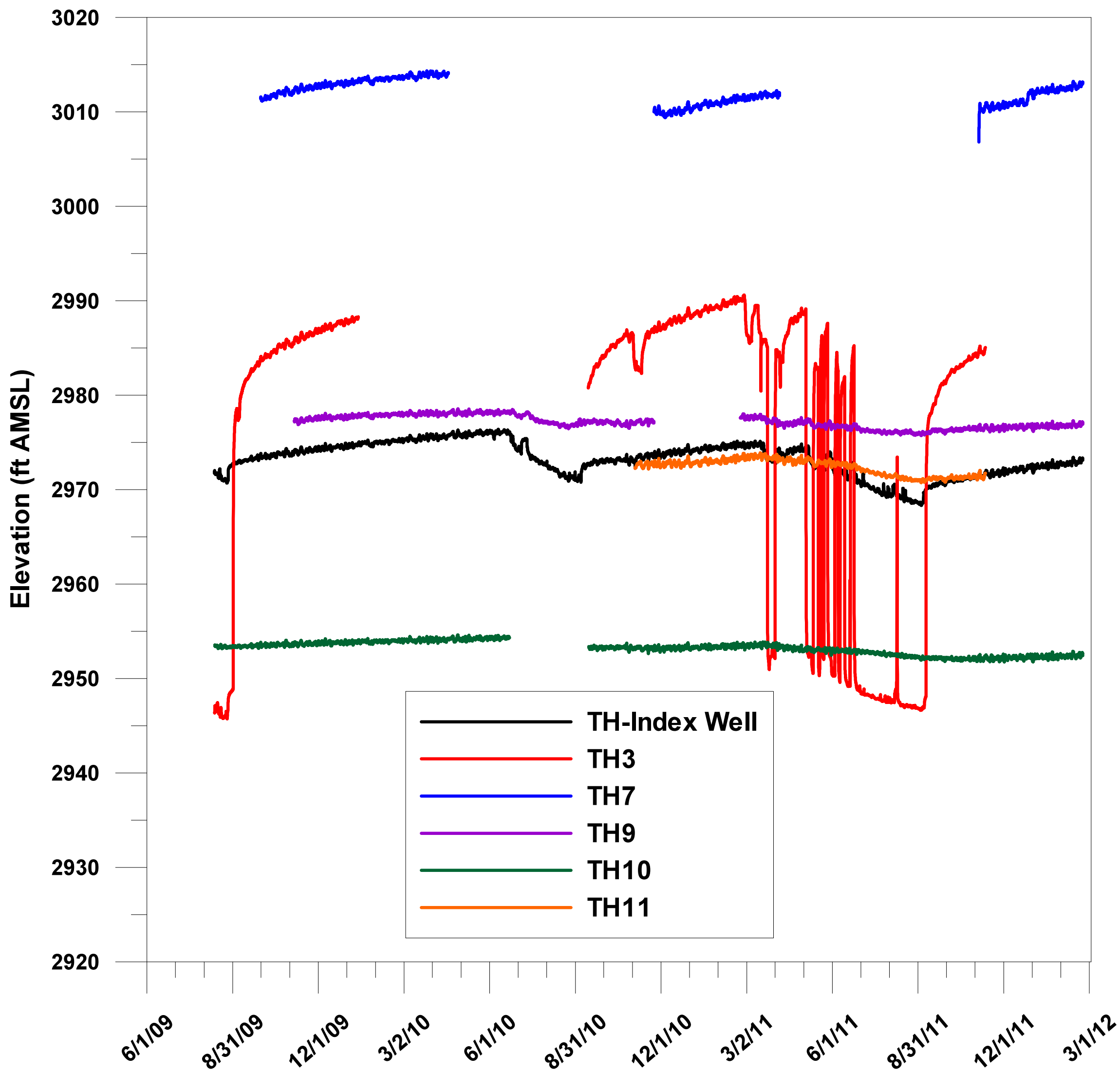

Figure 20: Hydrograph comparison from the Thomas expansion well program. The general water-level trend indicates west-to-east ground-water flow.

Additional information can be gained from the hydrographs of the Thomas expansion wells. For example, the hydrograph at well TH9 appears to be responding to the same pumping events as the Thomas index well (Figure 21). The responses are more subdued and smoothed (indicating a greater distance to the pumping wells) in TH9 but are still clearly apparent. Note that the closest irrigated section to TH9 is the section containing the index well.

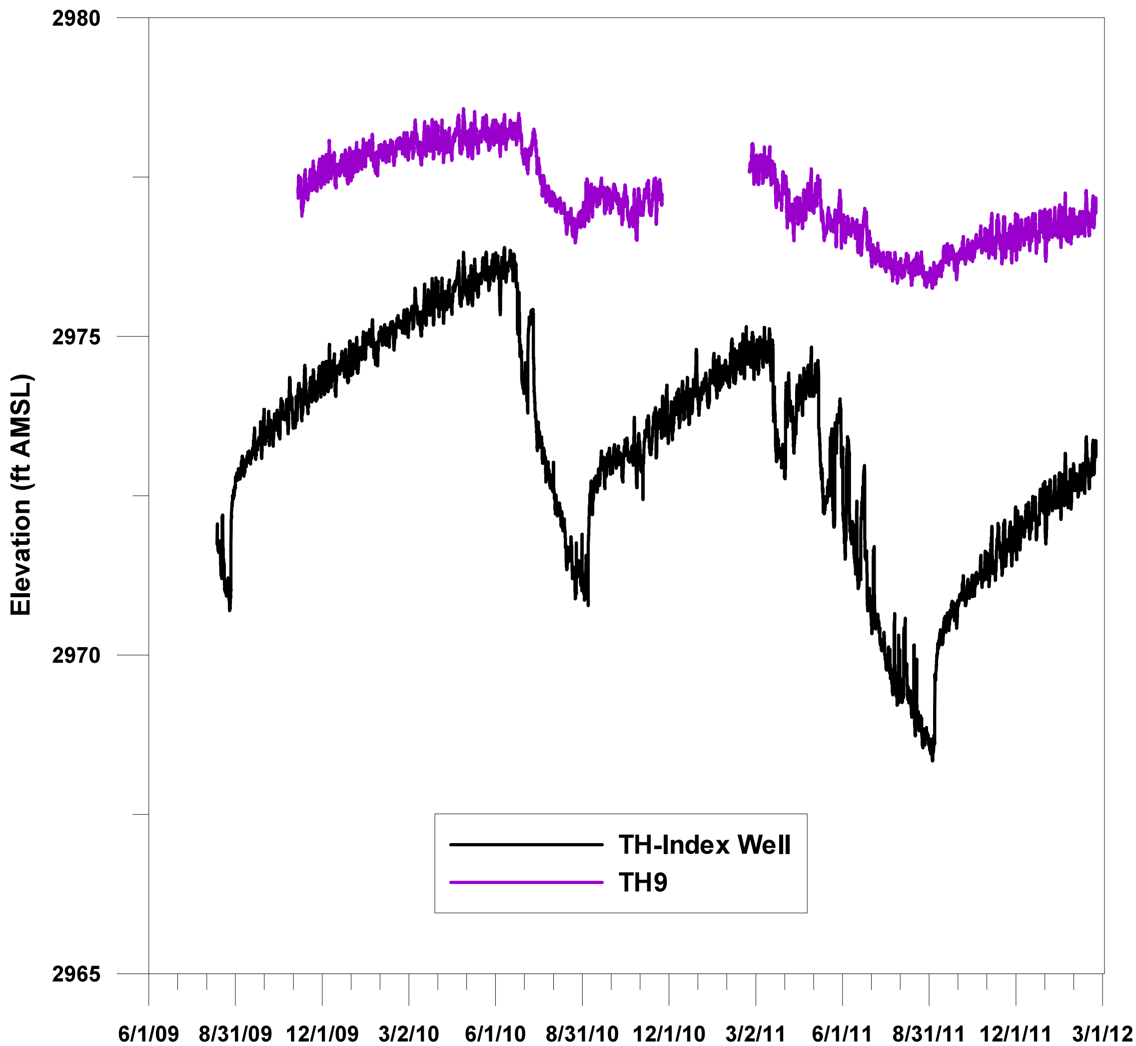

Figure 21: Hydrograph comparison of Thomas index well and expansion well TH9. TH9 is located approximately 1.5 miles NE of the index well (0.75 miles north, 1.25 miles east).

The water-level change at well TH3 is much larger than that at the index well (Figure 22) because of the proximity of TH3 to an active pumping well (Stotler et al., 2011). However, both wells appear to be responding to many of the same pumping stresses. The hydrograph for well TH3 is relatively complete for the 2009-10 and 2011-12 recovery reasons. Thus, the recovery records can be superimposed to reveal the same coincidence of recovery plots as observed at the Thomas index well (Figure 23). This coincidence indicates that the mechanisms controlling the recovery at the Thomas index well are not isolated to that well.

Overall, the incomplete data from the 2009-2011 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 2011-12 recovery and malfunctioning sensors replaced, the relationship between the index well and expansion wells should become clearer. This relationship will be explored further in year six.

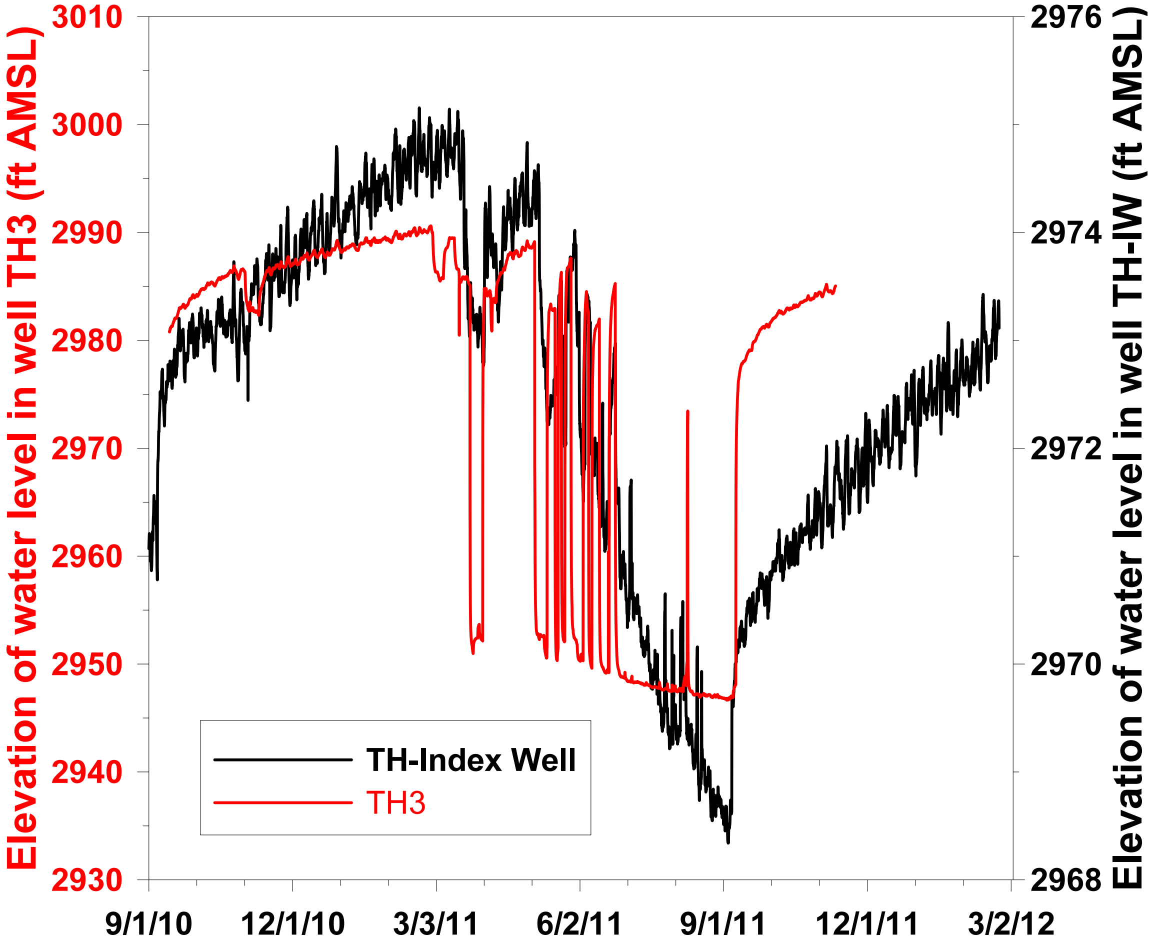

Figure 22: Hydrograph comparison of Thomas index well and expansion well TH3. This expansion well is located approximately 2.25 miles to the WSW of the index well (1.25 miles south, 2 miles west). The span of the vertical axis for the index well plot (right y-axis) is a factor of 10 less than that of well TH3 for illustrative purposes. Well TH3 is now plugged.

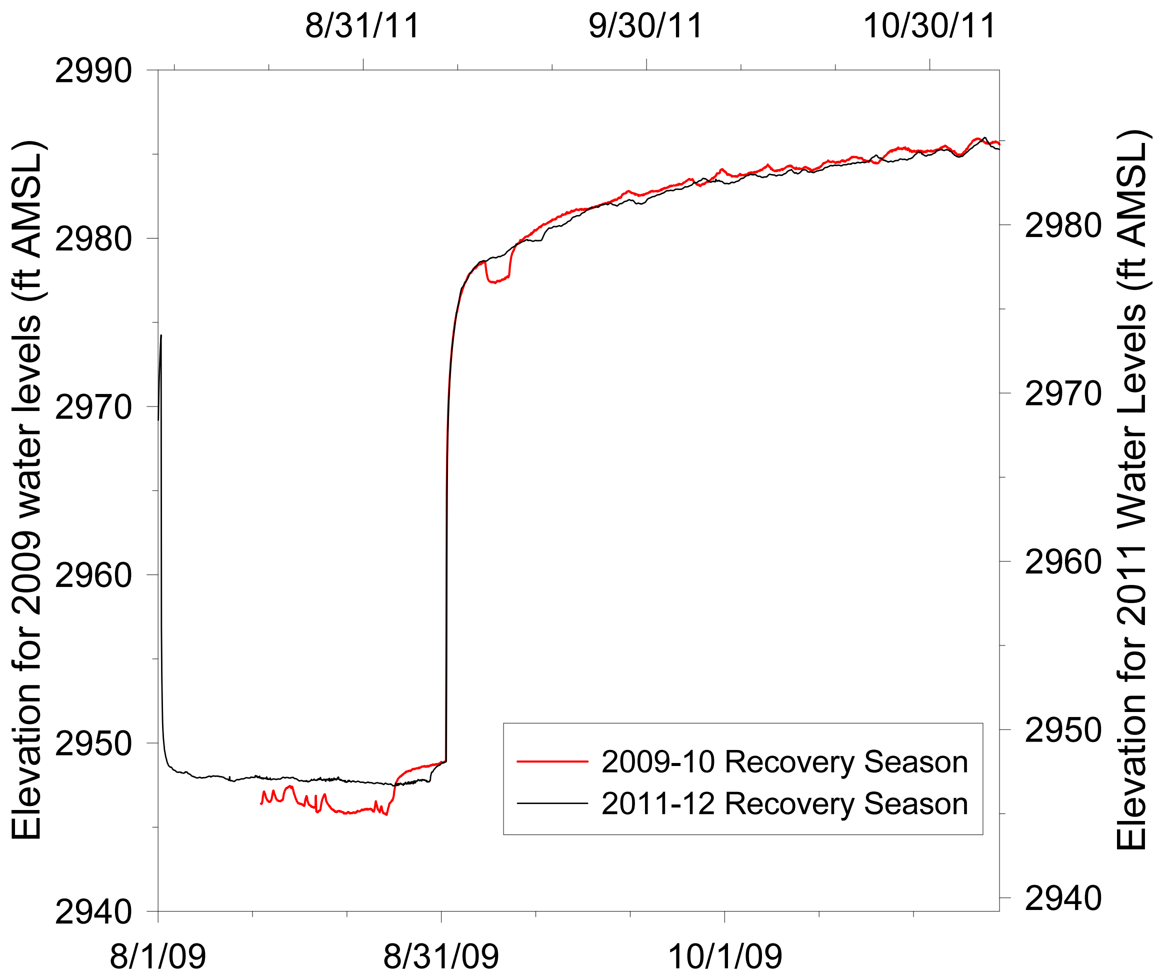

Figure 23: Hydrograph of the initial recovery period for TH3 from 2009 (bottom x-axis and right y-axis) and 2011 (top x-axis and left y-axis). Note that the spans of the two x-axes and the two y-axes are the same in this plot. Well TH3 is now plugged.

4.4. Additional Wells of Opportunity

Late in 2011, arrangements were made with landowners and GMD 1 to install KGS pressure transducers in two wells in the area of the Scott index well. The only continuous monitoring data we currently have from this area are the water-level records of the index well. Utilizing old USGS recording wells, sensors were installed in February 2012. One of the new locations is 6.5 miles south of the Scott index well and the other is 22 miles to the west (just north of Leoti). The water columns are short in both wells, 16 feet and 10 feet, respectively. When downloaded, data from these wells will be shared with GMD1 and the landowners.

In a continuing collaboration with DWR, the KGS is looking into additional water-level data that have been recorded by pressure transducers in the western tier of GMDs. Data from Rawlins and Stevens counties were presented in the year four annual report (Stotler et al., 2011), indicating generally similar water-level responses in Thomas and Rawlins counties, and in Haskell and Stevens counties.

This year, two additional datasets from DWR sensors were available to the project, one in Sheridan County and a second in northwestern Thomas County. These two sites are interesting as the former is located within the western edge of the Sheridan-6 sub-unit, whereas the latter is located between the Thomas County index well and the Rawlins County DWR wells analyzed in the year four report.

The well record from Sheridan County (Figures 24 and 25) is incomplete, but the data quality from the mid-late recovery periods for the 2005-06 and 2006-07 recoveries, and from the complete 2008 pumping season and most of the 2008-09 recovery appears to be quite good. The apparent "noise" in water levels is undoubtedly produced by barometric-pressure fluctuations as at the Thomas index well. As at the index well, full recovery was not achieved in any year during the monitoring period. The shape of the late-time recovery is also similar to that observed in the Thomas and Scott index wells (compare concave–upward curvature in lower right plot on Figure 25 with curvature in Figures 16 and 17 in Stotler et al. (2011)). This concave-upward curvature in the format of the lower right plot of Figure 25 is an indication of non-pumping-induced inflow, and undoubtedly would produce the same coincidence of recovery plots as seen at the Thomas index well and TH3. The maximum observed recovered water levels in 2005-06 and 2006-07 were approximately the same, but the maximum observed level was approximately 3.5 ft lower at the end of the 2007-08 recovery. An additional drop of 1 ft from the maximum observed water level in 2008 was observed at the end of the monitoring in May of 2009, but it is not clear if the end of the recovery had been reached. The one full pumping season indicates annual pumping season drawdown is on the order of 12 ft. Note that the pumping-induced drawdown plot in the lower left of Figure 25 does not show any indication of boundary effects.

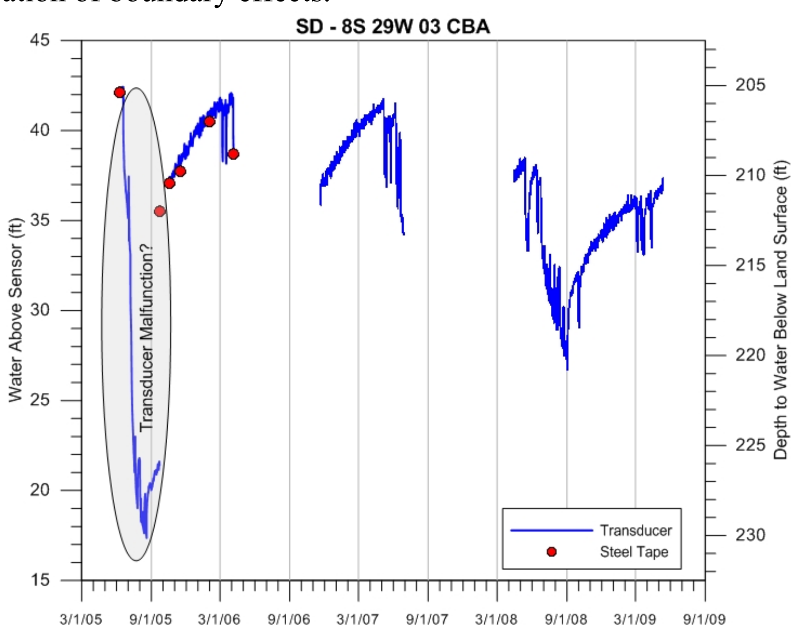

Figure 24: Hydrograph of well 8S 29W 03 CBA in Sheridan County.

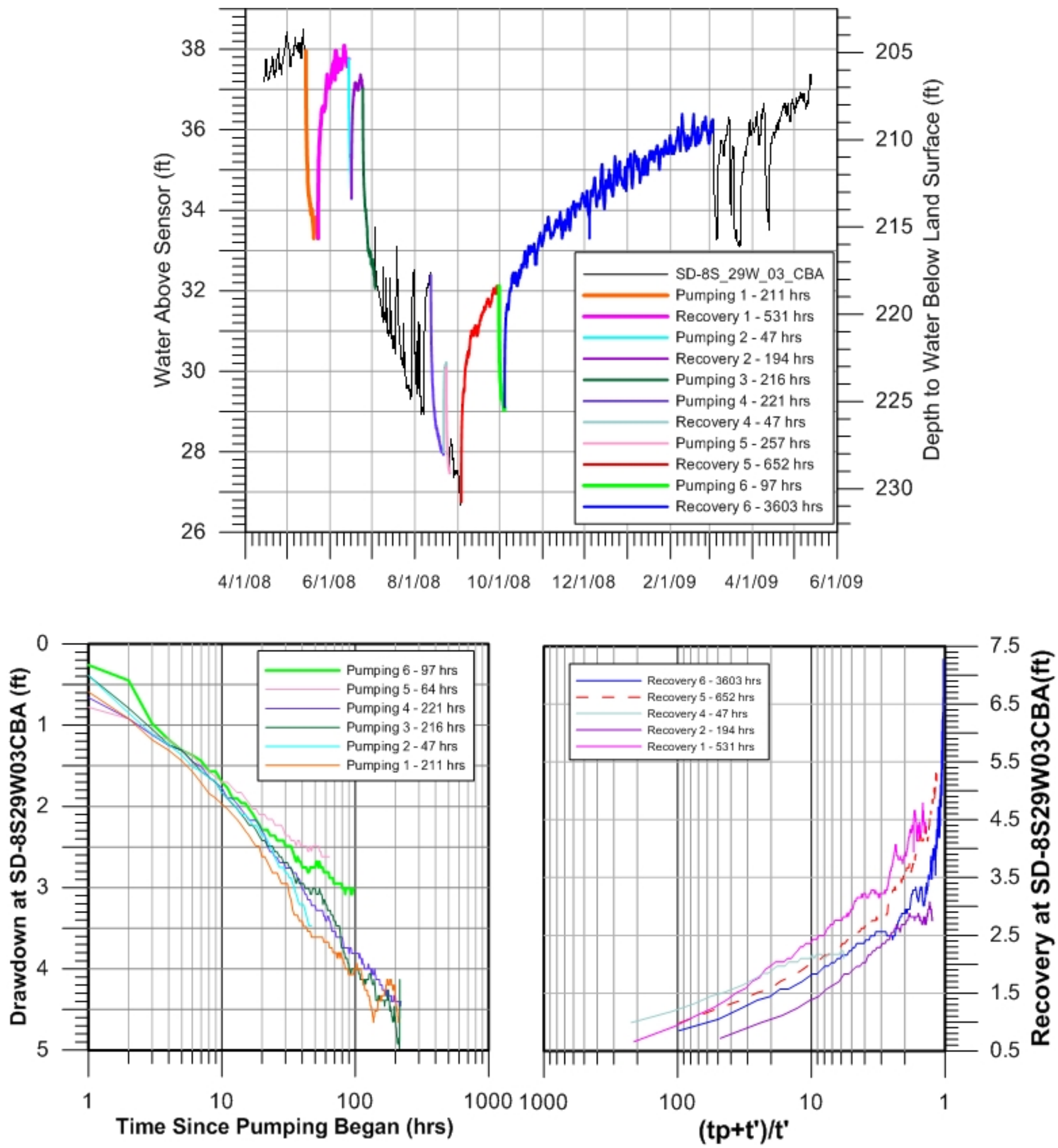

Figure 25: Pumping and recovery analysis for different periods in the Sheridan County well.

In contrast to the Sheridan well, the well record from northwestern Thomas County is more limited in duration (Figure 26). However, it is apparent that barometric-pressure fluctuations also affect water levels in this area, as would be expected from the greater than 165 ft depth to water. Total variation in water level over the course of the one complete pumping season that was monitored is relatively small (2 ft), undoubtedly due to the unconfined nature of the aquifer (distance to the nearest pumping well is unknown). The water levels appear to follow a nearly linear recovery pattern, indicating that inflow not induced by pumping is likely affecting the aquifer in the vicinity of this well. Thus, the data indicate that it would be worthwhile to collect additional information from this well.

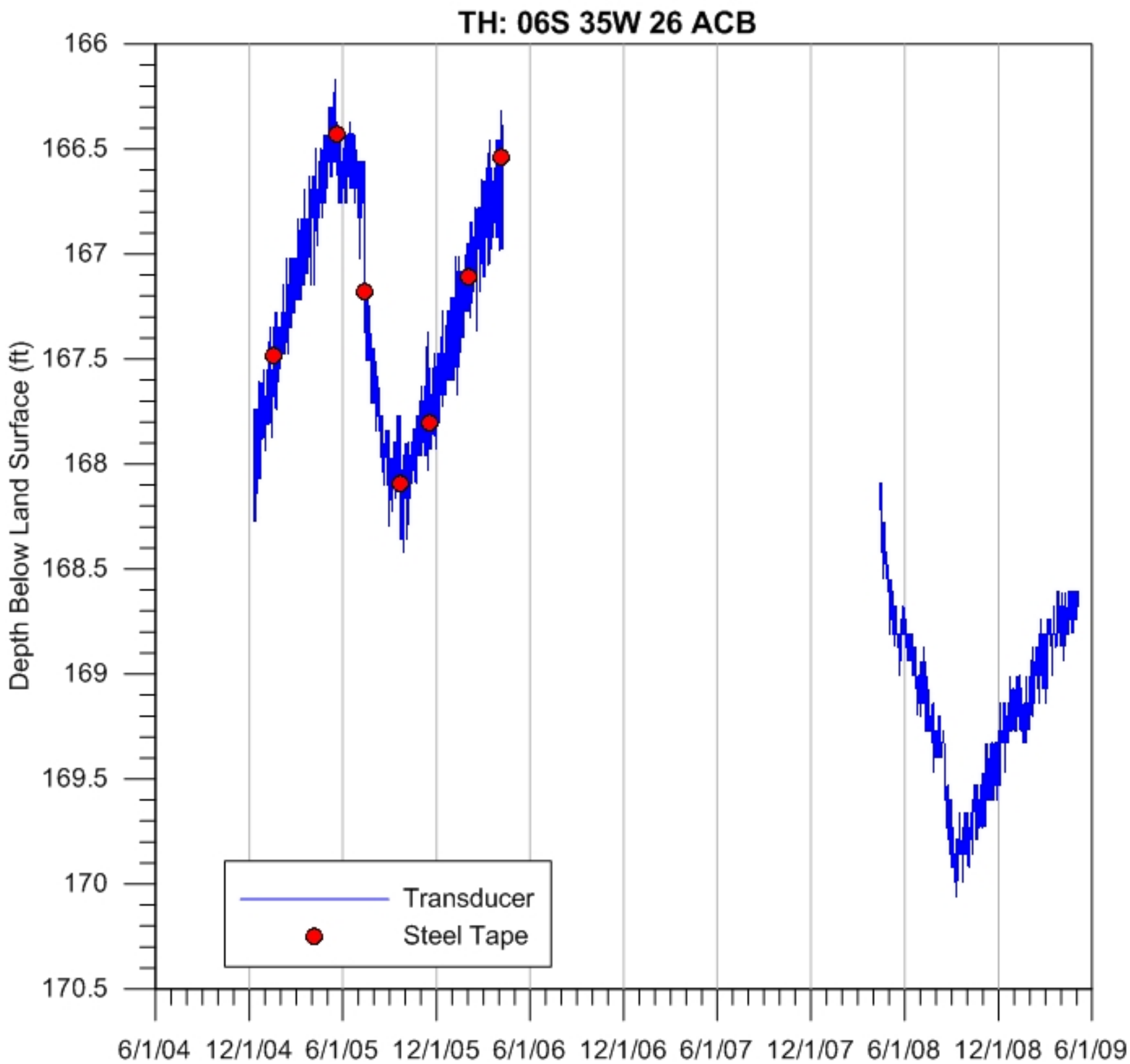

Figure 26: Hydrograph from the Thomas county KDA-DWR well 06S 35W 26 ACB.

These two additional sites illustrate the benefit of a continuous monitoring approach in areas of particular interest. Although the data are sparse and incomplete, the methods and knowledge gained through the intensive investigation at the index well sites can be applied to determine important aquifer characteristics with only a single year of pumping and recovery data. Obviously, data from additional years would increase confidence in any interpretations made from monitoring data for a single year.

5. Geochemical Sampling

As part of the effort to determine the sources of the water pumped from the HPA, water samples were collected from the Haskell and Scott index well in April 2011, from each of the index wells in mid-June 2011, and from four operating irrigation wells near the Thomas index well in September 2011. A Bennett pump was used to extract water from the index wells, while samples from the irrigation wells were collected at water sampling ports within 3 ft of the well column. Samples were collected for cation, anion, stable isotope ($\delta^2H/\delta^{18}O$), ^3H, and ^{14}C determination. Combined with the water-level information, these analyses will help clarify aquifer dynamics such as quantities and sources of recharge.

The water samples are all fresh (Table 9), and all of the Thomas County waters are relatively similar in composition. The samples from Thomas and Haskell counties have lower total dissolved solids (TDS) concentration than the sample from Scott County and are relatively similar in composition. The sample from Scott County may be affected a little by the higher TDS in ground water in the partially closed basin of the Scott- Finney depression. The Scott County sample has higher Cl and SO_4, as well as a relatively high silica concentration, although even higher silica values exist for parts of the HPA in western Kansas. The F concentration is also higher in the Scott County sample than in the other samples. A very general correlation exists between F and SiO_2 concentrations for High Plains aquifer waters (Bassett et al., 1980) and this sample fits in that general relationship. Sulfate and chloride concentrations are low, and are generally correlated with one another. SO_4/Cl mass ratios are highest in the Haskell County sample, and higher in the index wells than any of the irrigation wells. Given that the index wells are screened at the base of the aquifer and the irrigation wells are probably screened over the entire saturated thickness, this could be an indication of upward diffusion of solutes, or even recharge, from the underlying Cretaceous units. However, given the overall fresh quality of the water sampled at all sites, it would seem that none of the sites are being substantially affected by the more highly mineralized waters that are expected in the underlying bedrock.

Nitrate was detectable at all sites, but was highest in the four irrigation wells. Although concentrations at the index wells could be viewed as background concentrations, nitrate in three of the four irrigation wells is generally greater than expected for background. This could be a result of the difference in screened intervals between the index and irrigation wells, well construction, or an indication of more modern recharge to the HPA in Thomas County. A general correlation is also observed between nitrate and chloride concentrations.

Table 9: Selected chemical results – samples collected in June and September 2011.

	Sample	Ca	Mg	Na	K	SiO_2	HCO_3	Cl	SO_4	NO_3-N	TDS sum	^3H
Well Name	Date	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
HS index well	6/14/11	44.4	8.18	20.2	3.32	25.6	165	4.21	33.1	1.92	232	0.8
SC index well	6/14/11	38.0	20.6	33.2	6.06	55.0	215	10.05	49.0	2.88	336	<0.8
TH index well	6/15/11	43.7	13.7	28.2	5.60	25.2	230	6.14	18.7	2.39	269	<0.8
Irr 09S-33W-32BBA	9/1/11	41.9	13.2	28.4	5.5	23.8	229	10.7	15.6	4.20	275	<0.8
Irr 09S-33W-32A	9/1/11	47.2	15.0	28.3	5.6	24.5	228	14.9	24.3	5.56	301	<0.8
Irr 09S-33W-32DBC	9/1/11	41.4	13.0	29.1	5.2	24.0	229	8.3	17.7	2.83	269	<0.8
Irr 09S-32W-29B	9/1/11	43.4	15.2	29.8	5.5	24.3	226	14.6	21.1	4.90	291	1.1

Stable isotope ratio ($^{2}/_{1}H$ and $^{18}/_{16}O$) data (Table 10) provide insights into processes affecting HPA water, as water molecules composed of the different masses move through the atmosphere and near-surface environment at different rates. Isotope ratios are measured, compared with a standard, and reported as parts per thousand (‰) using the (δ) notation, where: $\delta_{sample} = [(Ratio_{sample} - Ratio_{standard})/Ratio_{standard}] * 1000$. For both hydrogen and oxygen, that standard is known as standard mean ocean water, collected and stored at International Atomic Energy Agency offices in Vienna (VSMOW).

Two processes potentially affect the stable isotope ratios of recharge to the High Plains aquifer: precipitation and evaporation. Aquifers with water that has recharged directly from precipitation have, on average, a $\delta^{2}H$ vs. $\delta^{18}O$ relationship of $\delta^{2}H = 8*\delta^{18}O + 10$, which is an average of annual worldwide precipitation (Global Meteoric Water Line (GMWL), Craig 1961). Locally, there can be minor variations, positive and negative, in both the slope and intercept of this line. Although such relationships have not been prepared for precipitation in western Kansas, a Local Meteoric Water Line (LMWL) has been established for the Pawnee Grasslands of northeastern Colorado (Figure 27, Harvey, 2005). When water evaporates, the slope of the line drops to between 3 and 6, as the lighter isotopes preferentially evaporate, enriching the remaining fluid with the heavier isotopes. Irrigation return water typically has an evaporated isotopic signature (e.g., Simpson et al., 1992; Komor and Emerson, 1994; Harvey and Sibray, 2001). If this water recharges the aquifer, isotopic analysis of water in the aquifer can reveal the influx of irrigation return flow or mixing between the evaporation-affected return water and native aquifer water that recharged under more typical conditions.

Table 10: Stable isotope results from the index wells and irrigation wells.

Well	Sample Date	$\delta^{18}O$ VSMOW (‰)	$\delta^{2}H$ VSMOW (‰)
HS Ind	14-Jun-11	-8.59	-60
HS Ind	19-Apr-11	-8.65	-60
SC Ind	14-Jun-11	-9.48	-63
SC Ind	14-Apr-11	-9.54	-64
TH Ind	15-Jun-11	-11.41	-78
9S-33W-32NE	1-Sep-11	-11.37	-79
9S-33W-32NW	1-Sep-11	-11.45	-79
9S-33W-32SE	1-Sep-11	-10.79	-74
9S-32W-29NW	1-Sep-11	-11.15	-77

Stable isotope data from the three study sites plot near the GMWL and show no evidence of evaporation (Figure 27). This is not surprising for the index wells, which are screened at the bottom of the HPA. It is interesting, however, that none of the irrigation wells in Thomas County exhibits an evaporation signature or any indication of mixing of native aquifer water with irrigation return flow, as these wells are likely screened across the entire aquifer. The separation of values between the three sites, with Haskell waters the most enriched in heavy isotopes (^{2}H and ^{18}O), Thomas the most depleted, and Scott in between, is a typical geographical trend, probably related to variations in average annual temperatures at the three sites that affected historic precipitation, especially if the historic periods of the precipitation that contributed to the bulk of the water differed at the sites. From this limited dataset, isotopic signatures indicate a precipitation source for HPA water that has not been significantly affected by recent anthropogenic activities. However, two ongoing related studies should soon provide additional insights into sources of recharge to the HPA in Thomas and Haskell counties (see Section 6).

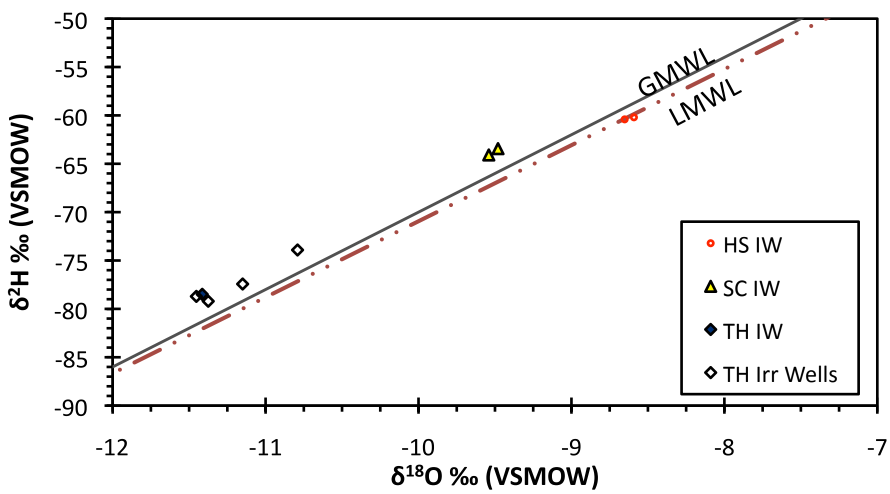

Figure 27: Relationship between $\delta^{18}O$ vs. $\delta^{2}H$ for the three index wells and for the four irrigation wells near the Thomas County index well. Craig's (1961) Global Meteoric Waterline (GMWL) and a Local Meteoric Waterline (LMWL) for northeastern Colorado (Harvey, 2005) are shown for reference.

Tritium (^3H) is an environmental tracer that was introduced to the atmosphere in large quantities during nuclear bomb testing in the 1950s and 1960s, and has a half-life of just over 12.4 years. Aquifer recharge originating from precipitation in the 1950s had greatly elevated ^3H activity. Although much of the original pulse has dissipated in the atmosphere and in most ground-water systems through decay and dispersion, trace amounts of ^3H may still be measured. Furthermore, small natural and anthropogenic sources of tritium still exist in the atmosphere today. Thus, sampling ground water for ^3H still provides a reasonable indicator of modern (<50 years) precipitation.

The ^3H results largely indicate the water from the index wells did not recharge within the last 50 years (Table 9). The trace activity of tritium in the Haskell well water was barely over the analytical threshold (0.8 T.U.), and could be an analytical artifact or an indicator of an improperly sealed well (either the index well or a nearby well). The low tritium activity is not surprising, given that each of the index wells is screened at the base of the aquifer. A similar result was found in three of the four irrigation wells sampled near the Thomas County index well. However, a small but significant amount of ^3H activity was observed in the northernmost irrigation well, an indication that there may be areas of focused downward recharge to the HPA in the vicinity. The quantity of focused recharge would not need to be substantial because a relatively high concentration of tritium in a small amount of recharge water could affect a large volume of aquifer water after mixing.

This is in contrast to the stable isotope data for water, which is representative of the volume of water rather than a particular solute. The tritium concentration in this case can be considered as a solute even though it is part of the water.

Carbon-14 (^{14}C) can provide an estimate of ground-water "age" once dissolution and precipitation of carbonates and exsolution of dissolved CO_2 are taken into account. Several models have been proposed to account for different processes affecting dissolved carbonate and provide a means for correction of measured ^{14}C activity in ground-water samples (e.g., Fontes and Garnier, 1979). Although some additional information is needed to determine exactly which correction is most appropriate for the HPA (or even each individual site), it is possible to calculate the results for each of the models using the geochemical modeling program NETPATH (Plummer et al., 1994; Parkhurst and Charlton, 2008) and make some preliminary determinations based on the range of values provided by the different correction models (Table 11).

Uncorrected laboratory results indicate dissolved inorganic carbon (DIC) in water sampled from both the Haskell and Scott index wells are of a similar age, ~11,700 years before present (ybp), whereas DIC sampled from the Thomas County wells is significantly younger, between 3900-4700 ybp. Applying corrections to these values introduces a significant range, and preliminarily confirms a conclusion that Thomas County DIC is significantly younger than that from the Haskell and Scott index wells. The corrected ^{14}C in DIC from the Thomas County wells may in fact indicate modern (since 1950) recharge or mixing of older HPA water with significant amounts of modern recharge. On the other hand, corrected ^{14}C in DIC sampled from the Haskell and Scott index wells indicate significantly older recharge, likely under different climatic conditions than present.

Table 11: Result of ^{14}C corrections using NETPATH for each of the ^{14}C models.

	HS-IW	SC-IW	TH-IW	TH-9S-33W-32BBA	TH-9S-33W-32A	TH-9S-33W-32DBC	TH-9S-33W-29B
Mass Balance	7434	7908	143	modern	modern	938	283
Vogel	10406	10316	2846	2594	2734	3396	3188
Tamers	6639	6291	modern	modern	modern	modern	modern
Ingerson and Pearson	864	1483	modern	modern	modern	modern	modern
Fontes and Garnier	810	1440	modern	modern	modern	modern	modern
Eichinger	modern	760	modern	modern	modern	modern	modern
No Correction	11749	11659	4190	3937	4077	4739	4531

6. Spin-offs and Related Research

During the fifth year of the Index Well Project, complementary research furthered the work of the project.

6.1. 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.

6.2. Department of Energy Grant

The KGS was recently awarded the second phase ($225K) of a grant subcontract from the Department of Energy to work together with Stanford University and Vista Clara, a company located near Seattle, WA, on assessing the potential of nuclear magnetic resonance (NMR) technology for estimation of water-filled porosity and permeability in small-diameter (2-5" ID) 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.

6.3 Kansas Water Resources Institute Grant

The KU Geology and Geography departments and the KGS were jointly awarded a $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.

7. Summary of 2011 Accomplishments and Plans for 2012

7.1. 2011 Accomplishments

- Continued collection and processing of data. Telemetered data from the three index wells have continued to be served on the web, and downloads have been used for analysis and presentation. DWR data collection has also continued at the Haskell site. Data collection and analysis from the Thomas expansion wells have continued. Real-time viewing of the Thomas index well hydrograph now available from the GMD4 website.
- Initiated detailed analysis of hydrographs at all three index well sites. Initial results of considerable practical significance were obtained for the Haskell and Thomas sites.
- Continued comparison of transducer data with the results of the annual water-level network.
- Publication of open-file report on spreadsheet to remove barometric pressure influences from water-level data; report published on the web and the spreadsheet downloadable from the KGS web site.
- Water samples collected from and analyzed for all three index wells and for four irrigation wells near the Thomas County index well.
- Preliminary interpretation of geochemical results to assess age(s) and source(s) of ground water in the vicinity of each sampled well.
- Presentations on the index well program given to the KWO, DWR, GMD boards and managers, Smoky Hills Audubon Society, the Feedgrains Advisory Committee of the Kansas Farm Bureau, the Water and the Future of Kansas Conference, and the American Institute of Hydrology Annual Meeting in Topeka, among others.

7.2. Planned Activities, 2012

- Recovery and pumping assessment for 2011 and 2012 periods.
- Continue detailed analysis of hydrographs from all three index well sites and any other data sets that we can find.
- Monitor and analyze water levels at two additional wells in the vicinity of the Scott County index well.
- Continue interpretation of geochemical results to assess age(s) and source(s) of ground water in the vicinity of each index well.
- Collection and analysis of 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.

- Develop a computer tool to readily identify susceptibility of point water-level measurements 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.

7.3. Outstanding Issues

Major unresolved issues include the following:

- the source of the vertical inflow, which is not induced by pumping activity, in the vicinity of the Thomas County index well;
- the areal extent of that inflow (Figure 19 indicates that the extent may be large);
- conditions in the aquifer at the Scott County site; understanding is still incomplete but inflow not induced by pumping may also be occurring in the vicinity of that site.

8. References

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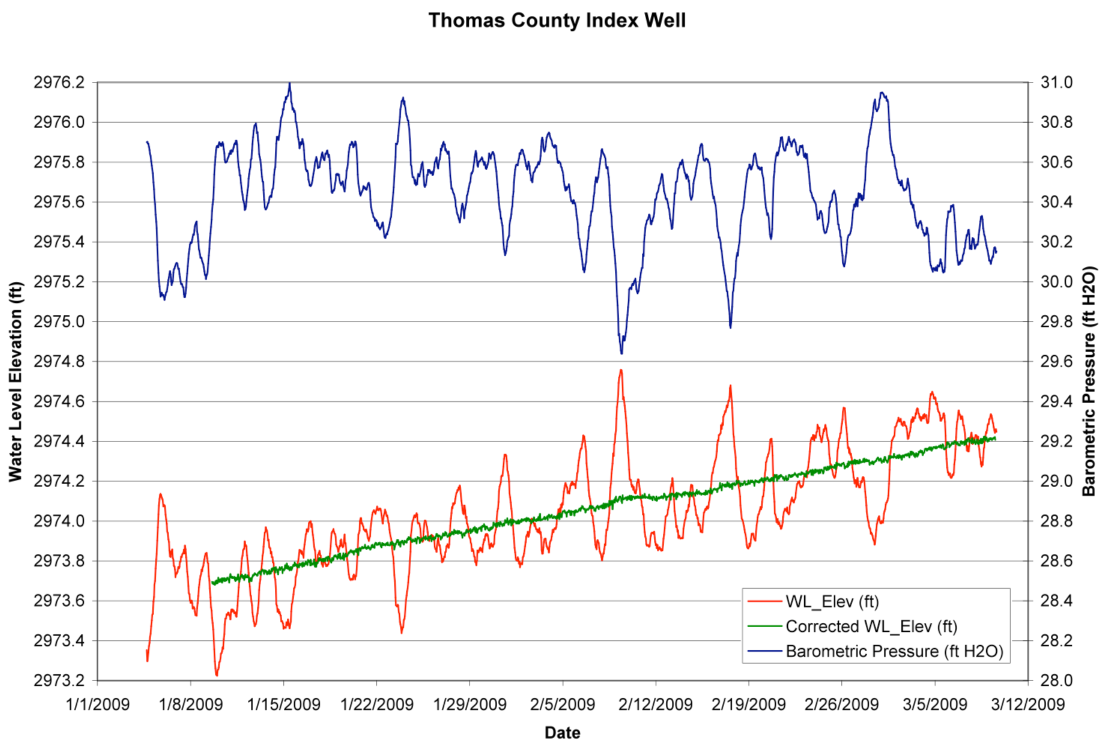
9. Appendix A

Kansas Geological Survey

Kansas Geological Survey Barometric Response Function Software User's Guide



By

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Kansas Geological Survey Open File Report 2011-10
August 2011

GEOHYDROLOGY

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Kansas Geological Survey Barometric Response Function Software User's Guide

Open-file Report No. 2011-10

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The software described in this report was a product of the calibration monitoring (index) well program of the Kansas Geological Survey. This program is a pilot study to develop improved approaches for measuring and interpreting hydrologic responses at the local (section to township) scale in the Ogallala-High Plains aquifer. 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 ground-water resources in western Kansas. We thank Bob Buddemeier, Dustin Fross, Ed Reboulet, and Randy Stotler for their comments on the current and earlier versions of this software.

Introduction

The KGS Barometric Response Function (BRF) software implements the method discussed in Butler et al. (2011) and Stotler et al. (2011) for computing a BRF and the method discussed in Stotler et al. (2011) for using the BRF to correct water level (WL) measurements for the influence of barometric pressure (BP) fluctuations. The software can also compute earth tide response functions (ETRF) and correct for the influence of earth tides. However, the calculation of ETRFs is still the subject of ongoing research. Our preliminary investigations indicate that ETRF estimation can be problematic when the influence of earth tides is small, so this option should be used with caution. The appendix describes how to compute theoretical earth tides for a given location using free software developed at the Royal Observatory of Belgium.

File Management

The KGS BRF software has two components, an Excel worksheet contained in the workbook **KGS_BRF.xls**, and a compiled program (executable) named **kgs_brf.exe**, both of which are contained in the zip file that includes this document. Questions should be directed to Geoff Bohling (geoff@kgs.ku.edu, (785) 864-2093).

The Excel worksheet serves as a front end to the executable, providing a template for managing the water level, barometric pressure, and (optionally) earth tide data. The worksheet contains three buttons, one to fill gaps in the data records, one to run the computations for estimating a BRF (and also correct water levels), and one to correct water levels using a BRF that has already been computed. The Visual Basic code that is behind these latter two buttons reads information from the worksheet, writes it out to a set of input files for the executable, runs the executable, and then reads the output from the executable back into Excel. This means that the Excel worksheet cannot work without access to the executable. Consequently, a copy of the executable file, **kgs_brf.exe**, has to exist in the folder that contains the Excel workbook with which you are working.

You may make copies of **kgs_brf.exe** using any of the methods provided by Windows Explorer – selecting an existing copy of the file, then copying and pasting the new copy in the desired folder, selecting and ctrl-dragging, etc. To see the full file name, with the extension, you will need to tell Windows Explorer to show you file extensions. But even if you don't, the Excel file, **KGS_BRF.xls**, should be tagged with an Excel icon, distinguishing it from the executable.

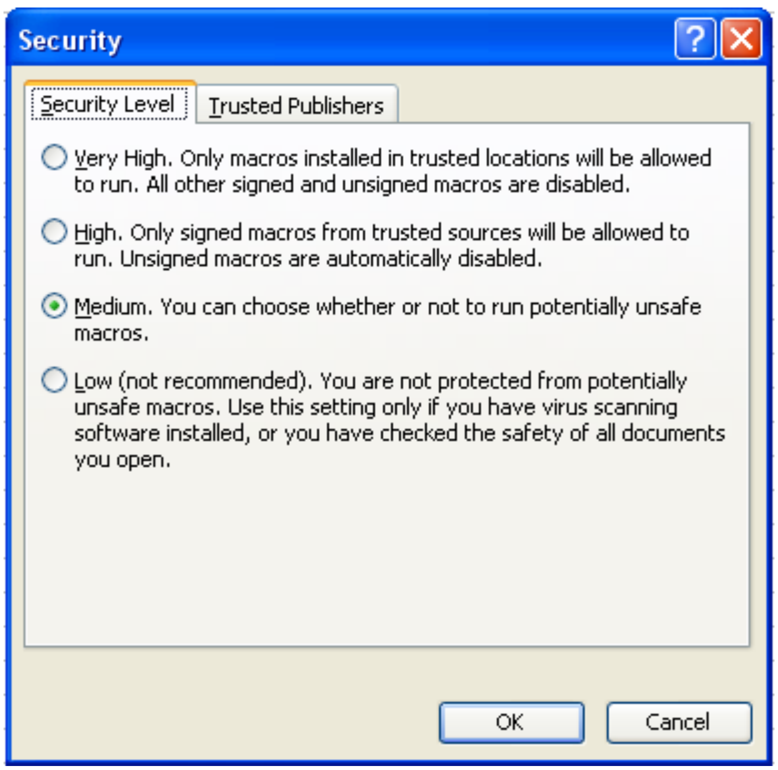
You will likely want to use workbooks that are named something other than **KGS_BRF.xls**. The Excel Visual Basic code is directly attached to the **Input_Template** worksheet in **KGS_BRF.xls**. This means that you can make copies of this worksheet and/or workbook, using any name you please, and the code will be part of each new copy. This allows you to create and save copies of the **Input_Template** worksheet using more meaningful names without "breaking" the software. But, again, you will need to copy the executable, **kgs_brf.exe**, to each folder that you work in. You cannot change the name of **kgs_brf.exe** because the Excel VB code looks for it by that name.

The executable program has been designed so that it can be used on its own, without the Excel front end. Using it involves creating a set of plain text input files (a parameter file and input data files) and then running the program in a DOS command window. The details of this process will be explained in a separate report. The Visual Basic code attached to the **Input_Template** worksheet automates the process of generating the input files and reading the output files.

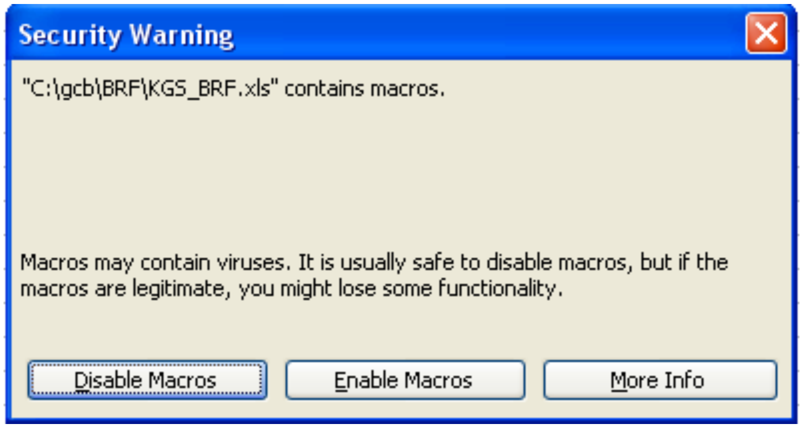
The Excel workbook (and included Visual Basic code) has been created in Excel 2003. It *should* also work in more recent versions of Excel.

Macro Security

To be able to run the Visual Basic code included in KGS_BRF.xls, you may need to alter Excel's macro security level from its current setting. In Excel 2003, you set the macro security level by selecting **Options…** from the **Tools** menu, then selecting the **Security** tab on the **Options** dialog box, and then clicking the **Macro Security…** button on that tab. On the resulting dialog box, you should set the security level to *Medium*:

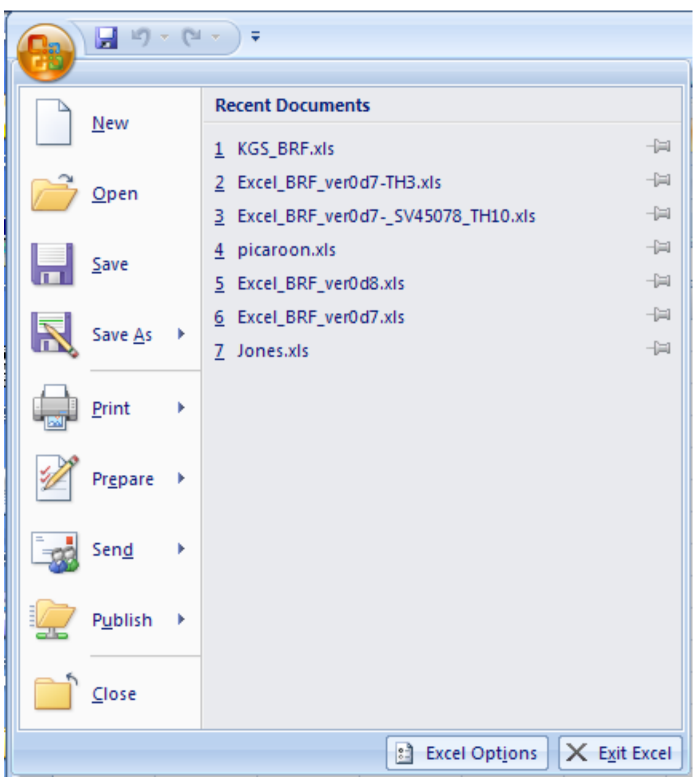


With the macro security level set to Medium, you will be presented with the following dialog box when you open KGS_BRF.xls (or any other workbook containing macros):

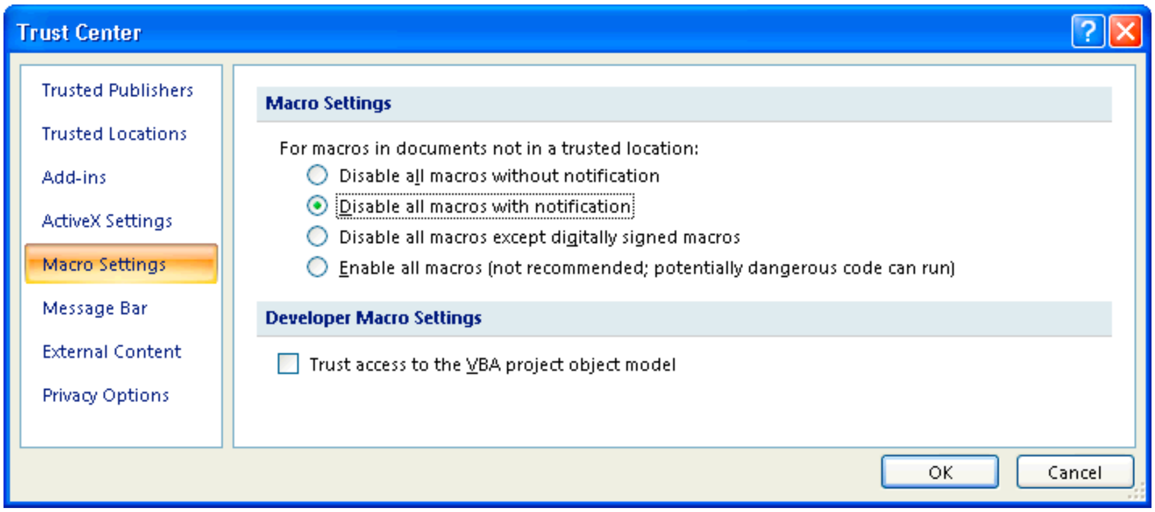


You should click the **Enable Macros** button on this dialog box. If you set the macro security level to *Low*, then Excel will just open a macro-bearing workbook with the macros enabled, without asking for your permission. As noted on the Security dialog box, this is not advisable.

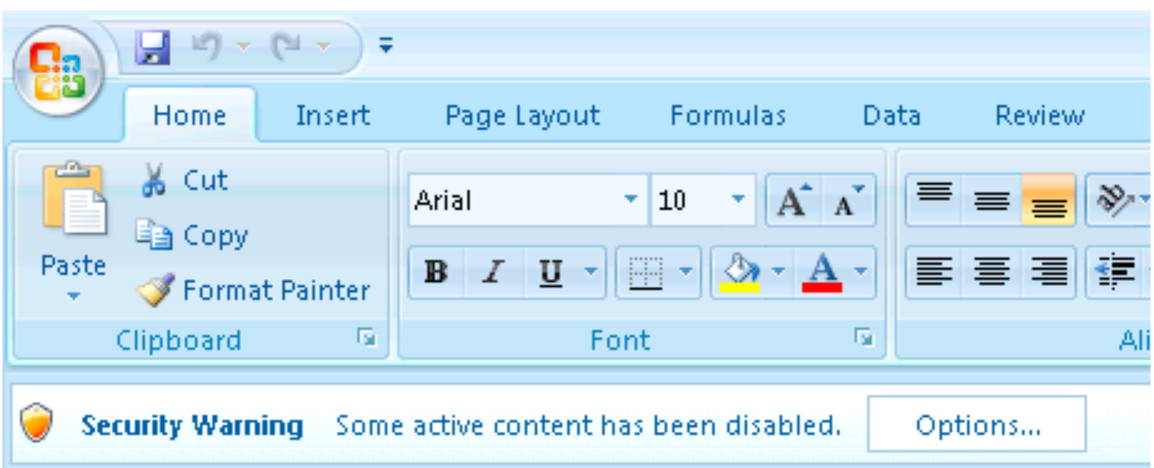
In Excel 2007, you modify the security options by first selecting the Office button in the upper left-hand corner of the Excel window to get the Office drop-down menu:



Select the **Excel Options** button at the bottom right on this menu, then select **Trust Center** in the list on the left side of the **Excel Options** dialog box. Click the **Trust Center Settings…** button (on the right) and then select **Macro Settings** from the list on the left of the **Trust Center** dialog box:



Select **Disable all macros with notification**, which is comparable to the *Medium* security setting in Excel 2003, then click **OK** (twice) to get back to Excel. With this security level setting, Excel 2007 will display a warning below the menu bar when you open a macro-bearing workbook:

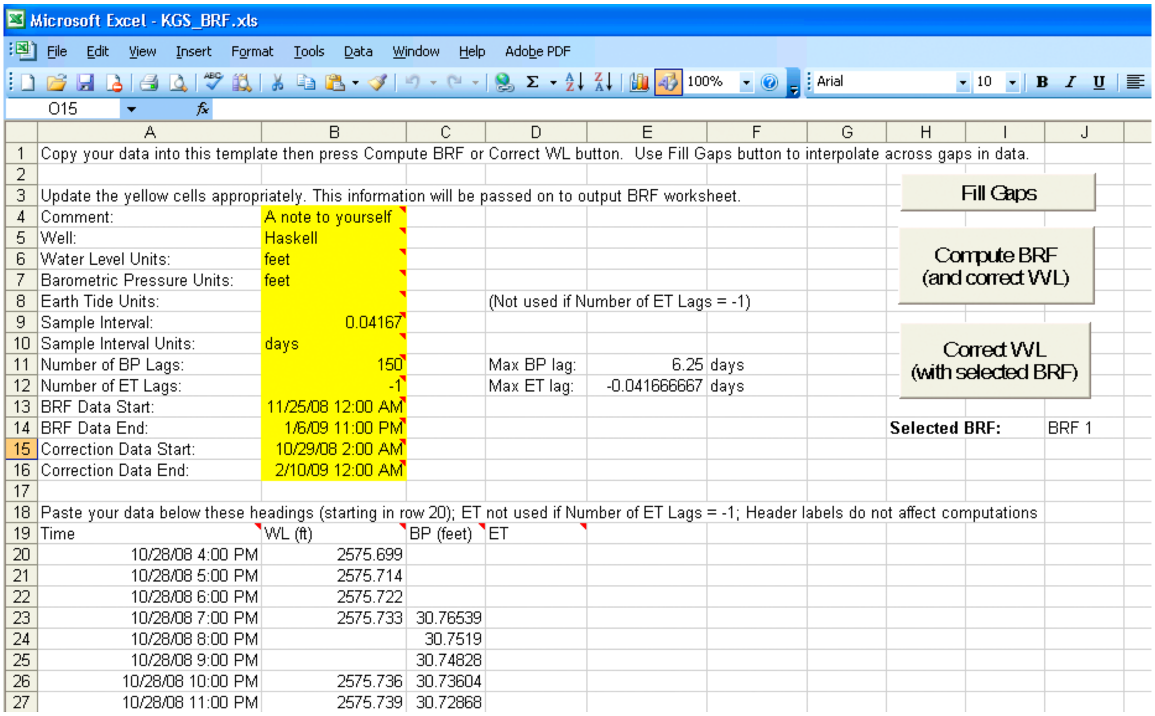


To allow the KGS BRF code to run, click the **Options** button to the right of the warning and select **Enable this content** on the resulting dialog box.

Alternatively, you could choose **Enable all macros** under **Macro Settings** in the **Trust Center** dialog box. This is comparable to the *Low* security level in Excel 2003.

The Input_Template worksheet

The (upper left corner of the) **Input_Template** worksheet looks like this:



	A	B	C	D	E	F	G	H	I	J
1	Copy your data into this template then press Compute BRF or Correct WL button. Use Fill Gaps button to interpolate across gaps in data.									
2										
3	Update the yellow cells appropriately. This information will be passed on to output BRF worksheet.									
4	Comment:	A note to yourself								
5	Well:	Haskell								
6	Water Level Units:	feet								
7	Barometric Pressure Units:	feet								
8	Earth Tide Units:			(Not used if Number of ET Lags = -1)						
9	Sample Interval:	0.04167								
10	Sample Interval Units:	days								
11	Number of BP Lags:	150		Max BP lag:	6.25	days				
12	Number of ET Lags:	-1		Max ET lag:	-0.041666667	days				
13	BRF Data Start:	11/25/08 12:00 AM								
14	BRF Data End:	1/6/09 11:00 PM						Selected BRF:		BRF 1
15	Correction Data Start:	10/29/08 2:00 AM								
16	Correction Data End:	2/10/09 12:00 AM								
17										
18	Paste your data below these headings (starting in row 20); ET not used if Number of ET Lags = -1; Header labels do not affect computations									
19	Time	WL (ft)	BP (feet)	ET						
20	10/28/08 4:00 PM	2575.699								
21	10/28/08 5:00 PM	2575.714								
22	10/28/08 6:00 PM	2575.722								
23	10/28/08 7:00 PM	2575.733	30.76539							
24	10/28/08 8:00 PM		30.7519							
25	10/28/08 9:00 PM		30.74828							
26	10/28/08 10:00 PM	2575.736	30.73604							
27	10/28/08 11:00 PM	2575.739	30.72868							

Hovering the cursor over the cells marked with triangles will reveal comments briefly explaining the cell contents. To use this spreadsheet, you update the information in the yellow cells appropriately; paste your measurement time, water level, and barometric pressure data into columns A-C, starting at row 20; and then press the **Compute BRF** or **Correct WL** button (the latter requires that you have already done the former). Neither the BRF nor water level correction (WLC) computations allow missing values in the measurements. If you have gaps in the data, like the WL measurements that are missing from cells B24 and B25 above, you should fill them using the **Fill Gaps** button, as explained below.

Important: The Visual Basic code looks for each piece of information by cell address. This means . . . *don't move anything*. Just revise the information in place.

In order to avoid mixing up your new data with the data that are already in the worksheet, we recommend that you delete the old data first, by selecting the data from row 20 on down and then deleting them. Clearing the cells using the **Delete** button should be sufficient. If the new data record is as long or longer than the old data record, so that pasting in the new data will completely overwrite the old data, then the deletion step is not necessary. However, it is advisable to delete the old data first, just to be sure.

The code determines the length of the data record based on the measurement time data starting in cell A20. It reads down this column from row 20 until it finds a blank cell. The cell above this first blank cell is the last data point in the record, *even if there are additional data below the blank cell*.

The measurement times listed in column A do not actually matter to the BRF and WLC computations. They are solely for informational and plotting purposes. The BRF and WLC computations assume that the data are (strictly) regularly sampled, with the sample interval given in cell B9. Time in these computations is given by the sample interval multiplied by the sample number (index). The code behind the **Fill Gaps** button, however, does use the measurement times and requires that they be in strictly increasing order (each time is strictly greater than the previous time).

You should modify cells B4-B16 (labels in cells A4-A16) to specify the following information:

Comment (cell B4): This is a place for user notes regarding the data and/or analysis. These notes will be passed on to the output BRF and WLC worksheets.

Well (cell B5): The well name.

Water Level Units (cell B6): The units of the WL measurements. This cell is implemented as a pick list allowing selection from the units listed in cells M5-M6 (feet and meters). *See information about units on page 11*.

Barometric Pressure Units (cell B7): The units of the BP measurements. This cell is implemented as a pick list allowing selection from the units listed in cells P5-P10. *See information about units on page 11*.

Earth Tide Units (cell B8): The units of the earth tide (ET) values. This information is not used if the number of ET lags is set to -1. If ET data are employed, the code will accept any units that you type into cell B8 and the ET response coefficients will end up having units of feet per earth tide unit, whatever that unit may be.

Sample Interval (cell B9): The sample interval for the measurements. The BRF and WLC computations assume that the measurements are regularly sampled at the sample interval, and ignore the actual measurement time values listed in column A (except when selecting the data subsets to use for BRF and WLC computations, as described below). Assuming that these measurement time values are Excel date/time values, then a convenient way to specify the sample interval is to set cell B9 equal to the difference between the first two measurement times, that is, cell A21 minus cell A20. This difference will yield a numeric value, which is in days (e.g., 0.4167 days if the measurements are one hour apart).

Sample Interval Units (cell B10): Or, in other words, the units of time. If the sample interval is specified as described above (difference between cells A21 and A20, with those cells containing Excel date/time values), then the sample interval will be in days.

Number of BP Lags (cell B11): The number of lagged values of BP to use in the analysis. This means the number of values preceding the current WL measurement. A lag of zero means the BP measurement at the same time as the current WL measurement, so the number of BP values used in the analysis is the number of BP lags plus 1. You could set the number of BP lags to 0 to use just the zero-lag BP value – meaning there would still be something to compute. To exclude BP values from the analysis, you should set the number of BP lags to -1. You would do this only if you wanted to analyze responses to earth tides alone.

Number of ET Lags (cell B12): Same as above, except for ET values, instead of BP values. If the number of ET lags is set to -1, then ET values (column D) are not required and will be ignored if they are present.

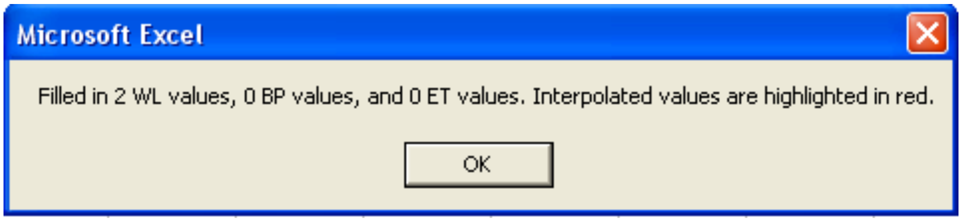
BRF Start Date and BRF End Date (cells B13 and B14): The BRF will be computed based on a subset of the data measured between the two date/time values specified in cells B13 and B14. The selection includes these two end points, assuming they correspond to actual measurement times in the data record. If you have set the number of BP lags to -1 (only analyzing responses to earth tides), the start and end dates will be for the ETRF calculation. *See further information on selection of start and end dates in Guidelines for Data Selection on page 10.*

Correction Start Date and Correction End Date (cells B15 and B16): The WLC process will be applied to the subset of data between the two date/time values specified in cells B15 and B16, again including the end points.

Filling Data Gaps

The BRF and WLC computations do not allow missing values of WL or BP within the range of measurement times spanned by the BRF or correction start and end dates (cells B13 and B14 or cells B15 and B16). The same applies to ET values when earth tides are considered. For the sake of illustration, the WL and BP columns shown in the screen dump on page 5 include a few missing values. You can use the **Fill Gaps** button to interpolate across gaps within the data series, like the gap in the water level series represented by the empty cells B24-B25. However, the **Fill Gaps** code will not fill empty cells at the beginning or end of the record, like the three missing BP values represented by cells C20-C22, since this would involve extrapolating beyond the available data.

The **Fill Gaps** code performs a linear interpolation between the observed data values on either side of the gap, interpolating to the provided measurement times for the missing data values. This code requires that the measurement times be in strictly increasing order and will display an error message and stop if they are not. Once it is done running, the code will present a dialog box showing the number of missing data values that it filled in:



As stated by the dialog box, the interpolated values will be highlighted in red:

18	Paste your data below these headings (starting in row 20); ET not used if Nu			
19	Time	WL (ft)	BP (feet)	ET
20	10/28/08 4:00 PM	2575.699		
21	10/28/08 5:00 PM	2575.714		
22	10/28/08 6:00 PM	2575.722		
23	10/28/08 7:00 PM	2575.733	30.76539	
24	10/28/08 8:00 PM	2575.734	30.7519	
25	10/28/08 9:00 PM	2575.735	30.74828	
26	10/28/08 10:00 PM	2575.736	30.73604	
27	10/28/08 11:00 PM	2575.739	30.72868	
28	10/29/08 12:00 AM	2575.752	30.71893	

The red highlighting is a change to the formatting of the cells and will not go away unless you change the formatting by some mechanism, such as explicitly changing the format or pasting in new values with formats included. However, the **Fill Gaps** code will also set (or re-set) the font color for non-empty cells to black. The reasoning for this behavior is that if we pasted in a new data record and then ran **Fill Gaps**, the black and red font colors would then correctly indicate the measured and interpolated values in this new record, even if we hadn't bothered to undo the red formatting of the interpolated cells in the previous record. However, a side effect of this behavior is that the code also eliminates the highlighting of interpolated cells if we run it again on a record that contains interpolated values. That is, if we ran **Fill Gaps** again with the worksheet in the state shown above, then the two interpolated WL values would be taken as "present" (not missing) and their font would be set to black. The resulting dialog box would also indicate that the code had filled in 0 WL values. *That is, running* **Fill Gaps** *more than once on the same data record will obliterate the distinction between measured and interpolated values.*

Computing a BRF (and Correcting Water Levels)

When you have your data in place and have modified the informational (yellow) cells appropriately, click on the **Compute BRF (and Correct WL)** button to

1) compute a BRF based on the WL and BP measurements in the worksheet with measurement times between the *BRF Data Start* and *BRF Data End* date/times (inclusive) specified in cells B13 and B14, and

2) use that BRF to remove (or significantly reduce) the influence of BP variations from the WL measurements in the worksheet with measurement times between the Correction Data Start and Correction Data End date/times (inclusive) specified in cells B15 and B16.

The coefficients of the computed BRF, along with confidence intervals on those coefficients, will be written out to a new worksheet that is added to the current workbook. The name of this new worksheet will be **BRF *n***, where *n* is an integer. The code will count all the worksheets in the active workbook whose names start with "BRF" and then set *n* to that number plus 1. The code will also add a plot to the BRF worksheet showing the BRF values (equation (2) of Butler et al. (2011)) with error bars.

If ET values are used, then the BRF worksheet will also contain the earth tide response function (ETRF) coefficients and a plot of ETRF values with the corresponding error bars.

This new BRF worksheet is yours to do with what you will: rename it, move or copy it, etc. It contains no links (via formulas) to the original data sheet or to the Visual Basic code and will not "break" if you move it. Nor does the BRF worksheet contain any VB code of its own, so if you copied or moved it to a new workbook, you would not be adding any macros to that workbook (leading to a need to enable macros when you open that workbook). All the VB code is associated only with the *Input_Template* worksheet (or copies thereof). *However*, if you want to use the BRF contained in this worksheet later to correct *other* water levels, then you should not alter the contents of this worksheet. When you correct water levels using a previously calculated BRF, the WLC code will expect to find the right information in appropriate cells in the BRF worksheet.

The corrected water levels will also be written out to a new worksheet, which will be named **WLC *n***, where *n* is 1 plus the number of worksheets in the current workbook whose names start with "WLC". This worksheet will include a plot showing the original and corrected water levels, along with the BP values (on the secondary Y axis). This corrected water levels worksheet is also yours to do with what you will. Unlike the BRF worksheet, there is no need to be concerned about altering the contents of the WLC worksheet, since it will not be accessed again by the VB code.

The listing of corrected WL values will not start until the number of measurements is equal to the number of BP lags plus 1. This is because this number of previous BP values has to be accumulated before the correction can be applied.

Correcting Water Levels (with selected BRF)

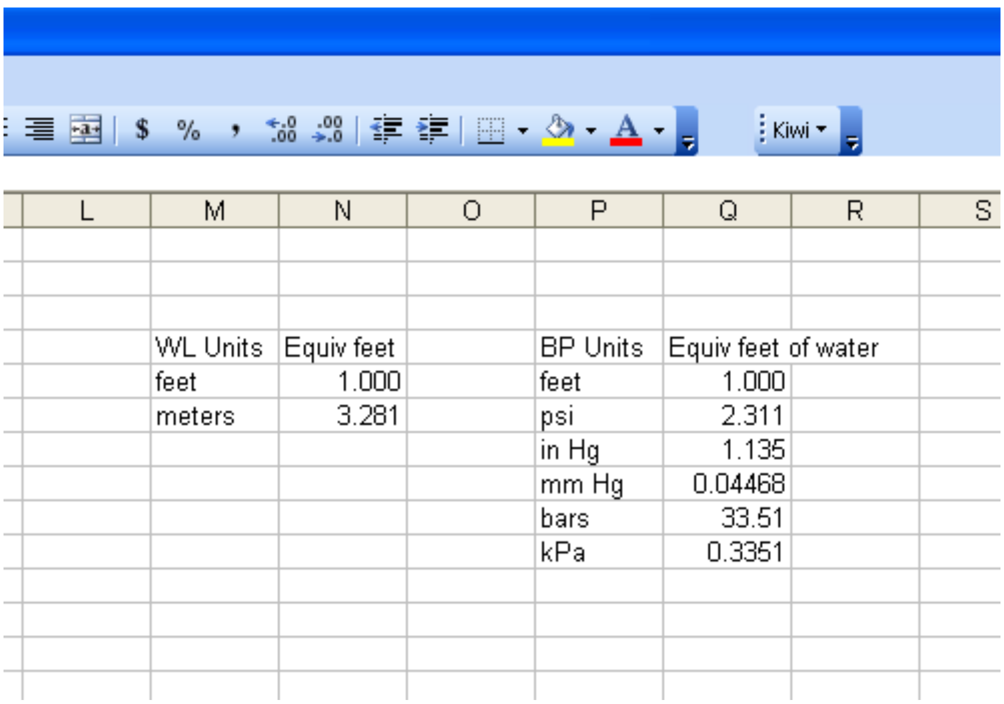
It is possible that you will want to correct a series of WL measurements using a BRF computed using some other series of measurements. You can accomplish this using the **Correct WL (with Selected BRF)** button. The correction will be applied to the measurements in the *Input_Template* worksheet (or copy thereof), but the BRF coefficients will be read from the worksheet whose name appears in cell J14 (following the **Selected BRF** label). Whenever you compute a new BRF, the code will put the name of the newly generated BRF worksheet into cell J14 on the *Input_Template* worksheet. However, you can replace this with the name of any other BRF worksheet by typing the name of that worksheet into cell J14. The BRF worksheet needs to reside in the active workbook, but this could be accomplished by copying the BRF worksheet from some other workbook.

Guidelines for Data Selection

When you compute a BRF, you should do so based on a reasonably stationary data record that clearly exhibits water level responses to barometric pressure variations, possibly superimposed on a long-term trend. The same proviso also applies to the estimation of an ETRF. You should avoid using data records showing abrupt or short-term changes in water level caused by other factors, such as onset or cessation of pumping, since these changes could adversely impact the estimation of the BRF (and/or ETRF) coefficients (see discussion following equation (1) in Butler et al. (2011)). You may apply the estimated BRF to filter out the influence of barometric pressure variations from more complicated data records, including those impacted by changes in pumping, as long as the record you are correcting shares the same barometric response characteristics as those exhibited by the data used to compute the BRF.

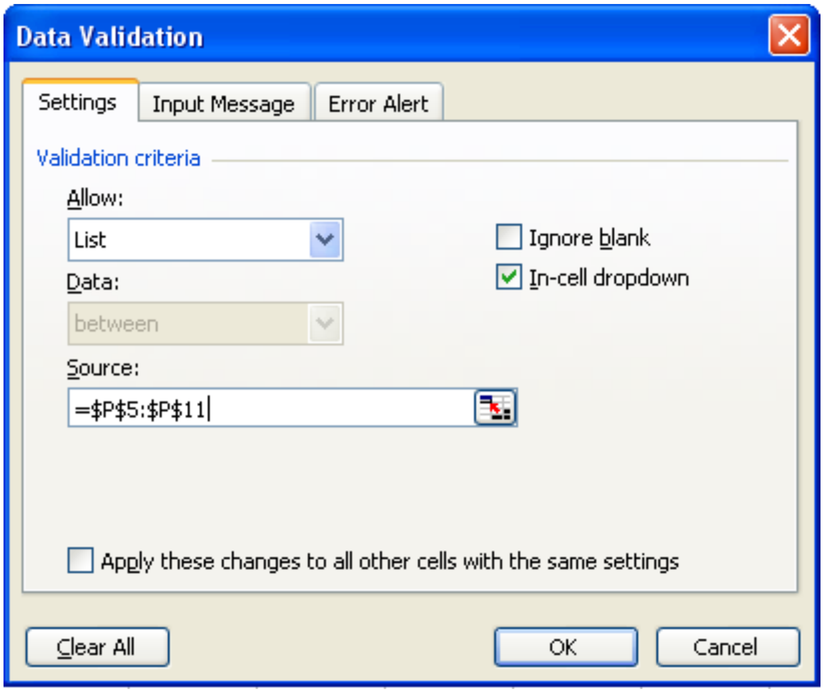
Water Level and Barometric Pressure Units

The cells for specifying the measurement units of WL and BP, cells B6 and B7 of the *Input_Template* worksheet, are implemented as drop-down pick lists using Excel's **Validation…** option (on the **Data** menu). Given the number of possible units that can be used for WL and BP and the challenge of anticipating what combinations are most probable for this application, the software finesses the issue by converting WL to feet and BP to equivalent feet of water, performing all calculations in those units, and then transforming back to the original units. Currently, the list of WL units in cell B6 comes from cells M5 and M6, which contain "feet" and "meters". Cells N5 and N6 contain the multipliers needed to convert each of these units to feet, namely 1 and 3.281. The code will use the multiplier corresponding to the selected units to convert water levels to feet. Similarly, the allowed BP units are listed in cells P5 to P10, with the multipliers required to convert them to equivalent feet of water listed in cells Q5 to Q10. The code will use the appropriate multiplier to convert BP to feet of water:



L	M	N	O	P	Q	R	S
	WL Units	Equiv feet		BP Units	Equiv feet of water		
	feet	1.000		feet	1.000		
	meters	3.281		psi	2.311		
				in Hg	1.135		
				mm Hg	0.04468		
				bars	33.51		
				kPa	0.3351		

Additional options could be added to these lists by adding the label for the units to the list in column M or P and adding the multiplier for conversion to feet to the adjacent cell in column N or Q. To add the new units to the drop-down list of options, select either cell B6 or B7, then select **Validation…** from the **Data** menu and expand the list of cells serving as the *Source* for the list. For example, to add *meters* to the list of allowable BP units, you could type *meters* in cell P11 and 3.281 in cell Q11, and then use the Data Validation dialog box to change the Source for the list in cell B7 to include cell P11:



References

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

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*, 175 p.

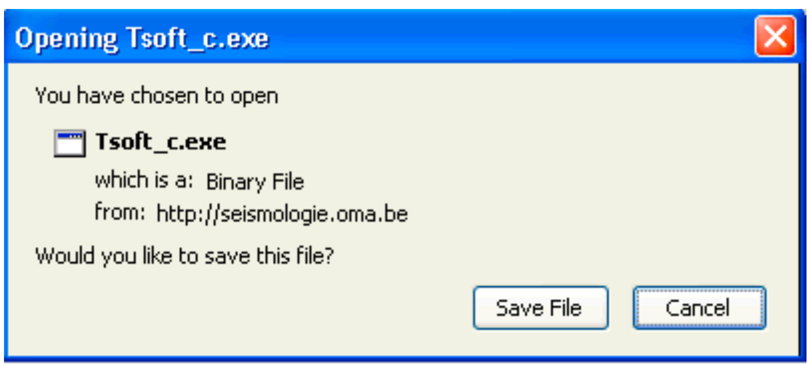
Appendix: Computing Theoretical Earth Tides Using TSoft

This appendix briefly explains how to obtain the program TSoft and use it to compute theoretical earth tides for any location. TSoft is a free software package for the analysis of time series, and gravity data in particular. The software, which was developed at the Royal Observatory of Belgium, is described in Van Camp and Vauterin (2005). Please refer to that paper and references therein for further details regarding the computation of theoretical earth tides.

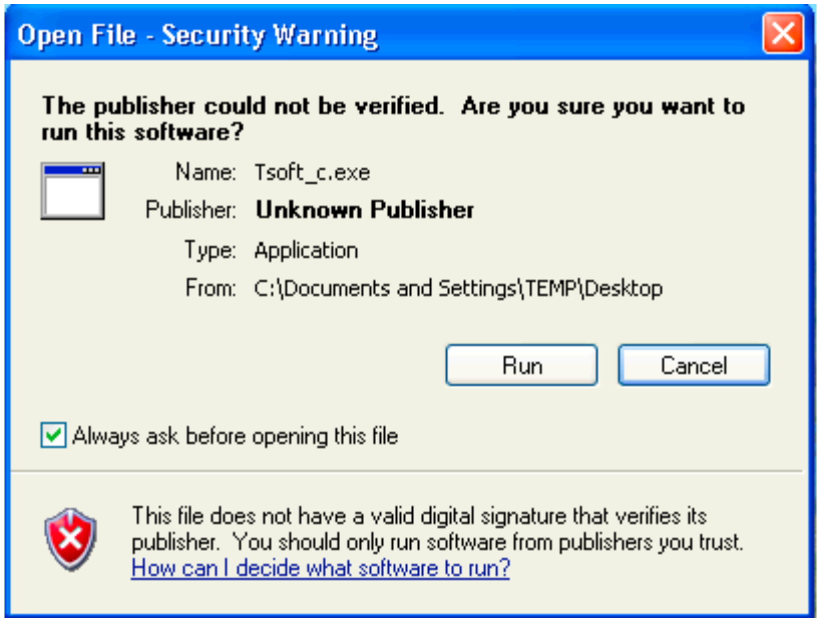
The TSoft web page is located at:

http://seismologie.oma.be/TSOFT/tsoft.html

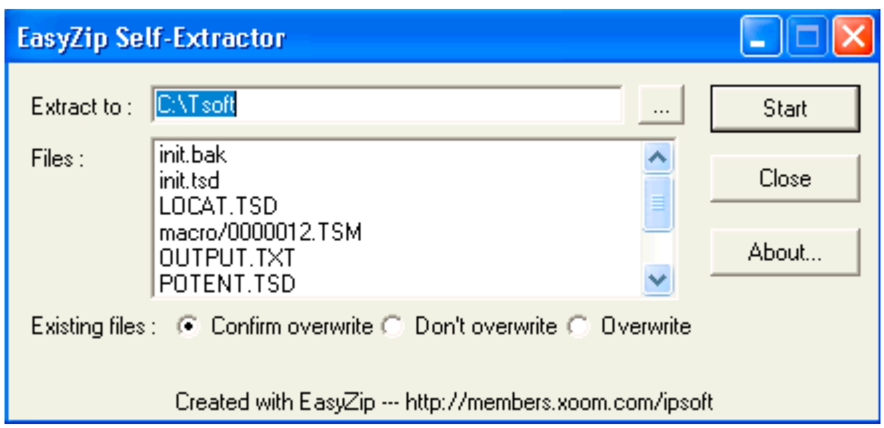
At the time of this writing, the software installation package could be downloaded by scrolling down to near the bottom of this web page and clicking on the link labeled "Download TSoft Package". (The current version at the time of this writing is 2.1.12.) The target of this link is a self-extracting archive named **Tsoft_c.exe**. After you click on the link, your browser will ask for confirmation that you want to download the file:



and then either save the file in the default location (e.g., your desktop or a downloads folder) or prompt for a location. After the file has been saved, navigate to that location in Windows and double-click on the file **Tsoft_c.exe** to extract (install) the software. Most likely, Windows will show you a security warning, asking for confirmation that you really want to run the extractor. To do so, click the appropriate button (e.g., **Run** or **OK**) on the warning dialog box:



You will then be prompted to specify a folder to which the software (and associated data files) should be extracted:

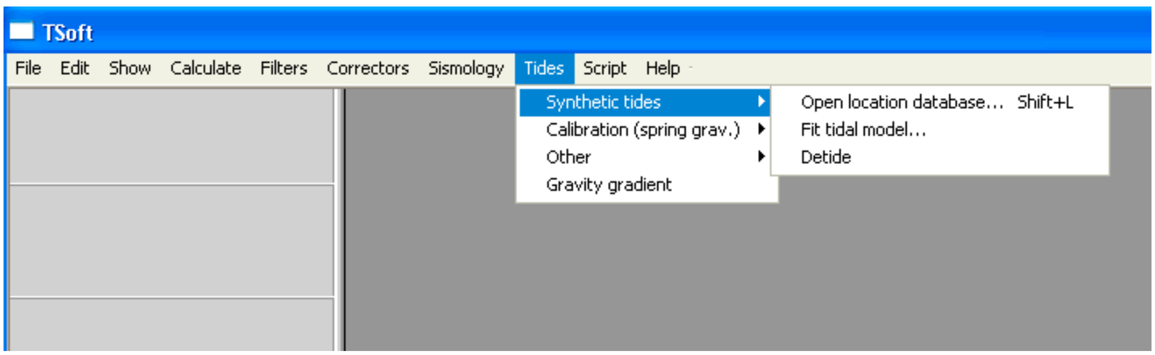


You can either accept the default folder (C:\Tsoft) or specify a different one by typing in a different folder name or using the browse (**…**) button. Then click the **Start** button to extract the files to the specified folder.

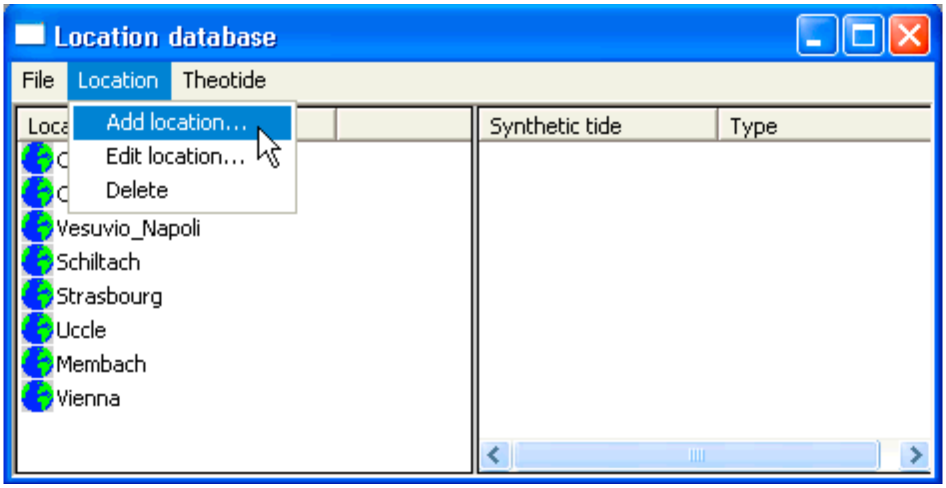
The Tsoft user's manual, **Tsman.pdf**, is available through the "Download TSoft manual" link near the bottom of the TSoft web page listed above. (The URL for the manual is http://seismologie.oma.be/TSOFT/Tsman.pdf.) It would make sense to save this file in the same folder as the software (e.g., C:\Tsoft). The computation of theoretical earth tides is discussed in the manual's fourth chapter, entitled "Synthetic tides". The remainder of this appendix presents the essential steps for computing theoretical earth tides at a desired location. Please refer to the TSoft manual for further information.

To start TSoft, navigate to the folder where you installed it (C:\Tsoft if you accepted the default location) and double-click on the icon for the file **tsoft.exe**. Depending on how you have Windows configured, you may not see the ".exe" extension. Nevertheless, the file's icon should look something like this:

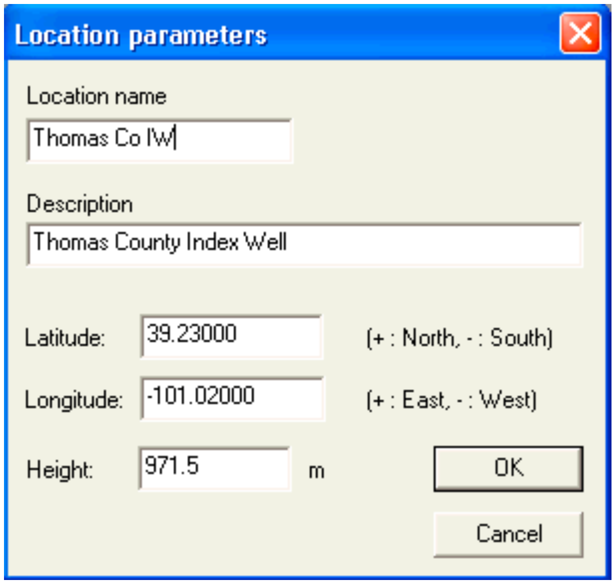
Once TSoft is running, the first step is to add the location at which you want to compute earth tides to TSoft's location database. To do this, go to TSoft's **Tides** menu, then select **Open location database…** from the **Synthetic tides** submenu:



In the **Location database** window, select **Add location…** from the **Location** menu:



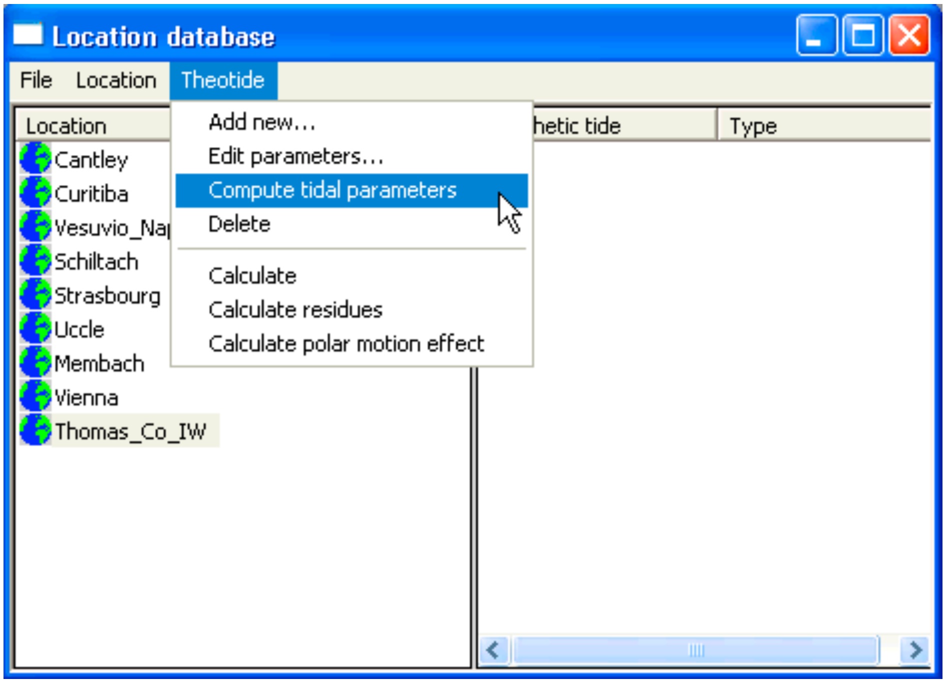
In the resulting **Location parameters** dialog box, enter a name and description for the new location, along with the latitude, longitude, and height:



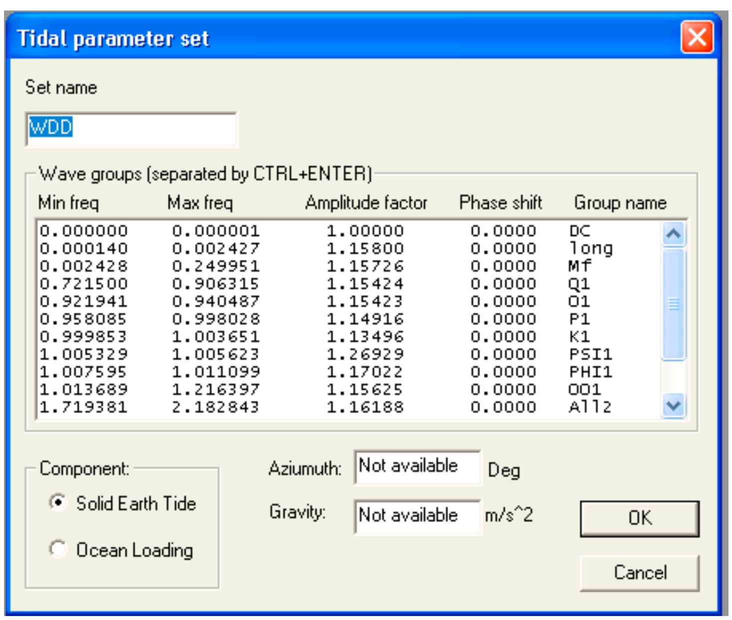
Note that latitude and longitude should be given in decimal degrees, with the sign conventions as shown on the dialog box. The height should be given as meters above sea level. Click **OK** and the new location will be added to TSoft's list of locations. (Note that TSoft will replace spaces in the name with underscores.)

The next step is to add a set of tidal parameters for the new location. These parameters will be used in a subsequent step to compute the theoretical earth tide at that location over a specified time frame. We will use TSoft's "default" approach for generating solid earth tide parameters. For additional information and options, please see the TSoft manual.

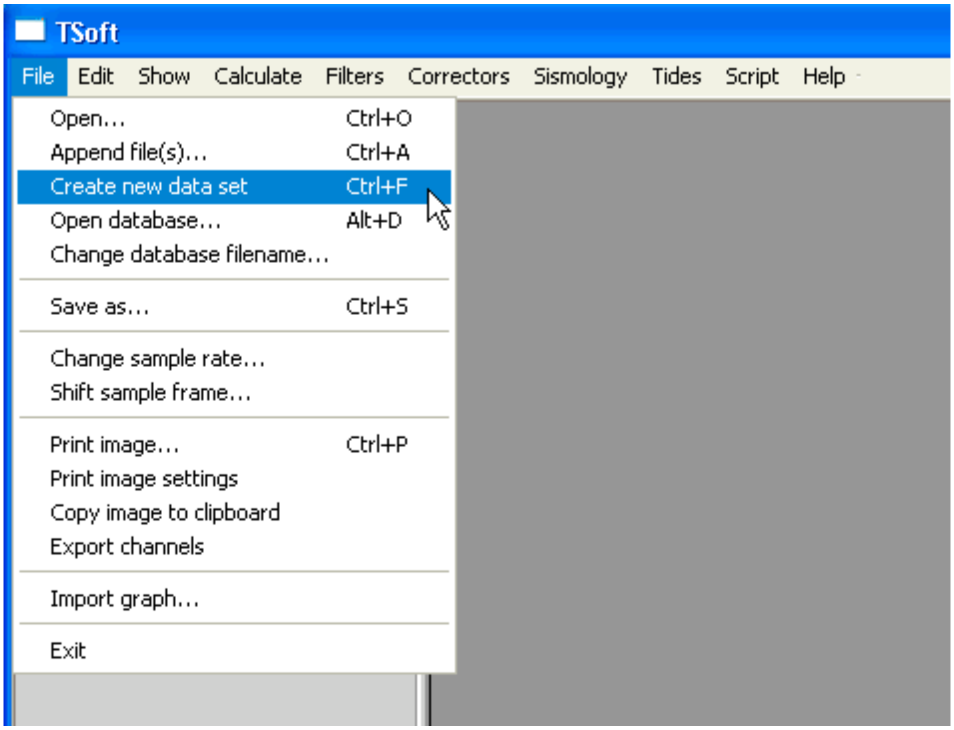
To create a set of tidal parameters for your newly added location, select the location name (with a single left click) and then choose **Compute tidal parameters** from the **Theotide** menu:



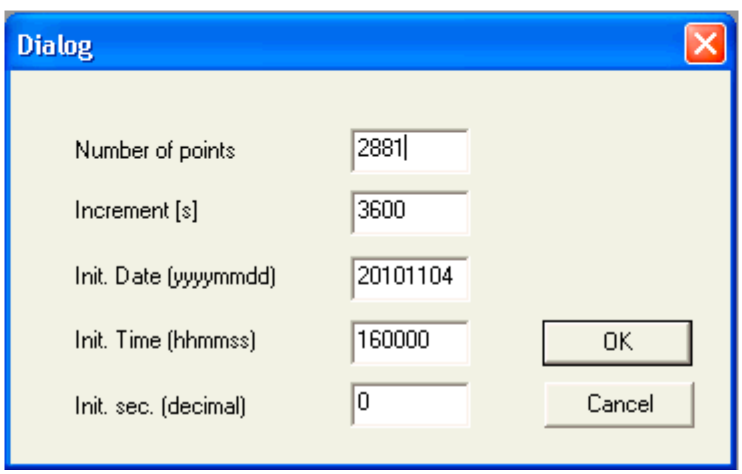
On the resulting Tidal parameter set dialog box, accept the default tidal parameter set by clicking **OK**:



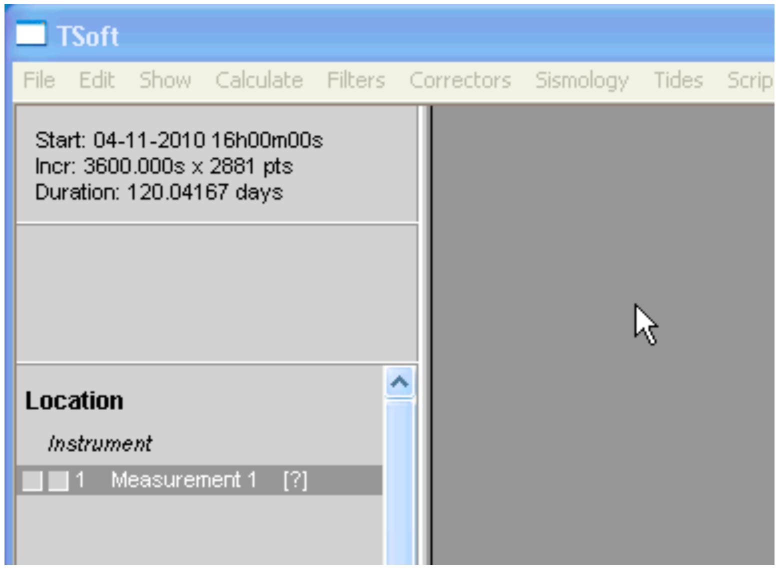
Now that you have created a set of tidal parameters, the next step is to create the series of times at which you want to compute the theoretical earth tide values. To do this, select **Create new data** set from TSoft's **File** menu:



You will then be presented with a dialog box asking for the time series specification. Presumably you will want to enter values that will generate a series of times corresponding to the measurement times for the water level data that you are analyzing. To generate a series of times at hourly (3600-second) intervals starting from 4:00 pm (16:00:00) on November 4, 2010, and extending for 120 full days to 4:00 p.m. on March 4, 2011 (2881 hourly samples, including both end points), you would enter:

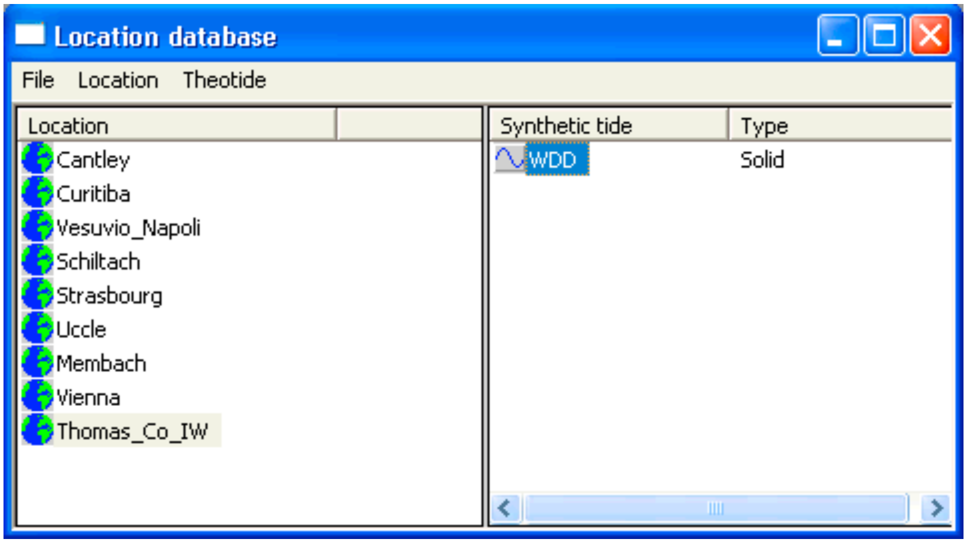


After you click OK on the dialog box, the data set (an empty time series) will be created and the upper left corner of the TSoft window will show summary information:

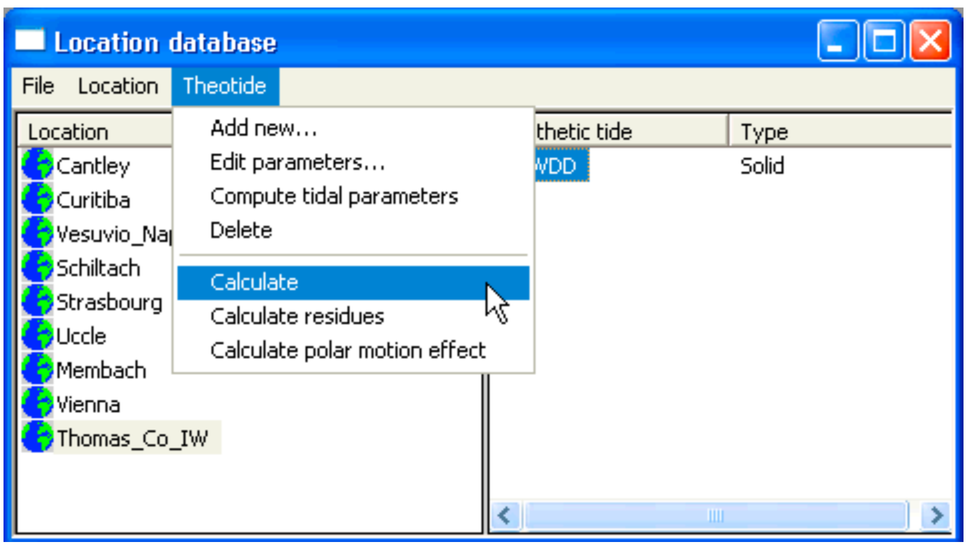


Note that the date format used in this display (and in time axis labels in the TSoft plot window) is dd-mm-yyyy, exactly the opposite of the format used in the previous dialog box. Also note that the duration shown (120.04 days here) includes the sample interval past the last sample time. The time span between the first and last sample times is given by (sample interval)*(number of sample points – 1), or, in this case, (3600 s)*(2880) = 120 days.

Now that you have generated the series of sample times, return to the **Location database** window (opening it if necessary by selecting **Open location database…** from the **Synthetic tides** submenu of the **Tides** menu, or using the Shift+L keyboard shortcut), select (single click) the location name on the left (**Thomas_Co_IW** in our example), and then select (also with a single click) the synthetic tide parameter set on the right (**WDD**):

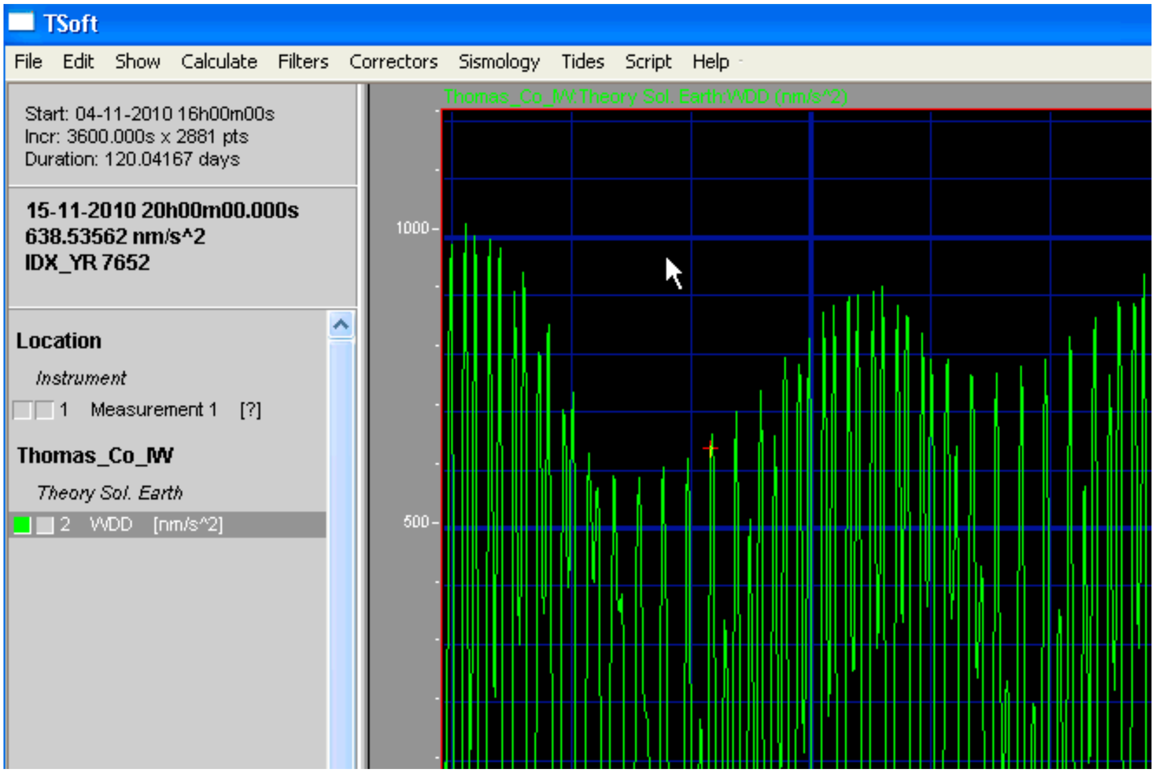


Take a moment to make sure that both the desired location and the synthetic tide parameter set are highlighted, and then select **Calculate** from the **Theotide** menu:



Once you click **Calculate**, the code will compute the theoretical earth tide values for the selected location and specified times.

The computed values will be added as a new "channel" in the time series. You can display these values in the plot window by clicking on the leftmost of the two squares next to the channel name:



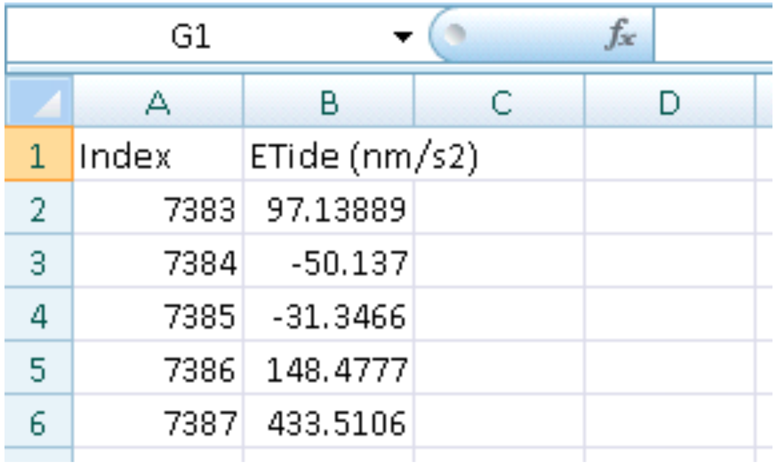
To export the computed values from TSoft, click the rightmost of the two squares next to the channel name. It will turn red to indicate that the channel is selected for export. Then select **Export channels** from the **File** menu. This will generate a plain text file named expchan.dat. For this example, the first few lines of this file contain:

```
7383       97.1388935
7384      -50.1369591
7385      -31.3465880
7386      148.4776570
7387      433.5105504
7388      732.7225562
7389      945.0343588
7390      986.9680693
7391      815.4135353
```

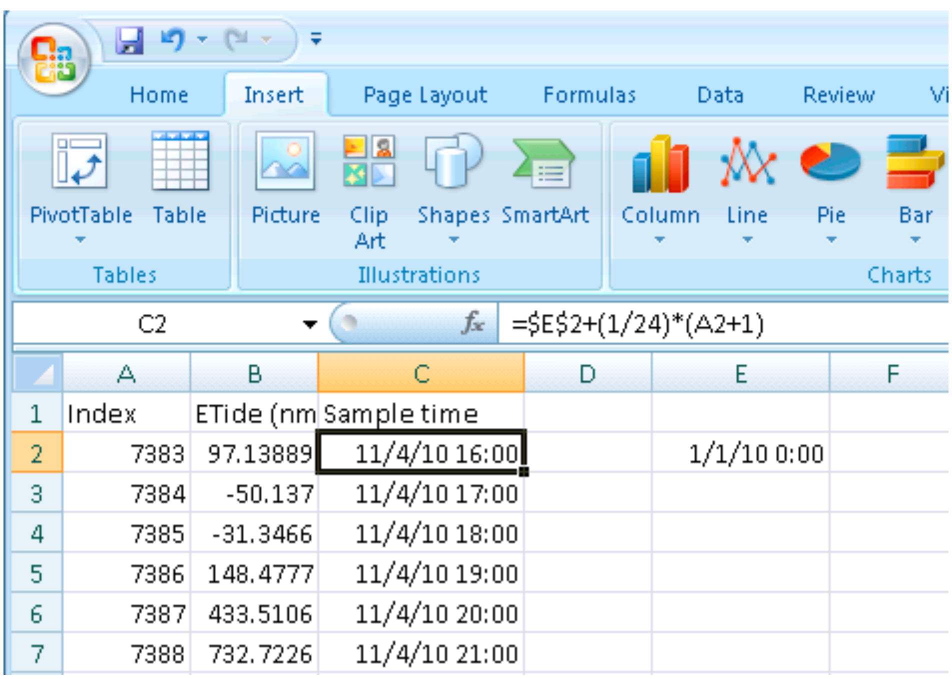
The first column contains a sample time index and the second column contains the theoretical earth tide value for that time, in nm/s^2 (nanometers per square second). According to the manual, the time index represents the "number of sample intervals since the first January of the first year of the current data series." A bit of experimentation has shown that the proper way to translate this index into the appropriate date/time value in Excel is essentially:

sample time/date = (1/1/yyyy 0:00) + (sample interval in days) * (index + 1)

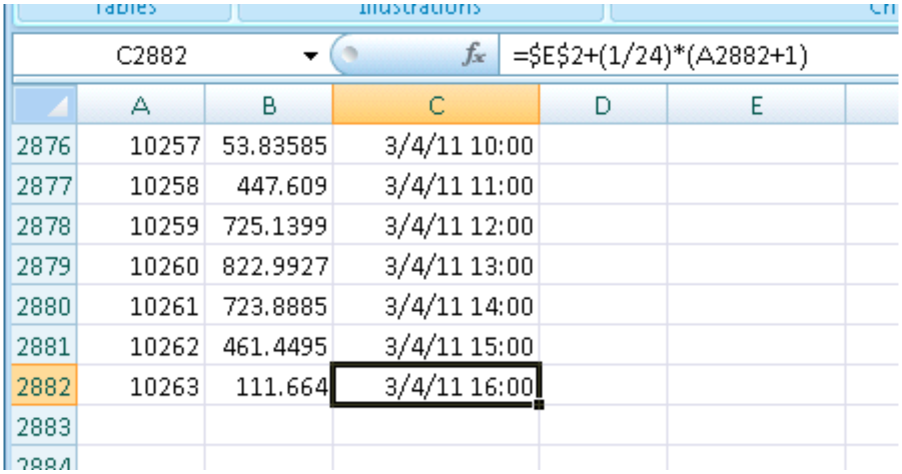
where yyyy is the year containing the first sample time in the series. In this example, if we import **expchan.dat** into Excel (as a space-delimited text file), and add a couple headers, we get:



Since the series starts in 2010, we can add sample times by entering midnight of Jan 1, 2010, as an "anchor" for the calculations, then generate a column of times using the formula above, formatting the results as date/time values:



The first sample time, in cell C2, is highlighted, and its formula appears in the formula bar above. E2 refers to the date in cell E2, with the dollar signs to fix that cell address as you fill down the column, (1/24) is the sample interval (one hour) expressed in days, and (A2+1) is first cell index plus 1. This generates a sample time that corresponds to the series start time shown in TSoft, and pulling down the formula to the last sample generates the intended end time of 3/4/2011 16:00:



C2882 =E2+(1/24)*(A2882+1)

	A	B	C	D	E
2876	10257	53.83585	3/4/11 10:00		
2877	10258	447.609	3/4/11 11:00		
2878	10259	725.1399	3/4/11 12:00		
2879	10260	822.9927	3/4/11 13:00		
2880	10261	723.8885	3/4/11 14:00		
2881	10262	461.4495	3/4/11 15:00		
2882	10263	111.664	3/4/11 16:00		
2883					

Generating a column of sample times in this fashion will help you confirm that you are properly matching up the computed earth tides with your water level measurements. Once you have done so, you can transfer the earth tide values column D of the **Input_Template** worksheet in **KGS_BRF.xls** (or a copy thereof) by copying and pasting.

Reference

Van Camp, M., and P. Vauterin, 2005. Tsoft: graphical and interactive software for the analysis of time series and Earth tides: *Computers & Geosciences*, 31(5), 631-640.