Kansas Geological Survey

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

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Kansas Geological Survey Open-file Report No. 2011-4
March 2011

GEOHYDROLOGY

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Acknowledgments

We are grateful for the support, assistance, and cooperation of the staff of the Kansas Water Office, the Kansas Department of Agriculture, Division of Water Resources, the managers and staff of Groundwater Management Districts 1, 3, and 4, and especially for the cooperation of Jarvis Garetson (the Garetson Brothers), KBUF, Inc., and Steve and Marilyn Friesen in making their properties available for installation of the wells. Mark Schoneweis assisted with graphics. ShyAnne Mailen assisted with final formatting. Susan Stover and Diane Coe of the Kansas Water Office provided instructive comments on drafts of this report. This project is funded by the State of Kansas Water Plan Fund.

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1. Introduction and Background

The calibration monitoring (index) well 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 (henceforth, 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 groundwater resources in western Kansas. The Kansas Department of Agriculture, Division of Water Resources (KDA-DWR), is providing assistance, in terms of personnel and equipment, 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 four of the study, monitoring data from three full recovery and pumping seasons and the start of a fourth 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 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) additional measurements at nearby [local (~township) scale] wells are needed through most of a recovery season to establish the representative area (areal reach) of an index well; (4) with a complete recovery record, it appears possible to extrapolate to fully recovered water levels; (5) local hydrogeologic variations and well construction need to be assessed and considered in the interpretation of well hydrographs; these factors may complicate use of wells of opportunity as index wells; and (6) water-level data collected using a pressure transducer and data logger provide a near-continuous water-level record that can help in the estimation of changes in the amount of extractable water and in assessing the uncertainty in those estimates.

This report will provide (a) an update of the hydrographs for the three index wells; (b) a detailed look at methods to estimate the elevation to which the water level would rise at full recovery in each of the index wells; (c) comparisons of the annual water-level changes measured at the index wells with those from nearby wells to assess the representative area sampled by the index wells; (d) interpretation of hydrographs from the index wells and the wells in the expanded monitoring areas in the vicinity of two of the index wells; and (e) an overview 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.

2. 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. There is one well 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 the area near an index well, thus providing more consistency and confidence in the calculation of the water-table surface and its changes in that general vicinity. However, the findings discussed in KGS-OFR 2010-03 (Buddemeier et al., 2010) led to the realization that more extensive measurements and calibration were necessary to develop a suitable measurement protocol. To achieve this, the project has been expanded to include "wells of opportunity" in the vicinity of two of the index wells:

1. The Haskell site, with numerous other wells instrumented by KDA-DWR, provides an opportunity for more extensive comparisons over a relatively short distance. However, the fact that the producing wells at the Haskell site may draw on and measure either or both of two separate aquifer units makes it more complicated than the commonly adopted view of the High Plains aquifer as a single unconfined aquifer.

2. The Thomas site, for which the commonly adopted view of the High Plains aquifer as a single unconfined aquifer appears appropriate, has been expanded to complement the comparisons at the Haskell site. With the collaboration of KDA-DWR and GMD4, six additional wells (two of which are annual program wells) have been equipped with transducers.

With increasing data, it has become apparent that these expansions enhance confidence in data gathered from the index wells and in estimates of the areal reach (representative area) of the index wells. Once a representative area of an index well has been determined, continued monitoring of the additional wells is not necessary and may be modified or discontinued.

3. Site Descriptions

Site characteristics are described and discussed in detail in previous publications (Young et al., 2007, 2008; Buddemeier et al., 2010), so they are only 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 portion 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. Well yields have deteriorated as water levels have continued to decline and an impairment complaint (since withdrawn) was filed before the commencement of this study. It appears that a two-zone aquifer system exists in the vicinity of the site: 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; KDA-DWR has installed transducers in a number of nearby wells in both aquifer zones and these wells are also 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 in aquifer characteristics and a more rapid rate of water-level decline.

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 steady declines in water level, these sites are vulnerable to resource exhaustion. The Scott County site has the only well that directly monitors the water level in the northern portion of the Scott-Finney depression, which serves as 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 important for relating aquifer lithology to well response characteristics. The Thomas County site has been the subject of previous water budget analyses (Appendix D) 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 High Plains aquifer. Both the Scott and Thomas sites are assumed to represent unconfined (water-table or phreatic) aquifer conditions, whereas the Haskell site represents confined aquifer conditions.

Table 1: Characteristics of the index well sites.

Site	2010 WL elev. (ft)[a]	2010 Saturated thickness (ft)	Bedrock depth (estimated ft below lsf)	Screened interval (ft below lsf)	2009 Water Use (AF)		
					1-mi circle	2-mi circle	5-mi circle
Haskell	2575.6	170.6	433	420-430	1935	8720	45754
Scott	2835.0	91.0	223	215-225	873	2955	16427
Thomas	2974.6	71.6	284	274-284	587	1917	7335

[a] 2010 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html)

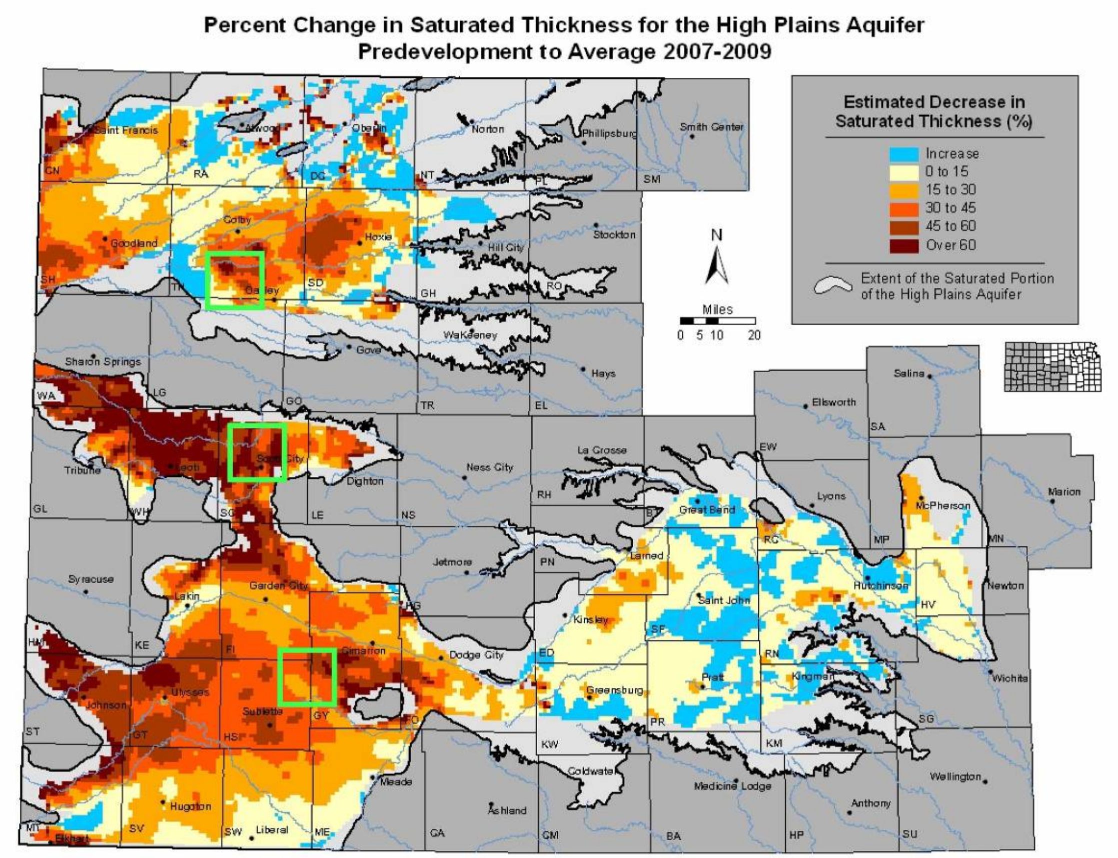


Figure 1: The Kansas portion of the High Plains aquifer, with aquifer and county boundaries shown. The colored pixels represent one section (1 mi^2), coded to show the degree of groundwater depletion from the beginning of large-scale development to the average of conditions in 2007-2009. The three green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

4. Overview of Index Well Sites and Monitoring Data

This section provides a brief overview of the hydrographs from all three sites. With over three 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 is of limited value for 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 was not interrupted by the next pumping season. This final recovered water level, which would provide a reliable basis for managers to assess the impact of changes in water use, can only be estimated through various extrapolation procedures. These extrapolation procedures were a major focus of the project this year, and will be discussed in detail in Section 7 of this report.

4.1. Haskell County

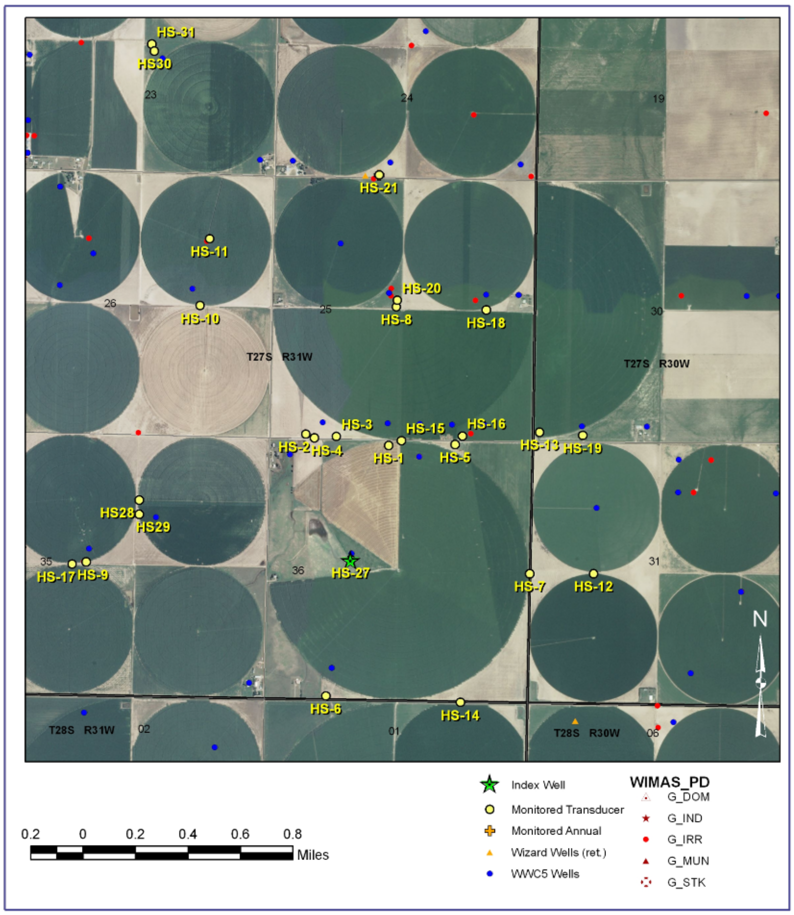


Figure 2: Haskell County site, showing the index well, adjacent monitoring wells, and points of diversion within the area of concentrated KDA-DWR studies. Most of the marked wells are equipped with transducers.

The Haskell County site is the most extensively monitored of the three sites because of its location within an area of concentrated KDA-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 KDA-DWR and used by the index well program, and the water rights within the area.

4.1.1. 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 115 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). Each year, the minimum recorded water-level elevation declined from the previous year. The lowest water level observed by far was in 2010; the minimum 2010 water-level elevation was 7 ft. lower than in 2008 or 2009 and 8.5 ft. lower than in 2007. This lower minimum water level was obtained despite a shorter pumping season in 2010 than in 2009. Water use within the 2-mile radius surrounding the index well was highest during 2008, and approximately 1200 ac-ft less during both 2007 and 2009 (2010 data are not yet available). Each year since the 2007-08 recovery season, the index well has recorded year-to-year declines in the maximum recovered water level between 4 ft. and 5 ft.. Given the much lower water-level minimum recorded in 2010, the expectation is that the decline in the maximum recovered water level will exceed the decline observed in previous years.

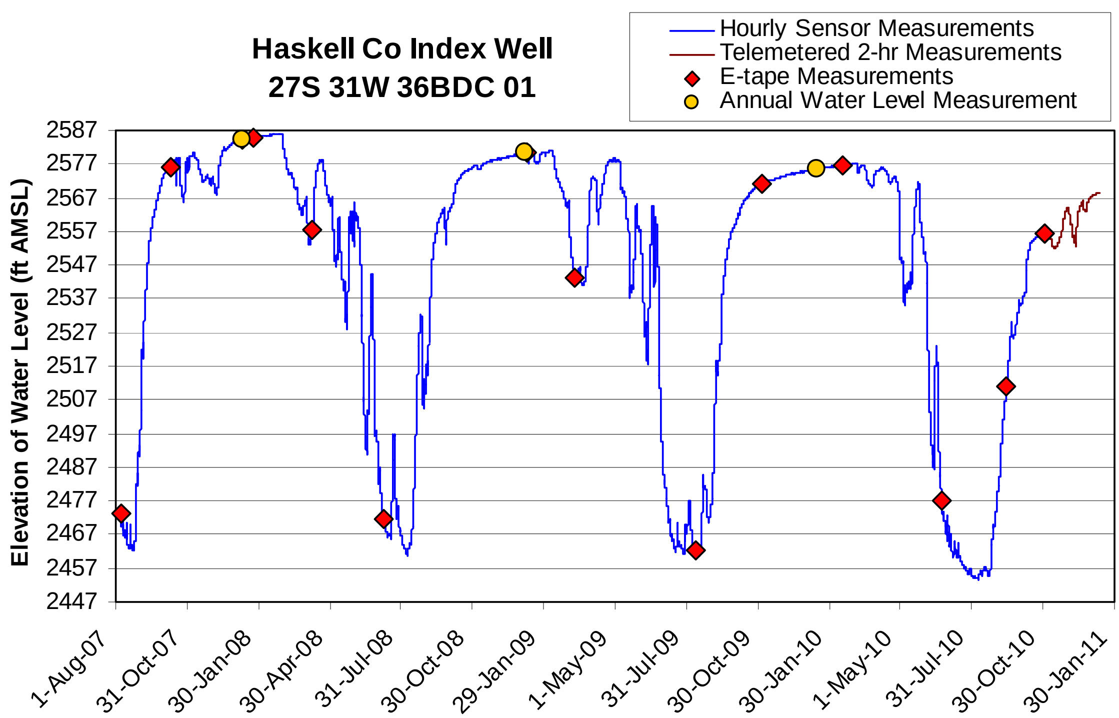


Figure 3: Haskell County index well hydrograph – total data run to 1/11/11. From 11/2/10 to 1/11/11, the provisional 2-hour telemetered data are used; before that period, data are hourly downloaded measurements.

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

		2007	2008	2009	2010
Mimimum Water-Level Elevation	Feet	2462.2	2460.8	2460.7	2453.8
	Date	8/23/07	8/8/08	8/16/09	8/9/10
Maximum Observed Recovery Elevation	Feet	NA	2586.1	2581.1	2577.2
	Date	NA	2/28/08	2/9/09	3/5/10
Apparent Recovery	Feet	NA	123.9	120.3	116.5
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-5.0	-3.9
Recovery Season	Start	NA	8/24/07	8/13/08	8/16/09
	End	NA	2/28/08	2/9/09	3/5/10
	Length (# Days)	NA	188.14	180.46	182.38
Pumping During Recovery Season	# Days	NA	41.5	19.96	5.25
Length of Pumping Season	Length (# Days)	NA	167.33	205.71	169.79
2-mi. Radius Water Use	Irrigated Acres	6475	7755	6259	NA
	Total Use (ac-ft)	8764.01	9931.71	8720.45	NA
	Use per Irrigated Acre (ft)	1.35	1.28	1.39	NA

4.1.2. Measurement Comparisons

The transducer measurements continue to compare well with the annual steel tape water-level measurements, indicating that the transducer provides an accurate representation of the instantaneous water level in the well (Table 3). When the barometric pressure effect is removed from the transducer measurement (see Section 5.1), the discrepancy between the annual manual measurements and the transducer measurements increases because the barometric effect has not been removed from the annual measurements. While the annual measurement program provides reasonable estimates of the water levels at the Haskell site, estimates of year-to-year changes in water level based on those measurements will be influenced by barometric pressure effects and incomplete recovery. The accuracy of those estimates is improved somewhat by correcting the water-level measurements for variations in barometric pressure. This is readily done by applying the same correction to the manual measurements as calculated for the transducer measurements.

Year-to-year water-level declines based on the annual measurement program were 4.1 ft. and 4.8 ft. between the 07-08 and 08-09 recovery seasons and the 08-09 and 09-10 recovery seasons, respectively (Table 3). These declines underestimated the water-level change based on the maximum recovered water level by 0.9 ft. for the first period, and overestimated the change by 0.9 ft. in the second. The primary reason for the difference between the annual water-level declines calculated from the manual measurement program and the annual declines in the maximum recovered water level calculated from the index well transducer is that the decline estimates are based on measurements taken at different points during the recovery season. These differences in the annual water-decline estimates are the justification for the development of the extrapolation procedures to estimate the water level at full recovery discussed in Section 7 of this report.

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]	-	Transducer
	2580.10[d]	-	Transducer
1/14/2010	2575.63	4.78 (3.9)	Steel tape
	2575.54[c]	-	Transducer
	2574.51[d]	-	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, not corrected for barometric pressure, 0800-1600
[d] average of values corrected for barometric pressure using the KGS barometric pressure correction program, 0800-1600

4.2. *Scott County*

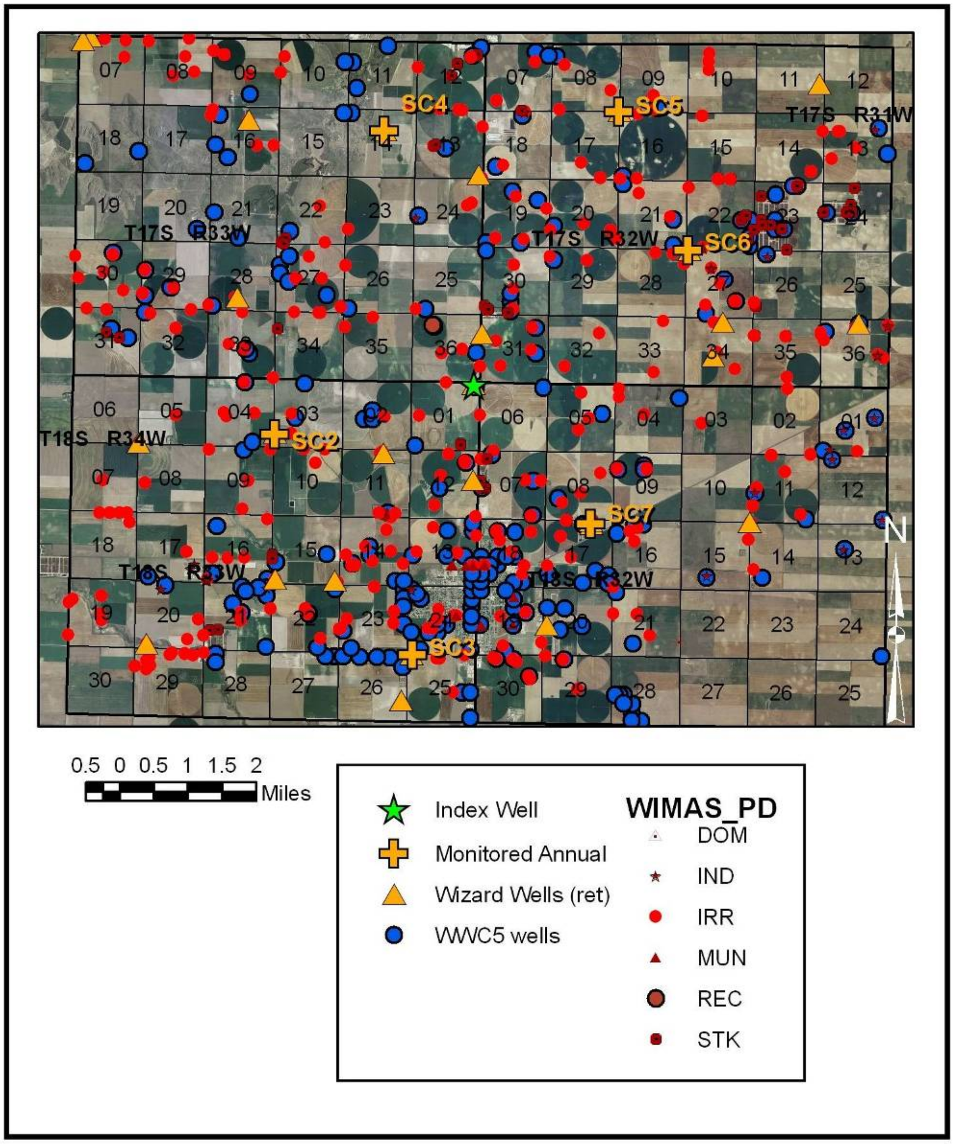


Figure 4: Scott County site, showing the index well and adjacent points of diversion.

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 water rights within the area.

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

The complete hydrograph for the Scott index well is shown in Figure 5 and its general characteristics 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. Each year, the minimum recorded water-level elevation has declined from the previous year, although there was only a small decline between

2009 and 2010. The 2010 low was slightly lower than 2009, more than 1 ft. lower than 2008, and probably more than 2 ft. lower than 2007 (note the index well was drilled during the 2007 recovery so the 2007 low was not recorded). The year-to-year declines in the maximum recovered water level were 1.3 ft. and 0.4 ft. between the 2007-08 and 2008-09 recovery seasons and the 2008-09 and 2009-10 recovery seasons, respectively. Similar to the Haskell site, water use within the 2-mile radius surrounding the index well was highest during 2008, and approximately 1000 ac-ft less during 2007 and 2009 (2010 data are not yet available).

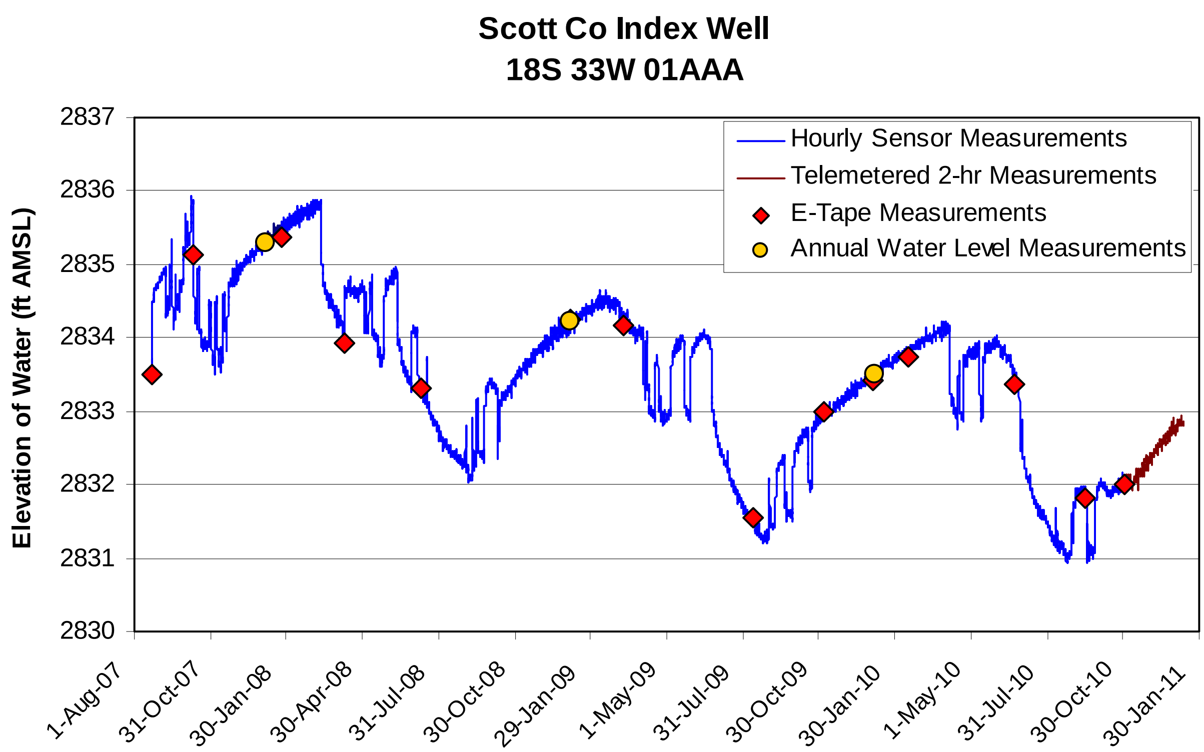


Figure 5: Scott County index well hydrograph – total data run to 1/11/11. From 11/2/10 to 1/11/11, the provisional 2-hour telemetered data are used; before that period, data are hourly downloaded measurements.

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

		2007	2008	2009	2010
Minimum Water-Level Elevation	Feet	<2833.4	2832.0	2831.2	2830.9
	Date	8/21/07	9/5/08	8/30/09	8/24/10 and 9/18/10
Maximum Observed Recovery Elevation	Feet	NA	2835.9	2834.6	2834.2
	Date	NA	3/4/08	2/17/09	3/2/10
Apparent Recovery	Feet	NA	>2.5	2.7	3.0
Apparent Water-Level Change from Previous Year	Feet	NA	NA	-1.3	-0.4
Recovery Season	Start	NA	<8/21/07	10/11/08	8/30/09
	End	NA	3/11/08	4/2/09	4/5/10
	Length (# Days)	NA	>203	204.71	217.79
Pumping During Recovery Season	# Days	NA	>48.21	13.7	21.04
Length of Pumping Season	Length (# Days)	NA	182.29	150.04	145.67
2-mi Radius Water Use	Irrigated Acres	4132	3950	3923	NA
	Total Use (ac-ft)	3175.09	4059.02	2955.48	NA
	Irrigation Use Only (ac-ft)	3095.78	4014.33	2955.48	NA
	Irrigation Use per Irrigated Acre (ft)	0.75	1.02	0.75	NA

4.2.2. Measurement Comparisons

Overall, the annual water-level measurements and the transducer measurements that have not been corrected for barometric pressure effects showed good agreement in the Scott index well record (Table 5). In 2008, 2009 and 2010, the discrepancy was 0.00 ft., 0.02 ft. and 0.01 ft., respectively.

Year-to-year water-level declines based on the annual well program were 1.1 ft. and 0.7 ft. between the 07-08 and 08-09 recovery seasons and the 08-09 and 09-10 recovery seasons, respectively (Table 5). These annual program water-level declines underestimated the water-level change based on the maximum recovered water level by 0.2 ft. for the first period, and overestimated the change by 0.5 ft. in the second.

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]	-	Transducer
1/7/2010	2833.49	0.74 (0.28)	Steel tape
	2833.48[c]	0.73	Transducer
	2833.55[e]	1.40	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, not corrected for barometric pressure, 0800-1600
[d] back extrapolated (quadratic best fit) from barometrically corrected values, 1/8/2009–2/18/2009
[e] average of values, corrected for barometric pressure using the KGS barometric pressure correction program, 0800-1600

4.3. Thomas County

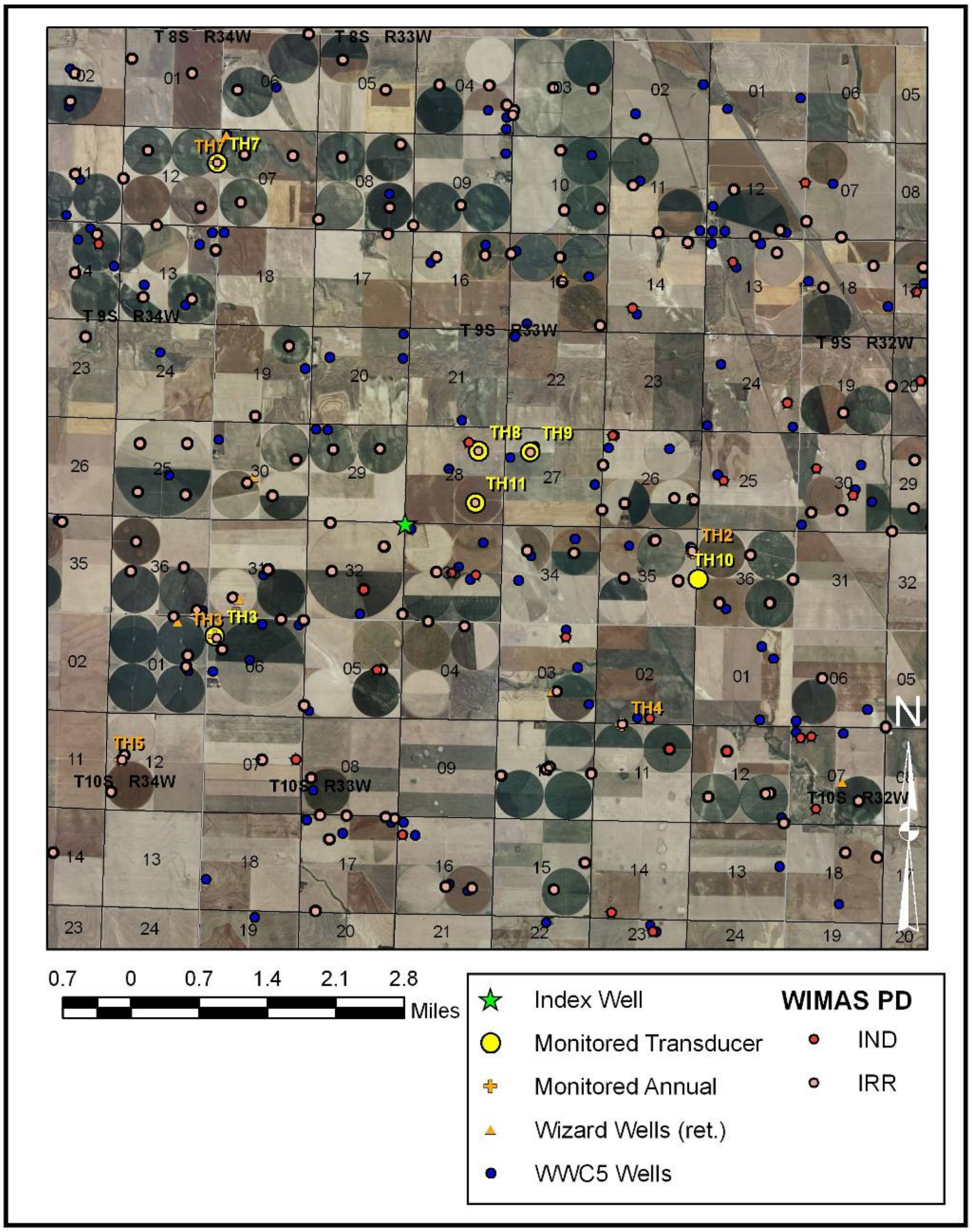


Figure 6: Thomas County site, showing the index well, nearby wells that have been equipped with transducers, surrounding annual wells, and points of diversion in the area.

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, the surrounding network of annual program wells, and the water rights within the area.

4.3.1. 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. In 2010, the lowest water level was recorded on September 5, and was nearly the same as in 2009, but 1.3 ft. higher than in 2008. The 2009-2010 recovery continued until June 22, and constituted the longest period of recovery observed at any of the index wells. Water levels in 2009-2010 recovered to the highest level recorded to date in the Thomas index well. Unlike the other two sites, water use within the 2-mile radius surrounding the index well was similar during 2007 and 2008, and approximately 1000 ac-ft less during 2009 (2010 data are not yet available).

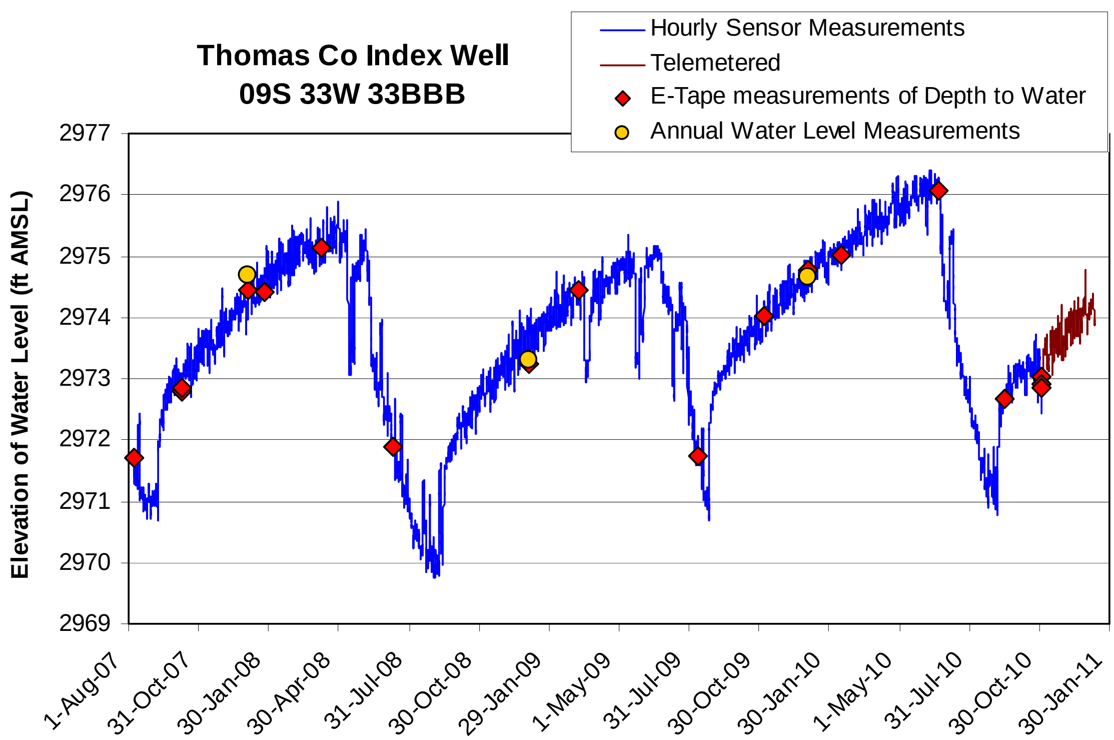


Figure 7: Thomas County index well hydrograph – total data run, 8/7/07 to 1/11/11. From 11/3/10 to 1/11/11, the provisional 2-hour telemetered data are used; before that period, data are hourly downloaded measurements.

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

		2007	2008	2009	2010
Mimimum Drawdown Elevation	Feet	2970.42	2969.71	2970.78	2971.04
	Date	9/2/07	9/8/08	8/25/09	9/5/10
Maximum Observed Recovery Elevation	Feet	NA	2975.54	2975.09	2976.20
	Date	NA	5/2/08	6/24/09	6/21/10
Apparent Recovery	Feet	NA	5.12	5.38	5.42
Apparent Water-Level Change from Previous Year	Feet	NA	NA	-0.45	+1.11
Recovery Season	Start	NA	9/8/07	9/8/08	8/27/09
	End	NA	5/12/08	6/24/09	6/21/10
	Length (# Days)	NA	247.21	289.42	298.46
Pumping During Recovery Season	# Days	NA	0?	17.04	2.17
Length of Pumping Season	Length (# Days)	NA	118.46	63.33	77.50
2-mi Water Use	Irrigated Acres	2983	3016	2958	NA
	Total (ac-ft)	2868.87	2825.21	1917.17	NA
	per Irrigated Acre (ft)	0.96	0.94	0.65	NA

4.3.2. Measurement Comparisons

Overall, the annual water-level measurements and the transducer measurements that have not been corrected for barometric pressure showed good agreement in the Thomas index well record (Table 7). In 2008, 2009, and 2010, the discrepancy was 0.06 ft., 0.11 ft., and 0.01 ft., respectively.

Year-to-year water-level changes based on the annual well program were -1.4 ft. and +1.4 ft. between the 07-08 and 08-09 recovery seasons and the 08-09 and 09-10 recovery seasons, respectively (Table 7). These changes overestimated the water-level decline based on the maximum recovered water level by 0.9 ft. for the first period, and by 0.2 ft. in the second. It is noteworthy, however, that both sets of change estimates agreed on the direction of the water-level change within each recovery season.

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 (-0.45)	Steel tape
	2973.18[c]	-1.43	Transducer
	2973.59[d]	NA	Transducer
1/2/2010	2974.64	+1.35 (+1.11)	Steel tape
	2974.74[c]	+1.56	Transducer
	2974.65[d]	+1.06	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, not corrected for barometric pressure, 0800-1600
[d] average of values, corrected for barometric pressure using KGS barometric correction program, 0800-1600

5. Water-level Correction

Significant effort has been expended on correcting water-level measurements recorded by the pressure transducers in the index wells. Mechanisms that can affect water levels in a well include changes in barometric pressure, changes in aquifer porosity due to earth tide forces (stretching and compressing of pores), and major surface loading changes associated with heavy rainfall and changes in flow in nearby stream channels. In previous reports, earth-tide effects were shown to have a negligible impact on water levels in the index wells, while the impact of changes in barometric pressure varied between the index wells. As part of this project, the KGS has developed an Excel spreadsheet to remove the effect of barometric-pressure fluctuations from water-level measurements (henceforth, water-level correction). Details and screenshots from this spreadsheet are available in Appendix C.

5.1. Water-level Responses to Change in Barometric Pressure

OFR 2010-3 (Buddemeier et al., 2010) provides a detailed explanation of how water levels in wells respond to fluctuations in barometric pressure, with an emphasis on hydrogeologic conditions similar to those found in the proximity of the three index wells. We are continuing to refine our methods for accounting for barometric-pressure impacts on water levels as part of a complementary research effort. Appendix E contains a paper, which will be published in the journal Ground Water in 2011, that describes complementary research done at a KGS research site in the High Plains aquifer in Pawnee County near Larned. The focus of that research is on assessing the range of hydrogeologic insights that can be gleaned from water-level responses to fluctuations in barometric pressure. Insights developed from that research have been particularly useful for interpreting the responses of the index wells to barometric-pressure changes.

The deep unconfined aquifer monitored by the Thomas index well displays the largest response to changes in barometric pressure. As explained in the introduction to the paper in Appendix E, a change in barometric pressure is instantaneously imposed on the water level in the well. However, in a deep unconfined aquifer, that change is not immediately imposed on the water table because of the time needed for the barometric-pressure change to be transmitted through the vadose zone. This timing difference (barometric lag) between when the well and the aquifer are affected by the barometric pressure change leads to relatively large water-level changes in the well. In the Thomas index well, changes in barometric pressure can change the water level by up to 1.4 ft. in a period as short as three days, even though the actual position of the water table in the formation has changed very little. The result is a large short-term variation in monitored water levels, which is easily observed during the recovery season and produces the band in the Thomas well hydrograph shown in Figure 7. The impact on the year-to-year change estimates based on the annual water-level measurement program can be large. For example, the annual water-level measurements in January 2008 and January 2009 were both taken at barometric pressure extremes (Figure 7, yellow circles). From the index well record, it is clear that changing the date of either measurement by just ± 3 days could have resulted in estimated annual water level changes ranging from a 1.4 ft. decline to a 0.3 ft. increase between 2008 and 2009. This clearly introduces a significant error considering the total water-level variation in this well is ~6 ft. over the entire record.

To account for the barometric lag between a well and the aquifer, simultaneous water-level and barometric-pressure measurements must be collected. Barometric pressure measurements were collected at each index site beginning in January of 2009. For the period prior to that, barometric pressure information is available from nearby weather stations. When the KGS Excel barometric pressure correction program (Appendix C) was applied to the data from the Thomas index well, the water-level uncertainty (the width of the band about the hydrograph) was greatly decreased (Figure 8).

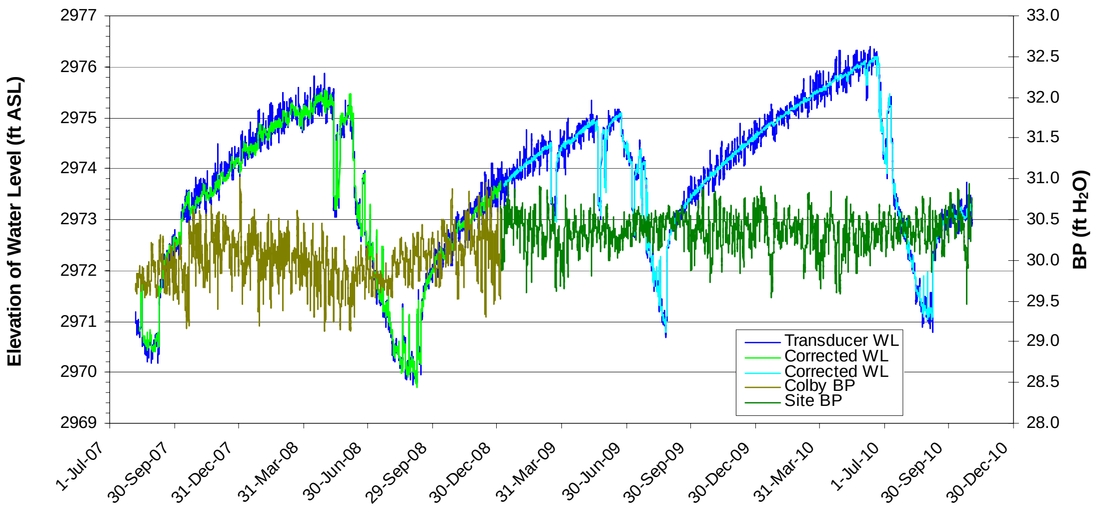


Figure 8: Thomas index well hydrograph (blue line), with corrected water levels (fluorescent green and turquoise lines). Before January 2009, barometric pressure (BP) data were only available from a permanent weather station in Colby, KS (olive line).

Correcting water-level measurements for changes in barometric pressure provides several advantages. Since water-level uncertainty (width of band on hydrograph) is reduced, a clearer understanding of water-level decline and recovery is provided. This increases confidence in fully recovered water-level determinations (discussed further in Section 7) and water-availability estimates. In turn, this enables assessments and decisions to be made sooner, since accumulating statistics over a number of years is not required.

6. Thomas County Expansion Project

To demonstrate the areal extent over which an index well represents aquifer conditions, KDA-DWR wells in the vicinity of the Haskell index well were made available to the project. However, the complex subsurface hydrogeology near the Haskell index well is not representative of conditions in the High Plains aquifer across most of western Kansas. To address the representative area issue in more typical High Plains aquifer conditions, additional "wells of opportunity" were sought in the vicinity of the Thomas index well for transducer installation and continuous water-level monitoring. An added benefit to monitoring the additional wells (in both Thomas and Haskell counties) is to provide a proof of concept for the "well of opportunity" index well monitoring approach detailed by Buddemeier et al. (2010) and in Section 8.

Initially, six wells, including retired and active irrigation wells and a domestic well, were selected and instrumented with pressure transducers provided by KDA-DWR to monitor the 2009-2010 recovery. Due to sensor malfunction and the desire to enhance data coverage, two KGS sensors were installed in the fall of 2010. A summary of sensor installation dates and other significant events is provided in Table 8. Hydrographs from the four monitored wells with minimal sensor malfunctions are given in Figure 9. Top of casing elevations are currently only available for TH3 and TH7; the remaining wells will be surveyed shortly. For general comparison, the well elevations for TH9 and TH10 were estimated using the Google Earth digital elevation model. Although full recovery information was not available for either TH3 or

TH7, water levels in both were clearly higher than in the index well. Water levels in TH10 were clearly lower than 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 groundwater flow field (Figure 10, Appendix D).

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

Well	Sensor	Installation Date	Notes
TH3	KDA-DWR	8/12/09	Malfunctioned 1/12/10
	KGS	9/13/10	
TH7	KDA-DWR	9/30/09	Active irrigation well; sensor removed 4/18/10; re-installed 11/23/10
TH8	KDA-DWR	11/5/09	Malfunctioned 12/4/09
TH9	KDA-DWR	11/5/09	Sensor removed 11/11 to 11/14/09 for well cap installation
TH10	KDA-DWR	8/12/09	
TH11	KGS	11/3/10	

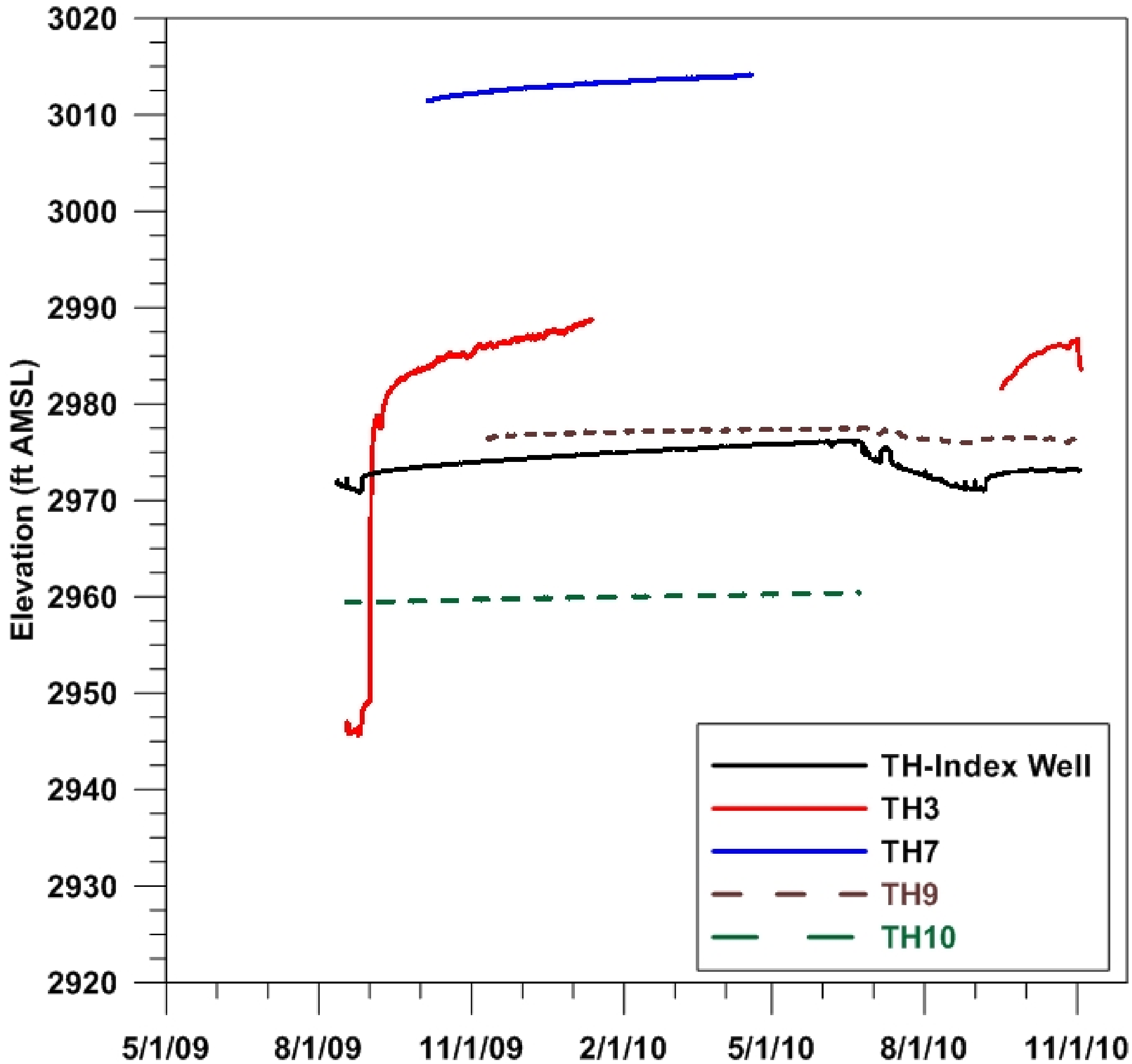


Figure 9: Hydrograph comparison from the Thomas expansion well program utilizing barometric pressure corrected water levels. Surface elevations for TH9 and TH10 are estimates using the Google Earth digital elevation model (an elevation survey will be completed shortly), but are likely accurate to within ±5 ft. The general water-level trend indicates west-to-east groundwater flow.

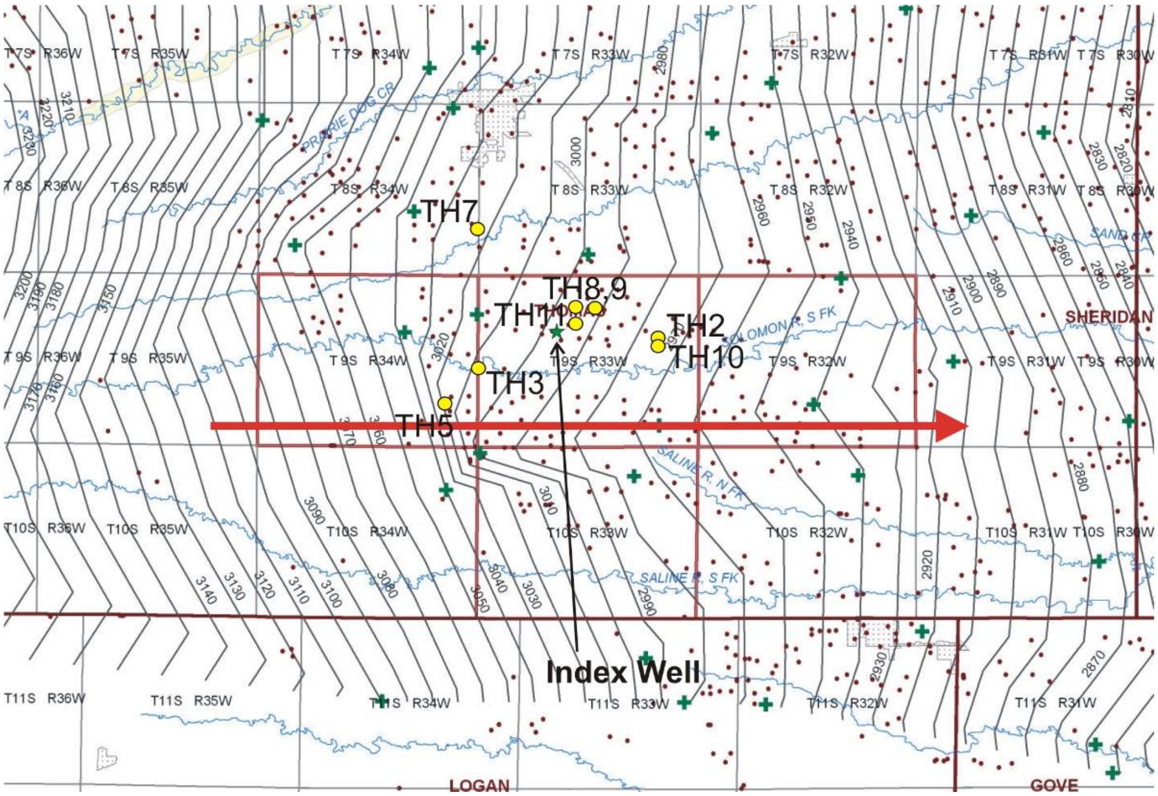


Figure 10: Groundwater elevation contours near the Thomas index well calculated from 2005 annual measurements (from Buddemeier et al., 2006 – see Appendix D).

Using the water-level data as feet of water above the sensor, some additional observations about the different wells are possible. TH3, TH7, and TH9 all show trends in water levels that are similar to that at the index well; when the index well transducer indicated rising water levels, so did these other three wells. Likewise, when the index well transducer recorded declining water levels, these other three wells did also. However, the magnitude of these water-level changes differed, particularly between TH3 and the other wells. With the exception of TH3, hydrographs indicated 1-3 ft. of recovery, somewhat lower than the recovery recorded in the index well (6 ft. of recovery). This apparent lower recovery can be attributed to the installation date of sensors for TH7 and TH9, which occurred at least 30 days after the commencement of recovery. The first 30 days of recovery are significant, as approximately 50% of the recovery in the Thomas index well was recorded during this period. Despite installation prior to the end of the pumping season, the transducer in TH10 only recorded a foot of water-level rise over the entire recovery period. Once the factors responsible for the small recovery recorded at that domestic well are clarified, it might prove to be a useful well of opportunity, since it appears subject to very little pumping perturbation.

The distance to the nearest pumping well also factors into the amount of drawdown and recovery. The recovery was relatively large at TH3, with water levels rising over 40 ft. prior to the transducer malfunction. TH3 is a retired irrigation well that is located quite close to its replacement well. The large water-level changes observed in TH3 are attributed to its immediate proximity to the replacement well. Thus, when pumping ceased in the replacement well, a large and rapid water-level change in TH3 was observed.

All of the expansion wells displayed pronounced water-level responses to fluctuations in barometric pressure, consistent with the responses observed at the Thomas index well and the expected response for this hydrogeologic setting (water table 200+ ft below land surface). The barometric response functions (BRF) for TH7, TH9, and TH10 indicate an unconfined system (Figure 11), similar to the Thomas index well (see Figure 3-5, Buddemeier et al., 2010). Using the BRF, water levels were corrected for barometric response (Figure 12), as in Section 5.1.

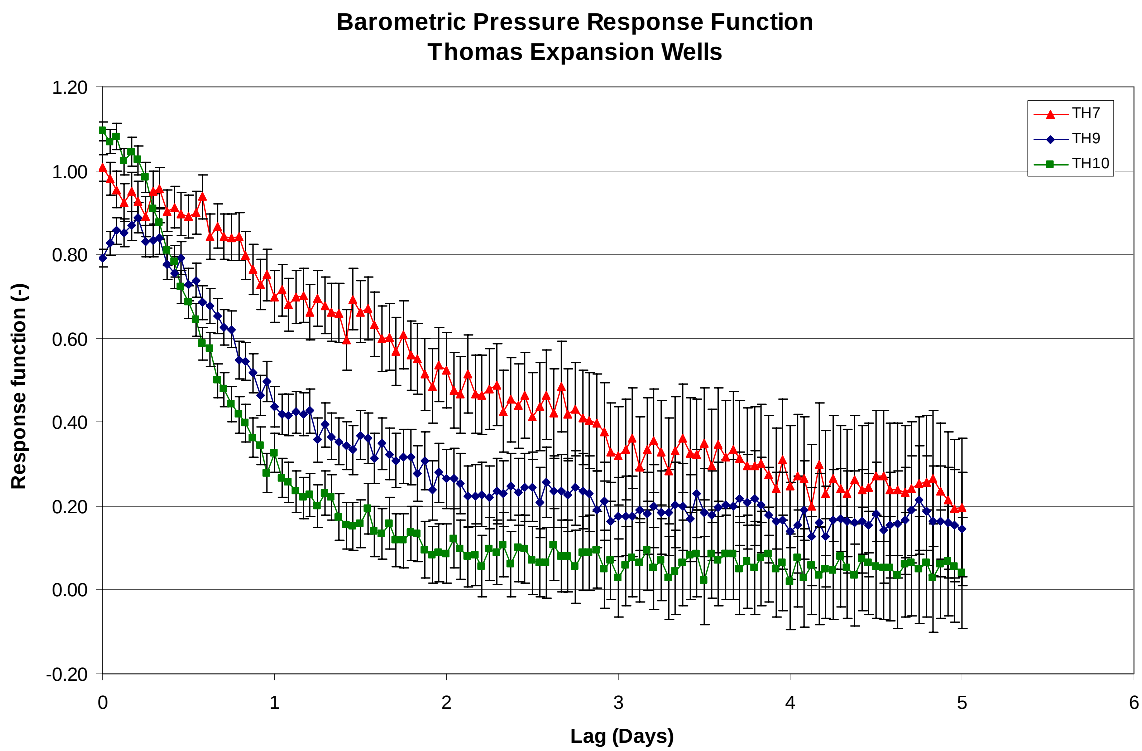


Figure 11: Barometric pressure response function for Thomas Co. expansion wells TH7, TH9, and TH10.

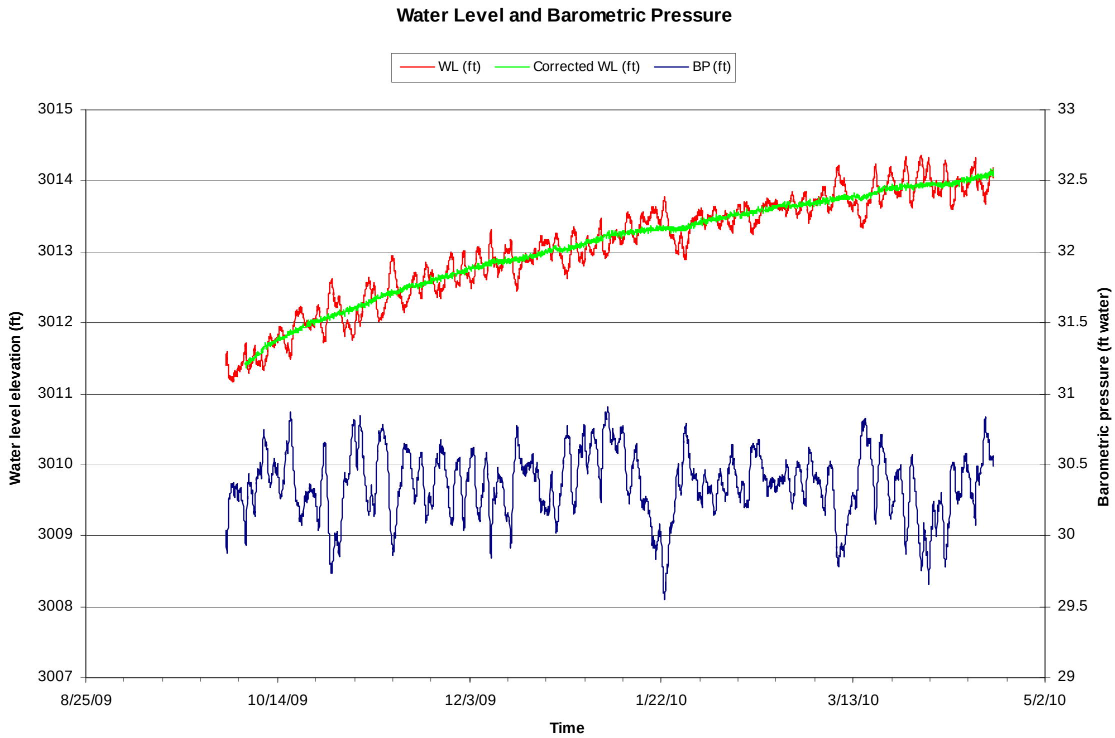


Figure 12: Well hydrograph, barometric pressure, and water level corrected for barometric response from Thomas Co. expansion well TH7.

Overall, data from the 2009-2010 recovery provide an initial view of what can be determined with more complete and extensive monitoring records. If all goes well during the 2010-11 recovery period, more definitive correlations between the index and expansion wells should be available in mid-2011. Transducers remain to monitor the 2010-2011 recovery, and the additional data provided will be invaluable for identifying the significance of the intriguing recovery trends identified in the Thomas index well recovery hydrograph (described below in Section 7.2).

7. Recovery Water-level Estimation Refinement

In OFR 2010-3 (Buddemeier et al., 2010), three different methods were presented for estimating the water level at full recovery: a polynomial fit method, a modified Horner recovery method, and a spreadsheet-based method using the Theis solution (Appendix B in Buddemeier et al., 2010). The reader is referred to OFR 2010-3 for a more detailed development of the theory and equations. The Horner recovery method appears to be the most promising of these methods, so a brief overview is provided here.

In the Horner recovery method, water-level measurements after pumping has ceased (henceforth, recovery data) are plotted against a time ratio (t_h), which consists of the duration of pumping (t_p) and the time since pumping ceased (t'), arranged as $t_h = (t_p+t')/t'$. For the purposes of this work, the water-level data are in the form of recovery (in ft) since the cessation of pumping, although the water-level elevation could also be used. The recovery data are plotted against the logarithm of the time ratio with the ratio decreasing from left to right (*t'* increasing). The recovery data are extrapolated to a t_h value of one (an infinite time of recovery); that extrapolated value is the estimated level to which the water would rise at full recovery.

Hydrographs from a few of the wells in the Haskell area indicate water levels actually fully recover in between pumping periods, and thus can provide proof-of-concept for the Horner recovery method. This example will focus on HS 20, an irrigation well that has a BRF indicative of a well screened in an unconfined aquifer. The hydrograph for HS 20 (Figure 13) indicates the well recovers quickly after cessation of pumping, with pumping for 2007 ending on August 30th. This was followed by a long period with no pumping, ending on March 20, 2008. Over the course of the seven-month recovery, water levels were remarkably consistent (Table 9), indicating water levels reached equilibrium at full recovery. A Horner-recovery plot constructed for this period indicated a similar recovered water level of 2596.53 ft. AMSL using early recovery data, and 2596.57 ft. AMSL using later recovery data (Figure 14). This suggests the Horner recovery method provides viable recovery estimates in the HPA.

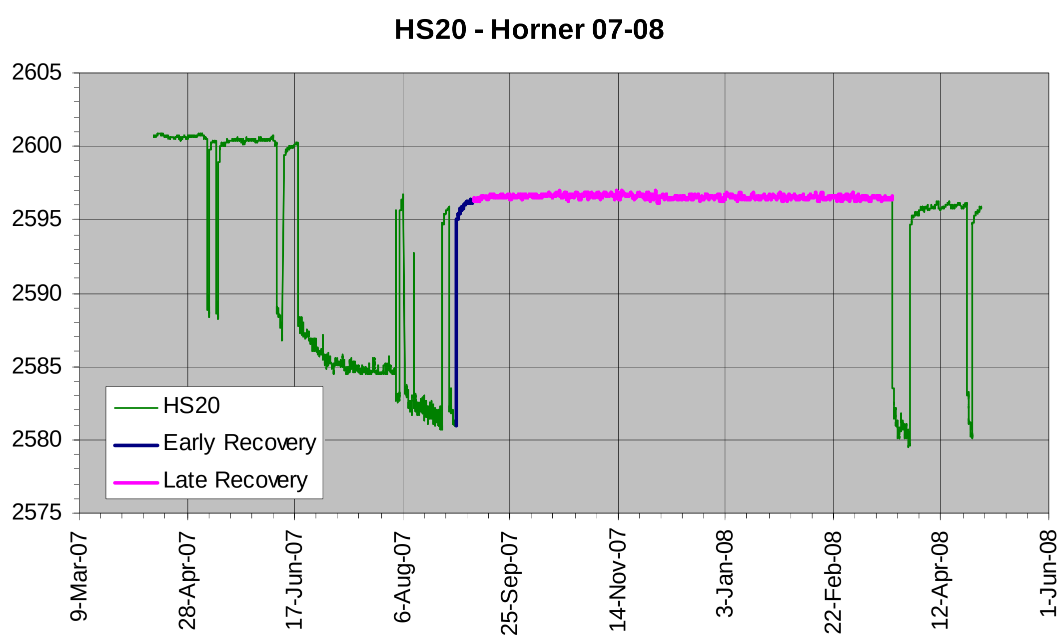


Figure 13: HS 20 hydrograph. Blue and pink portions of the recovery were used for the Horner recovery estimate, and correlate with the early and late recovery period estimates in Figure 14.

Table 9: Average water-level elevation (barometric effects not corrected), HS 20.

Month	Average Water Level (ft AMSL)
Sept. 2007	2596.40
Oct. 2007	2596.65
Nov. 2007	2596.65
Dec. 2007	2596.52
Jan. 2008	2596.54
Feb. 2008	2596.53
Mar 1 – Mar 20, 2008	2596.49

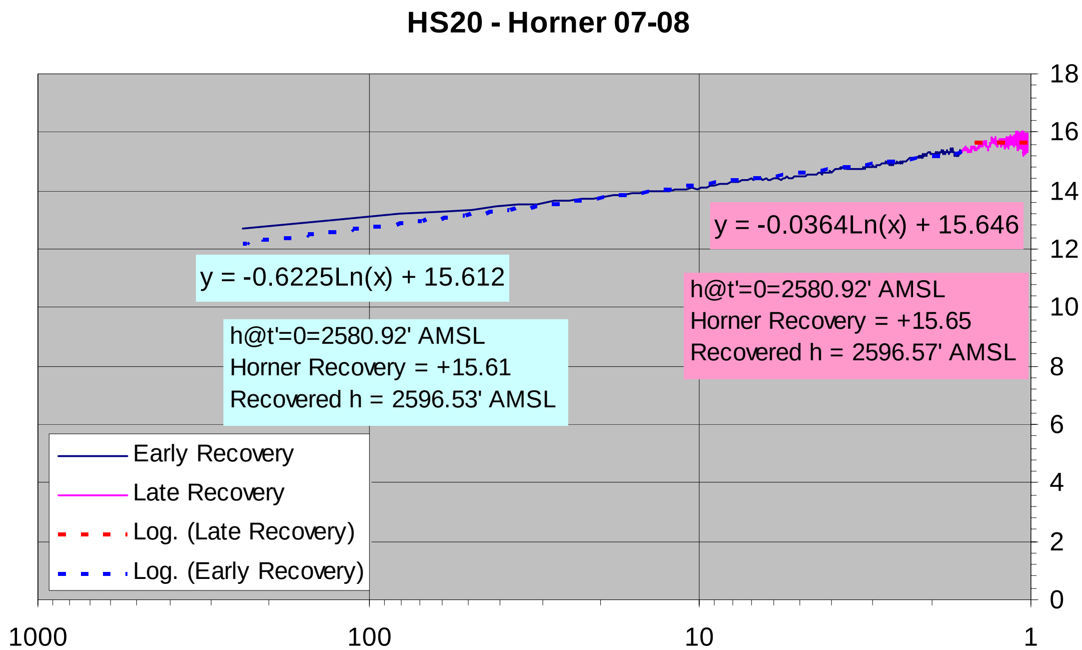


Figure 14: HS 20 Horner recovery plot from August 30, 2007, to March 20, 2008, with early recovery and late recovery estimates. Blue and pink portions of the recovery are the same as the blue and pink portions in Figure 13.

7.1. Index Well Horner Recovery Plots

Examples of water-level recovery curves and Horner recovery plots from the Haskell index well are provided in Figure 15. Panels A and B (Figure 15) use the minimum water level that was observed immediately before the end of the summer irrigation season, while panels C and D (Figure 15) use the water level observed immediately prior to the end of the final pumping period. Dates and water-level elevations corresponding to the end of pumping in Figure 15 are shown in Table 10. The water-level recovery curves behave as expected (Figure 15A); recovery progresses quickly for the first ~1000 hrs. At around 700 hours after the minimum water level, water-level recovery begins to slow down and the recovery curves begin to flatten out. Water-level recovery (from minimum water levels) was highest in the 2007-08 recovery and has decreased in each of the last two years. The Horner recovery plots (Figure 15 B-D) were calculated using an assumed pumping interval (duration of a single irrigation period at a well) of five days. Using this value and extrapolating recovery curves by hand to a t_h value of 1, the estimated final recovery levels for 2007-08, 2008-09, and 2009-10, to the nearest half foot, are 128.5 ft., 125.5 ft., and 121.0 ft. above the minimum water levels (or 2591.0 ft., 2586.5 ft., and 2582.0 ft. above sea level), respectively. This indicates a water-level decline of 4.5 ft. between 2008 and 2009 (between the 2007-08 and 2008-09 recovery seasons), and also between 2009 and 2010 (between the 2008-09 and 2009-10 recovery seasons). These values are consistent with the annual tape measurements (Table 3), which yield water-level declines of 4.1 ft. and 4.8 ft. between 2007-08/2008-09 and 2008-09/2009-10, respectively. These values are also consistent with the declines in the maximum recovered water level measured by the index well transducer of 5.0 ft. and 3.9 ft. for 2007-08/2008-09 and 2008-09/2009-10, respectively. However, these values differ significantly from the water-level decline based on the extrapolated quadratic fit values of 6.4 ft. for 2008-09 (Buddemeier et al., 2010, Table 3.1). While Horner recovery water-level values are approximate because of the uncertainty in the assumed pumping interval (five days) and the manual extrapolations, it is clear that water-level elevations continue to decline in successive years.

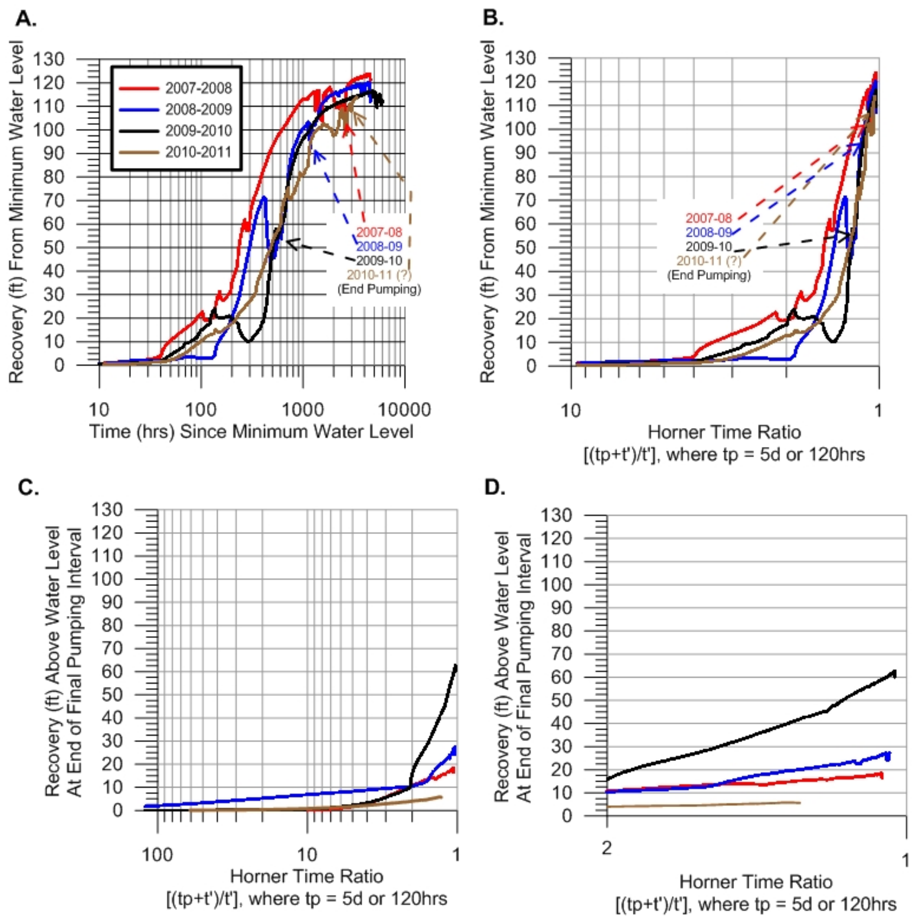


Figure 15: Haskell index well recovery for all three complete recovery seasons (2007-08, 2008-09, 2009-10) and the start of the 2010-11 recovery, plotted as semi-log recovery curves (A) and as Horner recovery curves (B), (C) and (D). As several pumping events occurred within the first month after the end of the pumping season, panels (C) and (D) display recovery from the final pumping event, rather than the lowest recorded water level.

Table 10: Comparison of reference water levels used in the Horner plot recovery analysis for Haskell County. Minimum water level is used in panel B of Figure 15, while the final pumping period is used in panels C and D.

	Minimum Water-Level		Water Level @ end of final pumping period	
	Date	ft AMSL	Date	ft AMSL
2007-08	8/24/2007	2462.38	12/7/2007	2567.67
2008-09	8/8/2008	2460.84	9/27/2008	2553.13
2009-10	8/16/2009	2460.73	9/8/2009	2514.47
2010-11	8/22/2010	2454.69	12/24/2010	2562.72

The Haskell index well recovery curves contrast with the two index wells screened in unconfined portions of the High Plains aquifer (Scott Co., Figure 16, and Thomas Co., Figure 17). The recovery rate changes for all three index wells around 1000 hrs (~42 days) after the end of the pumping season, resulting in two distinct recovery periods. However, while the slope of the recovery curve decreased in the Haskell index well, the slope of the recovery curve increased in the Thomas and Scott index wells. The difference in responses is primarily a function of the hydrogeologic setting. In the confined aquifer at the Haskell site, recovery is in its later stages and water levels are beginning to flatten towards a new equilibrium level. In the unconfined aquifers at the Thomas and Scott sites, recovery does not appear to "flatten" towards equilibrium. This difference between the confined and unconfined responses is a function of the difference in the storage parameters between these two hydrogeologic settings; a confined aquifer has a storage parameter on the order of 0.0001, while an unconfined aquifer has a storage parameter (specific yield) on the order of 0.1. The result is a much more rapid recovery of water levels in confined aquifers. Thus, for the same time since cessation of pumping, the recovery in a confined aquifer, as a proportion of the total recovery, is much greater than in an unconfined aquifer.

In the Scott index well (Figure 16), the recovery slopes were consistent, although the slope of late-time recovery in 2007-08 was lower than the other years, likely due to a shorter recovery that prevented full expression of the late-time recovery trend. Similar to conditions at the Haskell site, pumps were turned on several times in the vicinity of the Scott index well during the recovery in September and October in 2008 and 2009 after the primary irrigation season was over. This additional pumping affected the recovery at the index well. However, the recovery curves were consistent from year to year. This consistency indicates that the Horner method should also be a viable approach for estimating the full recovery level at the Scott index well.

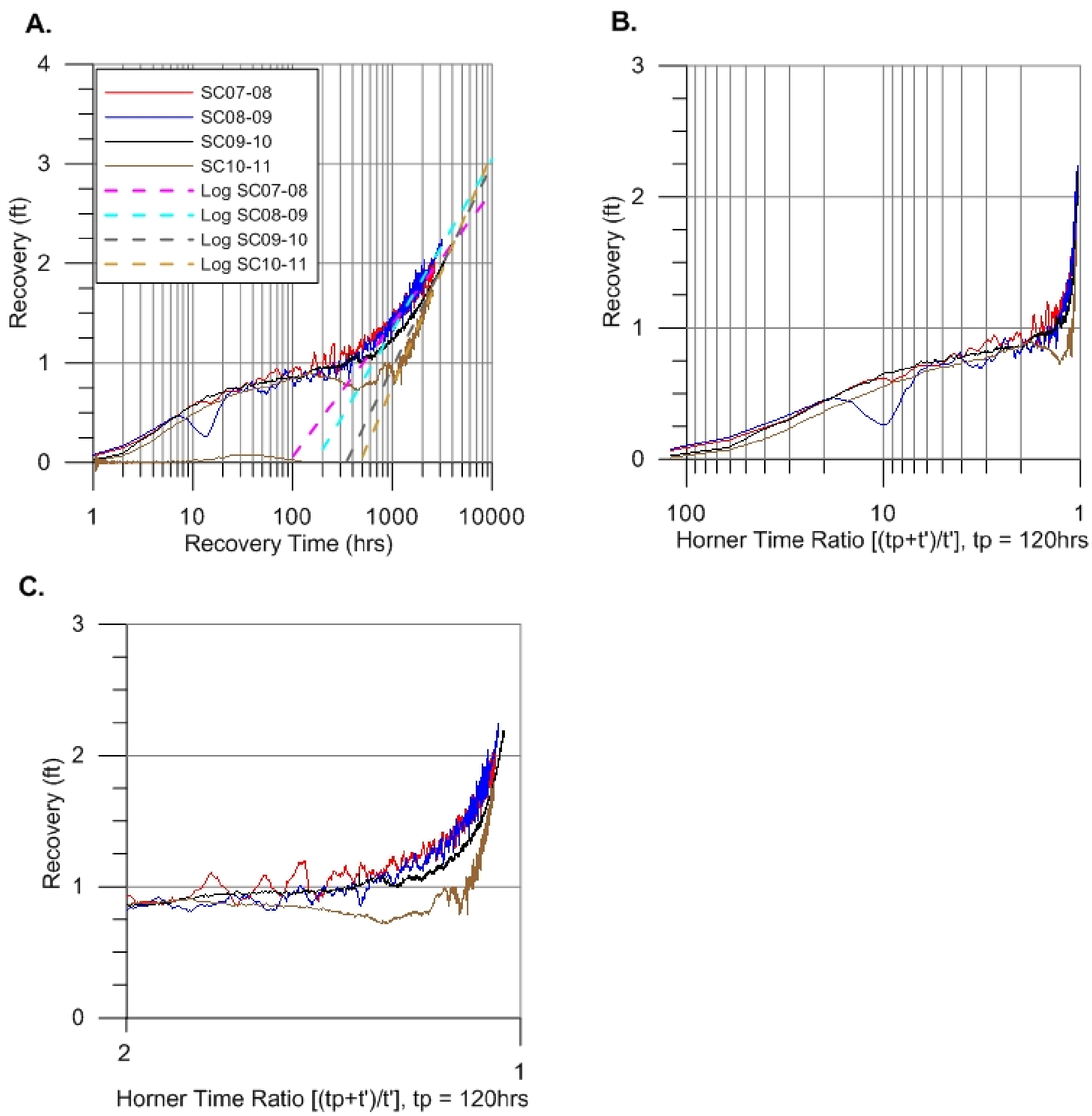


Figure 16: Scott index well recovery plotted as semi-log recovery curves with hand-fit slopes at the late time (A) and as a Horner recovery curve (B) and (C). Two distinct stages of recovery are clearly evident in all three plots, with an increase shown and clearly dominant ~1000 hrs from the final pumping period in all three complete recovery seasons (2007-08, 2008-09, 2009-10) and the start of the 2010-11 recovery.

For the Thomas index well (Figure 17), the slope of the water-level elevation recovery curve changed consistently in each of the three recovery seasons (2007-08, 2008-2009, 2009-10). The small slope of the early time recovery (<1000 hrs), which may be the recovery equivalent of the delayed yield phase of a pumping test in an unconfined aquifer (Batu, 1998) or simply a function of the specific yield of the aquifer and the distance of the index well from the closest pumping well, was consistent in each recovery period, as was the much larger slope for the late-time recovery. This consistency of late-time recovery slopes indicates that the Horner recovery method should be a viable approach for estimating the level to which the water would rise at full recovery at the Thomas index well. Further assessment of the distinct two-stage recovery curves at the Thomas and Scott index wells and the factors producing them is presented below.

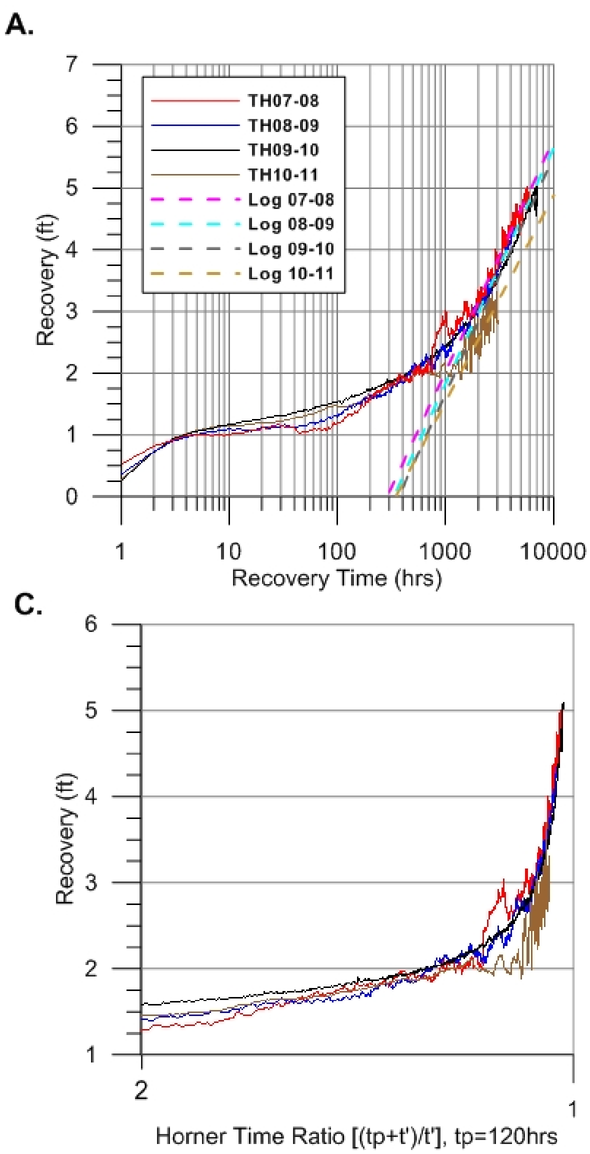


Figure 17: Thomas index well recovery, plotted as semi-log recovery curves with hand-fit slopes at the late time (A) and as a Horner recovery curve (B) and (C). Two distinct stages of recovery are clearly evident in all three plots, with an increase shown and clearly dominant ~1000 hrs from the final pumping period in all three complete recovery seasons (2007-08, 2008-09, 2009-10) and the start of the 2010-11 recovery.

7.2. Seeking Equilibrium: Evaluation of Two-stage Recovery and Recovered Water-level Estimation, Thomas County Index Well

The Thomas index well dataset for the 2009-2010 recovery season (Figure 18) was used for a detailed comparative analysis, since this is the most complete, uninterrupted dataset available for any of the sites. The 2009 pumping season got under way on June 24, with pumping ending August 27, a period of 63 days. Recovery was uninterrupted until June 4, 2010 – a period of 281 days. On August 27, 2009, the barometric pressure corrected (bp-corrected) water-level elevation was 2971.11 ft.; on June 4, 2010, the bp-corrected water level had recovered to 2976.10 ft. – and had not yet come to equilibrium. The highest observed recovered water level was 2976.20 ft., on June 21, 2010; just before major irrigation pumping commenced. All analyses discussed here consider only the time from June 24, 2009, until June 4, 2010.

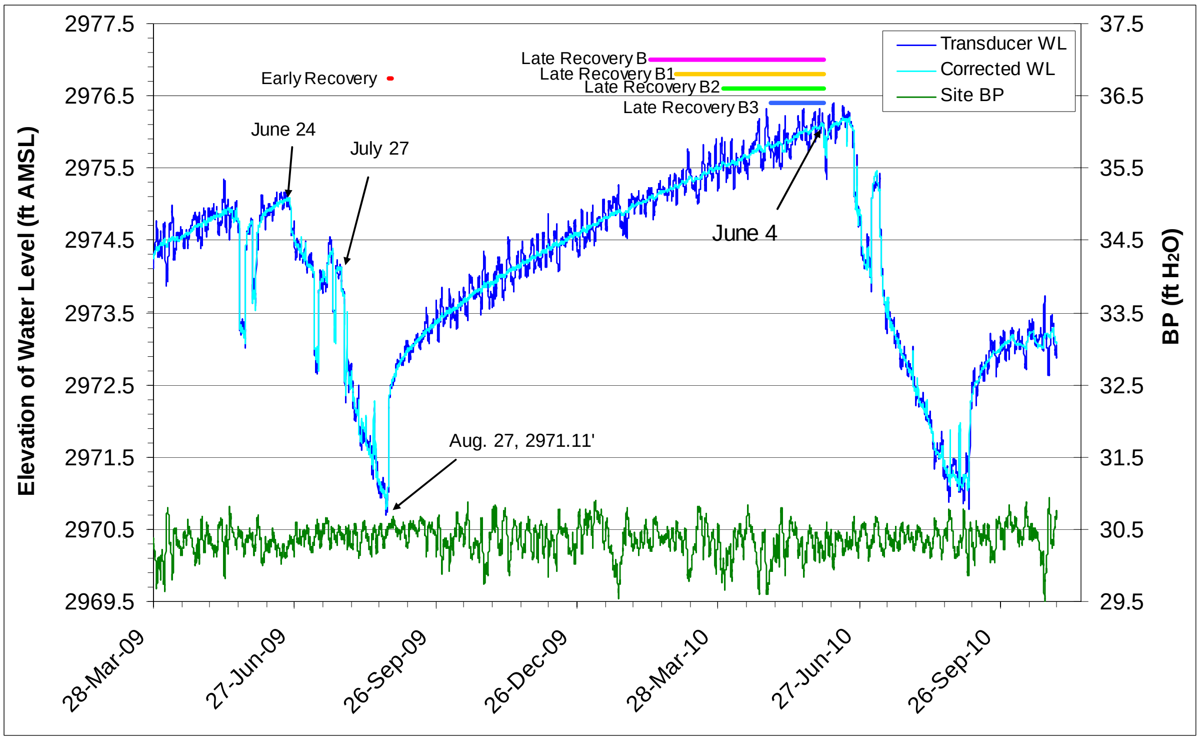


Figure 18: Hydrograph of the 2009 Thomas index well pumping season and the subsequent 2009-10 recovery. The graph displays barometric pressure (BP) readings (green line – reference values on the right y-axis), pressure transducer water-level readings (royal blue line – reference values on the left y-axis), corrected water-level measurements (bright blue – references values on the left y-axis), the period used for early-time (short red line) and late-time trend fits (pink, gold, bright green, and pale blue lines) in Figure 19 and Figure 20. The pink trend fit period encompasses the full length of the gold trend fit, which encompasses the full length of the bright green fit, which encompasses the full length of the pale blue fit.

Two scenarios were considered: one where the index well had been influenced only by a single pumped well for a standard pumping period of five days (Single Well, or SW), and the other where the index well had been influenced by pumping over the entire 63-day irrigation season (Season Pumping, or SP). This represents an upper limit, as consistent pumping did not start until July 27. For both scenarios, there is clearly a two-stage recovery. There is no single trend analysis (linear, log, power, exponential, polynomial) that describes the entire recovery curve without subdivision. This is the case even when the first two measurements (on the left in Figure 19) are ignored; these two measurements may indicate not all pumps in the area had turned off, or more likely, represent the early-time confined response typically observed in pumping tests in unconfined aquifers.

Since the recovery curves in the Horner Plots (Figure 19) appear to have two parts, trend-line analysis was applied to each part of the recovery. For the earlier, flatter part of the recovery, the SP and SW analyses indicated that recoveries from maximum drawdown were 1.91 ft. and 1.60 ft., respectively. For the later recovery, the trends indicated recoveries of 6.71 ft. and 5.55 ft., respectively.

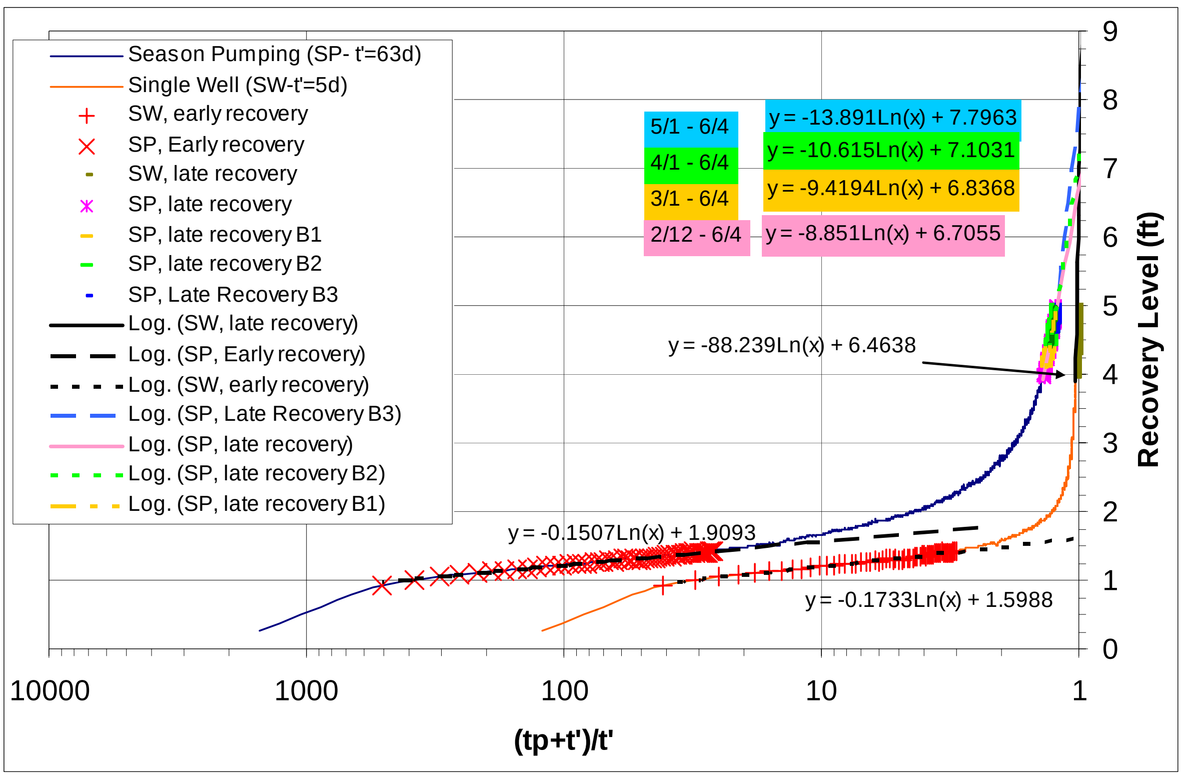


Figure 19: 2009-10 Thomas index well recovery estimation plot, displaying the differences between recovery estimates considering the full pumping season (SP, t_p=63d) and the average pumping time of a single well (SW, t_p=5d). Recovery estimates for early- and late-time periods are displayed for both the SP and SW calculations.

Table 11: Comparison of observed and predicted recovery estimations for the 2009-10 recovery of the Thomas index well.

Recovery Estimates	Initial WL (ft.)	Recovered WL (ft).	Indicated Recovery (ft.)
Annual Program	2971.11	2973.29	2.18
Max. Observed (transducer)	2971.11	2976.20	5.09
Whole Pumping Season (SP)			
Early time	2971.11	2973.02	1.91
Late time "B" (2/12-6/4)	2971.11	2977.82	6.71
Late time "B1" (3/1-6/4)	2971.11	2977.95	6.84 (↑ 0.13)
Late time "B2" (4/1-6/4)	2971.11	2978.21	7.10 (↑ 0.26)
Late time "B3" (5/1-6/4)	2971.11	2978.91	7.80 (↑ 0.70)
Single Well (SW)			
Early time	2971.11	2972.71	1.60
Late time	2971.11	2977.57	6.46

It is clear that the early-time trends do not represent full recovery. All late-time scenarios indicated recovered water levels higher than the highest observed water level (2976.20 ft.) and much higher than the early trend (2972.71 ft./2973.02 ft.) and annual program (2973.29 ft.) estimates. However, these late-time estimates are themselves lower limits on the probable recovered value. During trend analysis of the SP scenario, several late time periods were considered – one from February 12 to June 4, one from March 1 to June 4, one from April 1 to June 4, and a final one from May 1 to June 4. Each later time period provided increased estimates of the predicted recovered water level (Table 11 and red line in Figure 20). The increasing rate of recovery estimates considering later time periods indicates that late recoveries are still clearly trending upward even at the endpoint suggested by the original analysis. Based on the curves in Figure 18, it seems likely that full recovery could require a year or more.

Characterizing the recovery periods, amounts, and time constants is a first step toward understanding their causes. It seems likely that the two-stage recovery plots result from the unconfined nature of the aquifer in the vicinity of the Thomas index well. However, different portions of the aquifer will influence different portions of the recovery process so heterogeneity in aquifer conditions may also be playing a role. The late-time recovery pattern is most likely just the typical late-time recovery behavior observed in unconfined aquifers where specific yield is the appropriate storage parameter. However, the response could be interpreted to indicate that a recharge boundary has been reached at some distance from the index well.

In the case of the Thomas site, the second possibility cannot be ruled out. Water budget studies in 2005-2006 showed that the index well site is only 4-5 miles NE of an undeveloped aquifer fringe zone with higher water-table elevations and gradients, and with a flow direction generally trending NE (Figure 10, Appendix D). Several irrigation wells to the northeast of the index well have also been retired, with land use converted to dry-land farming, over the course of the project. Quantitative studies will be required to separate this mechanism from the typical unconfined aquifer response or lateral recharge from the stream channel to the north (which, although usually dry, serves as a water collector in wet years). There are data available to support at least preliminary modeling to test this lateral recharge hypothesis, and the Thomas expansion wells provide locations at which differences in the timing and rate of recovery can be used to develop inferences about the water source(s) driving the late recovery.

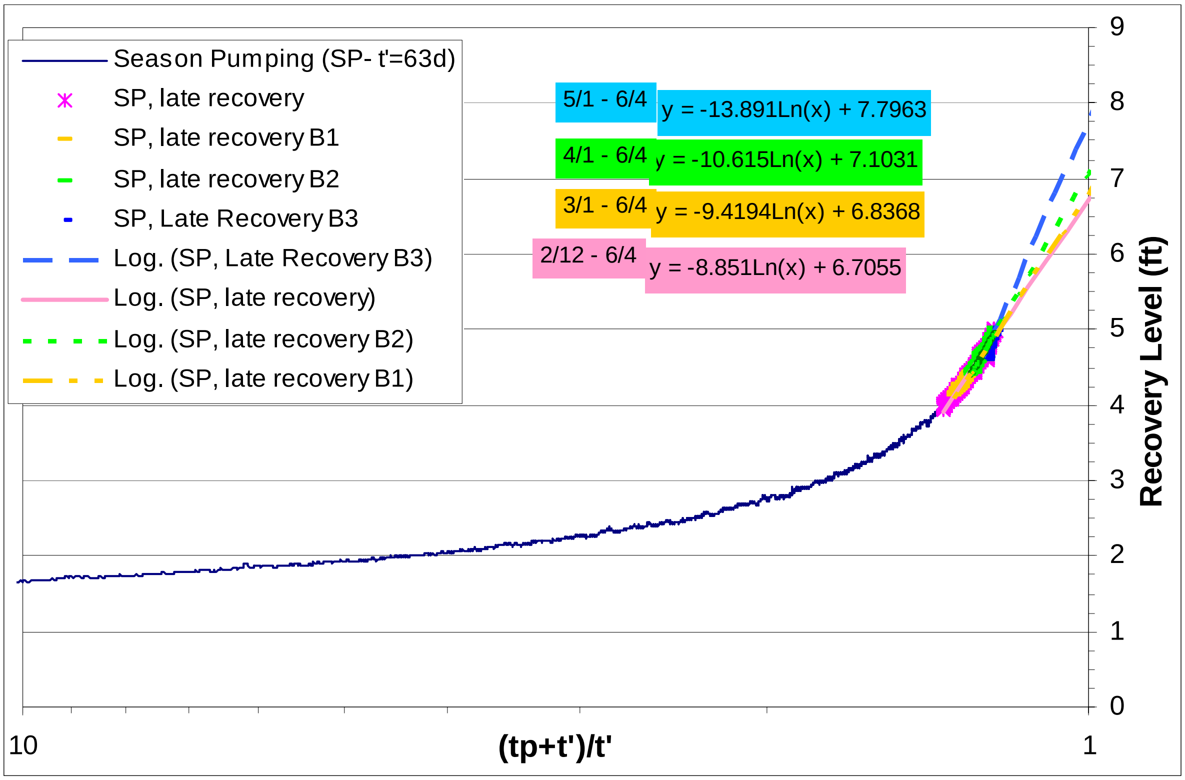


Figure 20: 2009-10 Thomas index well recovery estimation plot, displaying the differences between recovery estimates considering data from differing late time periods. The higher (t_p+t')/t'=1 intercept for later time period data indicates the slope of the late time data is still increasing.

Recovery estimates for the Thomas index well were prepared from each recovery period (Table 12). Pumping occurred during the 2007-08 and 2008-09 recovery, not as part of the main pumping season, but lasting for a clearly defined time-period. The recovery period after these pumping events did not last for sufficient time to observe the two-stage recovery. In 2007-08, recovery analysis of these late-period pumping events provided roughly similar water-level recovery estimates as from the late periods of the main recovery (considering only the single well pumping event for the main recovery season).

Table 12: Summary of recovered water-level estimates and observed values, Thomas index well. Graphs of each recovery period are available in Appendix B.

Recovery Year	Recovery Period	t_p (d)	$h_{t'=0}$ (ft)	Recovery (ft)	Recovered Elevation (ft AMSL)	Fit Period	Largest t' value (hrs)
2007-08	**Main (Start 9/8/07)**		**2970.53**	**5.01**	**2975.54**	**Observed**	**5933**
		60?		6.00	2976.53	1883-5933 hrs	
		5		5.71	2976.24	1883-5933 hrs	
	Period 2 (Start 5/21/08)	**2.83**	**2973.65**	**1.82**	**2975.47**	**Observed**	**476**
		2.83		2.58	2976.23	225-476 hrs	
		5		2.65	2976.30	225-476 hrs	
2008-09	**Main (Start 9/14/08)**		**2970.15**	**4.94**	**2975.09**	**Observed**	**4382**
		118		6.26	2976.41	2817-4382 hrs	
		5		5.72	2975.87	2817-4382 hrs	
	Period 1 (Start 3/23/09)	**7.54**	**2972.95**	**2.00**	**2974.95**	**Observed**	**1395**
		7.54		2.31	2975.26	659-1395 hrs	
	Period 3 (Start 6/2/09)	**2.67**	**2973.78**	**1.31**	**2975.09**	**Observed**	**532**
		2.67		1.43	2975.21	242-532 hrs	
2009-10	**Main (Start 8/27/09)**		**2971.11**	**5.09**	**2976.20**	**Observed**	**7163**
		63		6.71	2977.82	4077-7163 hrs	
		63		6.84	2977.95	4466-7163 hrs	
		63		7.10	2978.21	5209-7163 hrs	
		63		7.80	2978.91	5943-7163 hrs	
		5		6.46	2977.57	4077-7163 hrs	
2010-11	**Main (Start 9/6/10)**		**2971.08**	**2.22**	**2973.30**	**Observed* (Nov 2010)**	**1362* (Nov 2010)**
		77		2.73	2973.81	218-394 hrs	
		5		2.26	2973.34	159-683 hrs	

*2010-11 recovery is ongoing. As described in the text, early-time recovery estimates in Thomas County underestimate recovered water levels.

7.3. Summary: Recovery Water-level Estimation

The difference in recovery plots between index wells is primarily a function of the hydrogeologic setting: unconfined (water-table or phreatic) conditions versus confined conditions. The Scott and Thomas index wells are screened in unconfined aquifers, whereas the Haskell index well is screened in a confined aquifer. The hydrogeologic setting determination was based on a hydrostratgraphic analysis of the drillers' logs, consideration of water-level responses to pumping and the cessation of pumping, and an assessment of water-level responses to fluctuations in barometric pressure.

The numerous monitored wells in the vicinity of the Haskell site provide an opportunity to gain insight into the nature of the late-time change in recovery rate. Appendix A illustrates the range of responses observed at those wells during the 2007-08 recovery period. Although an assessment of the data in this and subsequent recovery periods is ongoing, some initial observations can be made. Using data from wells where there was a definable minimum water level at the end of the irrigation season and a complete recovery record, a change in recovery slope was observed ~1000 hrs into the recovery. Unlike at the Scott and Thomas index wells, however, the semi-log rate of recovery decreased in virtually all of the wells, as the recovery began trending towards a definable recovered water level. However, there are indications that exceptions to this behavior exist as the raw data from Haskell are corrected for barometric pressure response. Overall, the data indicate that the increasing rate of recovery observed in the Thomas and Scott index wells was not observed in the Haskell site wells at the same time since cessation of pumping. The exact significance of this observation has yet to be determined, but it most likely is a function of the large difference in storage parameters between confined and unconfined aquifers. However, the phenomenon might also be partly due to some additional source of water that must travel a greater distance to the well. The additional monitoring locations in Thomas County should provide more insight into these differences in recovery during the 2010-2011 recovery season. Regardless, the observations to date suggest that the two-stage recovery is associated with unconfined aquifers.

The two-stage recovery process observed in the Scott and Thomas index wells has a number of implications for interpretation and management. It helps to explain some of the variations noted in recovery estimations based on quadratic curve fits (Buddemeier et al., 2010), and it suggests that greater precision and confidence can be achieved when that late-time recovery slope is reached. At this time, although further refinement of the technique is necessary, the recovered water-level estimates gained from this procedure for the Thomas and Scott index wells should be considered a minimum value. Further analyses are required to assess how much these values underpredict the water level at full recovery. Despite the continued uncertainty in estimates of recovered water level at these sites, the monitored index well approach continues to provide substantial improvement over once-a-year water-level monitoring for enhanced management.

One additional question that has yet to be resolved is the influence of spatial variations in pumping on estimates of water level at full recovery. For example, will a well in a lightly pumped area surrounded by regions of greater annual drawdown likely yield a greater full recovery water level than nearby wells that are in more heavily pumped areas? Theory predicts that variations in pumping will not influence the fully recovered water level if the drawdown cones interact during the pumping period. However, the issue becomes more complicated if the drawdown cones do not interact. Answering such questions is vital to understanding the effectiveness of management strategies and resource sustainability on the sub-unit scale, and will become possible as more data from the expanded Thomas County study area are obtained (Section 6). The zone of influence (area within which drawdown is >0.1 ft.) of a 1000 gpm well in a medium- or high-transmissivity aquifer has been estimated as about 1.5 miles (Buddemeier et al., 2002, p. 21 Fig. 6), and the Thomas index well has 12-15 pumping wells within that approximate radius. Thus, it is doubtful if spatial variations in pumping will greatly influence estimates of fully recovered water level in the vicinity of the Thomas County study area.

8. Well Hydrographs and Use of Wells of Opportunity

As described in past reports (Young et al., 2008, Buddemeier et al., 2010), geology is an important consideration when interpreting and comparing water-level measurements. Variations in the thickness and distribution of geologic strata affect both the water level and the response to barometric pressure changes. Spurred on by the findings described in Section 7, efforts this year have focused on identifying and understanding how geology and well construction affect hydrographs in specific wells. Here, the additional water-level data collected in active and retired irrigation wells, observation wells, and domestic wells in Haskell and Thomas counties are examined to identify important characteristics of well hydrographs. The goal of this examination is to improve understanding of the areal extent over which findings from an index well are applicable, and to identify ideal characteristics for wells of opportunity for verifying index well data.

A number of different well responses were observed in both Haskell and Thomas counties. In some wells, water levels only recover a few feet after reaching their minimum water level (after a small maximum decline in water level during the irrigation season). In other Haskell County wells, however, water levels recover upwards of 130 ft. from their minimum levels. A number of Haskell DWR wells exhibit long, slow water-level decline, with minimal or no recovery. Finally, hydrographs from a separate group of pumping wells indicate a low efficiency or low transmissivity in the immediate vicinity of the well. These various categories are discussed further below.

Small water-level declines and subsequent recoveries (<10 ft.) are typically observed in wells located at some distance from pumping wells in unconfined aquifers. These will be the most common type of hydrograph from index wells located in the High Plains aquifer, and will also include other monitoring and retired irrigation wells. Examples include the Thomas and Scott index wells (Figure 5 and Figure 7), wells TH 7, 9, and 10 (Figure 9 and Figure 11), and wells HS 5, 6, 8, 12, and 28 (see Appendix A.4 in Buddemeier et al., 2010 for Haskell County well hydrographs and BRFs).

Significant water-level declines may be observed in inactive or active wells screened in confined aquifers, or in unconfined aquifers where the well is located near the pumping well (or is the pumping well, particularly in areas of low transmissivity or in cases of low well efficiency; the latter cases will be discussed further below). In the Haskell area, there are several examples of the former case, including the index well (Figure 3) and HS 1, 2, 18 (see Appendix A.4 in Buddemeier et al., 2010, for Haskell County well hydrographs and BRFs). TH3 in Thomas County (Figure 9) is an example of the latter case. In the absence of a well log, the difference in hydrogeologic setting between these cases can often be identified with the barometric response function (see Section 3.3 in Buddemeier et al., 2010 for a further discussion of barometric responses typical for confined and unconfined settings).

The group of wells with long, slow declines and minimal recovery consists entirely of retired irrigation wells found in Haskell County (HS 3, 10, 13, 14, 15, 17, 30; hydrographs are available in Appendix A.4 in Buddemeier et al., 2010). The BRFs for these wells indicate they are all screened in the unconfined portion of the aquifer – which is expected for retired irrigation wells in Haskell County. Water levels in these wells begin a long, slow decline over the course of the irrigation season. Nearly half of the wells decline beyond the end of the irrigation season into October or even early December, with little to no subsequent recovery. In all wells, declines were equal to ~5 ft. in 2007 and 3-4 ft. in 2008. The cessation of water-level declines roughly coincides with the late-time (1000-2000 hrs after minimum water level) reduction in the rate of water-level recovery in the Haskell index well. The similarity of water-level declines recorded in wells located within 2.5 linear miles of each other is promising. It is not clear at this time why water levels in these retired irrigation wells respond in such a delayed fashion. Although the screen location of these wells is in the unconfined aquifer whereas the index well is screened in the confined aquifer, a similar water-level decline is indicated by both the retired irrigation wells and the index well. This agreement is most probably due to water transmission through the clay layer separating the two aquifers at the Haskell site. Despite the unknowns regarding the water-level response, these hydrograph records still appear useful for determining recovered water levels.

Finally, hydrographs from several of the active irrigation wells indicated they could be operating at a low efficiency (e.g., HS 9, 11, 20, 21, 29, and 30; hydrographs are available in Appendix A.4 in Buddemeier et al., 2010). Hydrographs from these wells are characterized by water-level drops of >20 ft. immediately after pumping is initiated at the well, followed by an immediate rise in water level of nearly the same magnitude, although typically slightly less, once pumping ceases. Over the recovery season, water levels further rise another 1-2 ft.. Previous KGS work (Butler, 1988) has established that well inefficiency will not influence late-time responses, so these wells should still provide useful measures of water-level recovery for a sub-unit area.

9. Temporal and Regional Trends: Water Levels and Water Use

Quantifying the relationship between water use and recovered water levels at the three index well sites is an important part of this study. At this time, data are insufficient to draw conclusions with any statistical confidence, but it is worth noting that water use and recovered water levels are following expected trends and early indications suggest they are correlated (Table 13). At the Scott and Haskell sites, water levels decreased during both the 2008-09 and 2009-10 recoveries compared to the previous year. However, in both cases, the decline was less in 2009-10 than in the previous year, and was correlated with a reduction in water use in 2009 compared with 2008. In this limited dataset, water use appears to have had a direct impact on the recovered water levels – both observed and predicted. The magnitude of water-level change related to a change in water use will vary from site to site, based on local conditions including geology. At the Thomas site, water use within a 2-mile radius of the index well was ~900 ac-ft lower in 2009 than in 2007 or 2008. This resulted in an increase in both the observed and predicted recovered water levels. Although the increase could be a product of a longer recovery period (observed) or an inappropriate extrapolation to full recovery (predicted), it also could be providing important information about the behavior of the High Plains aquifer in the vicinity of the Thomas site. For example, if all the extracted water was being "mined" from the aquifer in the vicinity of the Thomas site, water-level declines, albeit smaller, should still have been observed. As water-level recovery estimates improve, and additional data become available, the relationship between water use and recovered water levels should provide a valuable resource for management on the subunit aquifer scale.

Table 13: Water use and recovered water levels at the three index well sites.

		Water Use[a] ac-ft	**Δ WU** ac-ft	**H_{max}**[b] **observed** ft AMSL	**Δ WL** ft	**H_{max}**[b] **predicted** ft AMSL	**Δ WL** ft
Thomas County	2007 (07-08 Recovery)	2868.87	-747.01	2975.54	NA	2976.53	NA
	2008 (08-09 Recovery)	2825.21	-43.66	2975.09	-0.45	2976.41	-0.12
	2009 (09-10 Recovery	1917.17	-908.04	2976.20	+1.11	2978.91	+2.50
Scott County	2007 (07-08 Recovery)	3095.78	-564.12	2835.9	NA	2836.26	NA
	2008 (08-09 Recovery)	4014.33	+918.55	2834.7	-1.2	2835.04	-1.22
	2009 (09-10 Recovery	2955.48	-1058.85	2834.2	-0.5	2834.61	-0.43
Haskell County	2007 (07-08 Recovery)	8764.01	-540.01	2586.1	NA	2587.03	NA
	2008 (08-09 Recovery)	9931.71	+1167.7	2581.1	-5.0	2581.64	-5.39
	2009 (09-10 Recovery	8720.45	-1211.26	2577.2	-3.9	2576.71	-4.93

[a] – within a 2-mile radius of the well.
[b] – H_{max} = maximum recovered water level; for predicted, using pumping season for t_p.

Determining the area represented by the recovered water-level estimates is also important to the success of the index well approach to aquifer subunit management. The area that water-level change in an index well represents is considered dependent on local conditions, including geology and spatial water use patterns. As the water table or piezometric surface elevation can vary considerably across a small area (as at the Thomas site, see Figure 10 and Figure 9), the recovered elevation is not as important for determining the representative area for any given index well as is the year-to-year *change* in recovered elevation.

The Haskell site, with multi-year hydrographs available from 20 wells near the index well (see Appendix A.4, Buddemeier et al., 2010, for details of each well) currently provides the only opportunity to investigate the representative area of the index well. In the Haskell area, the analysis is complicated by the subsurface geology, with wells screened in an unconfined or confined aquifer, or across both. The approach in this case is to compare changes in water level in wells with similar barometric response functions, indicating they are screened in similar aquifer units. The results of the recovery analysis for the Haskell wells are shown in Table 14, with a statistical summary provided in Table 15. None of the hydrographs in the Haskell area have been corrected for barometric lag, and a large amount of noise was evident in many of the hydrographs. Both of these issues disproportionately affect recovery estimations for wells screened in the unconfined aquifer. As such, there is an uncorrected error present in the calculations. Furthermore, many of the wells were not designed as monitoring wells, and are screened across large portions of the aquifer. In these wells, water levels represent an integrated value across the aquifer, and may not represent the true water table or the piezometric surface for the confined aquifer. The average year-to-year changes in water level for wells screened in the confined aquifer (Table 14 and Table 15) are within one standard deviation of the 4.5 ft. yearly change in estimated recovered water level at the index well. This agreement indicates that the index well provides a good indicator of water-level change in the confined portion of the aquifer in the Haskell area. If an index well were installed in the unconfined aquifer in the Haskell area, the analysis indicates that it would also provide a good indicator of water-level change over the area in question. Over the next year, the recovered water-level data will be refined as the hydrographs in the Haskell area are corrected for barometric lag. Complimentary data are also available from Rawlins and Stevens counties (Section 10.1), and with the addition of the Thomas county expansion wells (Section 6), additional insight into area of response similarity will be available in the next year.

Table 14: Water use and provisional recovered water levels in wells near the Haskell County index well.

HS	Type	Aquifer	Year	2 mi. Water Use	Δ WU	Hmax (Horner)	Δ WL year/year	Δ WL (07-08 to 09-10)
				ac-ft	ac-ft	ft. AMSL	ft.	ft.
1	Irrigation	Conf.	07-08	8756.78	-617.25	2591.32		
			08-09	8406.61	-350.17	2584.61	-6.71	
			09-10	8519.90	+113.29			
2	Irrigation	Conf.	07-08	8723.78	-529.25	2589.67		
			08-09	8433.89	-289.89	2585.98	-3.69	
			09-10	8901.90	+468.01	2583.24	-2.74	-6.43
4	Monitoring	Conf.	07-08	9081.78	-685.26	n.d.		
			08-09	8762.89	-318.89	2582.47		
			09-10	9243.90	+481.01	2580.66	-1.81	
18	Irrigation	Conf.	07-08	6998.14	-1364.28	2593.09		
			08-09	7264.19	+266.05	2586.73	-6.36	
			09-10	7139.45	-124.74	2583.13	-3.60	-9.96
Index	Monitoring	Conf.	07-08	8764.01	-540.01	2587.03		
			08-09	9931.71	+1167.70	2581.64	-5.39	
			09-10	8720.45	-1211.26	2576.71	-4.93	-10.32
3	Irrigation (ret)	Unconf.	07-08	8443.78	-479.25	2590.85		
			08-09	8147.61	-296.17	2587.14	-3.71	
			09-10	8768.90	+621.29	2583.13	-4.00	-7.71
5	Monitoring	Unconf.	07-08	7145.86	-1028.36	2592.87		
			08-09	7284.20	+138.34	2589.01	-3.86	

HS	Type	Aquifer	Year	2 mi. Water Use ac-ft	Δ WU ac-ft	Hmax (Horner) ft. AMSL	Δ WL year/year ft.	Δ WL (07-08 to 09-10) ft.
			09-10	7515.29	+231.09	2584.19	-4.83	-8.68
6	Monitoring	Unconf.	07-08	8397.86	-191.05	2589.39		
			08-09	8179.64	-218.22	2584.86	-4.53	
			09-10	8390.36	+210.72	2580.54	-4.32	-8.85
7	Irrigation	?Unconf.	07-08	7378.93	-1222.16	2593.96		
			08-09	7313.22	-65.71	2587.64	-6.32	
			09-10	7444.74	+131.52	2584.07	-3.57	-9.89
8	Monitoring	Unconf.	07-08	7126.21	-1095.67	2597.22		
			08-09	7483.61	-39.46	2592.93	-4.29	
			09-10	7444.15	+357.40	2589.38	-3.56	-7.84
9	Irrigation	Unconf.	07-08	10468.46	-1543.93	2591.13		
			08-09	10793.43	+324.97	2587.54	-3.59	
			09-10	11118.67	+325.24	2583.59	-3.95	-7.54
10	Irrigation (ret)	Unconf.	07-08	8090.95	-1048.69	2595.20		
			08-09	7922.55	-168.4	2591.01	-4.19	
			09-10	8651.65	+729.1	2587.10	-3.91	-8.10
11	Irrigation	Unconf.	07-08	8104.91	-1259.96	2596.46		
			08-09	7946.61	-158.30	2592.30	-4.16	
			09-10	8528.99	+582.38	2588.53	-3.77	-7.93
12	Irrigation (ret)	Unconf.	07-08	7380.58	-995.51	2593.02		
			08-09	7319.37	-61.21	2589.15	-3.87	
			09-10	7437.88	+118.51	2585.90	-3.25	-7.12
13	Irrigation (ret)	?Unconf.	07-08	6374.29	-873.66	2593.25		
			08-09	6431.40	+57.11	2590.80	-2.45	
			09-10	6511.7	+80.3	2585.00	-5.80	-8.25
14	Irrigation (ret)	Unconf.	07-08	8287.79	-207.96	2589.75		
			08-09	7822.50	-465.29	2586.10	-3.65	
			09-10	8070.03	+247.53	2585.00	-1.10	-4.75
15	Irrigation (ret)	Unconf.	07-08	7335.78	-692.26	2592.03		
			08-09	7374.89	+39.11	NA		
			09-10	7499.90	+125.01	2583.31		-8.72
20	Irrigation	Unconf.	07-08	6816.20	-1168.67	2597.08		
			08-09	7163.61	+347.41	2592.30	-4.78	
			09-10	7174.15	+10.54	2588.71	-3.60	-8.38
21	Irrigation	Unconf.	07-08	6423.20	-1134.67	2597.56		
			08-09	6772.61	349.41	2592.91	-4.65	
			09-10	6591.15	-181.46	2589.14	-3.77	-8.42
29	Irrigation	Unconf.	07-08	9631.73	-855.84	NA		
			08-09	9624.37	-7.36	2583.28		
			09-10	10095.69	+471.32	2576.79	-6.49	
31	Irrigation	Unconf.	07-08	8130.44	-877.98	2597.35		
			08-09	7821.54	-308.90	2593.41	-3.94	
			09-10	8072.52	+250.98	2589.86	-3.55	-7.49

Table 15: Statistical summary of water use and recovered water level from Table 14 for wells in the vicinity of the Haskell index well.

Aquifer	Year	**Δ WU**	**s.d.**	**Δ WL (Horner)**	s.d.
Confined Aquifer	07-08	-716.01	364.26		
	08-09	99.85	647.65	-5.54	1.35
	09-10			-3.27	1.32
Unconfined Aquifer	07-08	-903.43	401.55		
	08-09	-24.67	289.57	-4.14	0.85
	09-10			-3.96	1.20

10. Spin-offs and Related Research

As the Index Well Project progressed through the fourth year, several complementary efforts developed to further the work of the project.

10.1. Rawlins and Stevens Counties

KDA-DWR has supplied the KGS with several years of water-level data recorded by pressure transducers at sites in Rawlins and Stevens counties. These data are being processed and analyzed with the techniques developed in the course of this project. This will allow the KGS to further test the usefulness of wells of opportunity, explore aquifer similarities and differences at additional locations, and enhance confidence in the techniques developed to date.

10.1.1. Rawlins County

The KDA-DWR site in Rawlins County consists of three wells in section 25 of 3S 36W. The well designated 23289 is an active irrigation well (depth 253 ft.) in the NW quarter of the section, obs23289 is an observation well (depth = 250 ft.) in the SW quarter, and obs28290 is an observation well (depth = 252 ft.) in the NE quarter (http://abyss.kgs.ku.edu/pls/abyss/wwc5). The observation wells are each several hundred yards away from 23289, and obs28290 is close to another irrigation well (28290). The two observation wells are nearly a mile apart.

Hydrographs displaying the available records for all three wells are shown in Figure 21. Other than the expected differences in drawdown between the pumping and observation wells, the hydrographs are very similar in overall form.

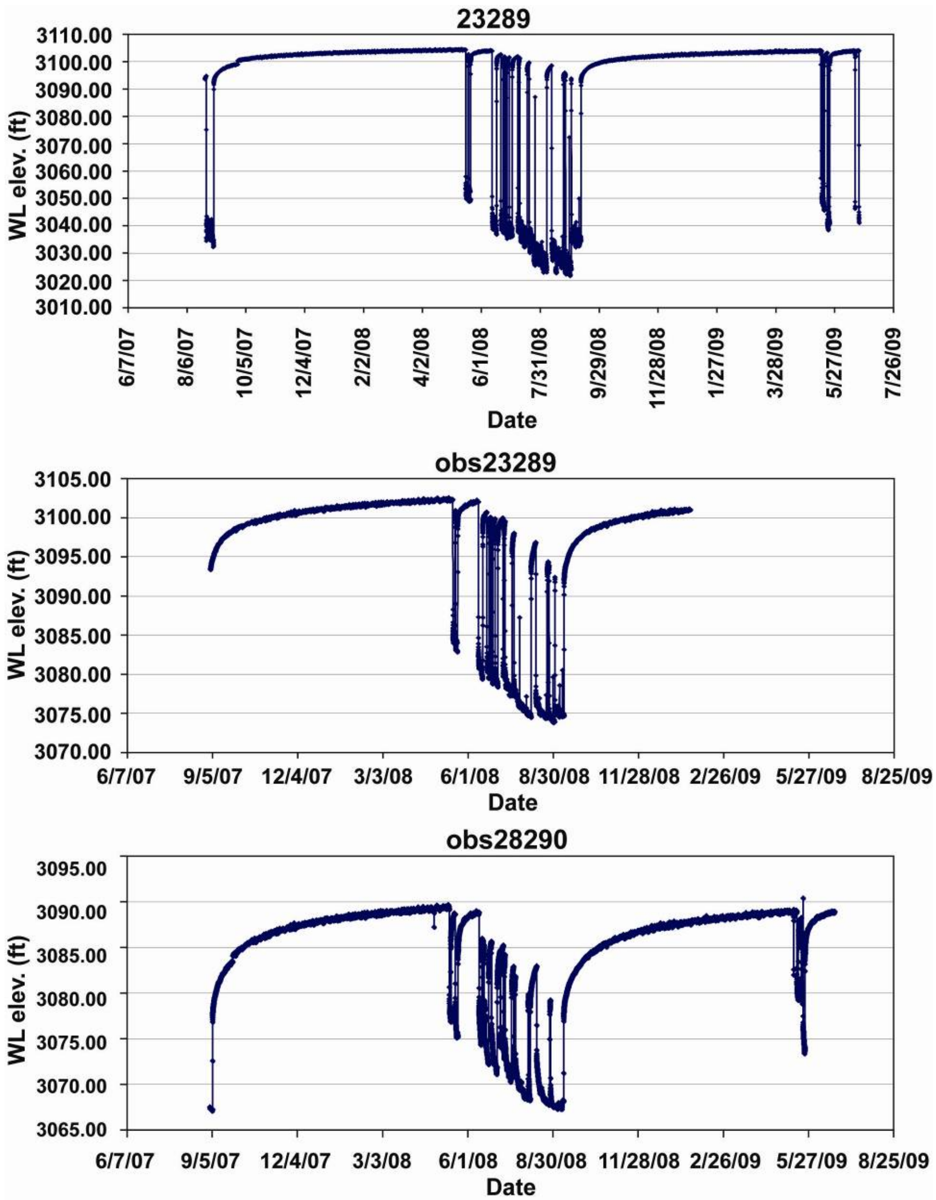
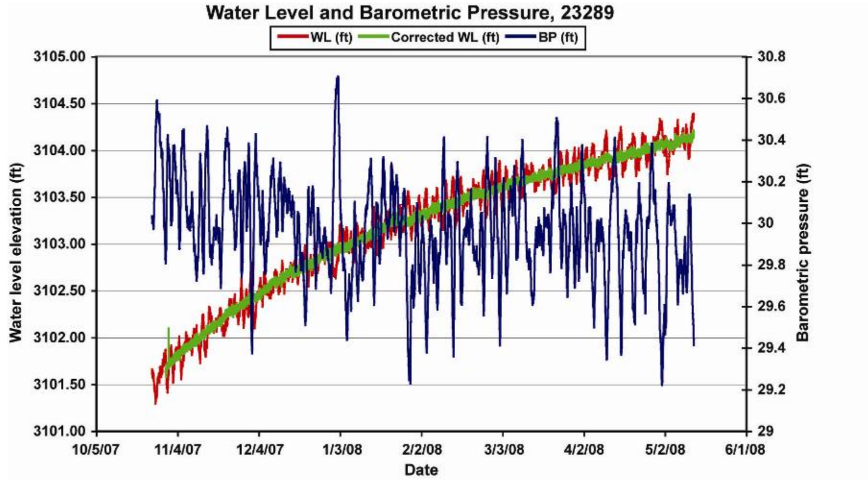
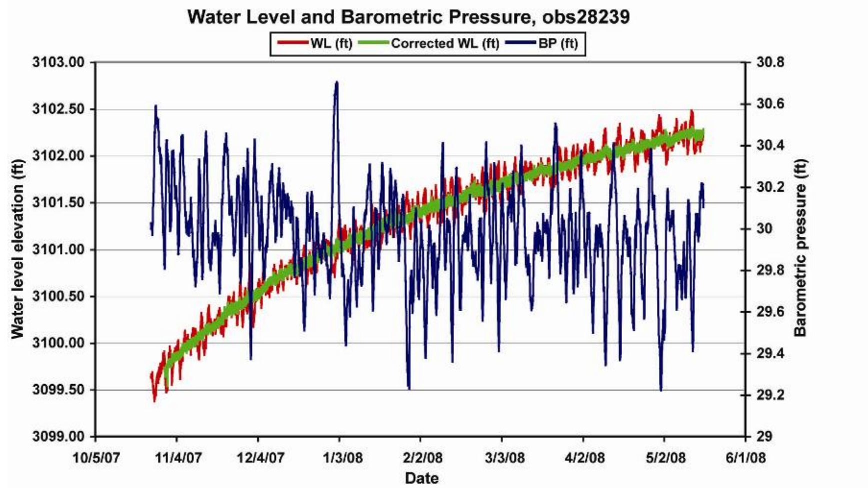


Figure 21: Hydrographs of wells 23289, obs23289, and obs28290 in sec. 25, T. 3 S., R. 36 W., Rawlins Co.

Water levels in all three wells were still rising when pumping resumed in May of 2008 and 2009, and it appears that the fully recovered water levels would be a significant fraction of a foot lower in 2009 than in 2008. The records have not yet been analyzed for the two-stage recovery.

The 2007-2008 recovery period in all three wells was analyzed using the barometric response correction spreadsheet tool. Figure 22 - Figure 23 compare the water-level correction plots and the BRF plots for the same period in each of the wells.





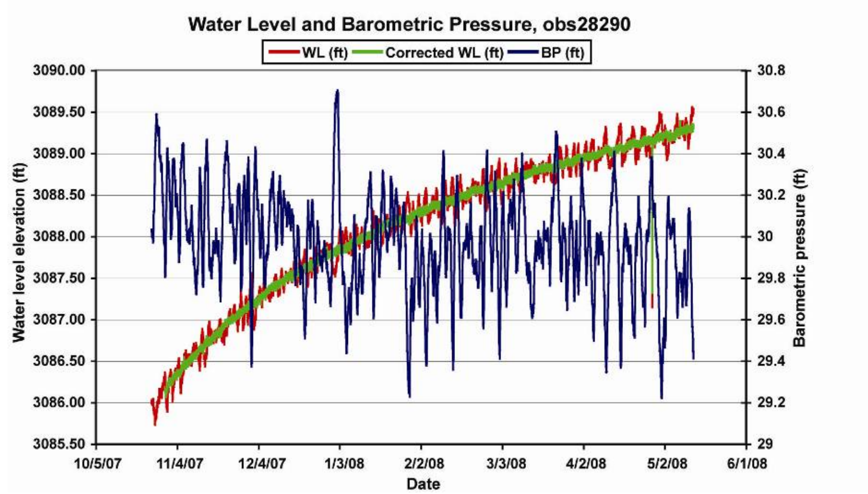


Figure 22: Measured water levels, barometric pressures, and corrected water levels for wells 23289, obs23289, and obs28290 in sec. 10, T. 3 S., R 36 W., Rawlins Co.

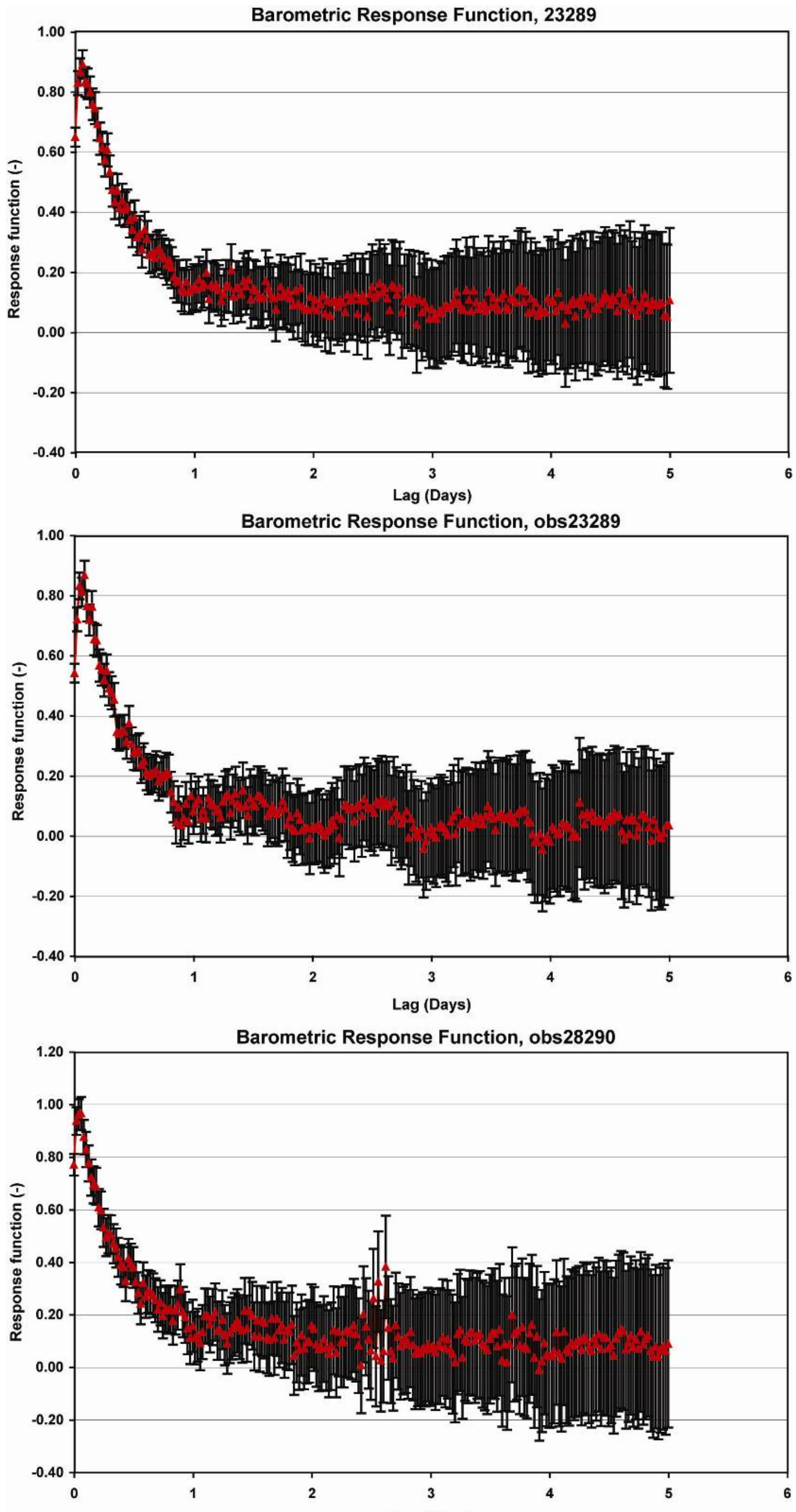


Figure 23: Barometric response functions for wells 23289, obs23289, and obs28290, in sec. 10, T. 3 S., R 36 W., Rawlins Co.

The three water-level recovery curves, both corrected and uncorrected, are very similar, as are the three barometric response functions. Additionally, the 07-08 and 08-09 recovery periods in the well 23289 hydrograph were compared; as expected, the BRF plots from those two periods were essentially identical. In all cases, the BRF plots indicate that the Rawlins Co. wells are screened in an unconfined aquifer overlain by a thick vadose zone.

These results indicate that the aquifer characteristics vary only to a very minor degree over the section-level range of this study, and show that for this location and scale, the index well concept is very well supported. Even more significantly, the results are very similar to those observed at the Thomas index well, approximately 30 miles to the south. This provides reason to be hopeful that index wells in the northern (GMD4) section of the HPA would be representative of conditions over relatively large geographic areas.

10.1.2. Stevens County

Data from the Stevens County site consist of records from six different wells, located in secs. 4,5,6, 8, and 9, T. 35 S. R. 36 W. Portions of the available hydrographs for these wells are shown in Figure 24. The difference between maximum and minimum water levels in all wells was more than 150 ft. and the difference was greater than 200 ft. in three of the wells. These differences are even larger than those observed in the confined aquifer at the Haskell County site (Figure 3), which strongly suggests that the Stevens County wells are also screened in a confined or semi-confined aquifer.

A preliminary check of the barometric response functions has been made, and all appear to be similar to those from the Haskell Coounty index well (Buddemeier et al., 2010, Figure 3-5). This also supports the confined aquifer interpretation, but additional analysis of the barometric response functions is needed.

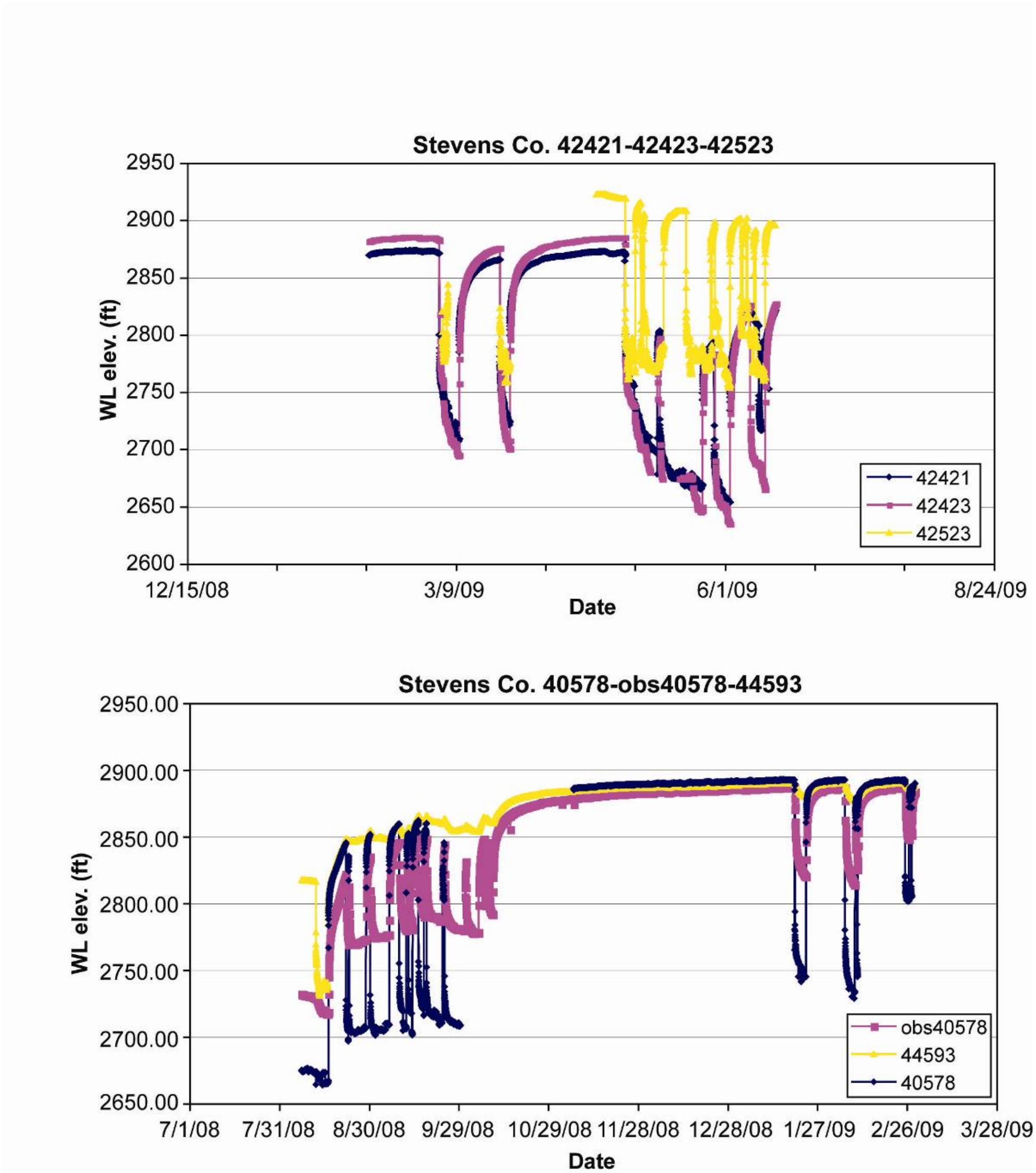


Figure 24: Hydrographs for wells 42421, 42423, 42453, 40578, obs40578, and 44593 in Stevens County. Note that the two graphs do not cover the same time period; the upper plots begin shortly before the lower ones end.

10.2. 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 will be the focus of this investigation. At least one of the boreholes drilled during this study will be located adjacent to the Haskell County index well. If possible, as part of this complementary project, a second monitoring well will be completed at the Haskell site just above the clay confining unit. This would enable a more controlled comparison with the index well data and the development of a better understanding of recovery responses in the unconfined aquifer at the Haskell site.

10.3. Department of Energy Grant – NMR Investigations of Index Wells

In the fall of 2010, the KGS was awarded the first phase ($21K) of a grant subcontract from the Department of Energy to work together with Vista Clara, a company located near Seattle, Washington, and Stanford University on assessing the potential of nuclear magnetic resonance (NMR) technology for estimation of water-filled porosity and permeability using small-diameter (2-5" ID) wells. Although still in the development and testing stages, the new NMR tool was applied to the Thomas and Haskell index wells in the late fall of 2010 to develop a better understanding of the hydrostratigraphy at each site. The Scott site was not selected due to concerns about electrical interferences from the nearby radio tower. Data from these tests are still preliminary and are currently being analyzed.

11. Summary and Conclusions

We now have collected hourly water-level data from each of the three index wells for four years; data are available publicly online via satellite telemetry. Additional water-level data have been collected from nearby wells in Haskell and Thomas counties, and from two additional groups of wells in Rawlins and Stevens counties. This large body of water-level data has increased our confidence in water-level results from the index wells and has provided the opportunity to demonstrate the utility of an index well for improving estimates of water-level change in an aquifer sub-unit area.

Through this dataset, it has become clear that, for a variety of reasons, measurements collected during the annual program do not provide full recovery estimates. In fact, water levels in most of the wells do not recover prior to the start of the following pumping season. Thus, a major focus of the project has been on the development of methods to estimate the elevation to which water levels would recover in the absence of further pumping. This year, rigorous approaches for extrapolation of water levels to full recovery were developed further. These techniques have already increased understanding of recovery characteristics, providing information critical to the accurate determination of changes in water in storage, and therefore to the evaluation of the effectiveness of any enhanced management procedures. The two-stage recovery process identified in the Scott and Thomas index wells potentially has a number of implications for interpretation and management.

The data from all of the wells show that water-level measurements are affected by changes in barometric pressure, thus simply monitoring water levels was not sufficient to accurately determine recovered water levels. At sites similar to the Thomas County index well, changes in barometric pressure alone can produce changes in water level exceeding a foot. Thus, a major focus of the project has been on the development of methods to remove the impact of barometric pressure changes from the water-level data (i.e. “correct” the water-level data). A spreadsheet was developed (Appendix C) for that purpose. A manuscript was completed in 2010 and will be published in 2011 on complementary work at the KGS Larned Research Site (Appendix E). This complementary work has been extremely valuable for the interpretation of index well responses to fluctuations in barometric pressure.

A key question concerns the areal reach of an index well, i.e. how broadly, in a geographic sense, can the findings from an index well be applied. In order to address that question, water-level data from additional wells in Haskell, Rawlins, and Stevens counties were made available by KDA-DWR, and additional wells of opportunity were instrumented in Thomas County. The data from Haskell County demonstrate the index well is representative of local conditions and have enhanced our overall understanding of the subsurface in that area. Similarities of responses in Thomas and Rawlins counties and Haskell and Stevens counties point to the encouraging potential for index well application at other sites with either confined or unconfined aquifers. These observations indicate that future index well installations can be calibrated for their areal reach by acquiring relatively short-term additional pressure transducer data from nearby wells of opportunity (at least five additional wells for one to two recovery seasons).

In the fifth year of this project, we will primarily focus on the following five activities:

1) Complete processing of all the water-level data from the three index wells, the Haskell and Thomas expansion wells, and the additional wells in Rawlins and Stevens counties;
2) Finalize the approaches for extrapolation of water levels to full recovery;
3) Further our understanding of the relationship between changes in the estimated water level at full recovery and water use at the index wells and auxiliary sites;
4) Provide more definitive calibration of the areal reach of each index well; and
5) Develop procedures for incorporating uncertainty produced by barometric pressure into annual water-level survey measurements.

In the report of the fifth year of the project, we will summarize the major findings of the project to date and suggest avenues for expanding the index well approach to elsewhere in the High Plains aquifer and for incorporating the approach directly into practical management and assessment activities.

12. References

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Appendix A: Haskell County Recovery Plots

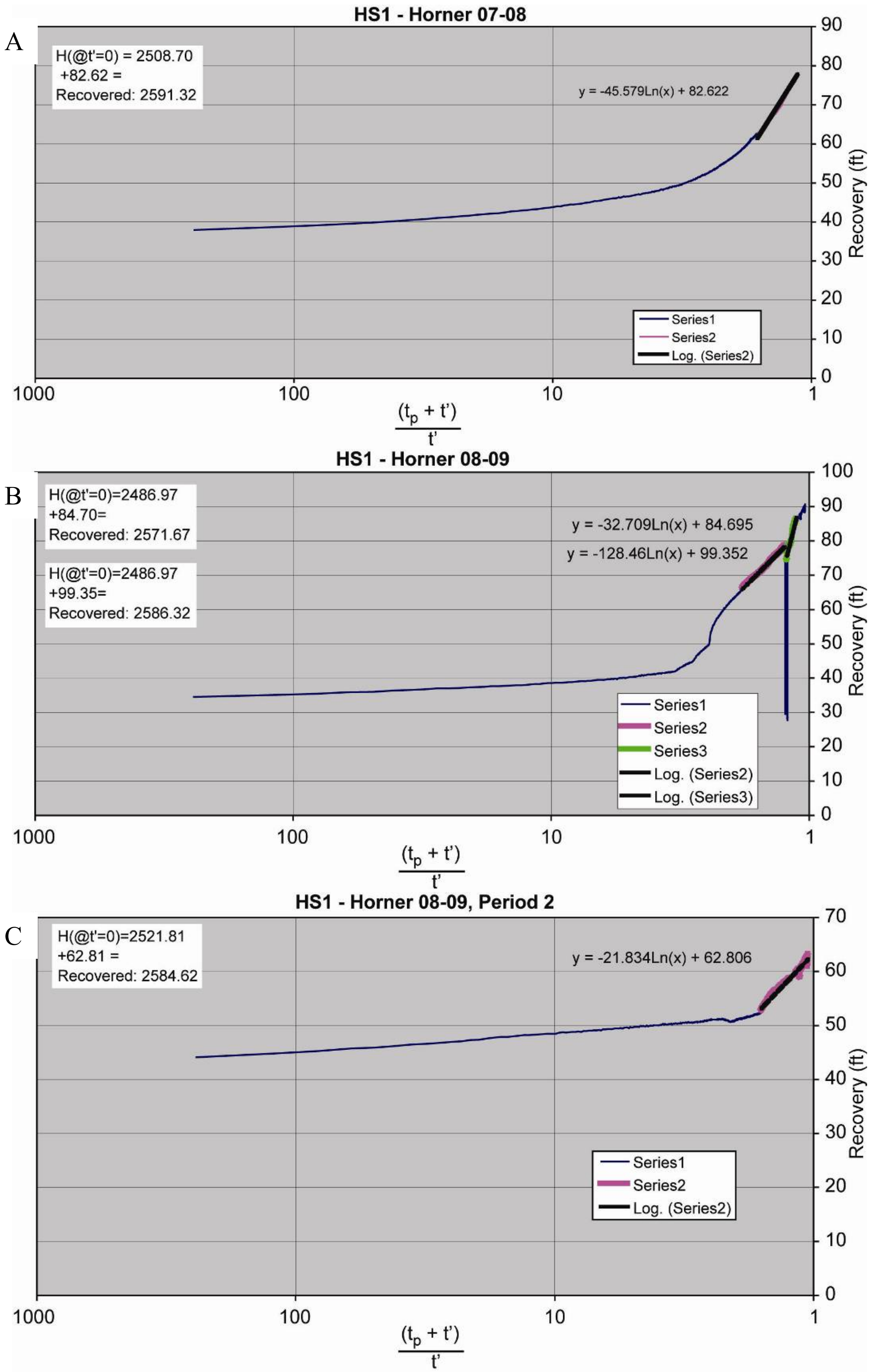
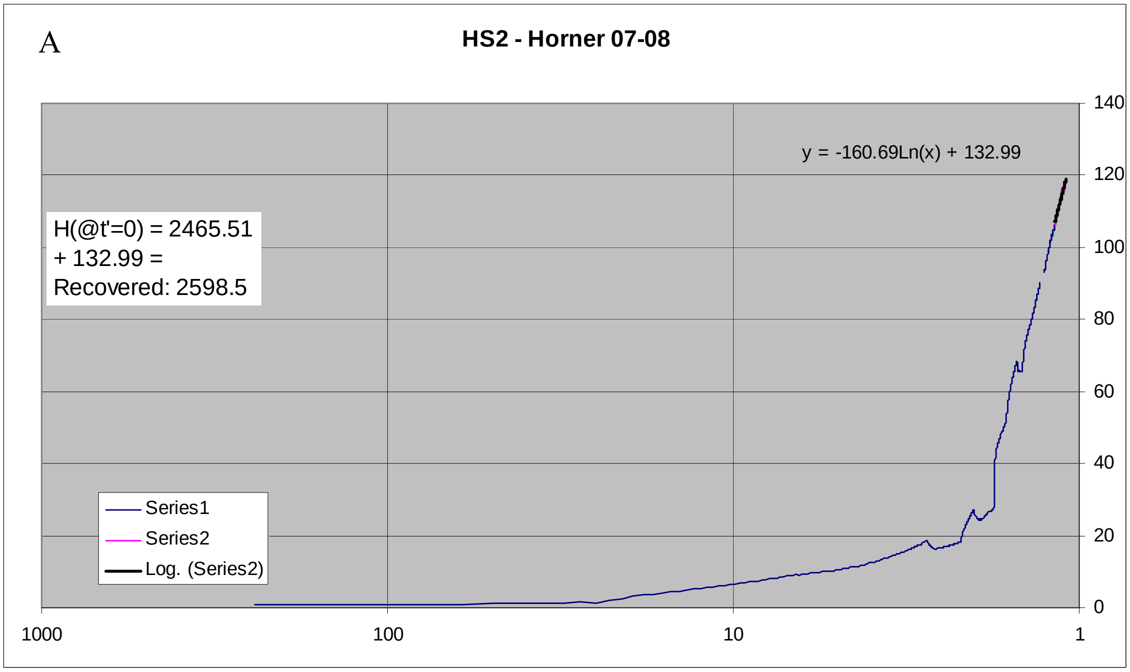


Figure A - 1: Horner recovery estimation HS1, (a) 2007-08; and 2008-09: (b) entire recovery period, (c) only the recovery after the final pumping event.



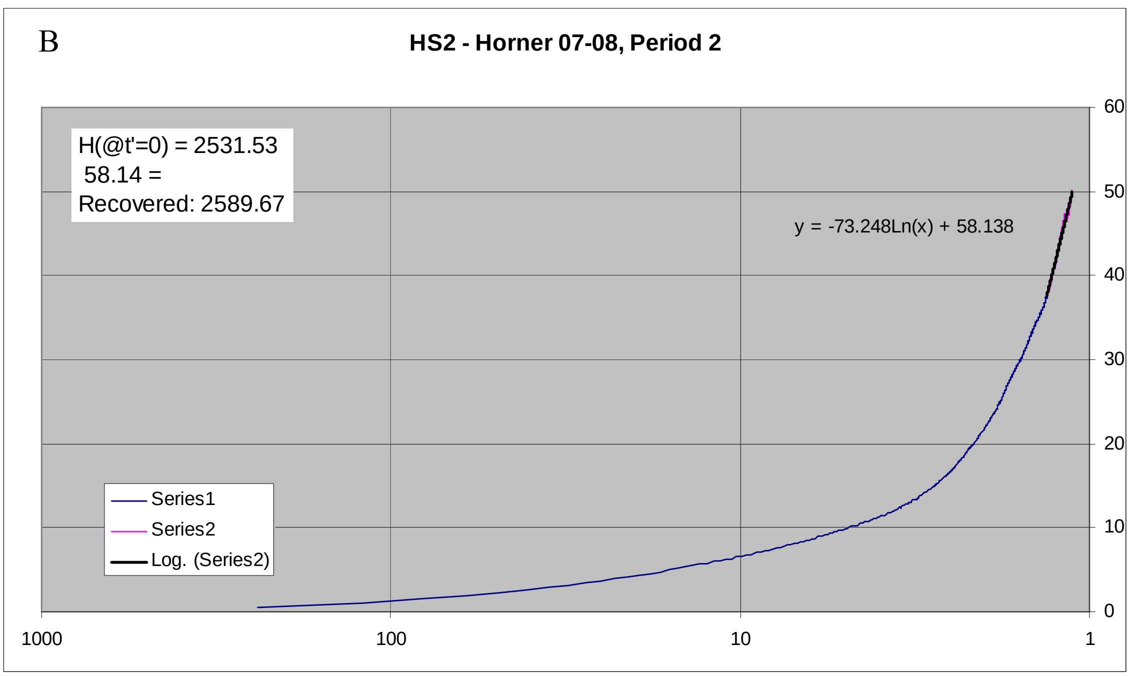
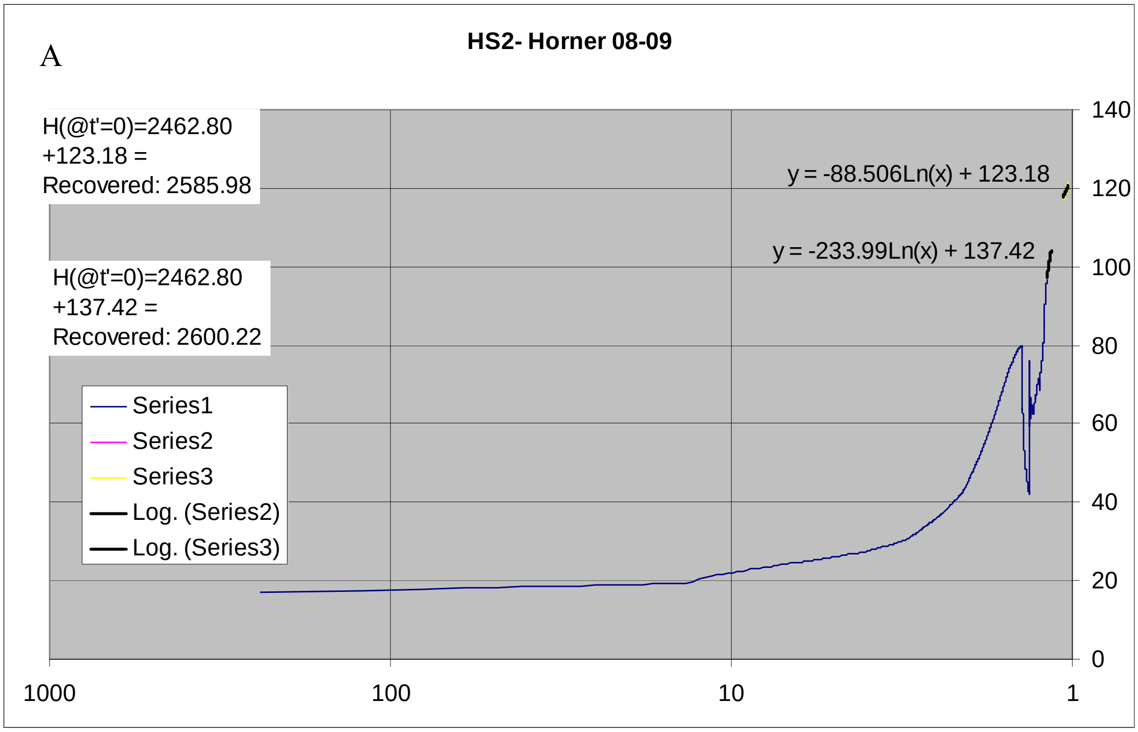


Figure A - 2: Horner recovery estimation HS2, 2007-08; (A) entire recovery period, (B) only the recovery after the final pumping event.



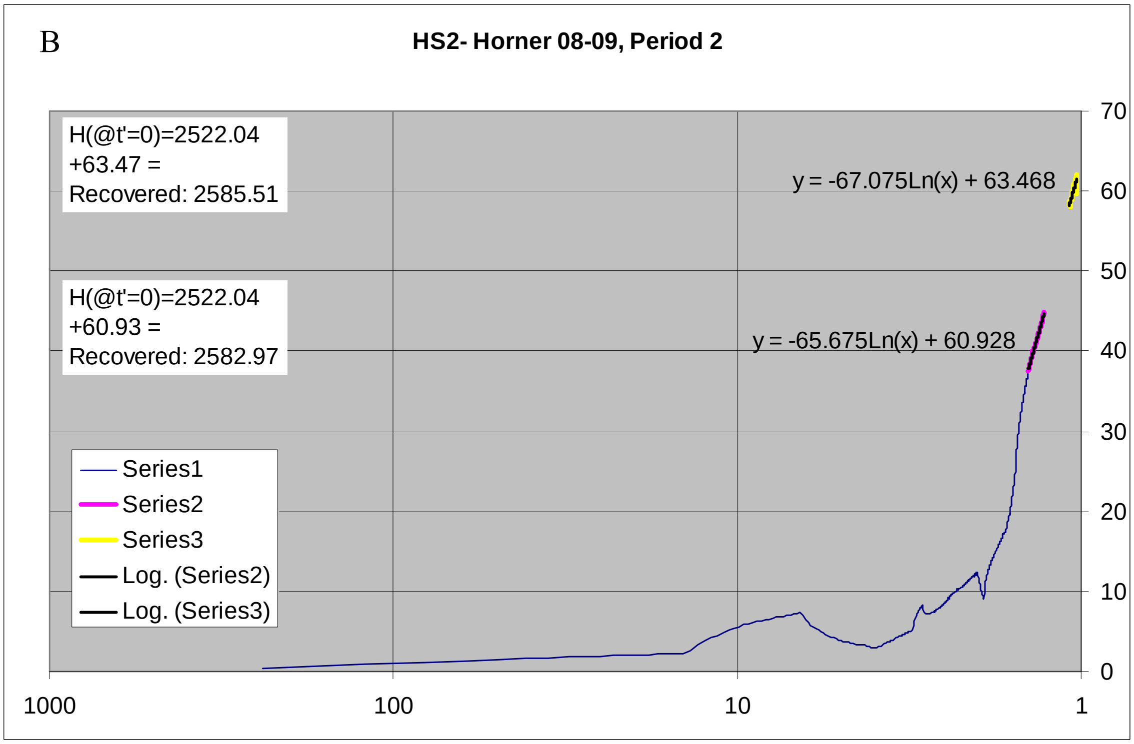


Figure A - 3: Horner recovery estimation HS2, 2008-09; (A) entire recovery period, (B) only the recovery after the final pumping event.

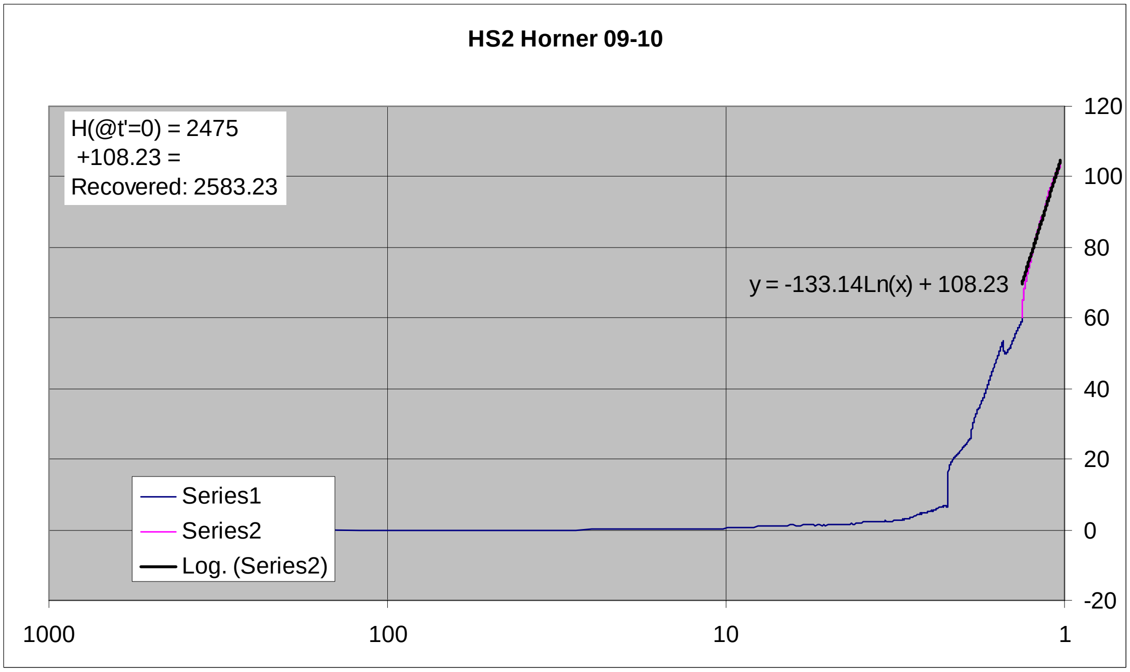


Figure A - 4: Horner recovery estimation HS2, 2009-10.

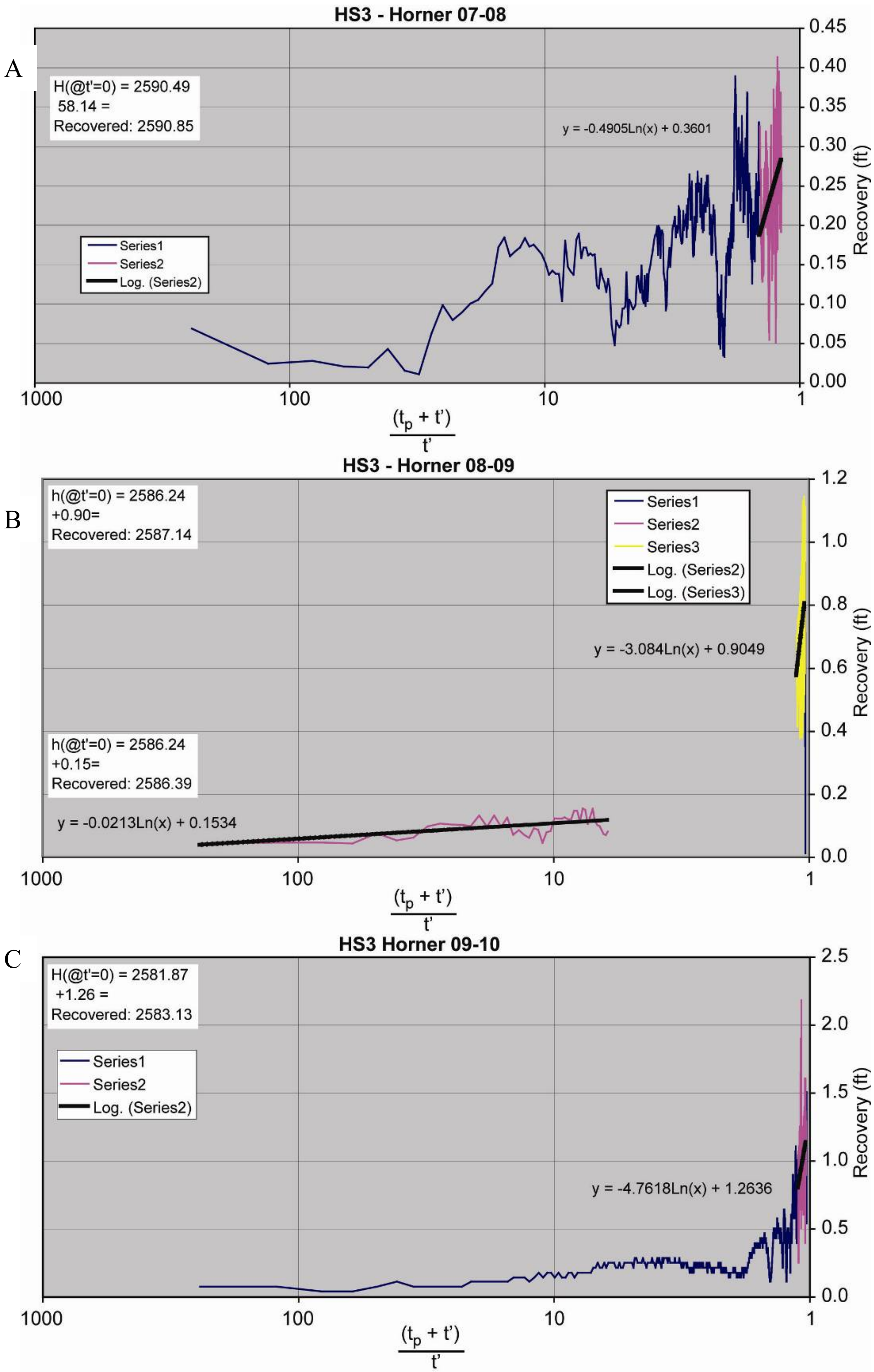


Figure A - 5: Horner recovery estimation HS3, (a) 2007-08, (b) 2008-09, (c) 2009-10.

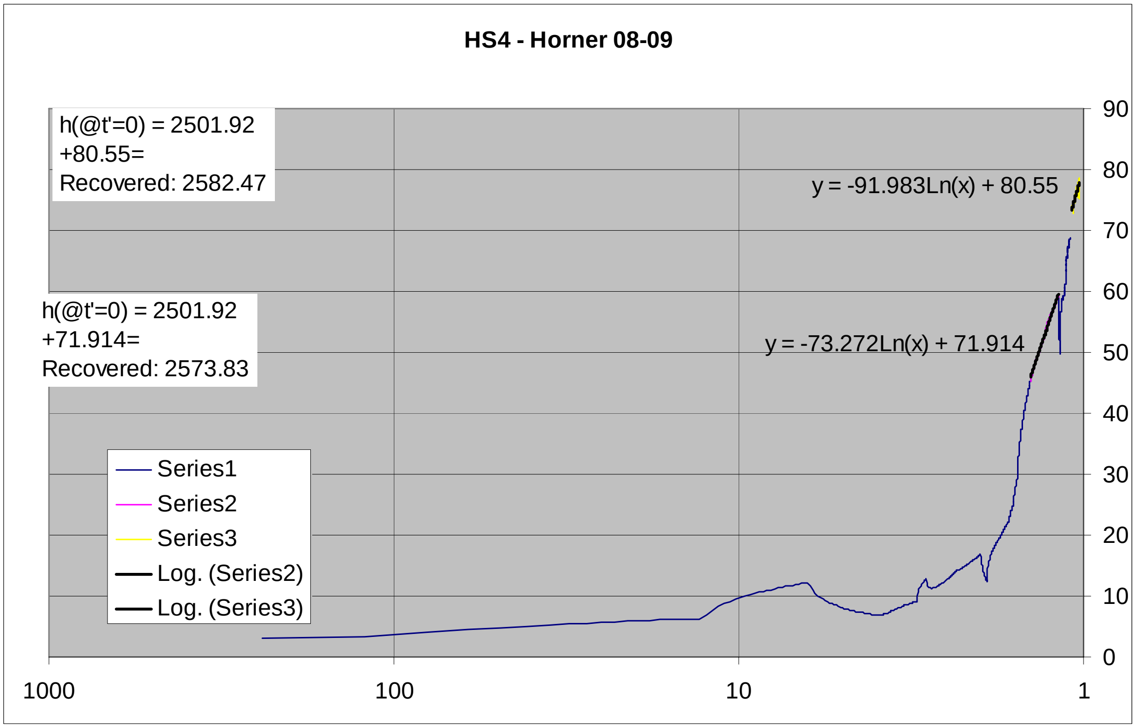


Figure A - 6: Horner recovery estimation HS4, 2008-09.

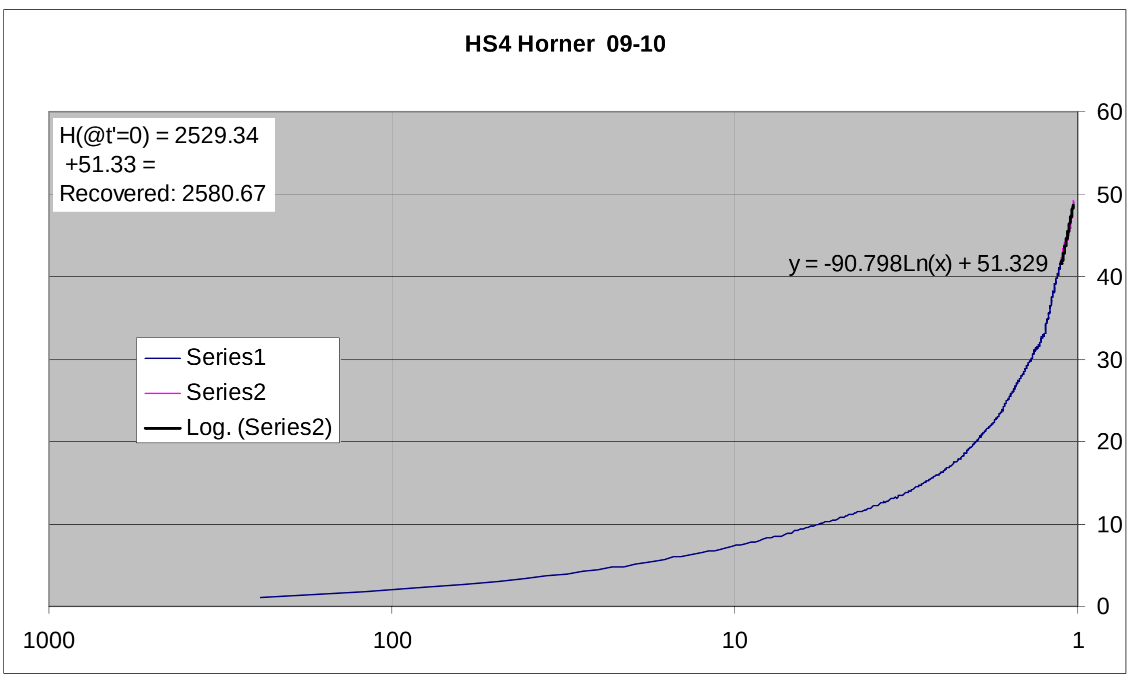


Figure A - 7: Horner recovery estimation HS4, 2009-10.

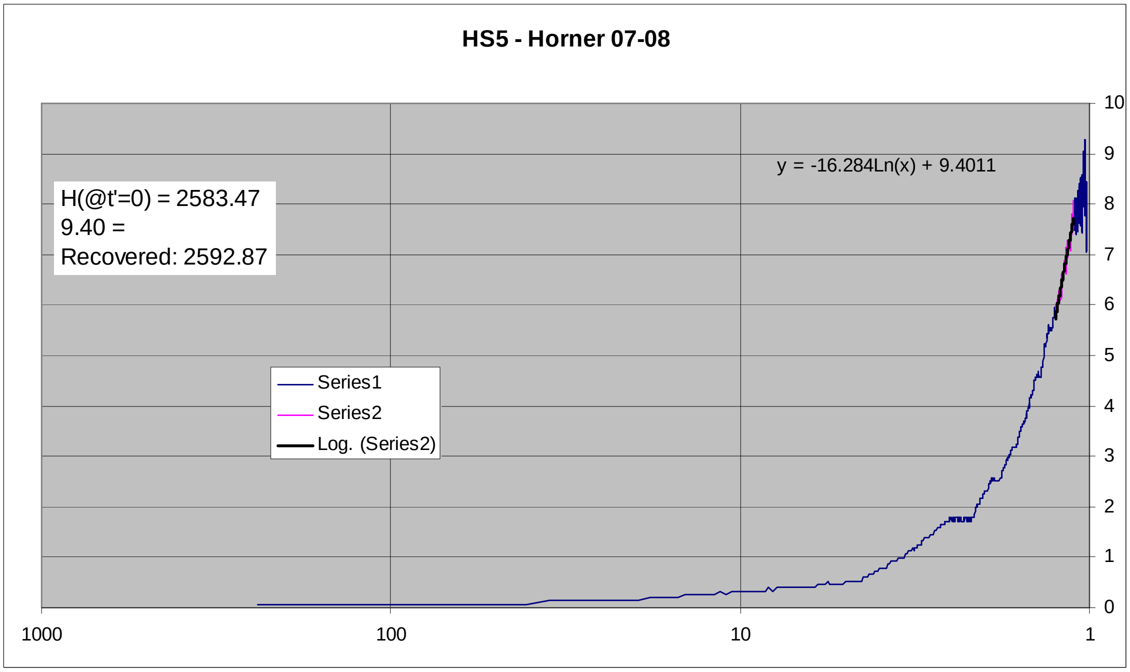
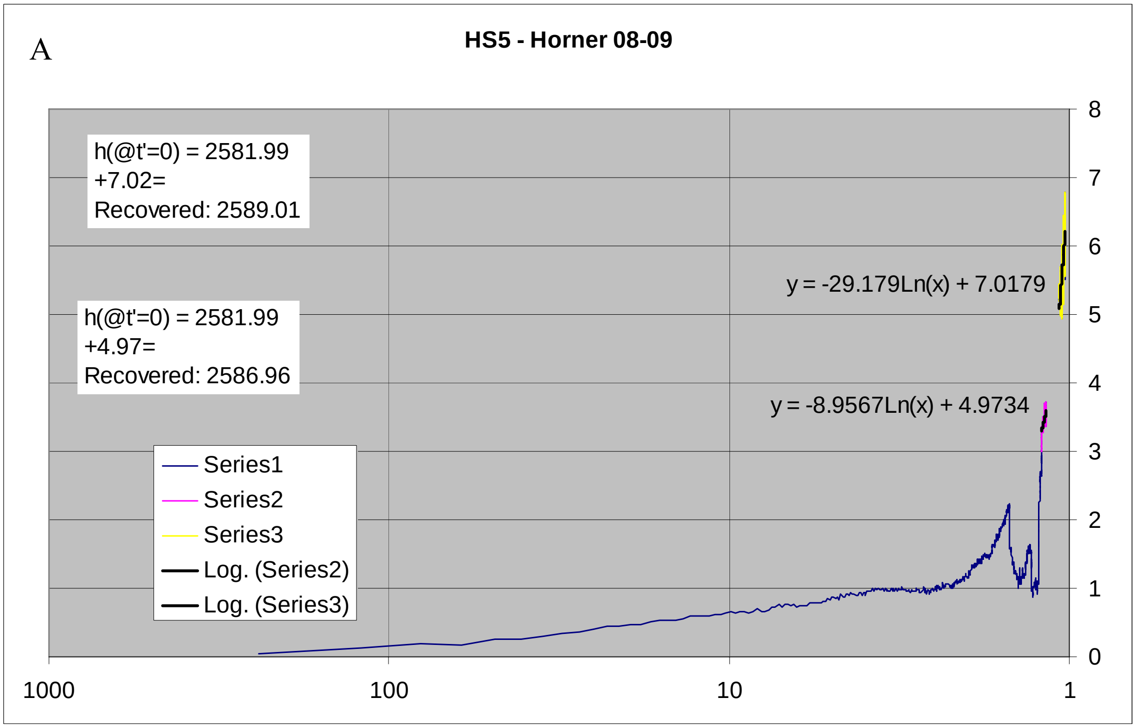


Figure A - 8: Horner recovery estimation HS5, 2007-08.



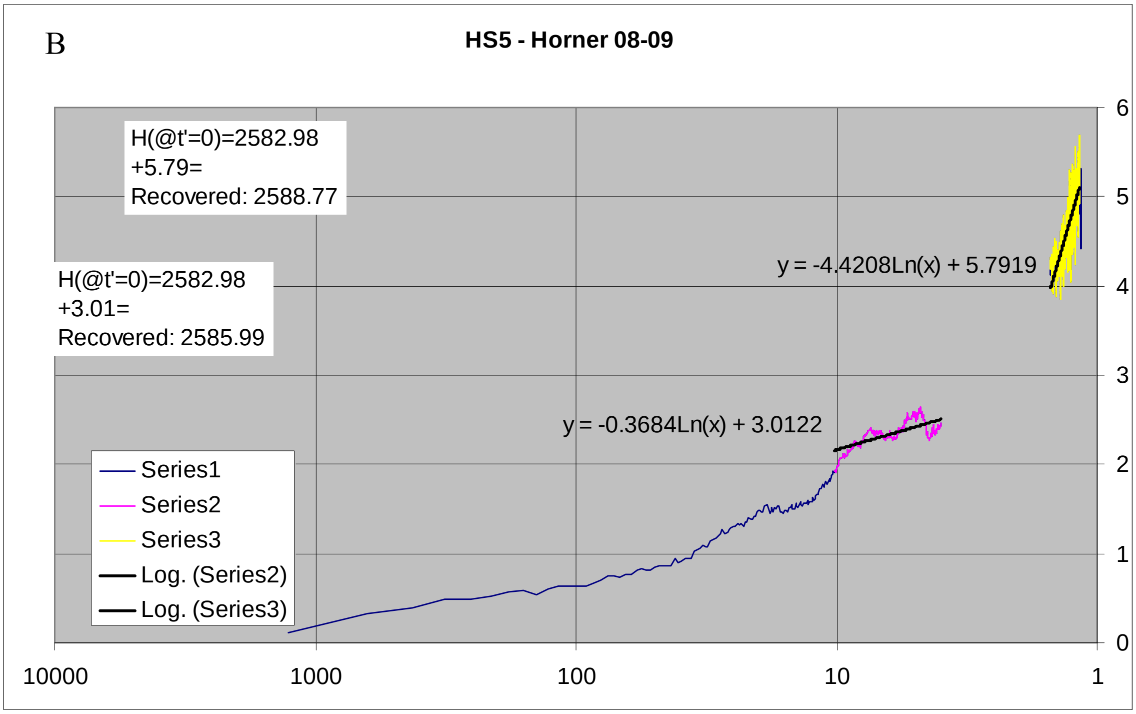


Figure A - 9: Horner recovery estimation HS5, 2008-09; (A) entire recovery period, (B) only the recovery after the final pumping event.

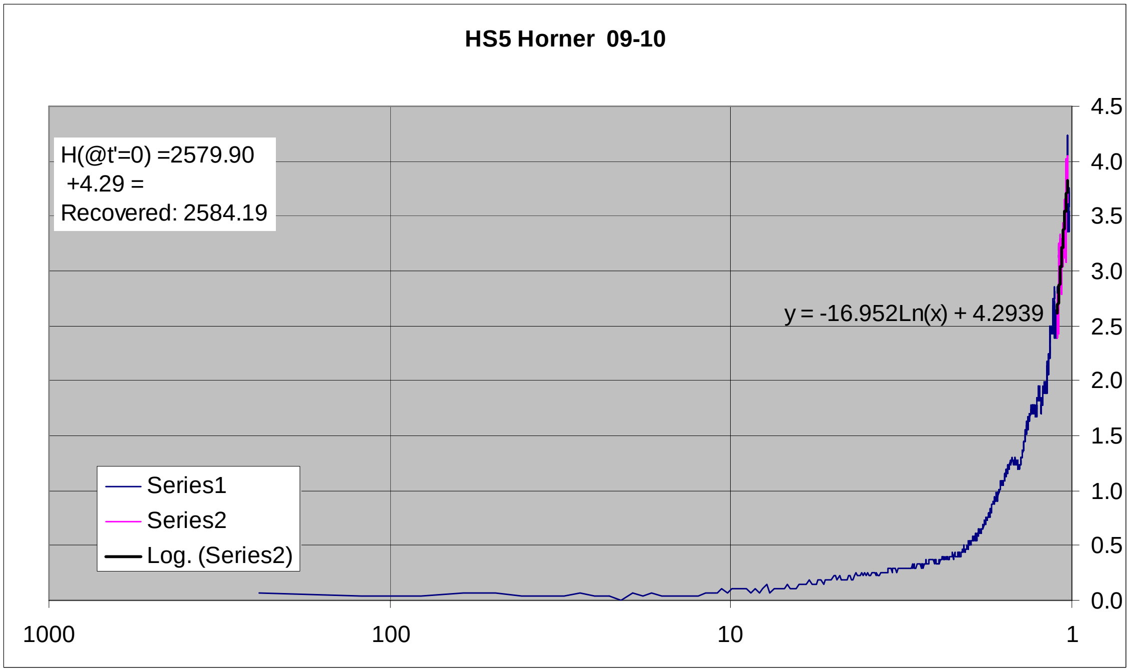
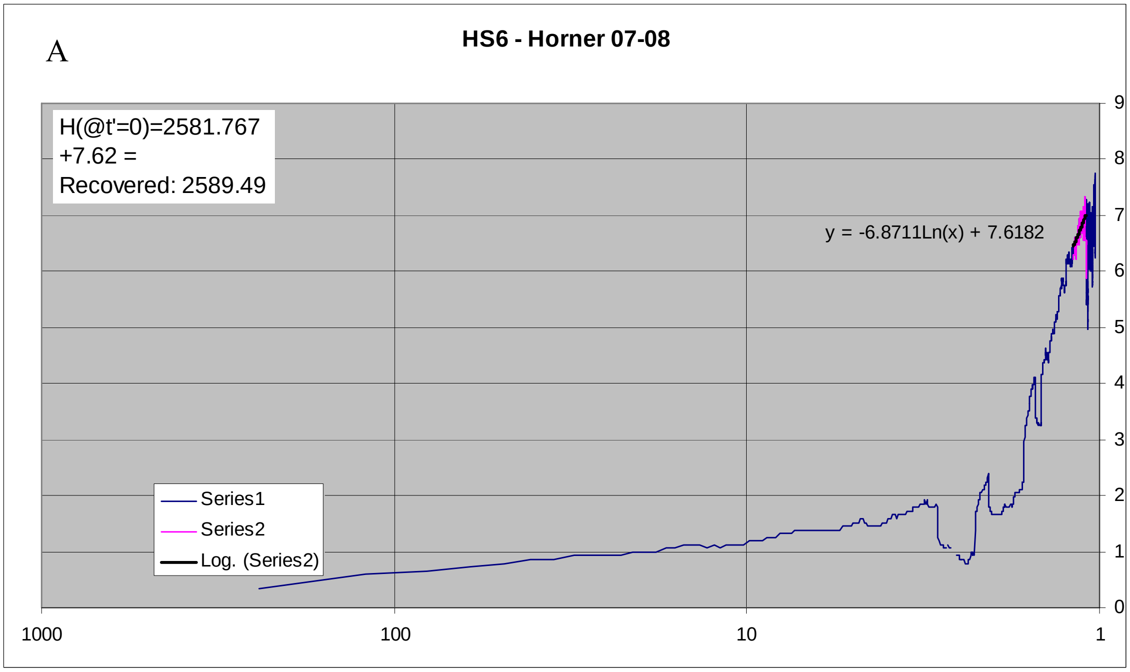


Figure A - 10: Horner recovery estimation HS5, 2009-10.



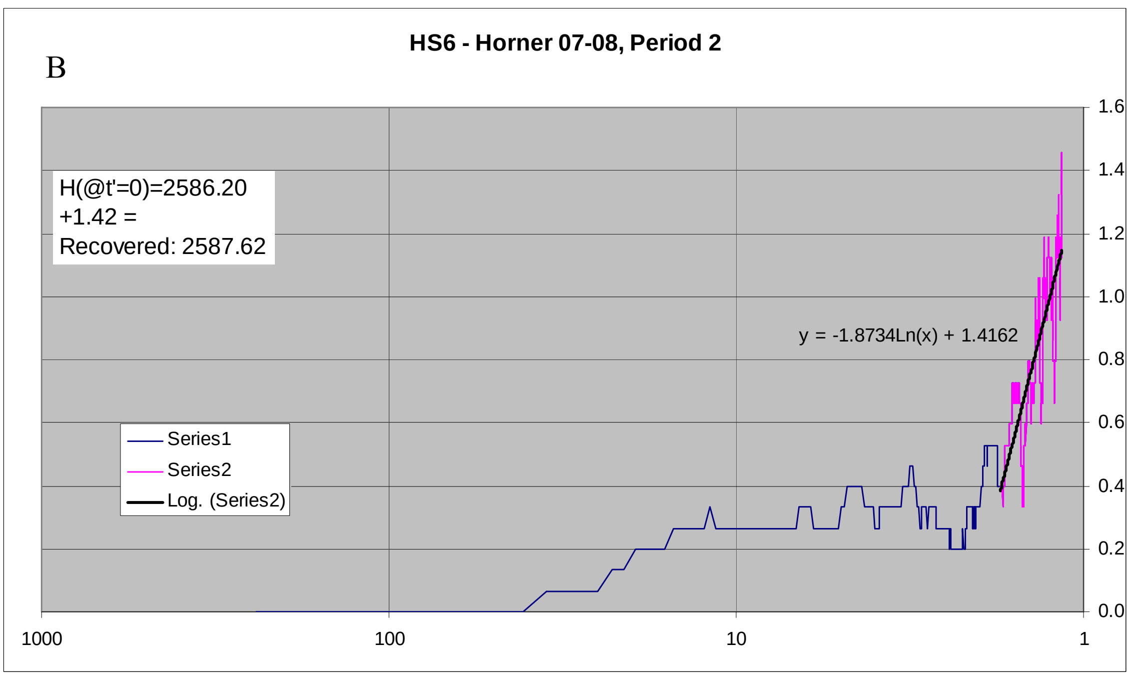


Figure A - 11: Horner recovery estimation HS6, 2007-08; (A) entire recovery period, (B) only the recovery after the final pumping event.

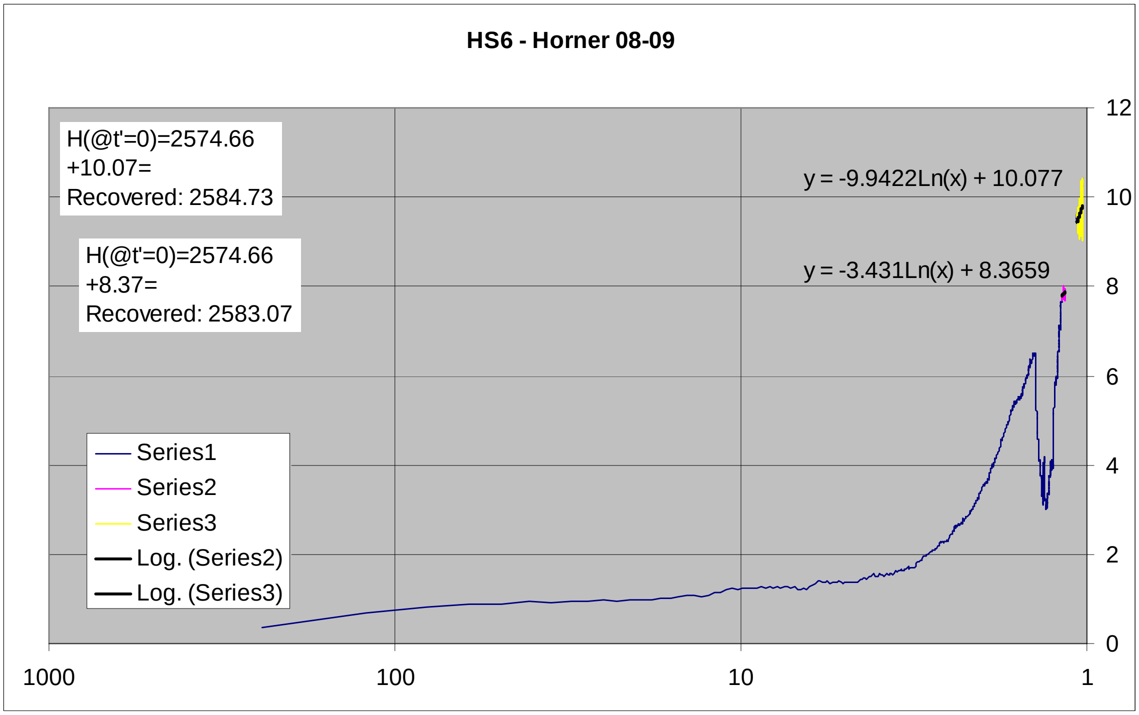


Figure A - 12: Horner recovery estimation HS6, 2008-09.

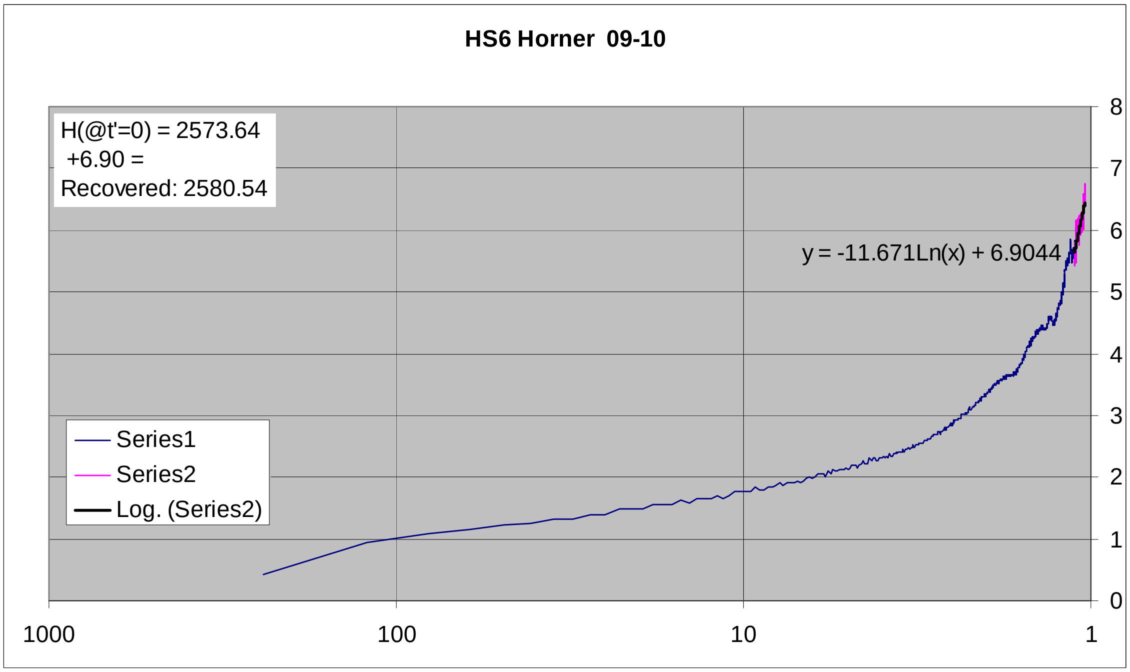


Figure A - 13: Horner recovery estimation HS6, 2009-10.

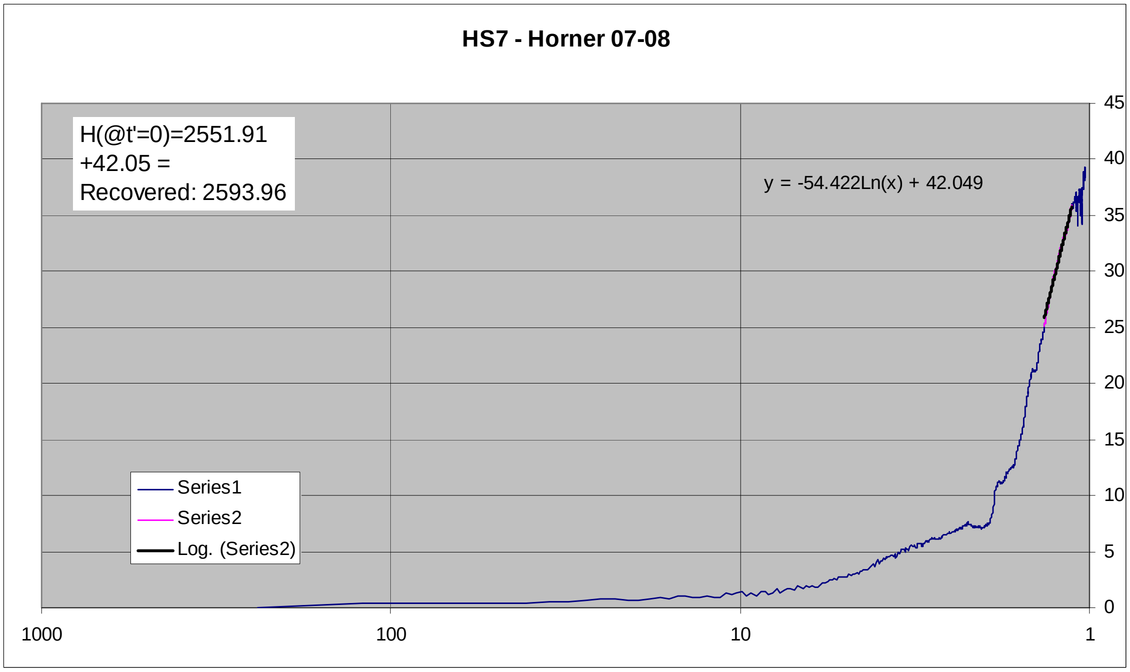
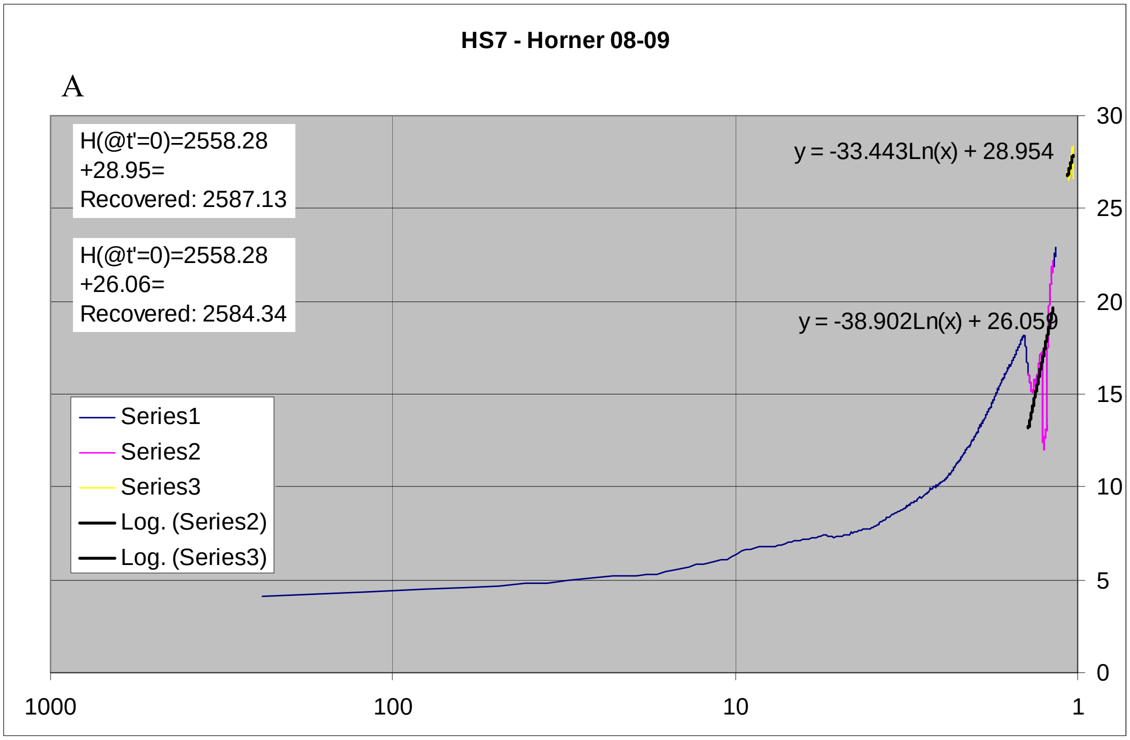


Figure A - 14: Horner recovery estimation HS7, 2007-08.



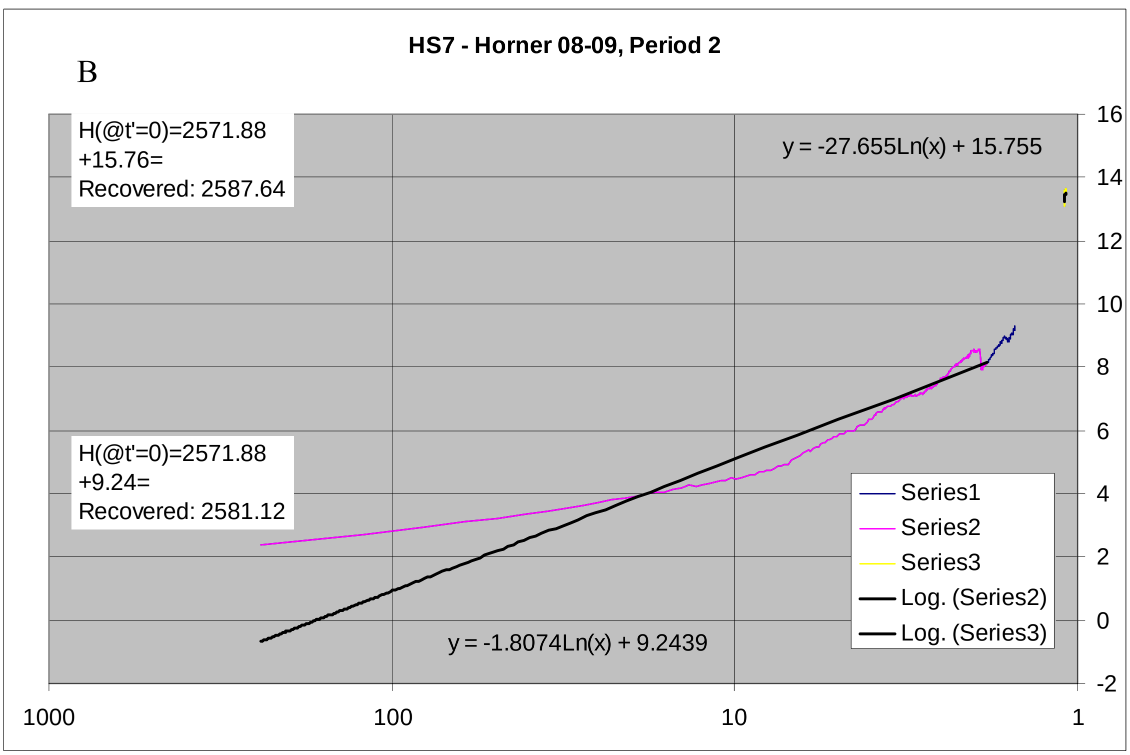


Figure A - 15: Horner recovery estimation HS7, 2008-09; (A) entire recovery period, (B) only the recovery after the final pumping event.

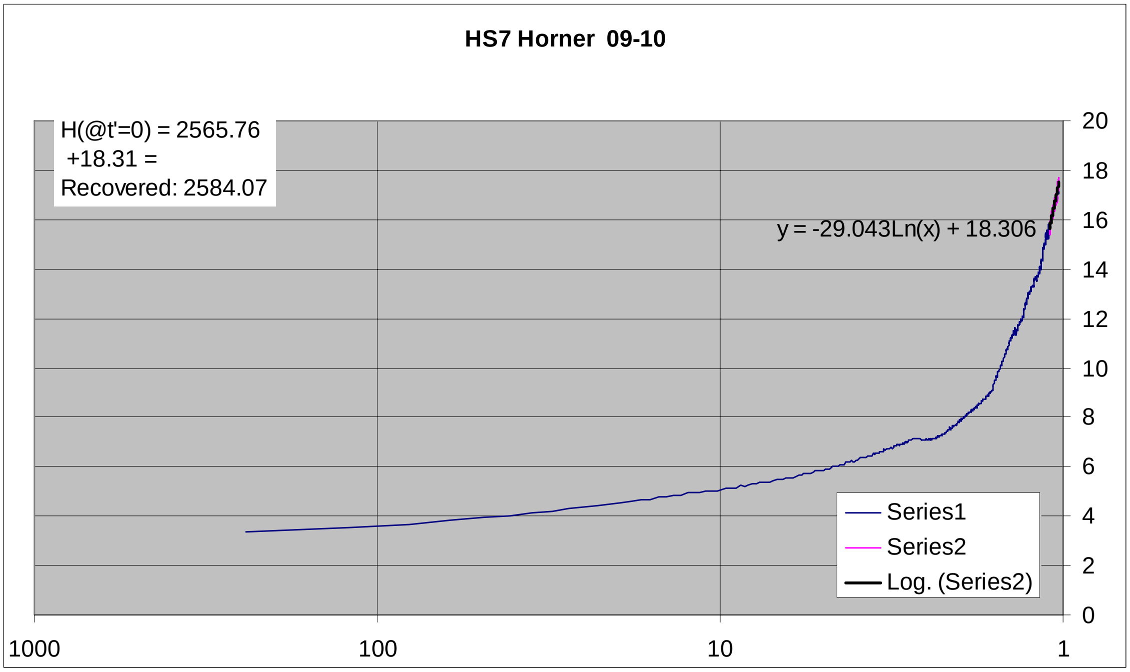
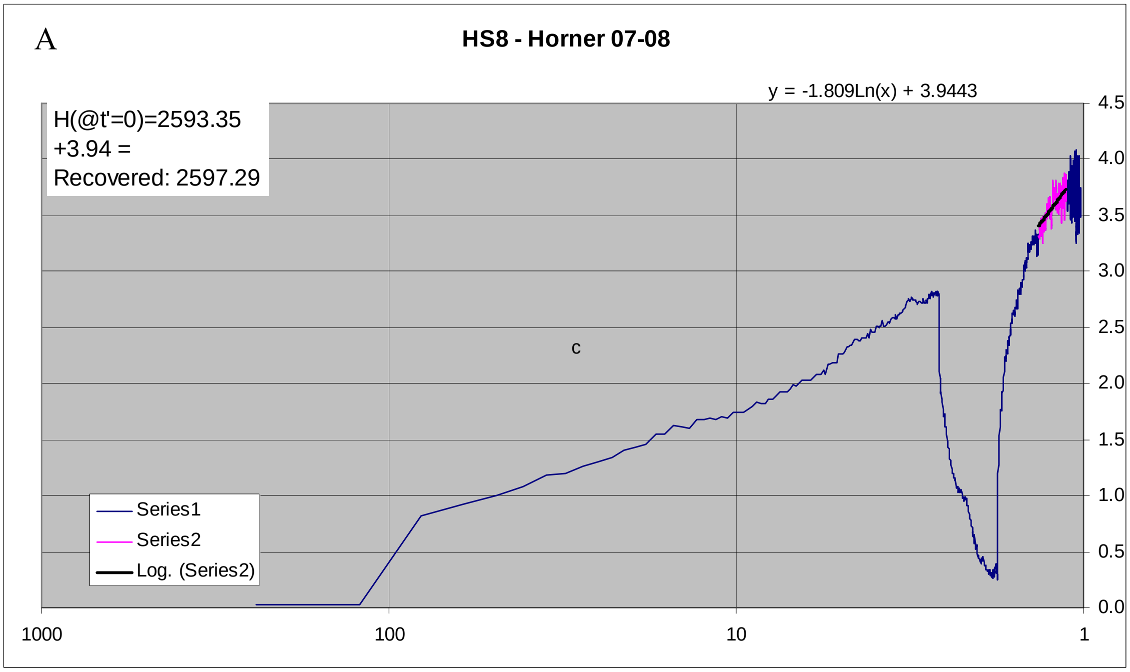


Figure A - 16: Horner recovery estimation HS7, 2009-10.



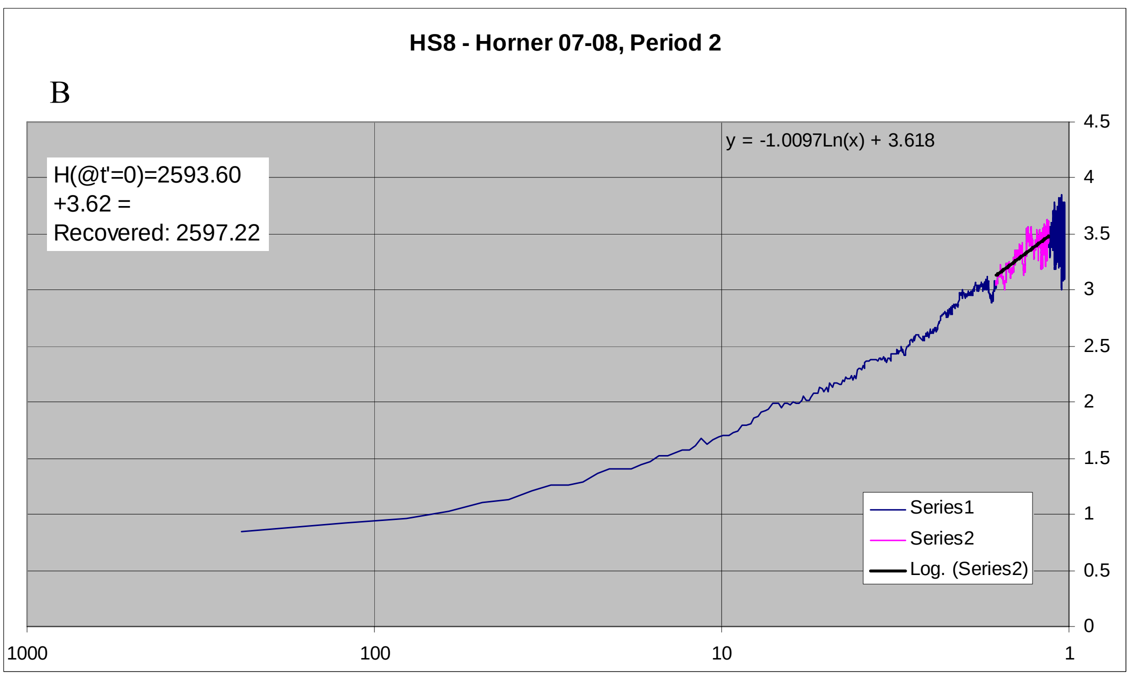


Figure A - 17: Horner recovery estimation HS8, 2007-08; (A) entire recovery period, (B) only the recovery after the final pumping event.

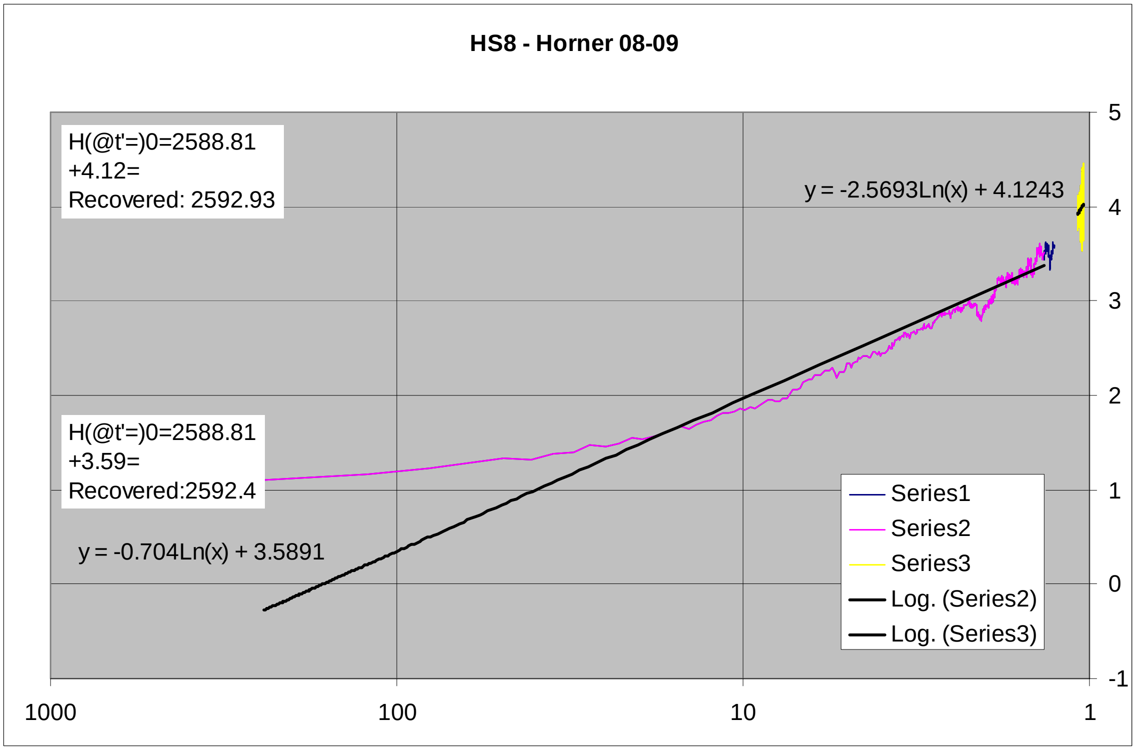


Figure A - 18: Horner recovery estimation HS8, 2008-09.

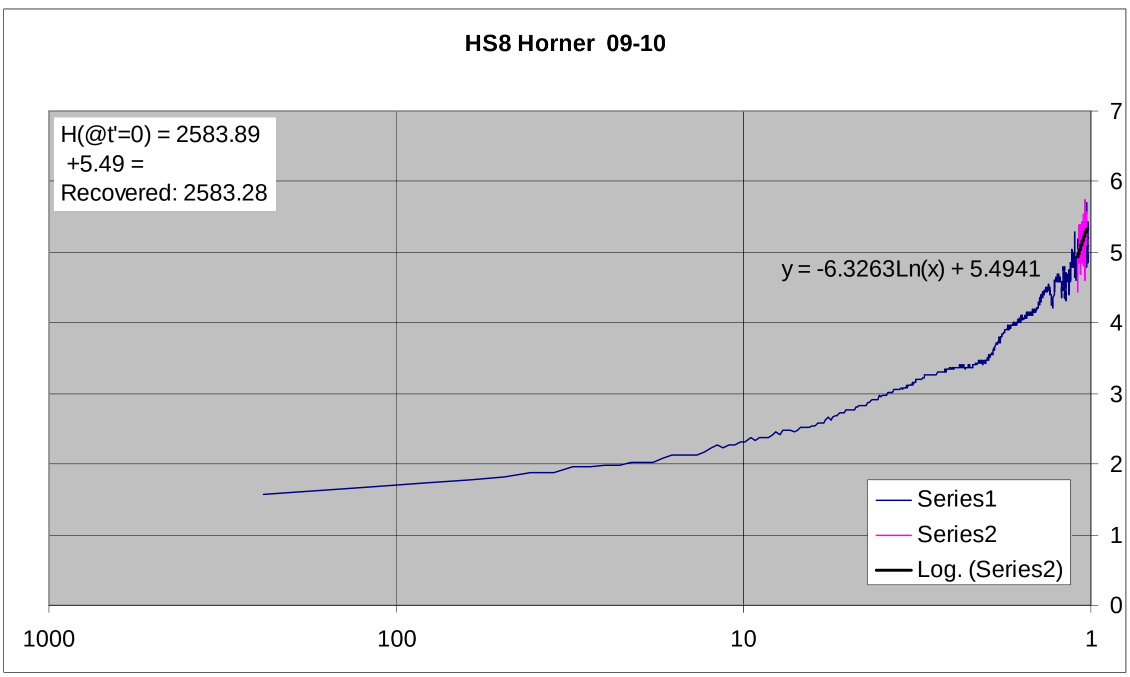


Figure A - 19: Horner recovery estimation HS8, 2009-10.

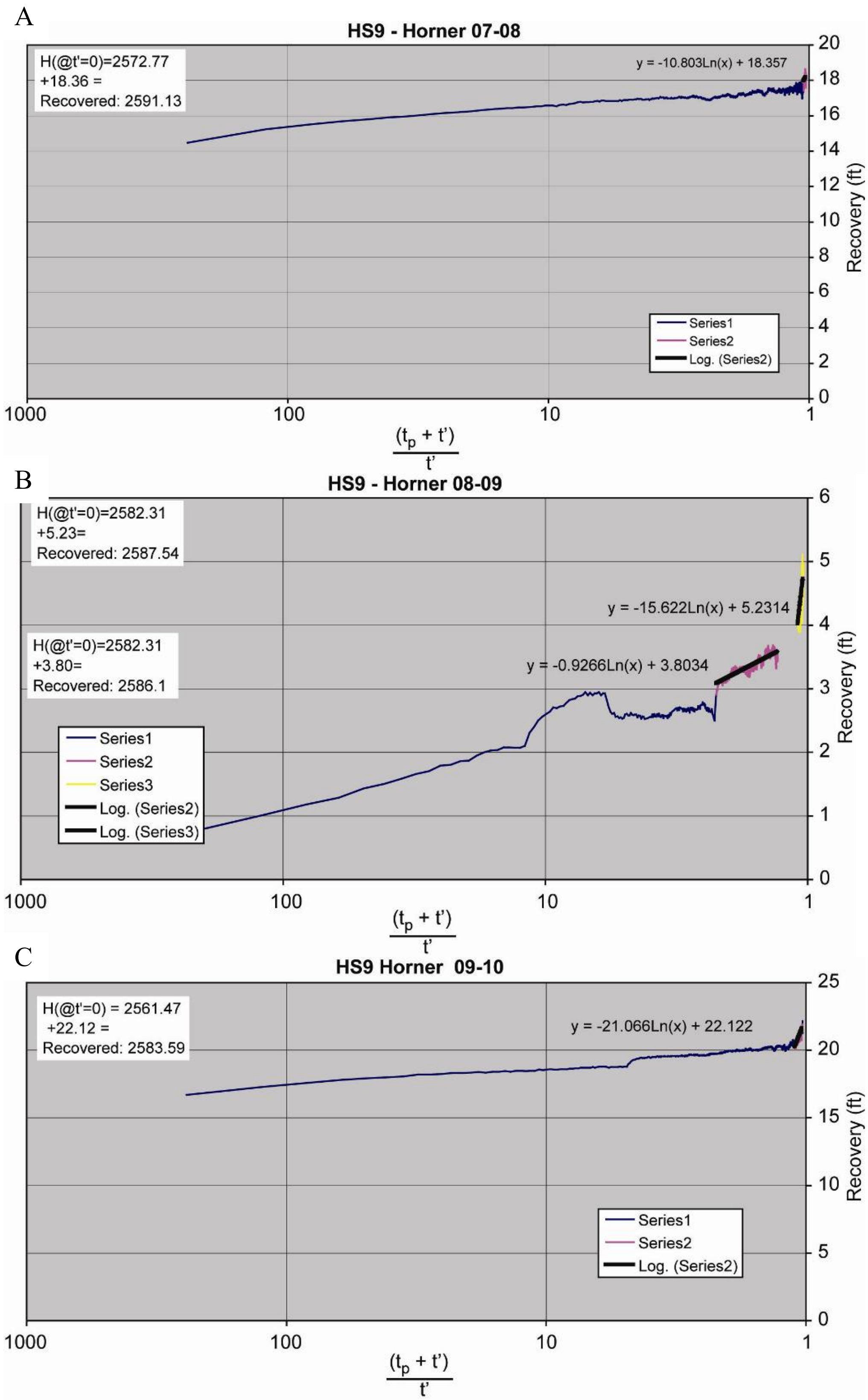


Figure A - 20: Horner recovery estimation HS9, (a) 2007-08, (b) 2008-09, (c) 2009-10.

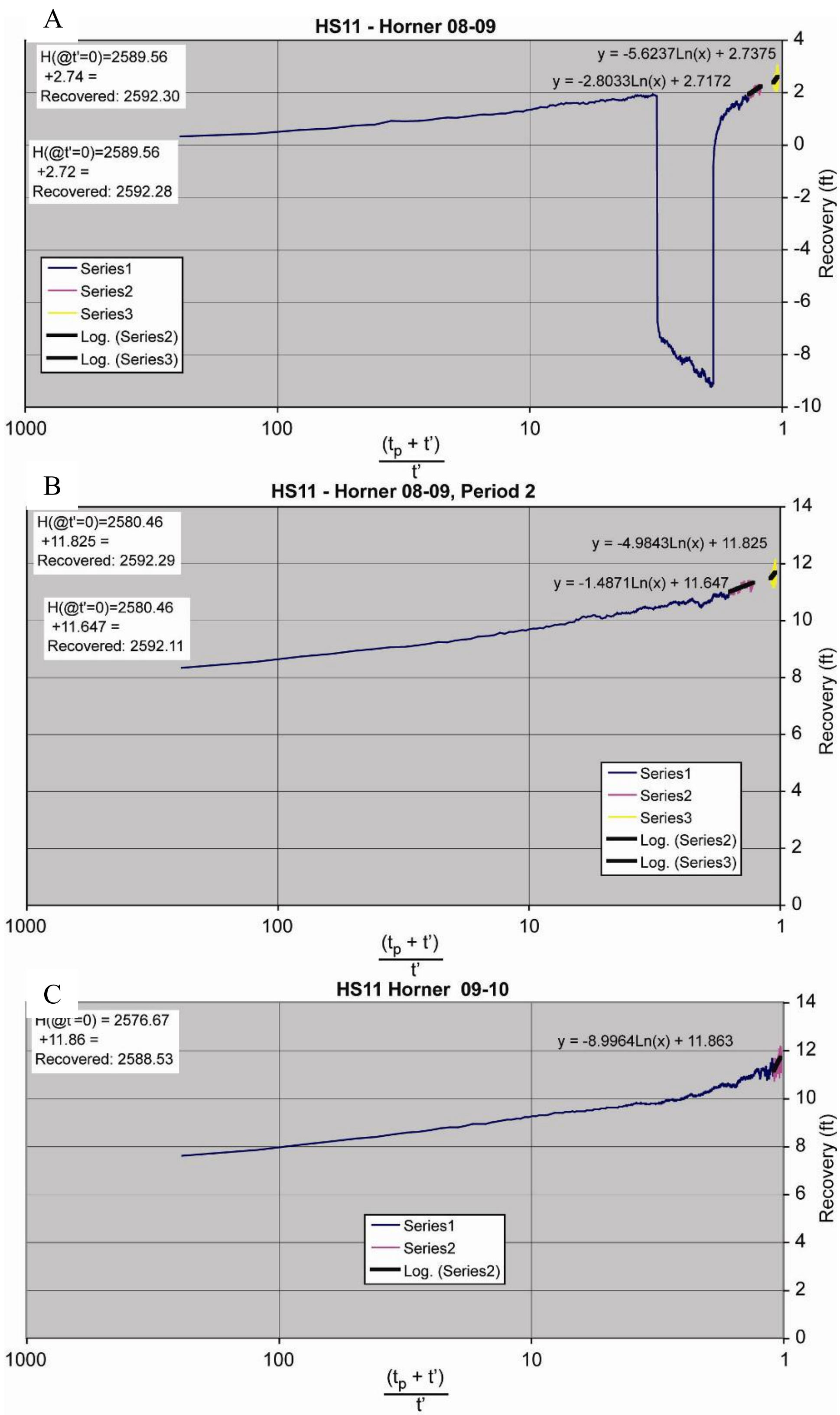


Figure A - 21: Horner recovery estimation HS11, 2008-09; (a) entire recovery period, (b) only the recovery after the final pumping event, and (c) 2009-10.

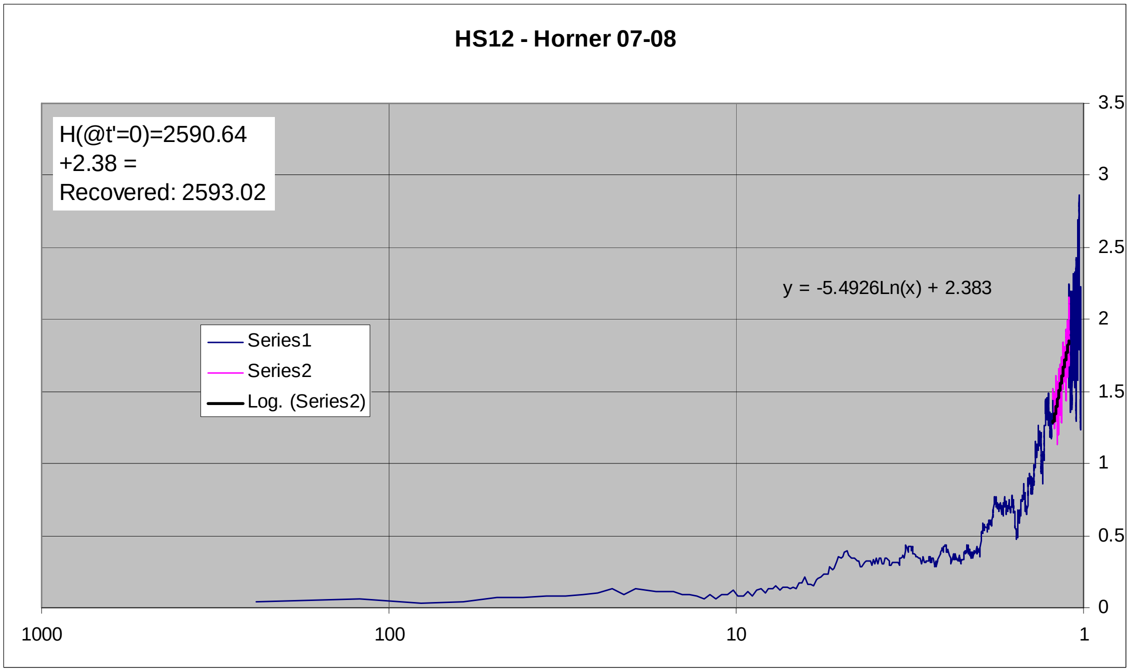


Figure A - 22: Horner recovery estimation HS12, 2007-08.

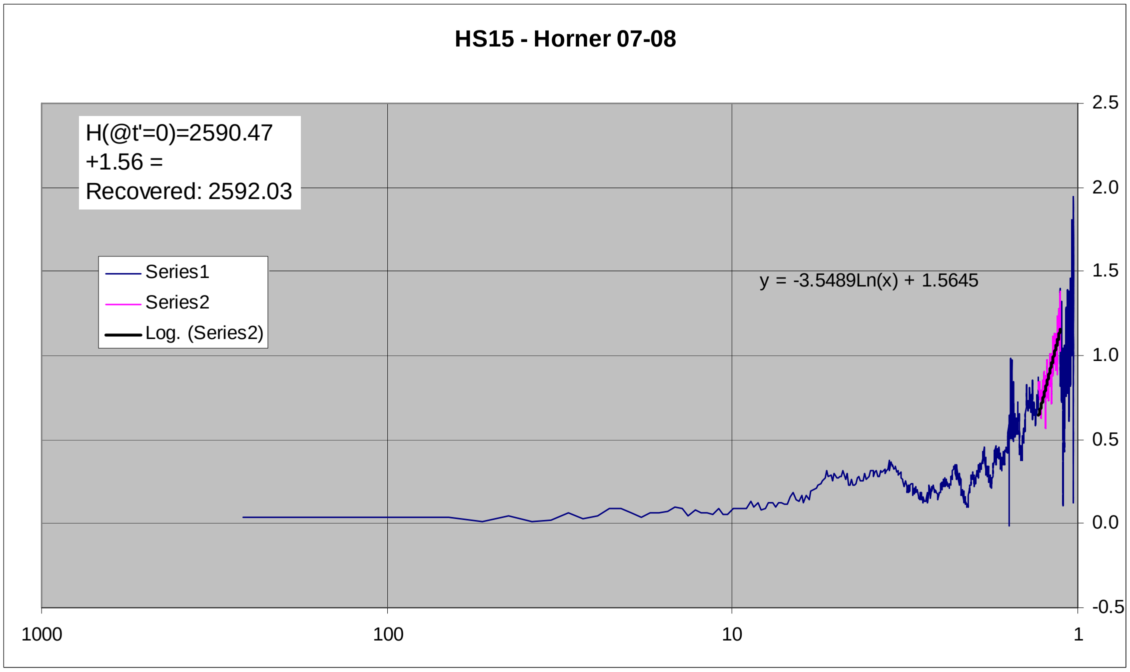


Figure A - 23: Horner recovery estimation HS15, 2007-08.

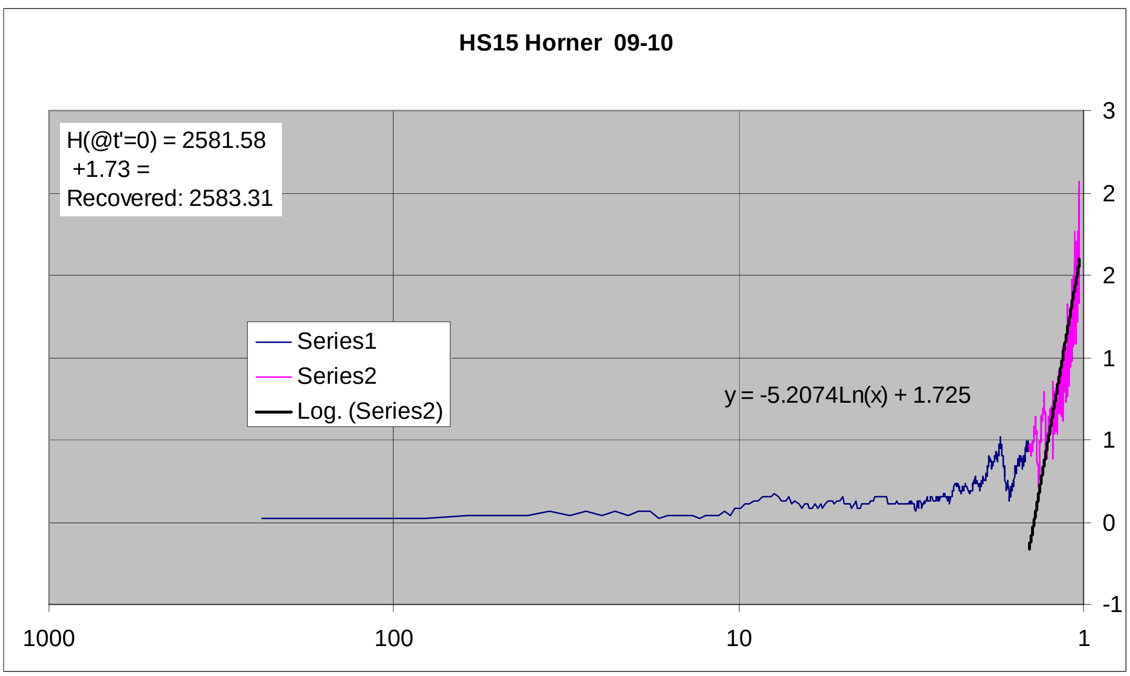
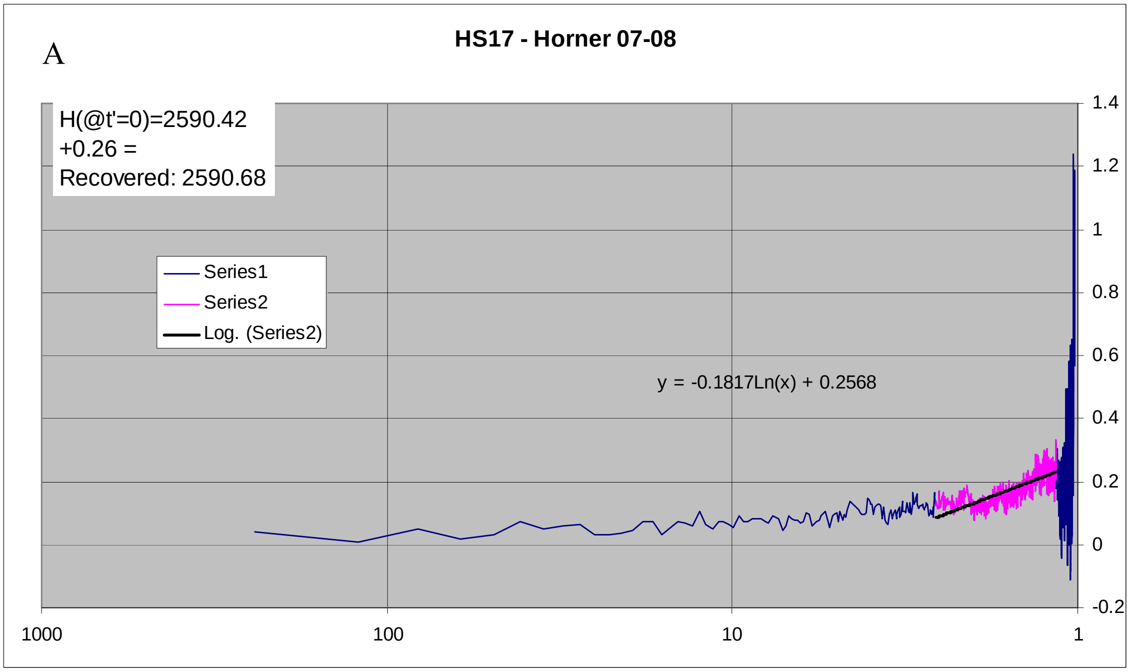


Figure A - 24: Horner recovery estimation HS15, 2009-10.



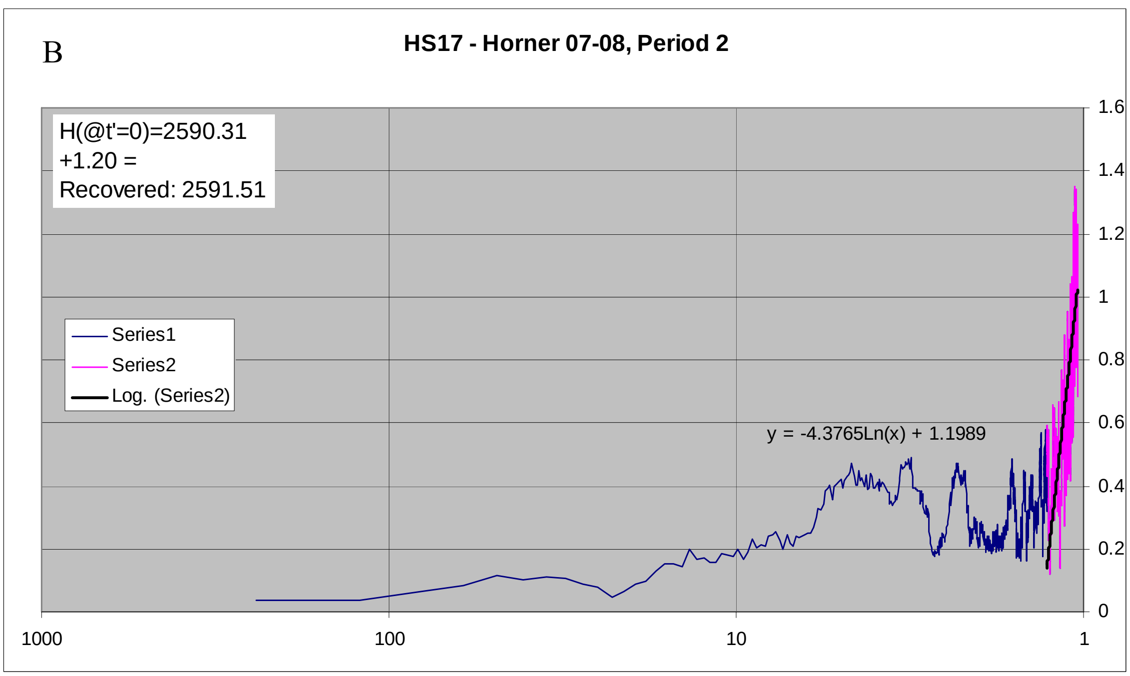
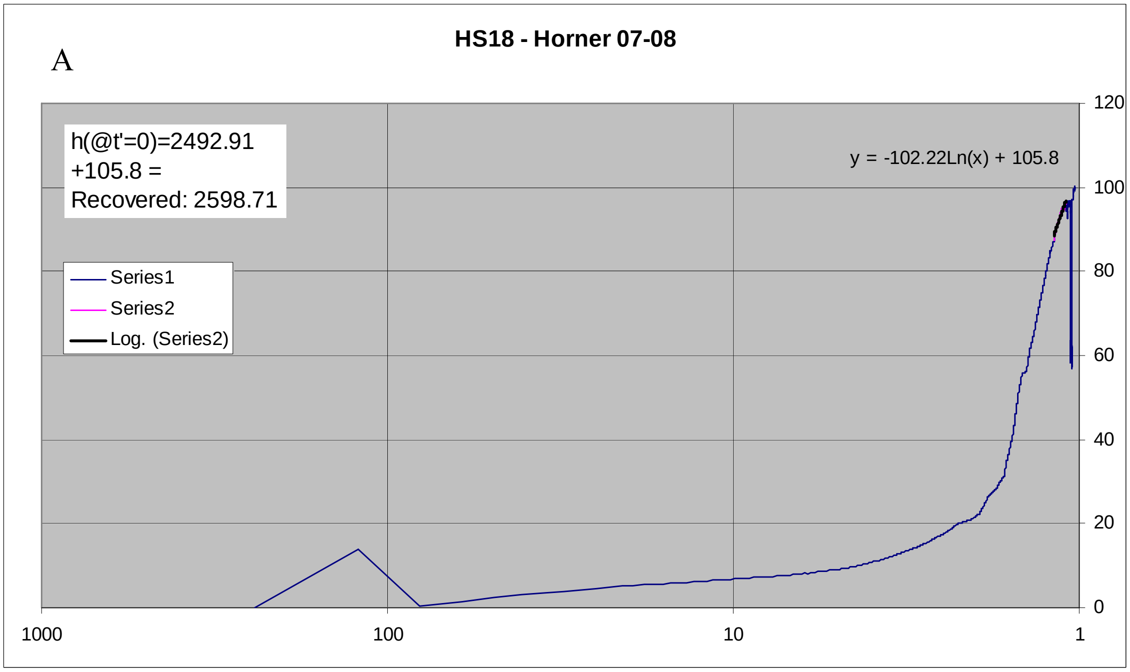


Figure A - 25: Horner recovery estimation HS17, 2007-08; (A) entire recovery period, (B) only the recovery after the final pumping event.



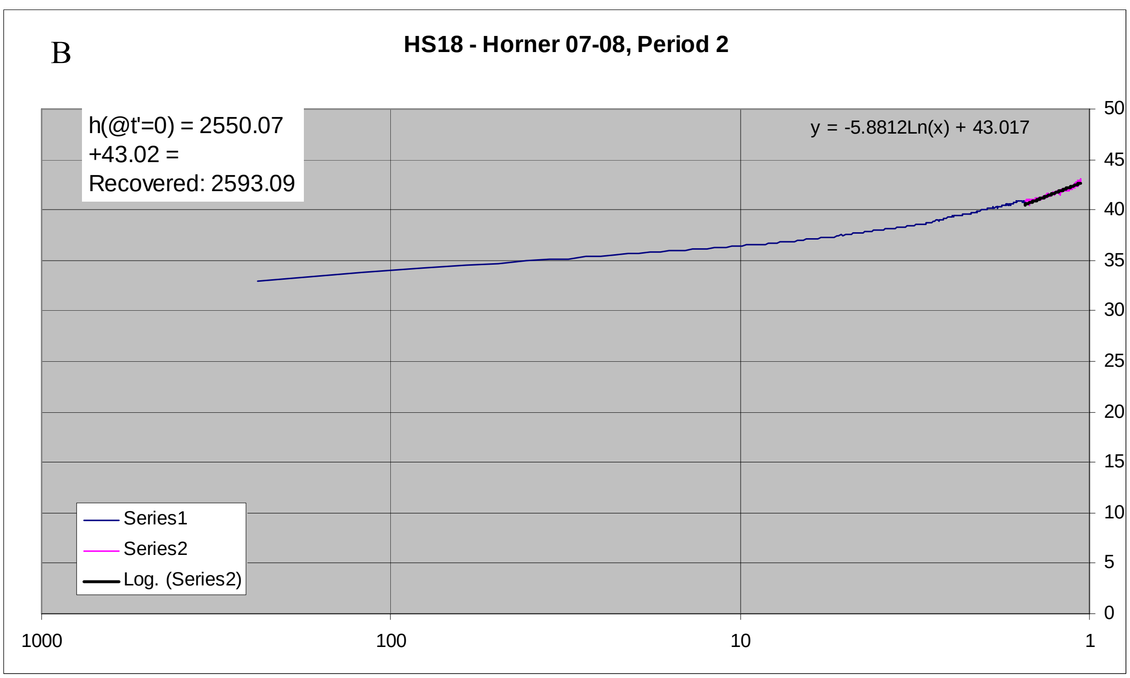
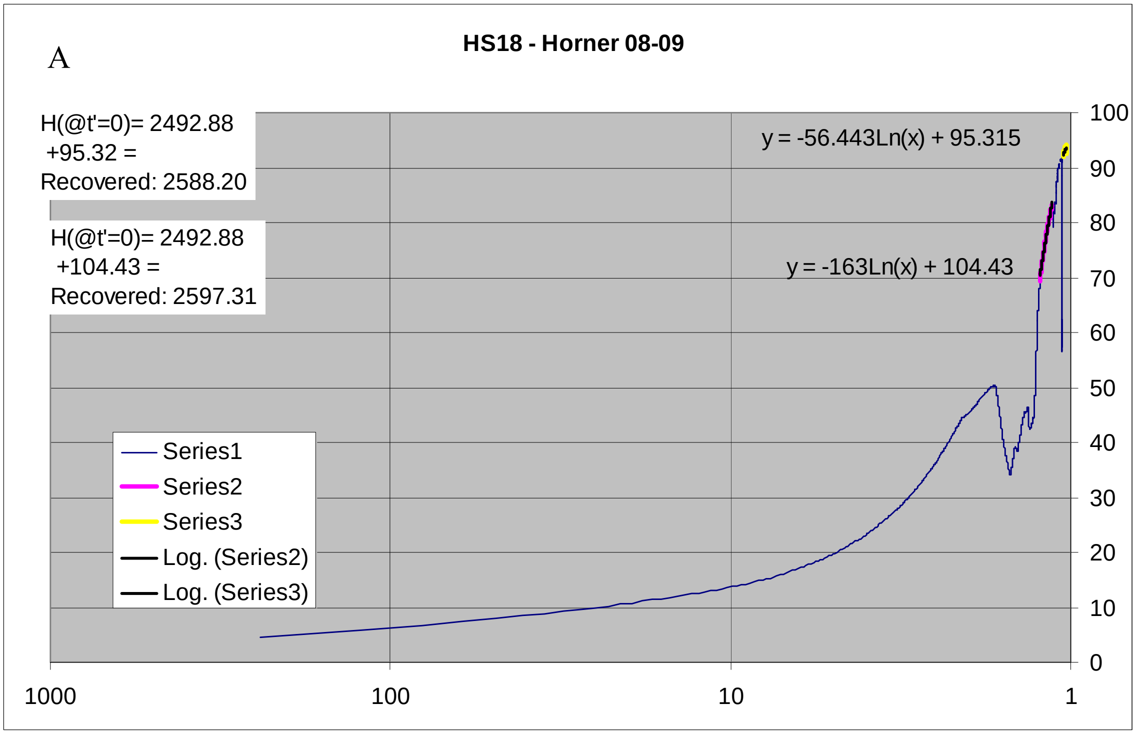


Figure A - 26: Horner recovery estimation HS18, 2007-08; (A) entire recovery period, (B) only the recovery after the final pumping event.



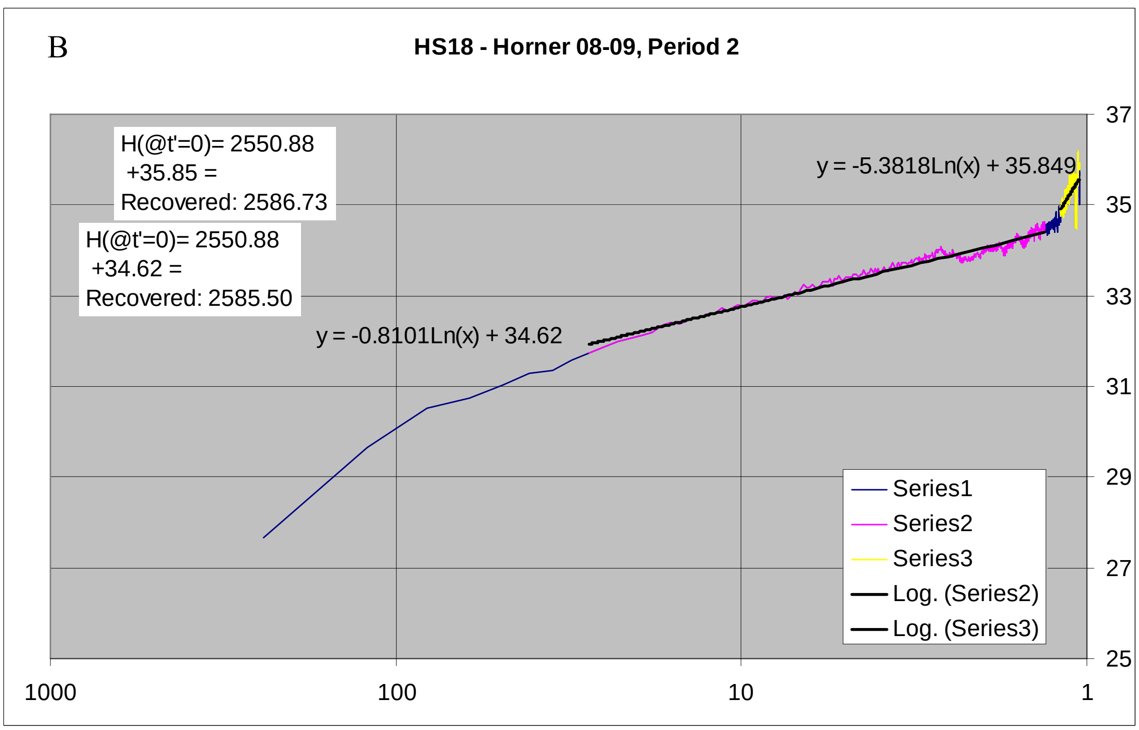


Figure A - 27: Horner recovery estimation HS18, 2008-09; (A) entire recovery period, (B) only the recovery after the final pumping event.

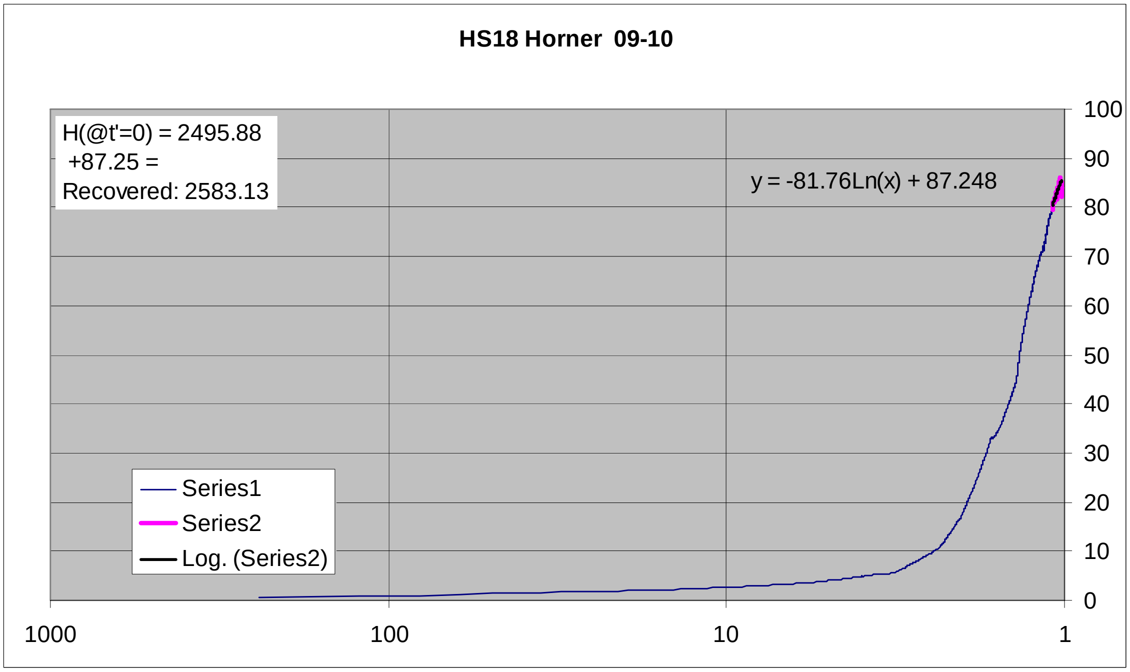
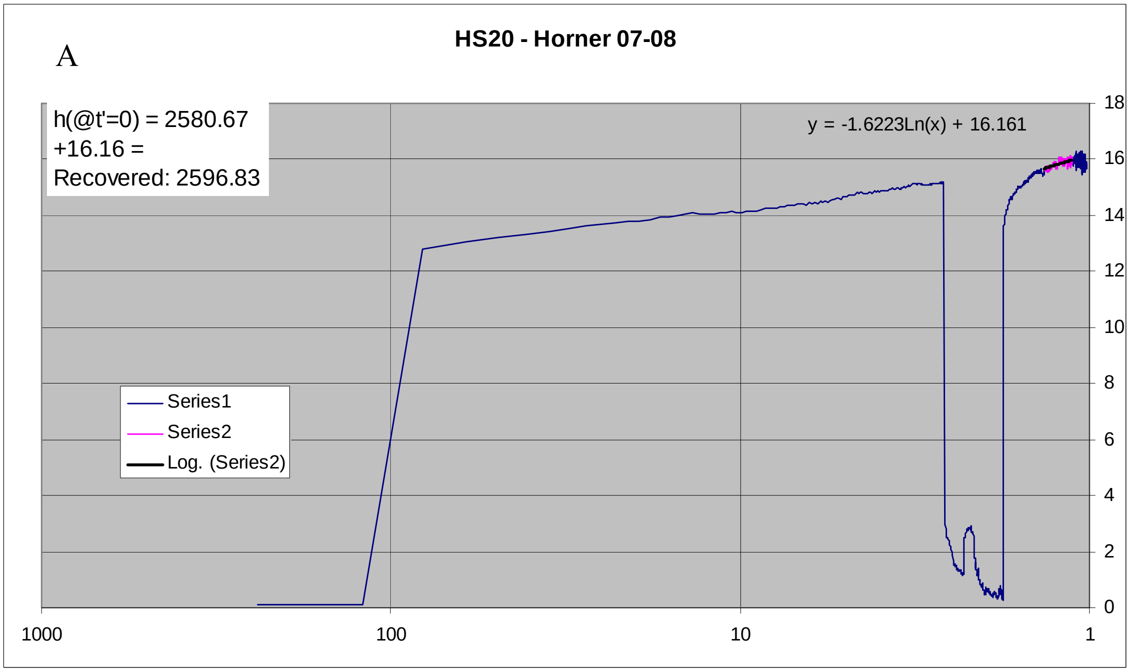


Figure A - 28: Horner recovery estimation HS18, 2009-10.



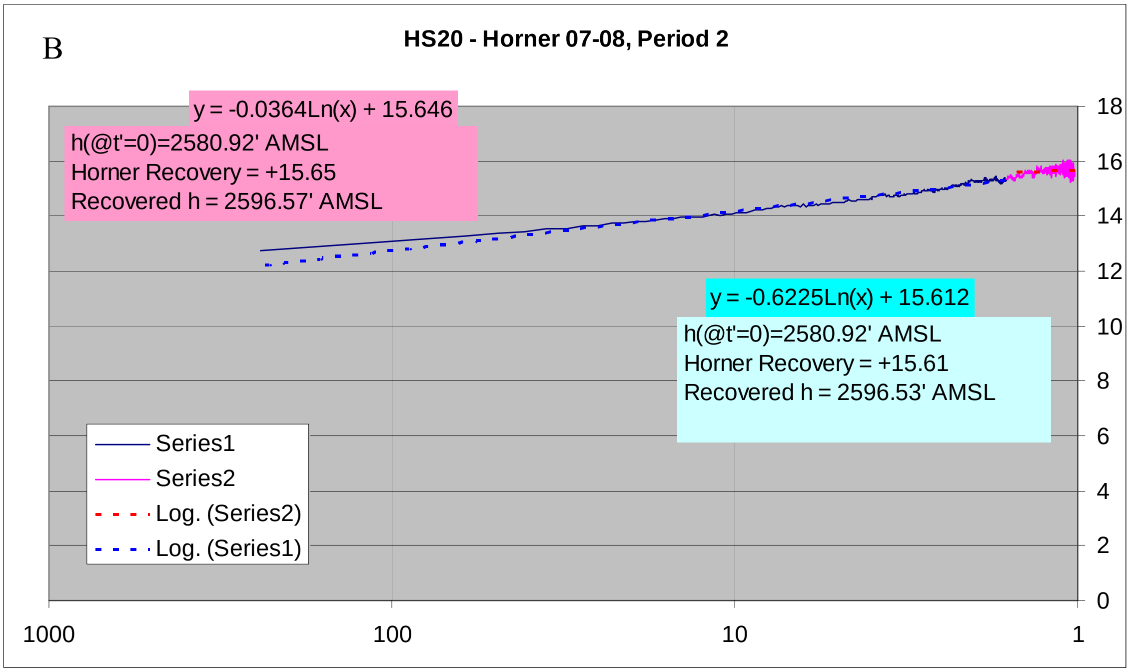


Figure A - 29: Horner recovery estimation HS20, 2007-08; (A) entire recovery period, (B) only the recovery after the final pumping event.

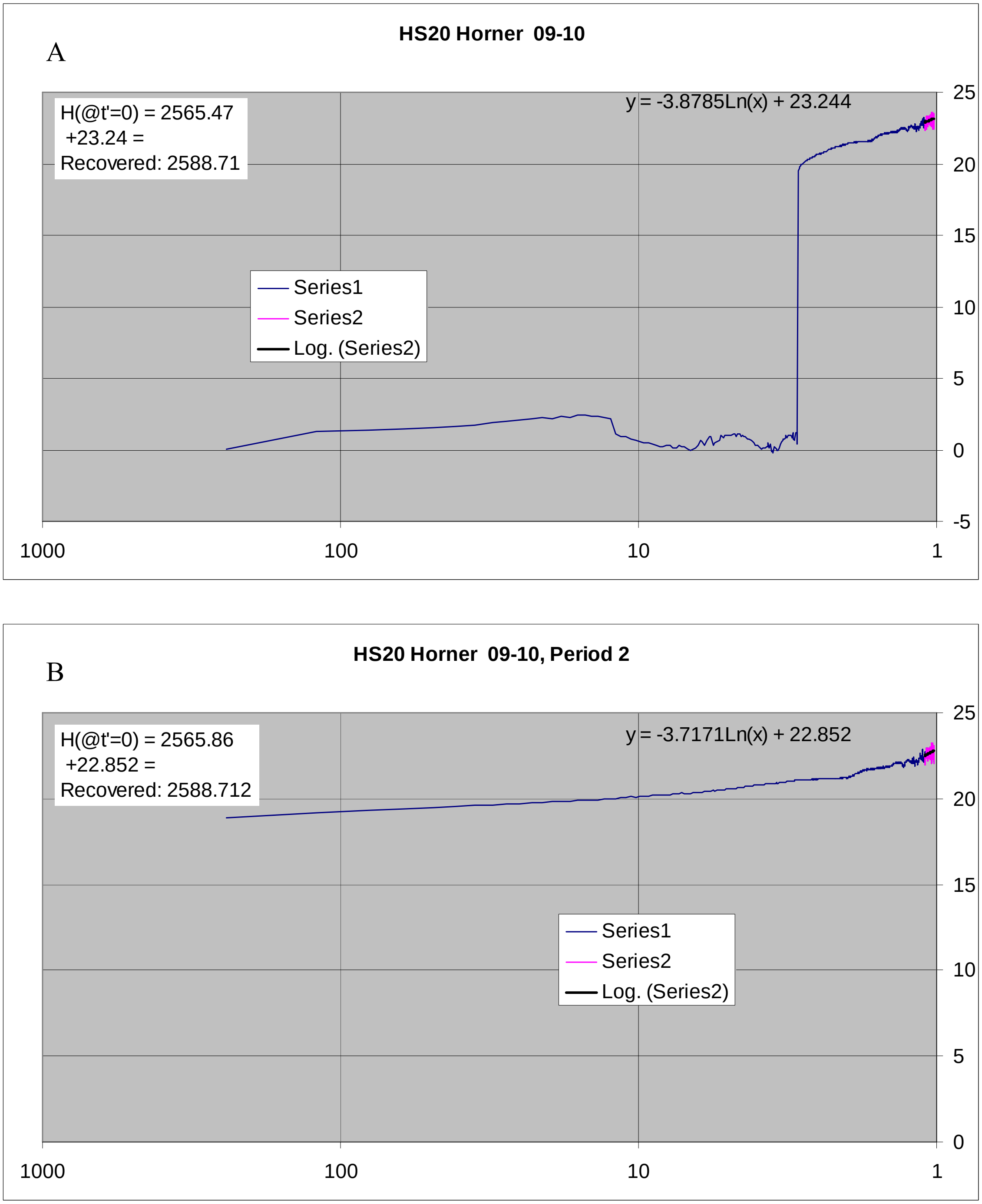


Figure A - 30: Horner recovery estimation HS20, 2009-10; (A) entire recovery period, (B) only the recovery after the final pumping event.

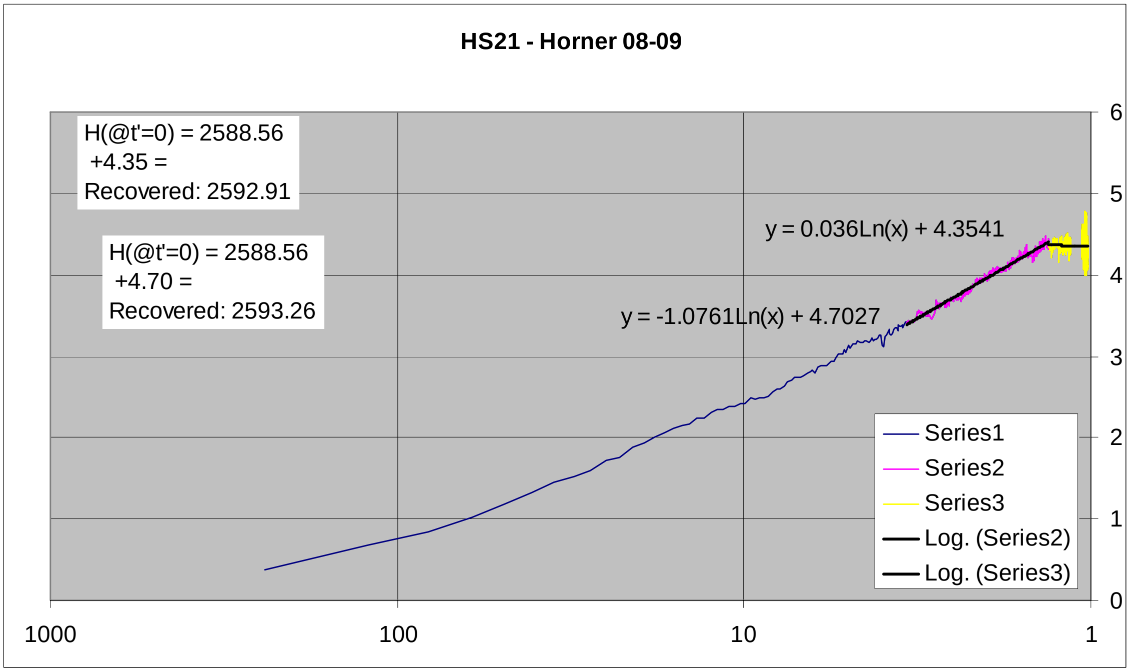


Figure A - 31: Horner recovery estimation HS21, 2008-09.

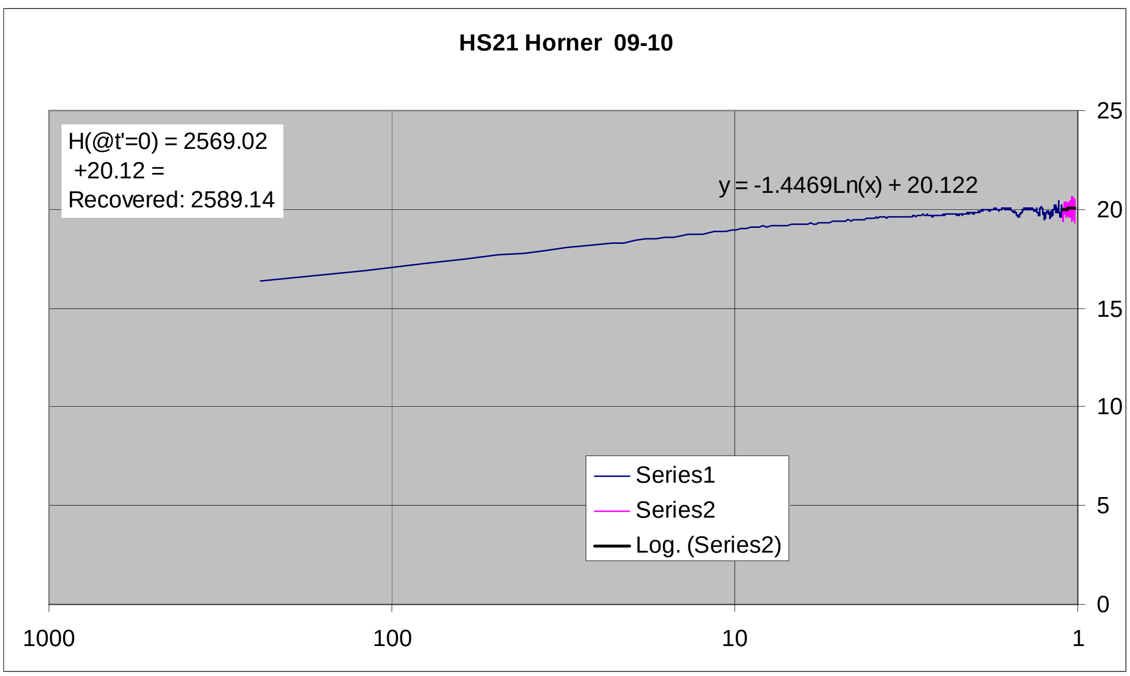


Figure A - 32: Horner recovery estimation HS21, 2009-10.

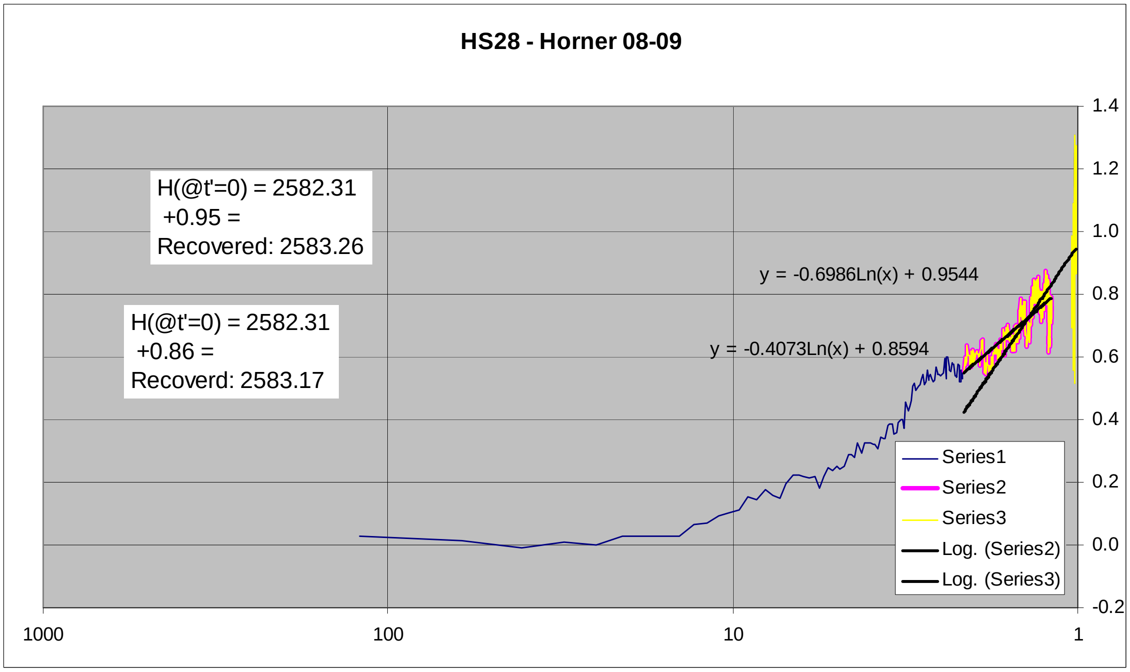


Figure A - 33: Horner recovery estimation HS28, 2008-09.

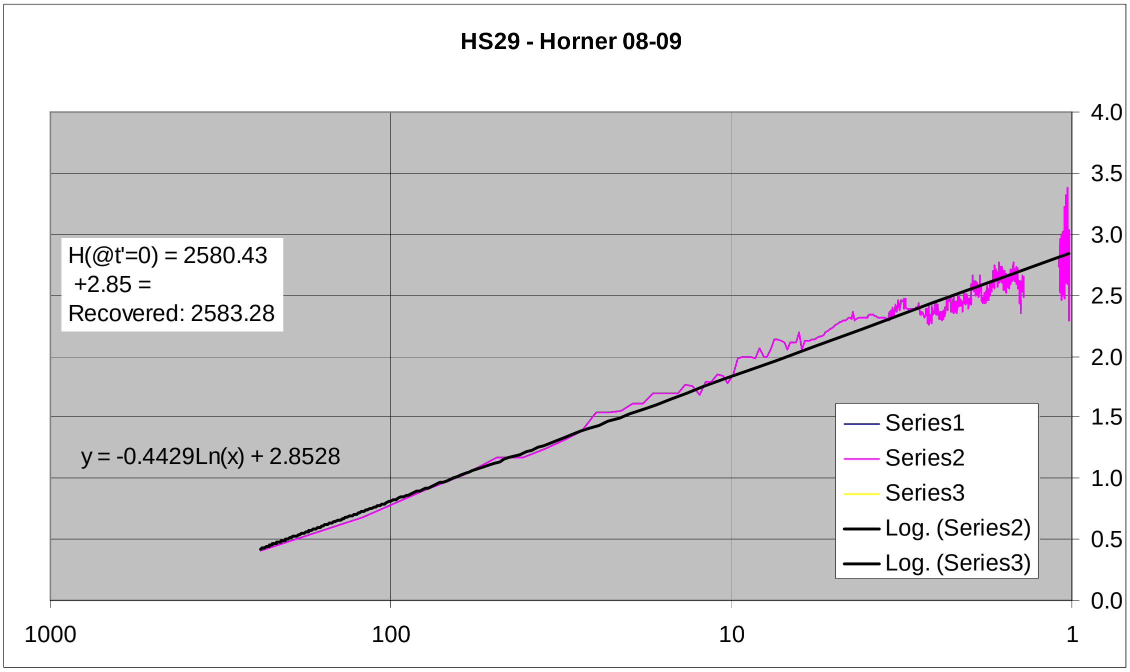
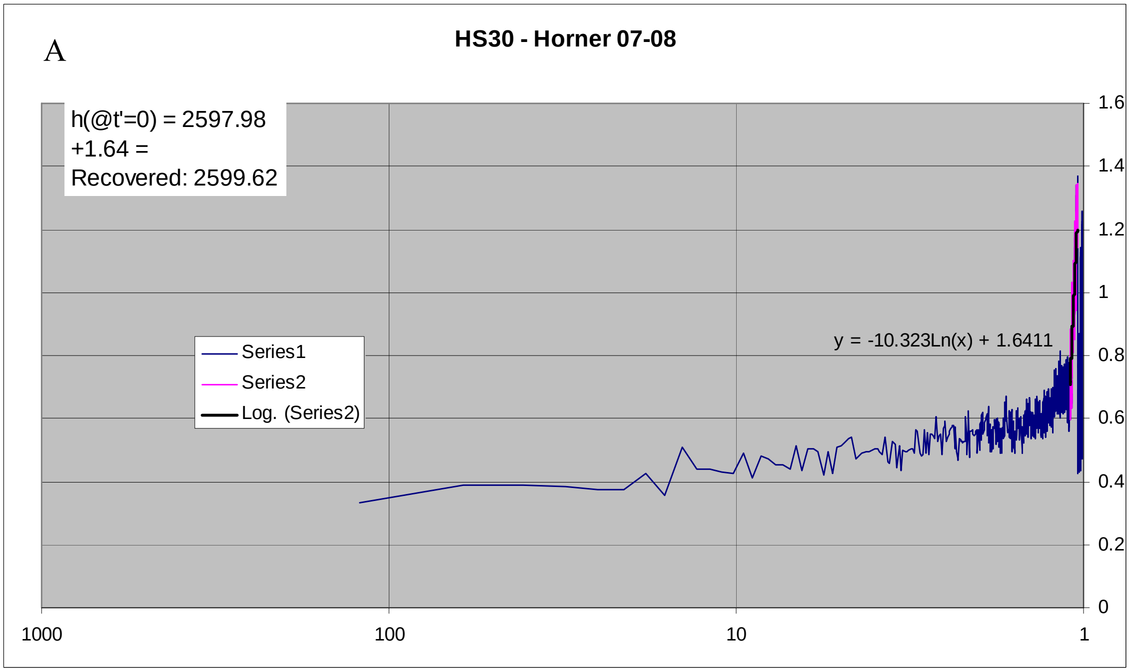


Figure A - 34: Horner recovery estimation HS29, 2008-09.



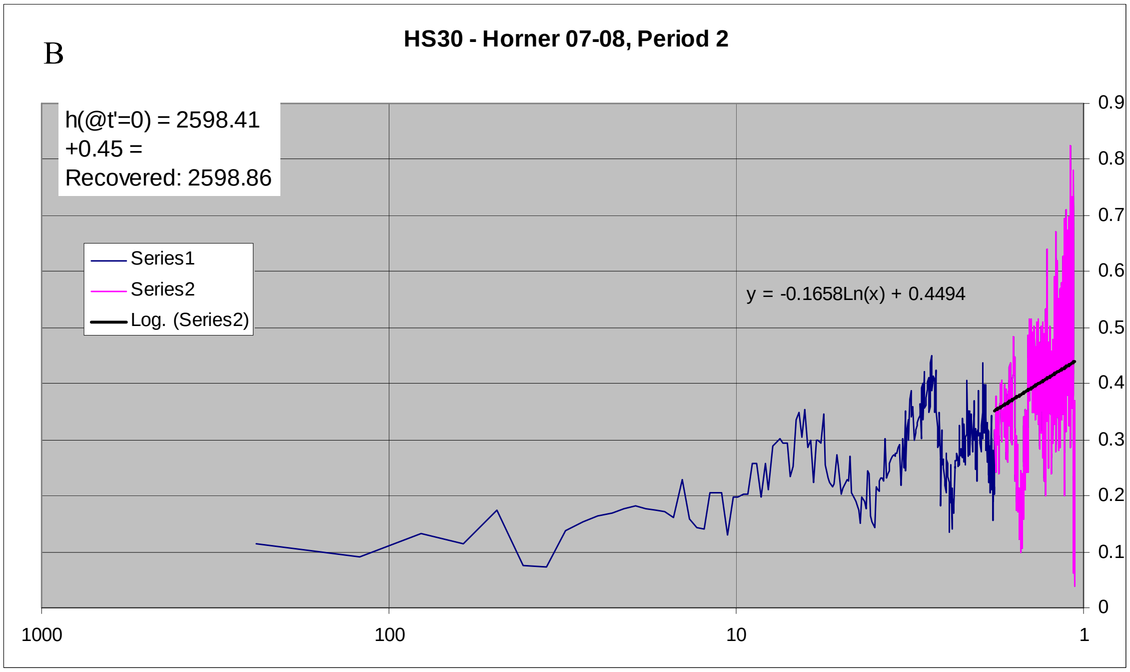


Figure A - 35: Horner recovery estimation HS30, 2007-08; (A) entire recovery period, (B) only the recovery after the final pumping event.

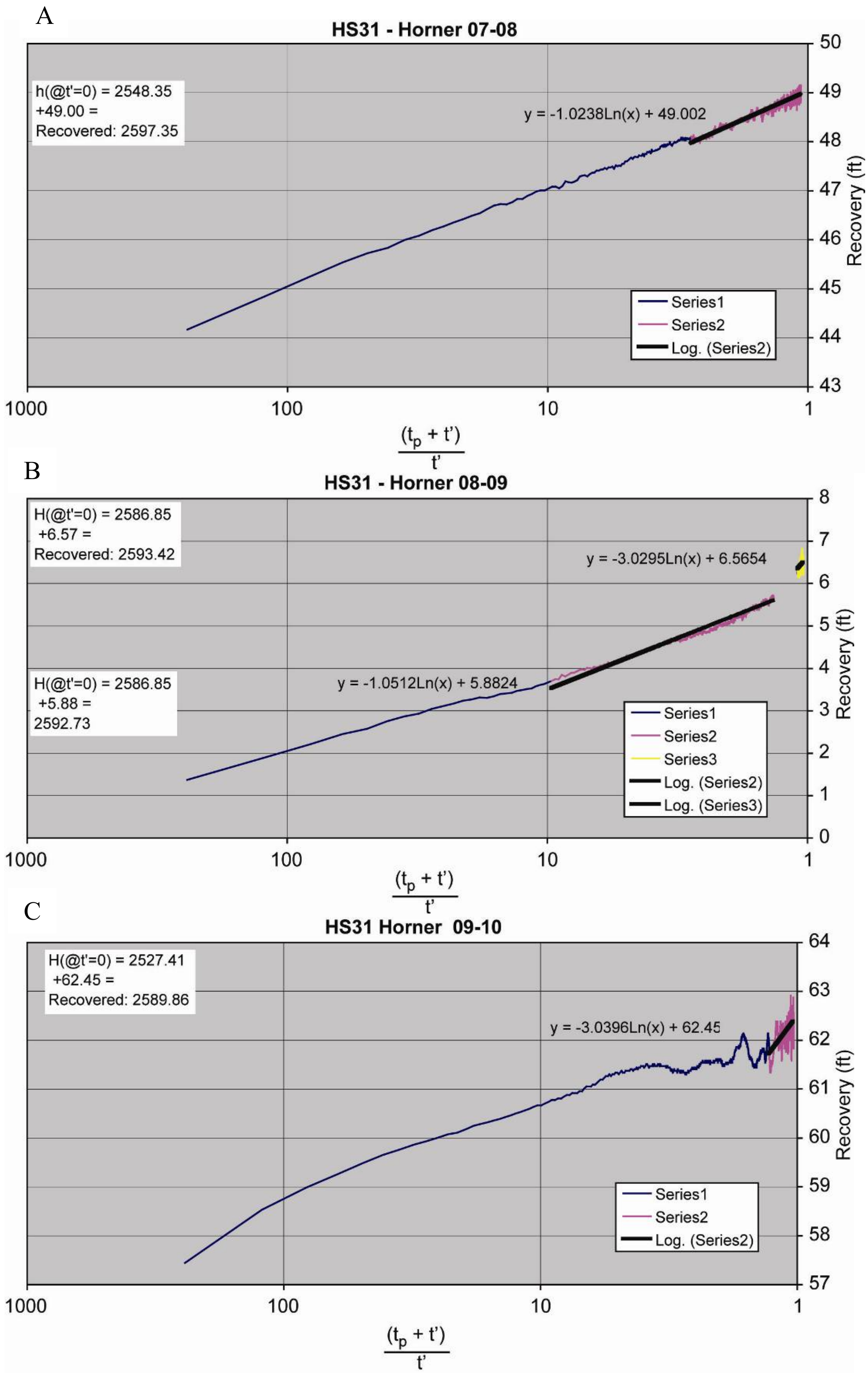


Figure A - 36: Horner recovery estimation HS31, (a) 2007-08, (b) 2008-09, and (c) 2009-10.

Appendix B: Thomas County Recovery Plots

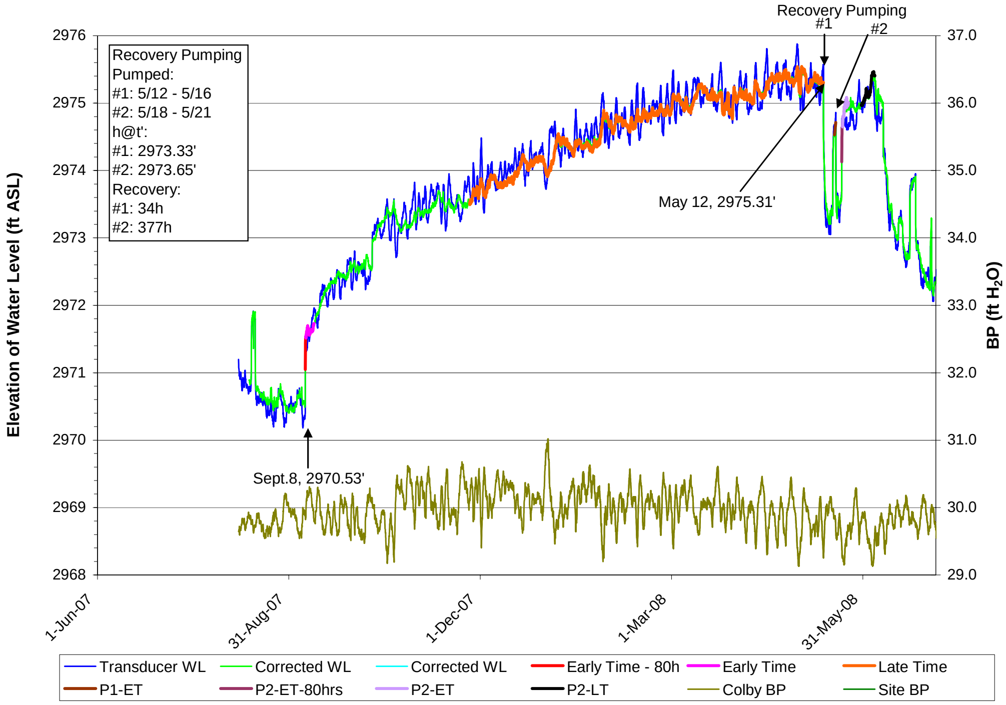


Figure B - 1: Thomas Co. index well hydrograph, barometric pressure, and corrected water level, 2007-08 recovery.

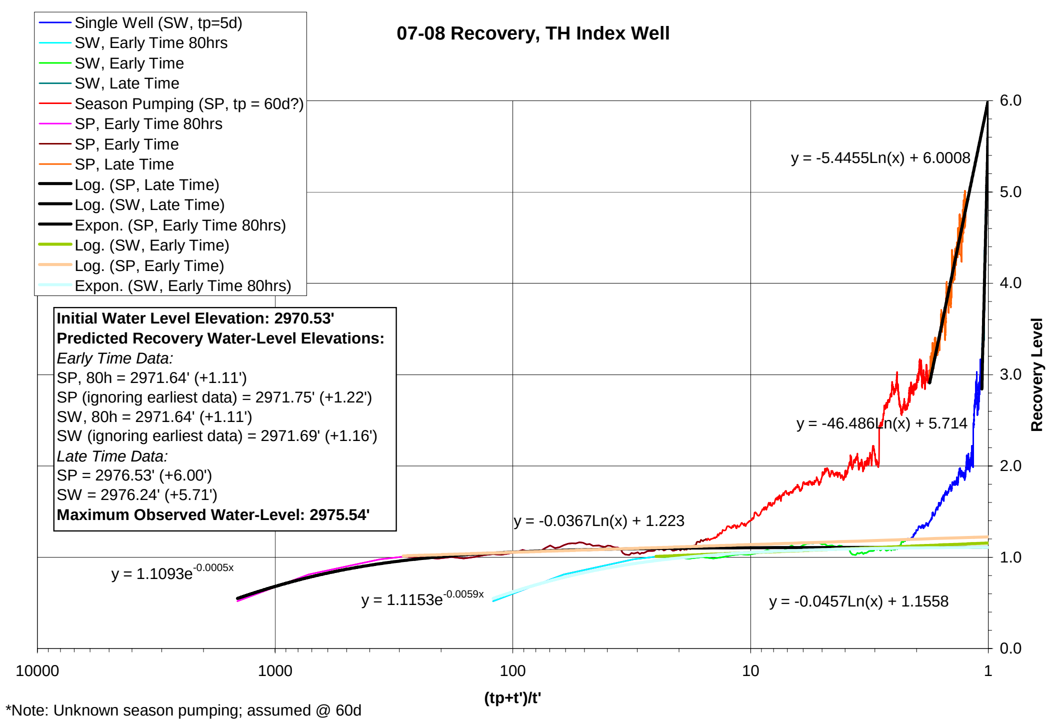


Figure B - 2: Horner recovery estimations, Thomas Co. index well, 2007-08 recovery season.

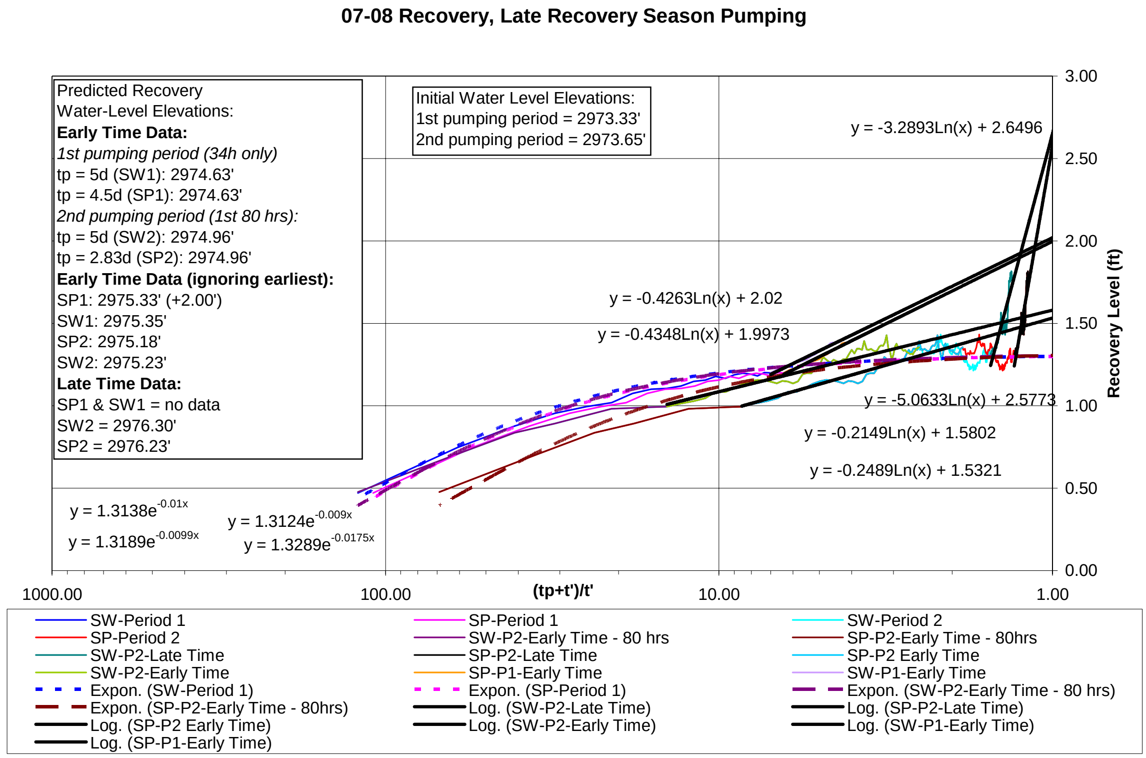


Figure B - 3: Horner recovery estimations, Thomas Co. index well, following pumping periods #1 and #2 in 2008.

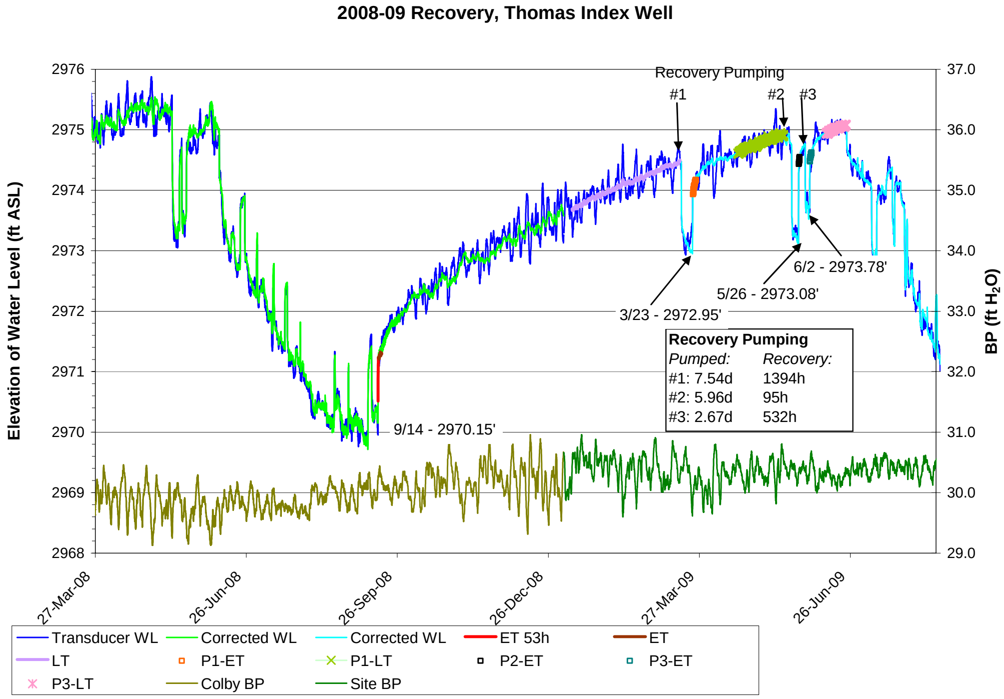


Figure B - 4: Thomas Co. index well hydrograph, barometric pressure, and corrected water level, 2008-09 recovery.

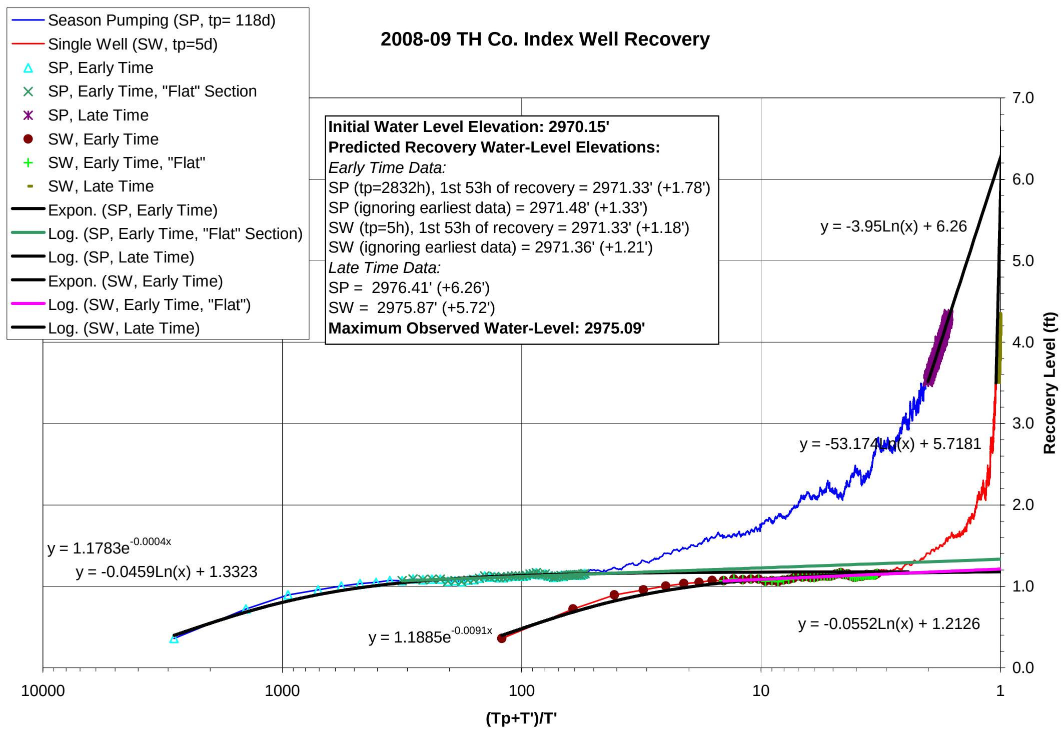


Figure B - 5: Horner recovery estimations, Thomas Co. index well, 2008-09 recovery season.

Thomas Co. 2008-09 Recovery, Late Recovery Pumping Periods

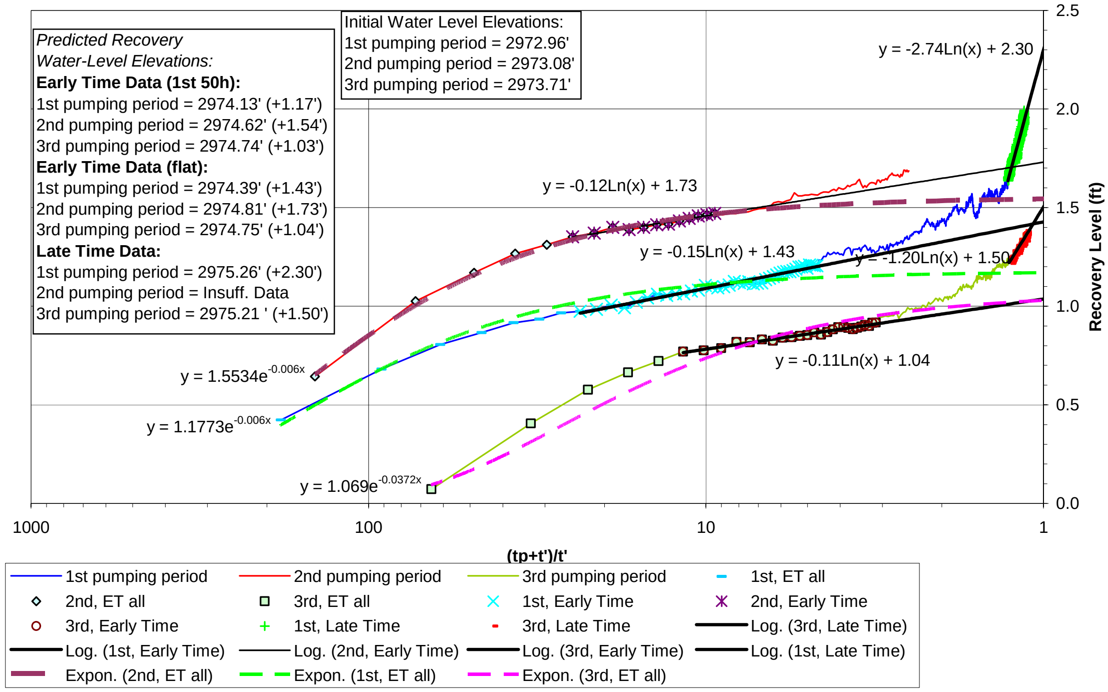


Figure B - 6: Horner recovery estimations, Thomas Co. index well, following pumping periods #1, #2, and #3 in 2009.

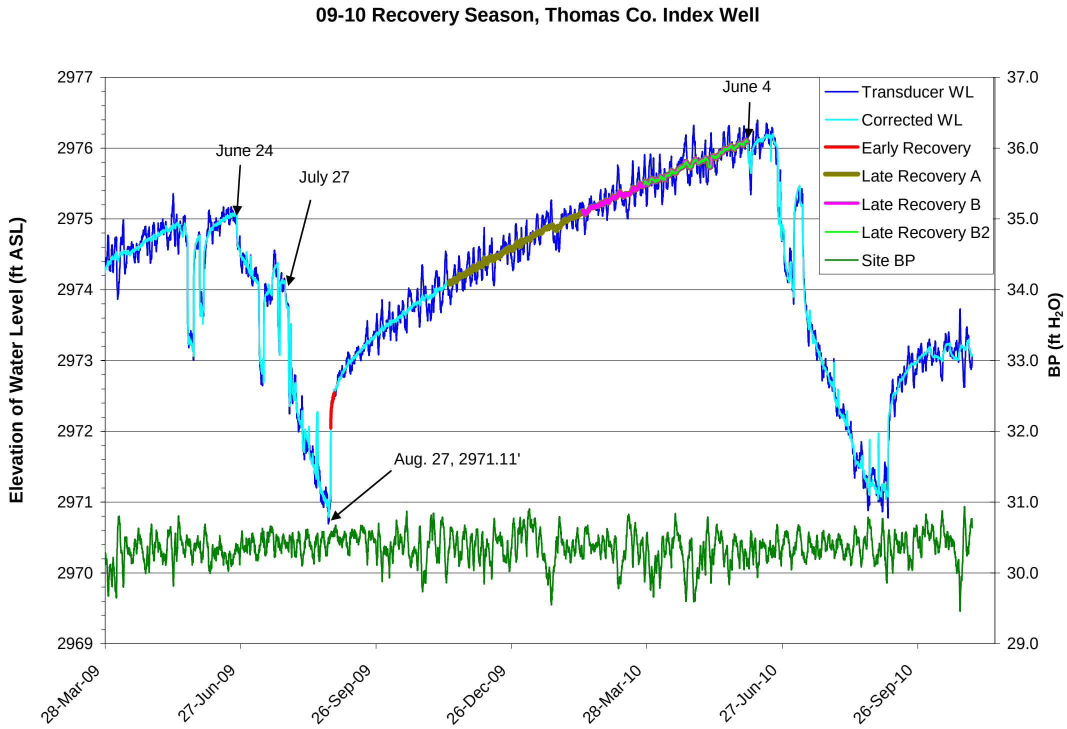


Figure B - 7: Thomas Co. index well hydrograph, barometric pressure and corrected water level, 2009-10 recovery.

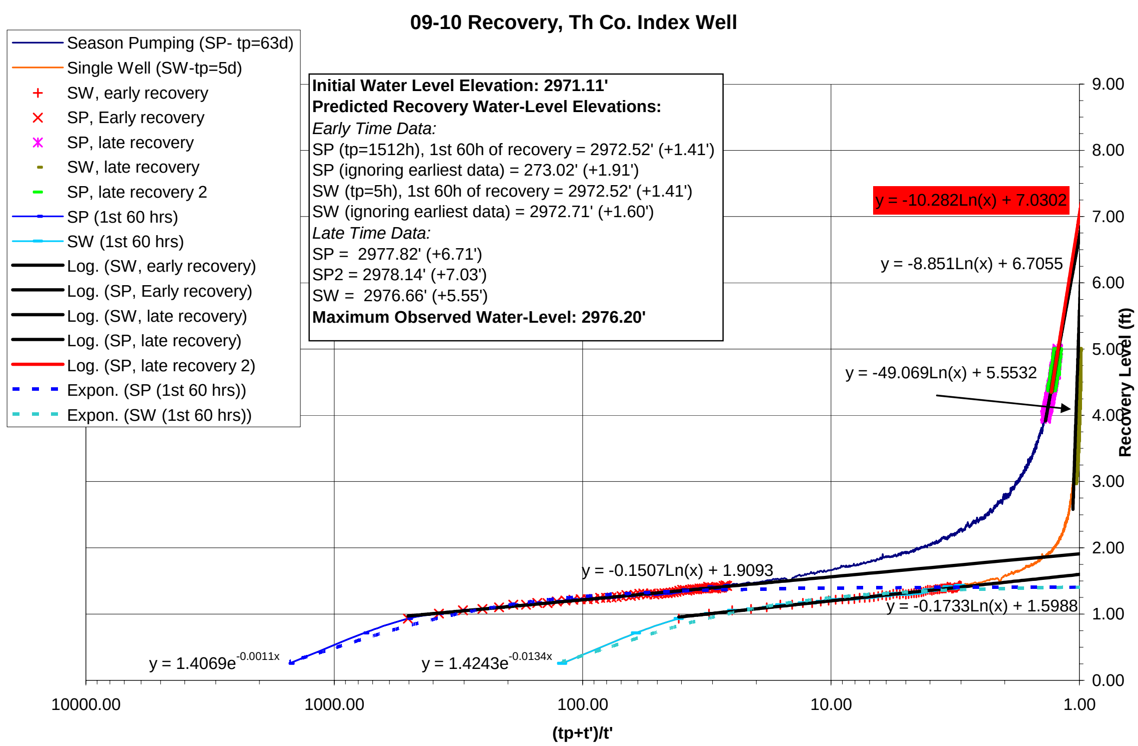


Figure B - 8: Horner recovery estimations, Thomas Co. index well, 2009-10 recovery season.

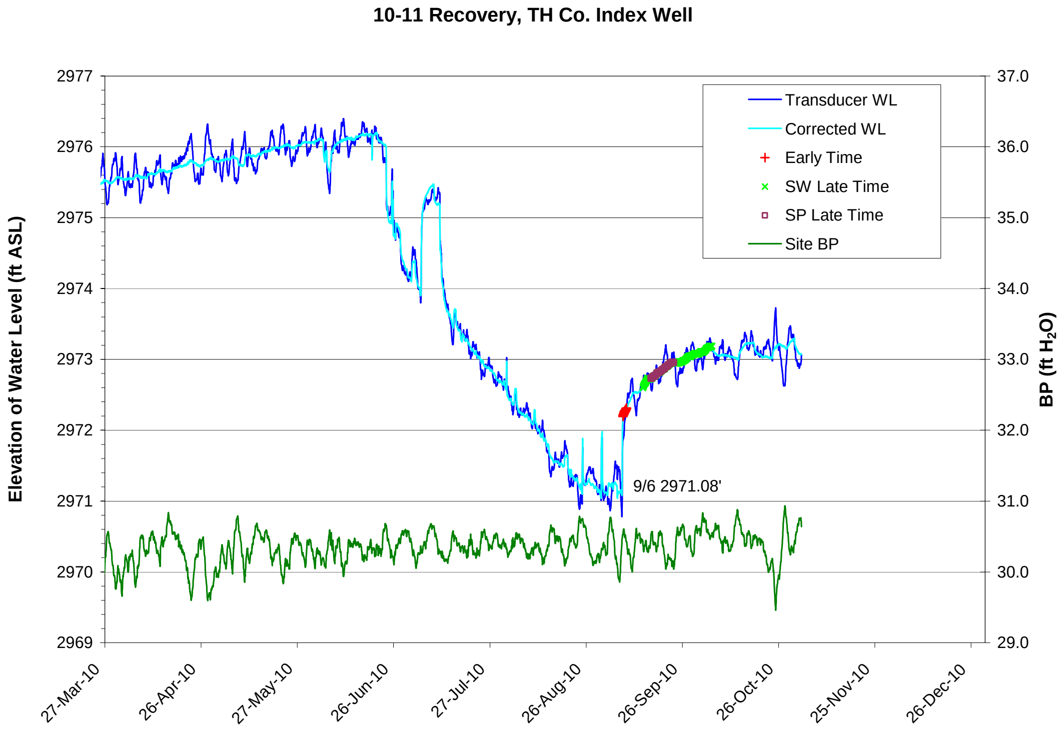


Figure B - 9: Thomas Co. index well hydrograph and corrected water level, 2010-11 recovery.

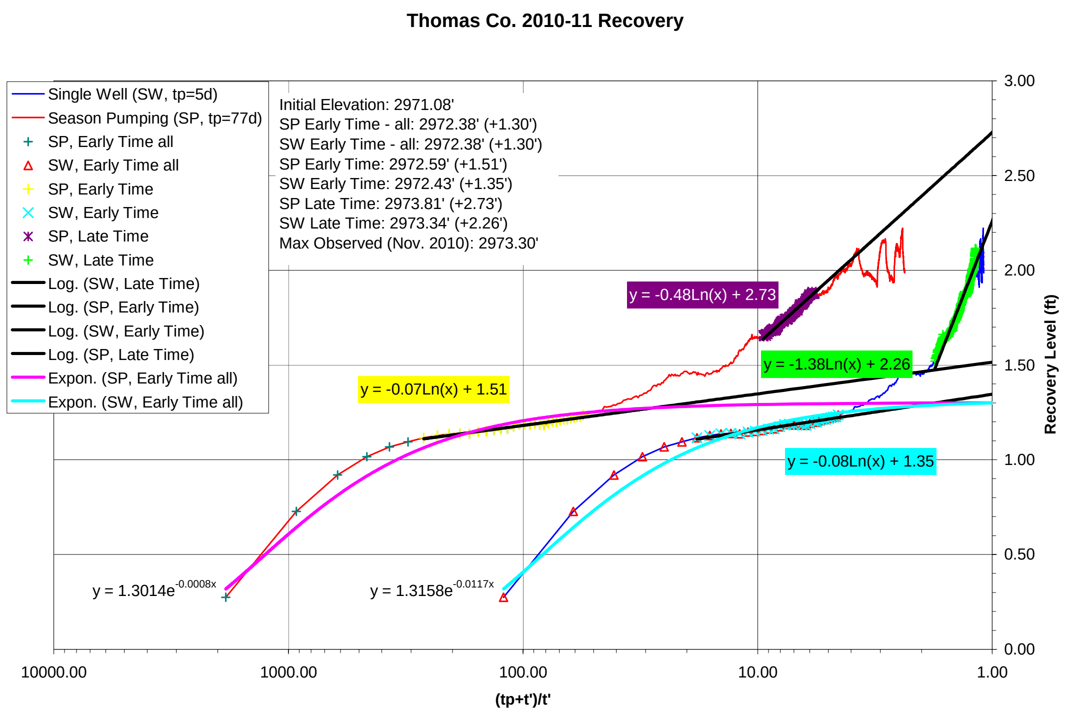


Figure B - 10: Horner recovery estimations, Thomas Co. index well, 2010-11 recovery season.

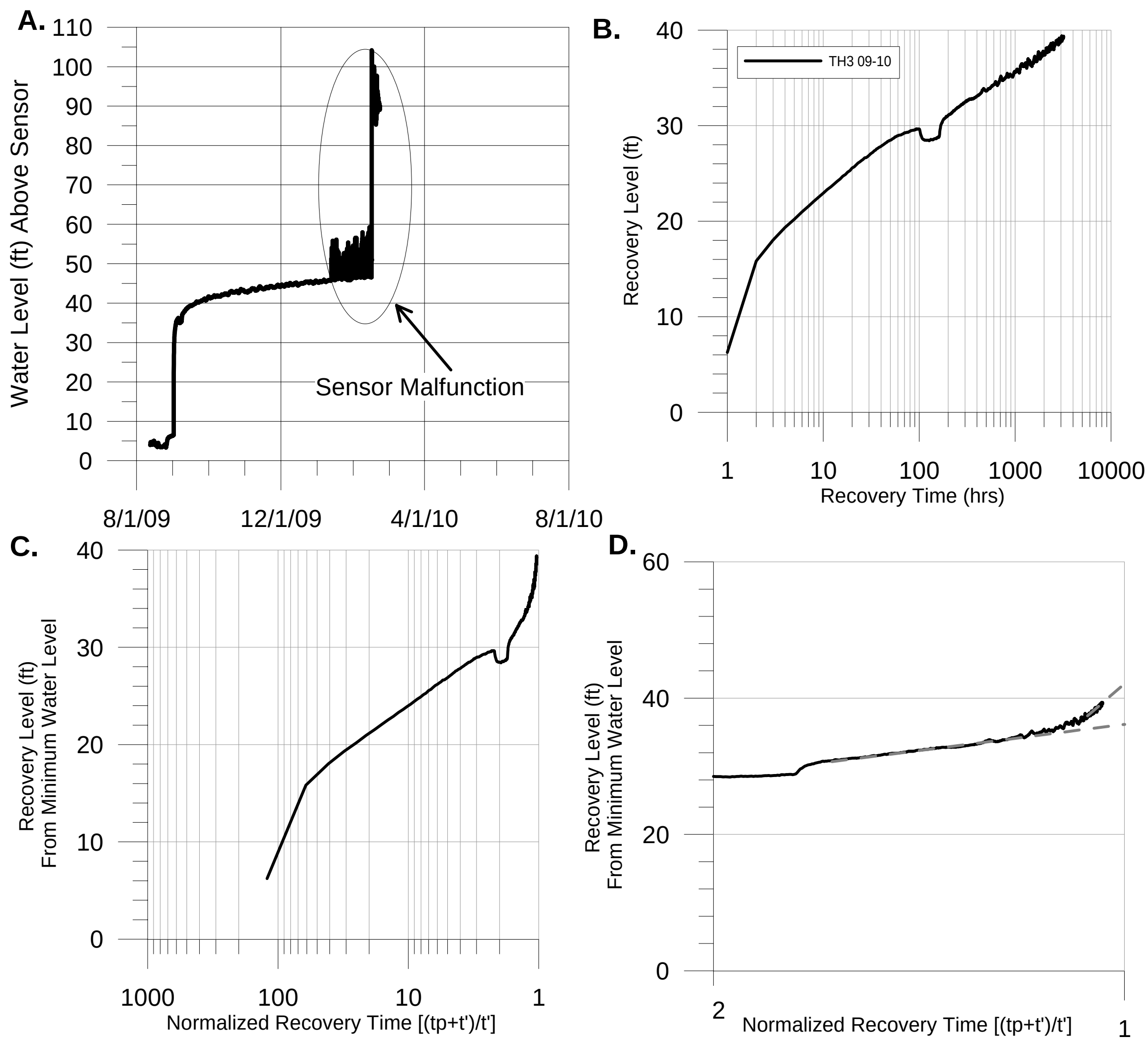


Figure B - 11: 2009-10 hydrograph (A) and recovery from Thomas Co. well TH3. Recovery is plotted as semi-log recovery (B) and as Horner recovery (C) and (D). The reference time and water level elevation for water level recovery are 8/25/2009 10:00, 2948.92 ft..

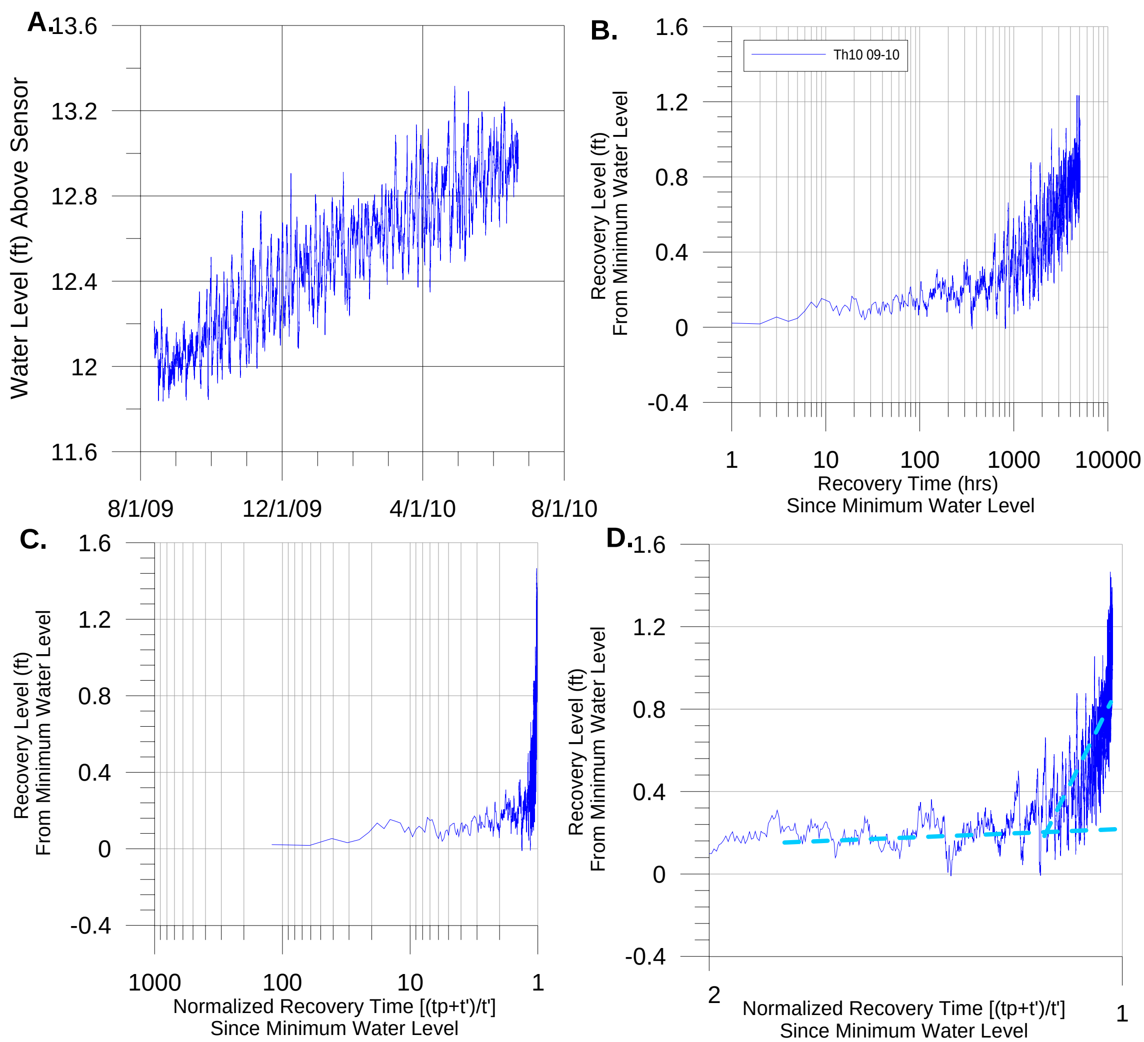


Figure B - 12: 2009-10 hydrograph (A) and recovery from Thomas Co. well TH10. Recovery is plotted as semi-log recovery (B) and as Horner recovery (C) and (D). The reference time for water level recovery is 8/25/2009 10:00. Surface elevation of the well is unknown, but estimated at 3132 ft AMSL from the Google Earth digital elevation model.

Appendix C: Using the KGS Barometric Pressure Correction Spreadsheet and Related Software (KGS_BRF.xls and kgs_brf.exe)

Introduction

Changes in barometric pressure affect water levels in all three index wells. These barometric-pressure-induced fluctuations in water level can introduce uncertainty into estimates of annual water-level changes at the index wells and elsewhere. The KGS has therefore developed an Excel spreadsheet to remove the effect of barometric-pressure fluctuations from water-level measurements. This spreadsheet calculates a Barometric Response Function (BRF) to characterize the relationship between changes in barometric pressure and changes in water level. This BRF is then used to remove (correct) the impact of fluctuations in barometric pressure from the water-level measurements. Further information about BRFs is provided in Appendix E.

File Management

The KGS barometric pressure correction software has two components, an Excel worksheet contained in the workbook **KGS_BRF.xls** and a compiled program (executable) named **kgs_brf.exe**. 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 to correct water levels using that BRF, 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 spreadsheet cannot work without access to the executable. At the moment, this means that 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.ex**e 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.

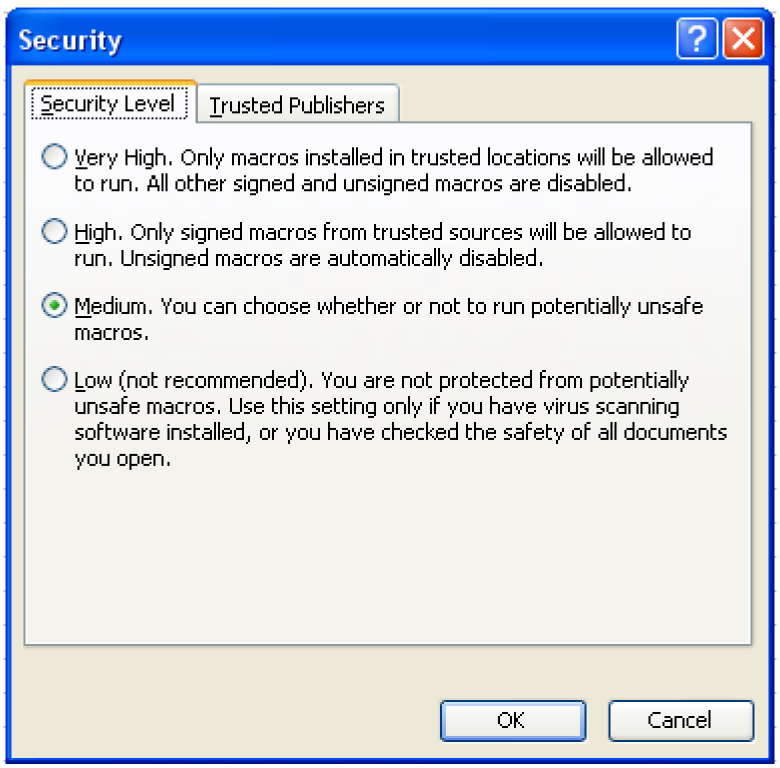
Furthermore, it is quite likely that you will end up using workbooks that are named something other than **KGS_BRF.xls**, anyway. The Excel Visual Basic code is directly attached to the **Input_Template** worksheet in the **KGS_BRF.xls**. This means that you can make copies of this worksheet and/or workbook, 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 are not allowed to 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 another report. The Visual Basic code attached to the **Input_Template** worksheet automates the process of generating the input files and reading the output files.

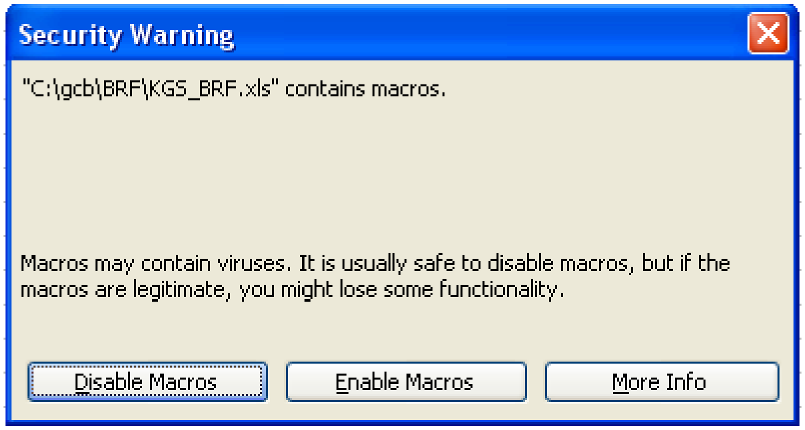
The Excel workbook (and included Visual Basic code) has been created in Excel 2003. It *should* also work in more recent versions of Excel.

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*:



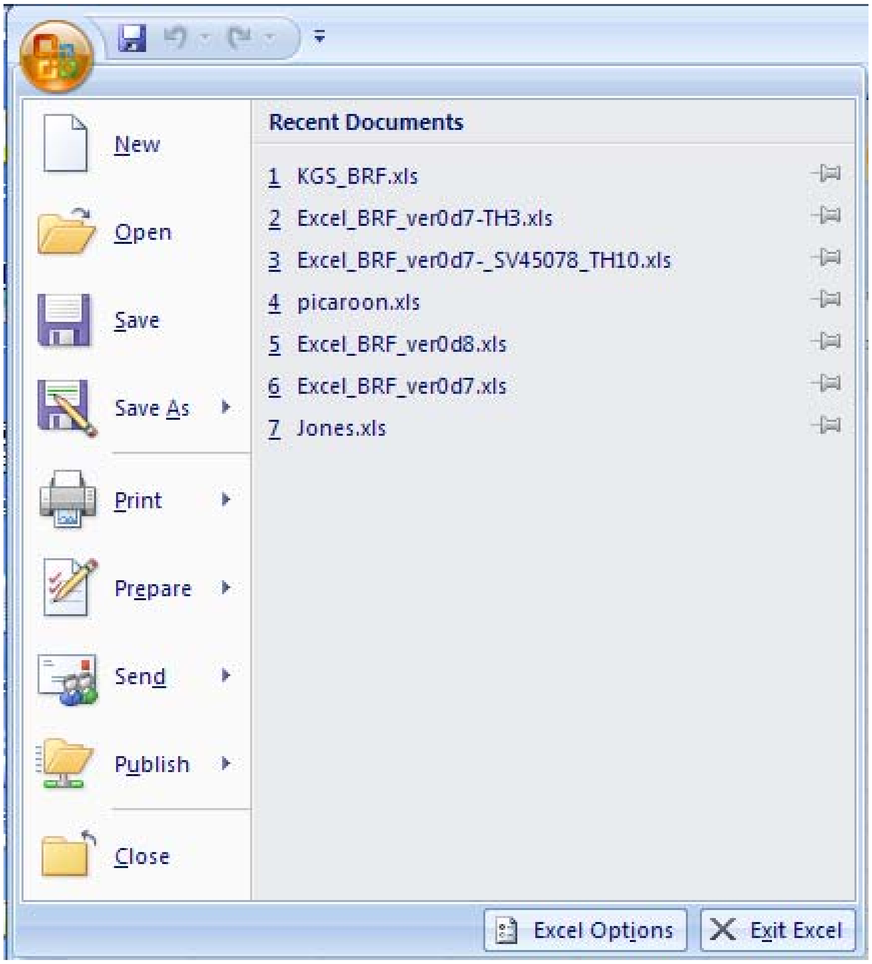
With the macro security level set to Medium, you will be presented with the following dialog box when you open **KGS_BRF.xls** (or any other workbook containing macros):



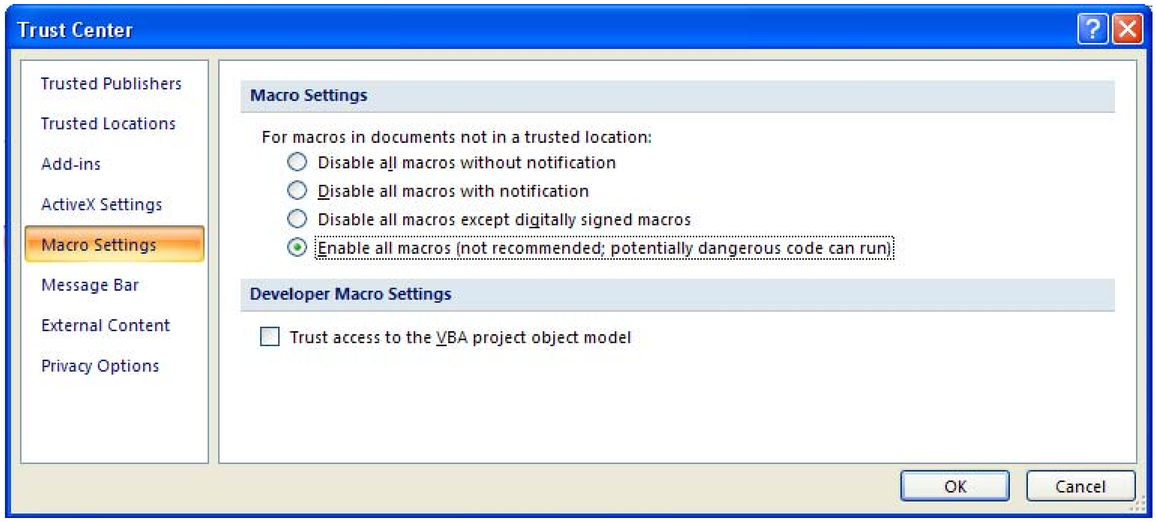
You should click the **Enable Macros** button on this dialog box. If you set the macro security level to *Low*, then Excel will just open a macro-bearing workbook with the macros enabled, without asking for your permission. As noted on the Security dialog box, this is not advisable.

In Excel 2007, you change the security settings as follows:

Select the Office button in the upper left hand corner of the Excel window to get the Office drop-down menu:



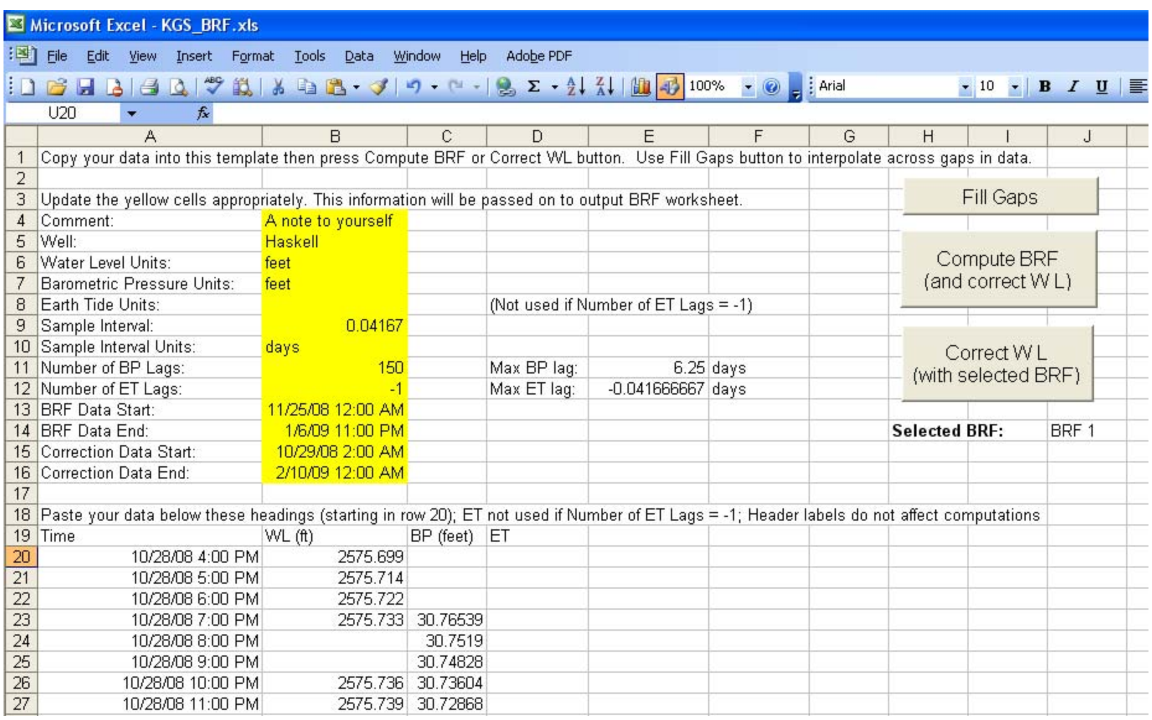
Select the **Excel Options** button on this menu, then select **Trust Center** in the list on left side of the **Excel Options** dialog box, then click the **Trust Center Settings…** button (on the lower-ish right), then select **Macro Settings** from the list on the left of the **Trust Center** dialog box, and then select **Enable all macros**:



This is the same as the *Low* security setting in Excel 2003. As the dialog box says, this setting is not recommended, but it will have to do until we figure out how to create digitally signed macros. Unfortunately, Excel 2007 does not have a macro security level corresponding to the *Medium* setting in Excel 2003.

The Input_Template spreadsheet

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



To use it, you do what the note in Cell A1 says: Copy your data into the template and then press the **Compute BRF** or **Correct WL** button (the latter requires that you have already done the former). This means that you paste your measurement time, water level, and barometric pressure data into columns A-C, starting at row 20, update the information in the yellow cells appropriately, and then press the appropriate button. Neither the BRF nor water level correction computations allow missing values in the measurements. If you have gaps in the data, like the water level 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, it is advisable to delete the old data first, by selecting the data from row 20 on down and then deleting it. Clearing the cells using the **Delete** button should be sufficient, or you can really mop things up by selecting all the cells (or rows) and then selecting **Delete…** from the **Edit** menu. 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 water level correction (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 times the sample number (index). The code behind the **Fill Gaps** button, however, actually employs 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 note to yourself regarding the data and/or analysis. It will be passed on to the output BRF and water level correction spreadsheets.

Well (cell B5): The well name

Water Level Units (cell B6): The units of the water level 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 10*.

Barometric Pressure Units (cell B7): The units of the barometric pressure 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 10*.

Earth Tide Units (cell B8): The units of the earth tide values. This information is not used if the number of earth tide lags is set to -1. If earth tide data are employed, the code will accept any units that you type into cell B8 and the earth tide 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 water level correction computations assume that the measurements are regularly sampled at the sample interval, and ignore the actual measurement time values listed in column A (except for the sake of 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., 0.04167 days if the measurements are one hour apart).

Sample Interval Units (cell B10): This entry defines 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 barometric pressure to use in the analysis. This means the number of values preceding the current water level measurement. A lag of zero means the barometric pressure measurement at the same time as the current water level measurement, so the number of BP values used in the analysis is actually 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, but since the code does not yet handle earth tides, this option presently does not make any sense.

Number of ET Lags (cell B12): Same as above, except for earth tide (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.

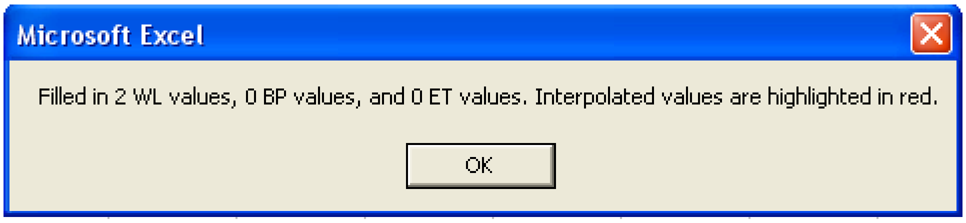
BRF Start Date and BRF End Date (cells B13 and B14): The BRF will be computed based on a subset of the data measured between the two date/time values specified in cells B13 and B14. The selection includes these two end points, assuming they correspond to actual measurement times in the data record.

Correction Start Date and Correction End Date (cells B15 and B16): The water level correction 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 water level correction 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 ET is used. For the sake of illustration, the WL and BP columns shown in the screen shot 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 spreadsheet 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 spreadsheet 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 correct for the influence of BP variations on the WL measurements in the spreadsheet 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 spreadsheet which is added to the current workbook. The name of this new spreadsheet will be **BRF *n***, where *n* is an integer. The code will count all the spreadsheets 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 cumulative coefficients (big A) with error bars.

If ET values are also employed, then the BRF worksheet will also contain the earth tide response function (ETF) coefficients and a plot of cumulative earth tide coefficients (big B) 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 water level correction 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 correct water levels, along with the barometric pressure 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.

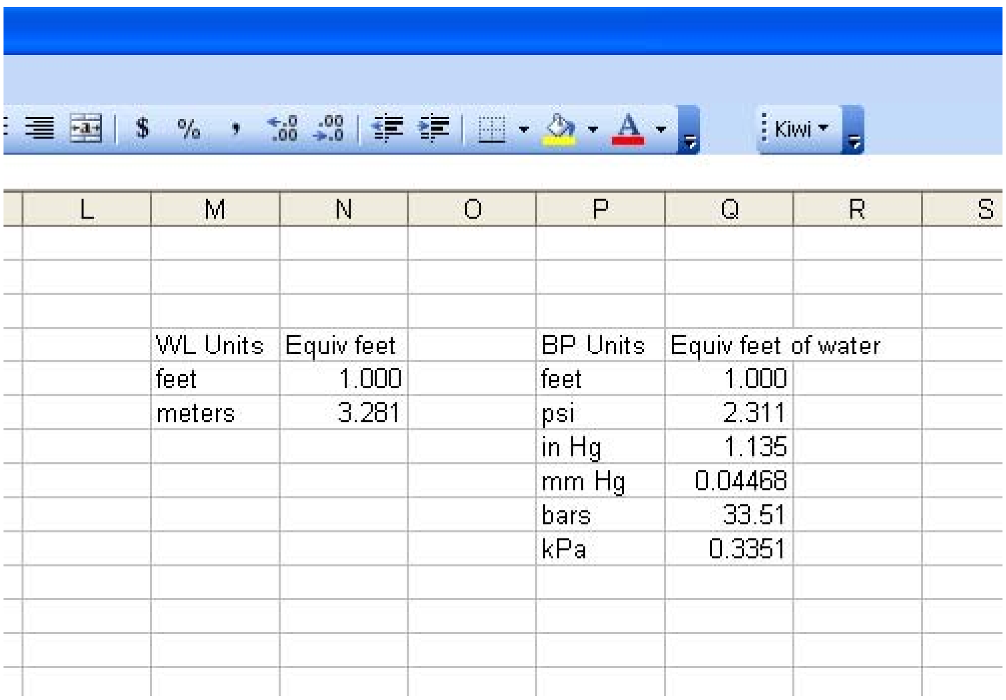
The listing of corrected water level values will not start until the number of measurements is equal to the number of BP lags plus 1. This is because this number of previous BP values has to be accumulated before the correction can be applied.

Correcting Water Levels (with selected BRF)

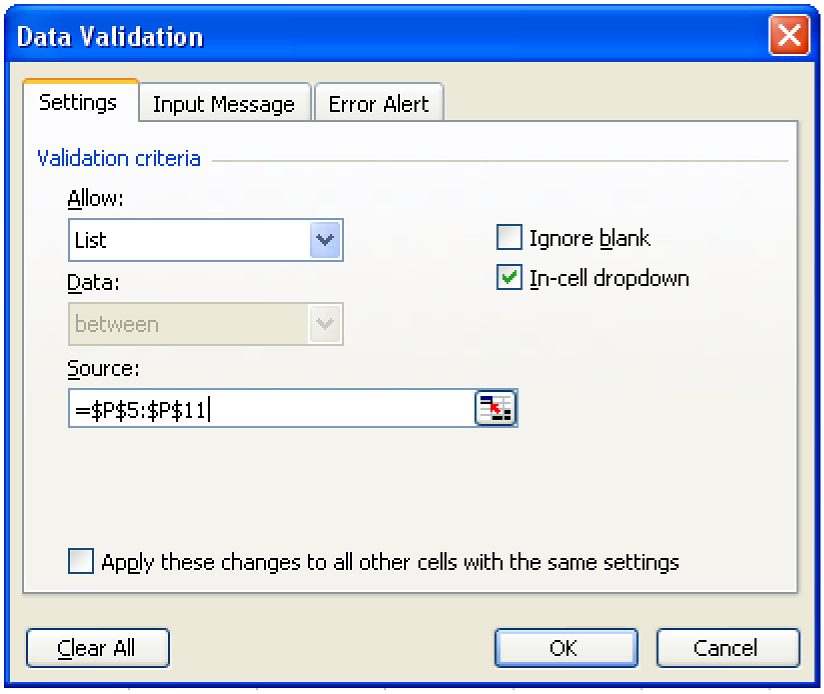
It is possible that you will want to correct a series of water level measurements using a BRF computed using some other series of measurements. You can accomplish this using the **Correct WL (with Selected BRF)** button. The correction will be applied to the measurements in the *Input_Template* worksheet (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.

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, at least in Excel 2003). 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:



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 (in Excel 2003), 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 *Atmospheres* to the list of allowable BP units, you could type *atm* in cell P11 and 33.96 in cell Q11 (one atmosphere corresponds to 33.96 feet of water at 68 degrees F), and then use the Data Validation dialog box to change the Source for the list in cell B7 to include cell P11:


Data Validation
Settings
Input Message
Error Alert
Validation criteria
Allow:
List
Ignore blank
In-cell dropdown
Data:
between
Source:
=$P$5:$P$11
Apply these changes to all other cells with the same settings
Clear All
OK
Cancel

Appendix D: KGS Four-township Thomas County Region Water Budget Study

Introduction

In 2005 a group of water right holders in southern Thomas County entered into discussions about the possibility of voluntarily forming a special groundwater management subunit within Groundwater Management District Number 4. The area in question was within a candidate region for designation as a priority subunit, as defined by the Kansas Water Office.

At the request of GMD4, the Kansas Geological Survey undertook a study of the area in order to assemble and interpret the available hydrogeologic information within the area of interest. This was formulated as a water budget for the area in question, in order to provide the interested parties with the best available quantitative estimates so that they could explore possible "what-if" effects of various decisions or management scenarios.

The study was completed under time pressures imposed by meetings and practical deadlines already scheduled within GMD4. The attached material was prepared and made available for both internal and external review on January 12, 2006, and was presented at a public meeting in GMD4 on January 20.

Although the data assembly and analyses were rigorously and carefully performed, time did not allow development of the presentation into either a fully technical report or a document completely oriented to the lay public. In spite of its technical merit, it was not issued as a formal KGS publication or open-file report because of the lack of stylistic development and completeness.

The existence of the budget study was one of the reasons for siting the GMD4 experimental index well within the area. The increasing inventory of quantitative data obtained from that well and other expansion wells within the study area are in turn meshing with the budget study to suggest further explanations and hypotheses for characteristics and behavior of the groundwater resources in the area.

In order to make the findings available in a more formal, citable fashion, the original report is included as an Appendix in this open-file report.

Water Budgets, Four-township Thomas County Region

R. W. Buddemeier, D. P. Young, B. B. Wilson

Background

The four townships outlined in Figure D - 1 are the target of a water budgeting exercise. Groundwater flow in the area is generally from west to east; this, plus the absence of significant development to the west and the south make the area of interest rather hydrologically isolated. There may be some interactions with wells external to the area along the north boundary in general, and along the south boundary of 9-32, but it seems like a very good first approximation to treat the region as an isolated entity.

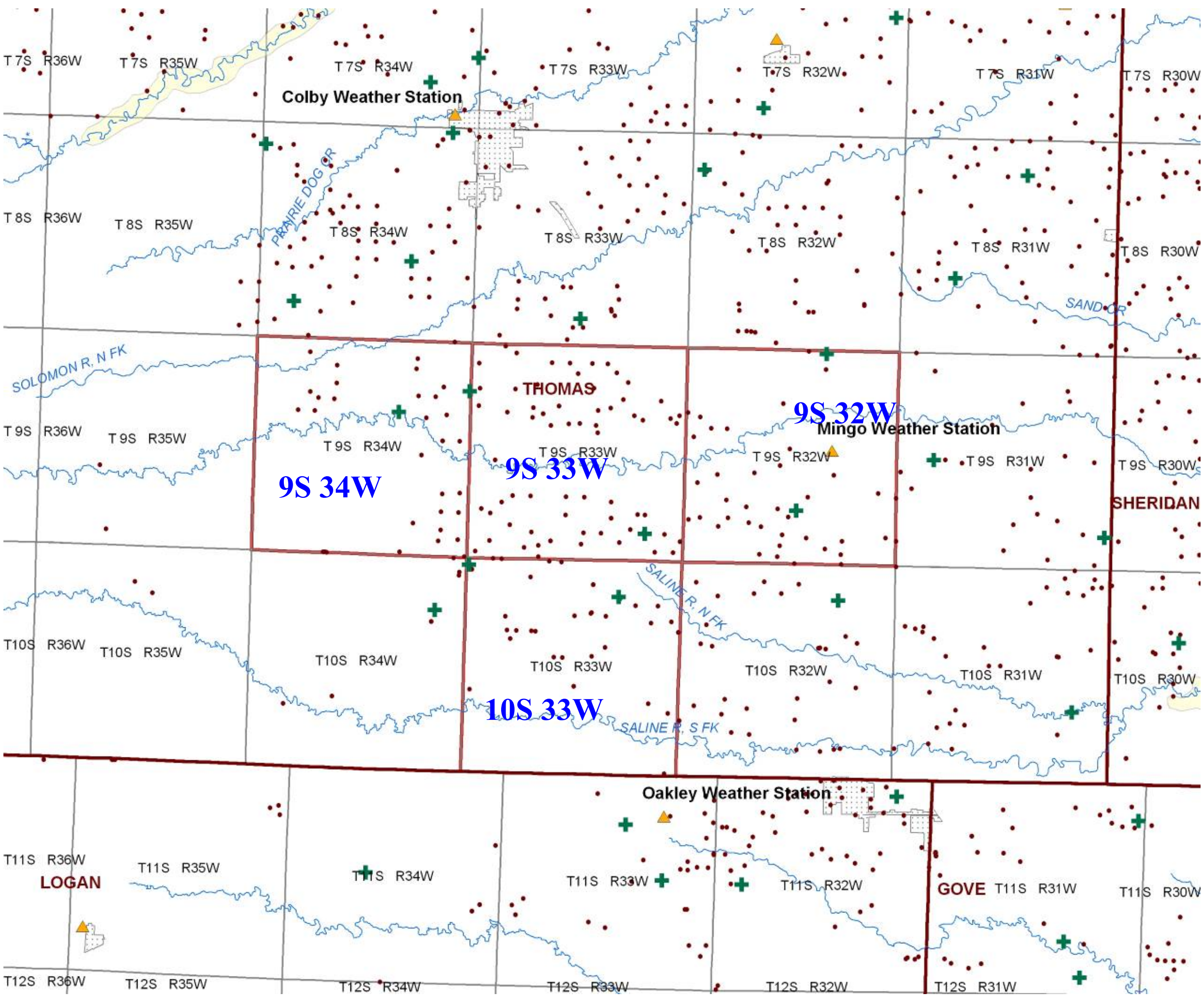


Figure D - 1: T. 9 S. Rgs. 32-34, and T. 10 S., R. 33 W., in Thomas County, with surrounding area. Dots are water rights locations and crosses indicate monitoring wells.

Within the four townships, the wells can be grouped by township or by some other affinity grouping (for example, N and S of the South Fork Solomon River).

The objectives in constructing the water budget(s) are to obtain better information on the feasibility and potential effects of instituting a water conservation program in the area that would extend the usable life of the aquifer, and to provide both general and specific information to the irrigators in the area.

The conceptual basis is shown in the Figure D - 2. The primary measure of concern is the amount of groundwater in storage (saturated thickness times area times specific yield). If inputs are equal to outputs, the water level will remain constant; if not, the volume will change (reflected in a rise or decline in the water table).

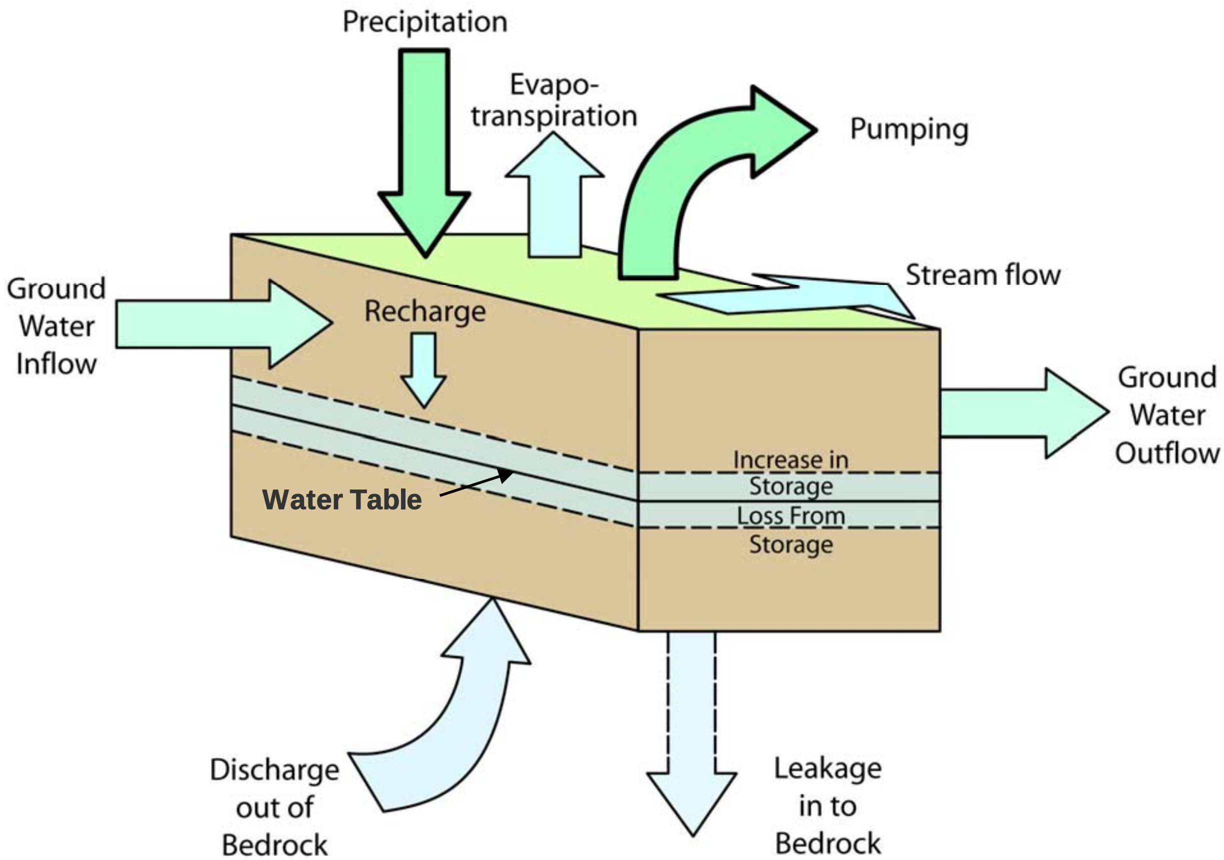


Figure D - 2: Terms in the water budget of a region. If water loss is greater than gain, the elevation of the water table will decline. Typically, we have measurement-based estimates of annual pumping, precipitation, and annual water table elevation, plus some data on bedrock elevation, and the specific yield and hydraulic conductivity of the aquifer.

Data Used

Data used for the analysis were primarily derived from the KGS section-level database for the High Plains aquifer (http://hercules.kgs.ku.edu/geohydro/section_data/hp_step1.cfm) and from updates to that dataset (all section-scale values assigned to section center coordinates prepared by Brownie Wilson). These updates include

1. Annual water table elevations, 1996 through 2005 (individual year data, not multi-year averages).
2. Changes in water table elevation, 96-97, 97-98, 98-99, 99-00, 00-01, 01-02, 02-03, 03-04, and 04-05. These were calculated from the changes in the individual year elevations at each monitoring well, and the change values interpolated to the section centers.
3. Reported water use for each section for the years 1996 through 2004.
4. Use-density, 2 mile radius - this smoothes the water use by averaging the individual points over a 2 mile radius, combining and extending the effects of unevenly spaced wells to give a better picture of the effects on the water table over a reasonable zone of pumping influence. Only a two-mile radius (rather than the usual 2, 5 and 10 mile calculations done for the aquifer as a whole) was used in order to minimize the edge effects that would be substantial because of the extensive and rather distinct boundaries between irrigated and non-irrigated areas.
5. Hydrographs and measurements for the monitoring wells and others in the area from the KGS Wizard database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html).

In addition, we acquired the monthly NCDC precipitation data for Colby, Mingo and Oakley (http://lwf.ncdc.noaa.gov/oa/ncdc.html). The experience and local knowledge of GMD4 and DWR staff familiar with the area, and of local irrigators, was also taken into consideration. Other information available includes the KGS WWC5 well log database and available literature, in particular the dissertation of Gary Hecox, who performed a detailed model analysis of the GMD4 region (Hecox 2003).

Budget Components – Description and Assessment:

Water Elevations and Changes

Water elevations and changes are measured annually in early January by KGS and DWR. The primary measurement is of depth to water from a datum, and the best available estimate of the elevation of the datum is used to calculate the water table elevation at that point. Water table elevations at other locations are calculated using a triangulation interpolation network (TIN) to create a calculated surface connecting three wells, and then sampling the elevation of the surface at the point of interest. Figure D - 3 shows the monitoring wells and TIN network for the region of interest.

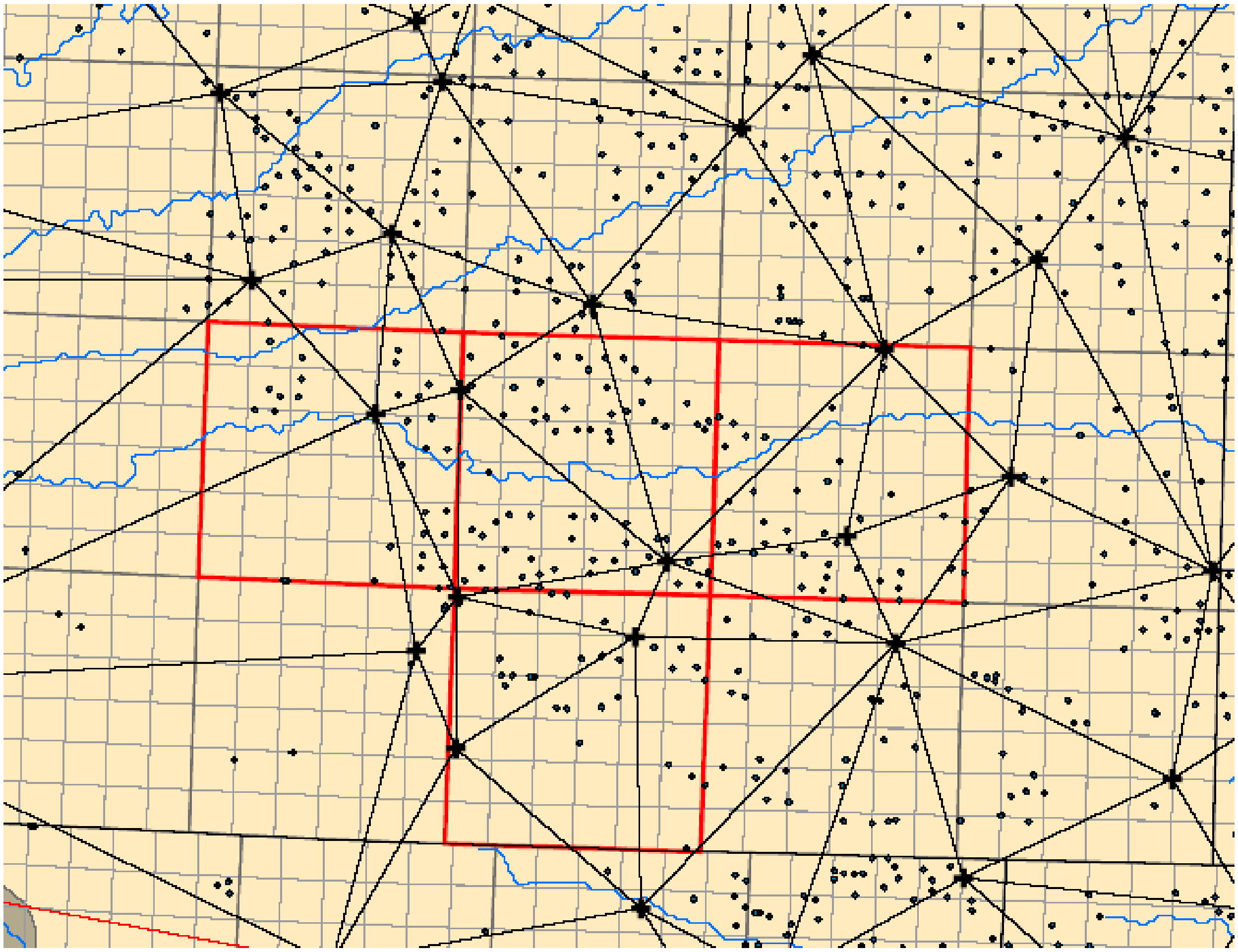


Figure D - 3: The four townships of interest are outlined in red; wells used by the annual monitoring program are indicated by crosses, and points of diversion by dots. The lines connecting the monitoring wells define the TIN boundaries used to calculate water levels that fall between the measuring points.

The well network was originally designed based on a well density that corresponded approximately to one per township, but in some areas this has been highly modified due to problems in finding accessible wells in good condition.

As a general rule, the results of the annual monitoring program are regarded as being suitable for assessing changes in the state of the groundwater resource over times of 5-10 years and spatial scales greater than a township in size. This is because there are a number of potential errors and uncertainties in assuming that the measured water level is an accurate representation of the region around it, and all wells are measuring comparable conditions, corresponding to a water table that is nearly recovered from seasonal pumping stresses. Over small times and distances, these uncertainties can result in misleading results, but over longer times and distances they tend to "average out," resulting in a robust estimate of general trends.

Any program evaluating programs or managing resources at local or aquifer subunit level will almost certainly need to obtain more, and possibly different, measurements than provided by the annual monitoring program. Because we are pushing the data to its useful limit in trying to evaluate water budgets over times of years at the township level, we list some of the major possible perturbations of the data:

1. Interference by pumping – wells are not necessarily always shut down outside of the irrigation season, and if a monitoring well or nearby wells have been recently pumped, an artificially low water table will be measured – and the following year the water table will show an apparent rise.
2. Incomplete recovery – even if all wells in an area have been off for the preceding four months, the water table may not have fully recovered by early January. This has been demonstrated in a variety of studies, and since the degree of recovery is likely to vary from year to year, the relationship to a stable water table is a moving target.
3. Accuracy of land surface elevation – well elevations are estimated from a topographic map and rarely can be considered to be accurate to better than $\pm$ 5 feet. This has no effect on differences measured in the same well, but if wells are added or replaced, there can be a relative shift in local water table elevations. In addition, when elevations are used to calculate hydrologic gradients to determine the direction and rate of groundwater flow, errors in elevation can have a significant effect (see the calculations discussed below).

Water Extracted

Water extracted was determined from the KGS WIMAS database (http://hercules.kgs.ku.edu/geohydro/wimas/index.cfm). Reported water use for the nine years considered was extracted for each section with active water rights, and included in the update database. Table D - 1 and Figure D - 4 show the township-level use value sums.

Table D - 1: Acre-feet per year of reported use for the four townships.

Twp/Year	1996	1997	1998	1999	2000	2001	2002	2003	2004
9-32	3993	4164	3786	3326	4738	3498	4504	3884	4275
9-33	7949	9558	7813	6247	11174	8382	10353	9398	9940
9-34	3720	4307	3568	2706	4724	4063	4985	4540	4548
10-33	3144	3876	3436	2996	4134	3277	4181	3863	4343
ALL	18806	21905	18602	15276	24771	19220	24022	21685	23106

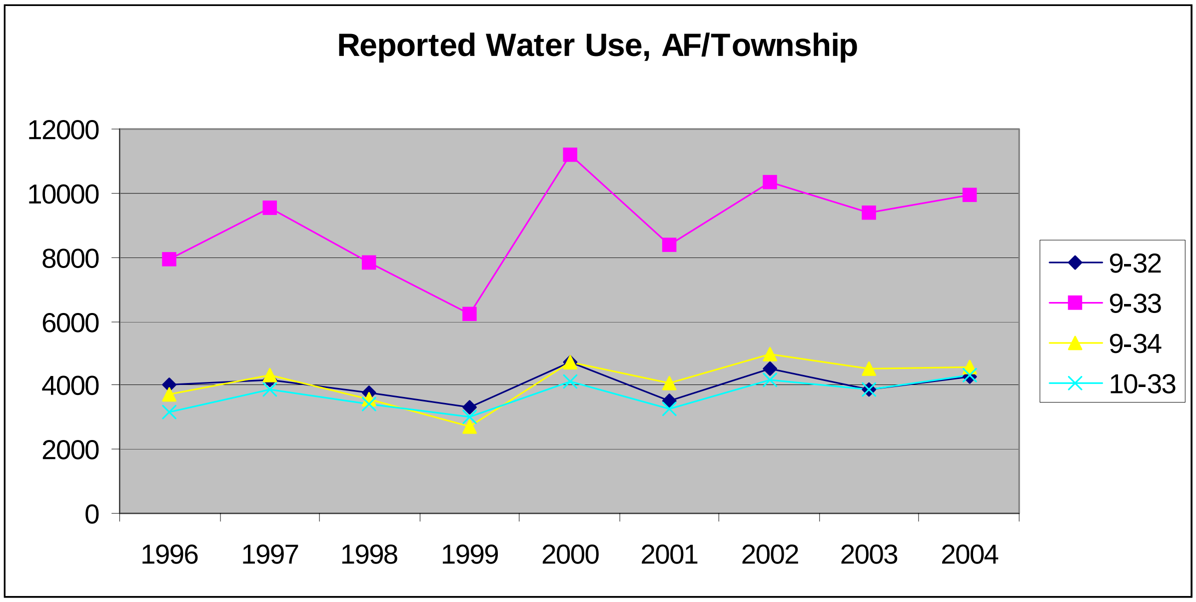


Figure D - 4: Reported water use for the four townships. Note that patterns of use are very similar, and that there is a slight rising trend that counters the declining trend in precipitation (Figure D - 5).

Although there is an uncertainty of about 20% in the relationship between the reported values and the actual volume pumped (Hecox, 2003), the year-to year changes are probably quite accurate on a relative basis. Overall, these are some of the best quantitative data that we have to work with in the budgeting process. For comparison, if one inch of rain fell uniformly on a standard-size township, the volume of water deposited would be 1920 AF. If this same amount of water were transported to the water table with perfect efficiency and the aquifer had a specific yield of 17%, the water table elevation would rise by ~0.59 ft. If there were not replacement for any of the water shown above as pumped, the water table would be expected to fall about 2 ft./yr under 9-33, and slightly more than 1 ft./year under the other townships.

Precipitation Data

Precipitation data for the three weather stations close to or in the area of interest are shown in Table D - 2 and Figure D - 5 and Figure D - 6. All three stations show similar patterns, with no systematic differences, so the average was applied to all four townships. Although most of the precipitation returns to the atmosphere through evapotranspiration, the amount of precipitation during and just before the growing season can influence water demand for irrigation during that year, and precipitation is also a factor in determining the amounts of both natural and "enhanced" recharge, which is discussed subsequently.

In general, most recharge originates with infiltration during the wettest years, and the increase or decrease in water demand is typically seen most clearly in very dry or very wet years.

Table D - 2: Precipitation measurements in and near the Thomas County area of interest (See Figure D - 1 for station locations).

YEAR	GROWING SEASON (MAR-OCT)					ANNUAL				
	COLBY	MINGO	OAKLEY	AVG	STD DEV	COLBY	MINGO	OAKLEY	AVG	STD DEV
1990	15.53	16.43	17.91	16.62	1.20	18.12	18.68	20.88	19.23	1.46
1991	15.9	17.69		16.80	1.27	18.81	21.08		19.95	1.61
1992	22.27	20.63		21.45	1.16	26.24	23.91		25.08	1.65
1993	26.24	26.87	22.36	25.16	2.44	30.79	29.71	25.12	28.54	3.01
1994	21.26	16.12	18.81	18.73	2.57	24.42	18.72	21.51	21.55	2.85
1995	21.37	18.94	16.38	18.90	2.50	22.22	20.05	17.72	20.00	2.25
1996	25.59	17.16	22.33	21.69	4.25	26.09	18.17	23.42	22.56	4.03
1997	18.4	18.16	16.84	17.80	0.84	20.19	21	19.02	20.07	1.00
1998	19.38	17.83	18.34	18.52	0.79	22.41	21.68	22.79	22.29	0.56
1999	18.64	20.17	18.97	19.26	0.81	19.32	21.11	19.87	20.10	0.92
2000	14.35	16	15.9	15.42	0.93	16.37	18.24	18.16	17.59	1.06
2001	15.42	16.88	20.25	17.52	2.48	18.61	20.11	22.64	20.45	2.04
2002	12.81	9.49	14.39	12.23	2.50	13.7	9.72	15.05	12.82	2.77
2003	13.85	12.89	10.7	12.48	1.61	14.52	13.61	11.91	13.35	1.32
2004	16.78	16.44	16.84	16.69	0.22	20.07	19	19.83	19.63	0.56
9604 avg	**17.25**	**16.11**	**17.17**	**16.84**		**19.03**	**18.07**	**19.19**	**18.76**	
9604stdev	**3.88**	**3.16**	**3.39**	**3.08**		**3.87**	**3.96**	**3.79**	**3.54**	

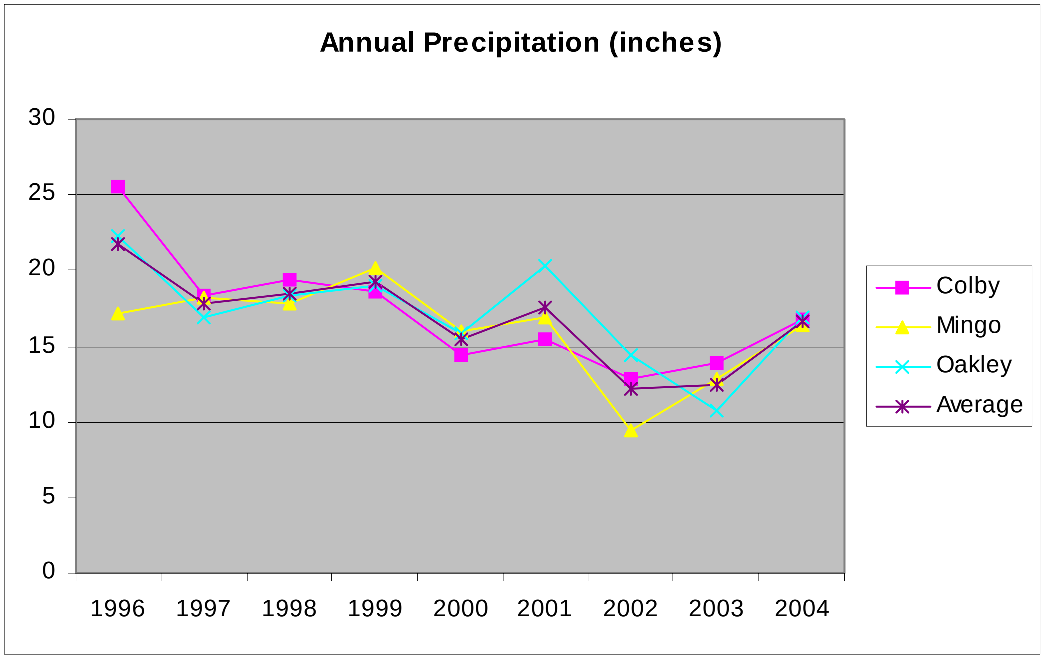


Figure D - 5: Total annual precipitation values for the years 1996-2004 for the three weather stations in or near the area of interest. Note that the period preceding 1996 was generally relatively wet (see Table D - 2).

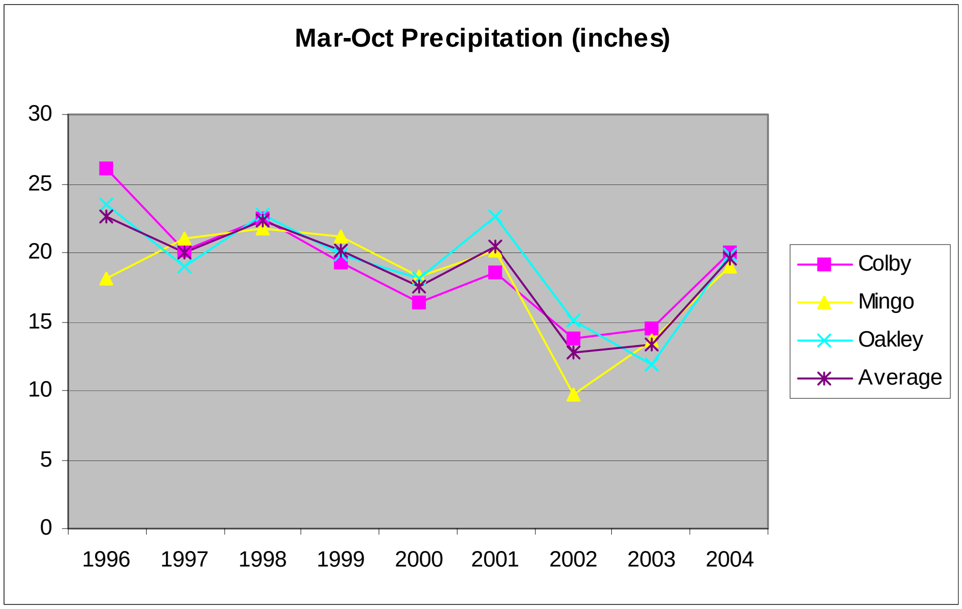


Figure D - 6: Rainfall during the months associated with the growing season, for the same time periods as shown in Figure D - 3.

Groundwater Flow

Groundwater flow cannot be measured directly, but must be calculated from other data. Average fluxes in and out of the pilot area were estimated for the nine-year period. We determined both N-S and E-W water table gradients at each township boundary for each row or column of sections, and summed the flows calculated from those results.

Input data included water levels and bedrock surface elevations from the KGS section-level database and USGS hydraulic conductivity (which has been incorporated into the section-level database).

Darcy's Law was used to calculate groundwater flow with the following formula:

$Q = KiA$, where

Q = flow (ft^3/day) and converted to (af/yr)
K = hydraulic conductivity (ft/day)
i = hydraulic gradient (unitless)
A = cross sectional area of saturated portion of aquifer (ft^2).

Saturated thickness is the difference between the water table and bedrock elevations.

West to east and north to south cross sections were produced for all the rows and columns of sections using the data mentioned above. The cross sections extend one township west, east, and north of the pilot area, but only a short distance to the south because of lack of data. In addition to the data listed above, predevelopment water table and land surface data from section-level database were also obtained and plotted.

Figure D - 7 is an example of the cross sections. This section runs from west to east across the area, in the sixth row of sections down from the north boundary, essentially across the center of the area. It shows that saturated thickness is low in southwestern 9-34, that the gradient steepens sharply at the boundary between 9-34 and 9-33, and that it then flattens out and remains that way through 9-32. [See Appendix D3 for more data and example cross section figures.]

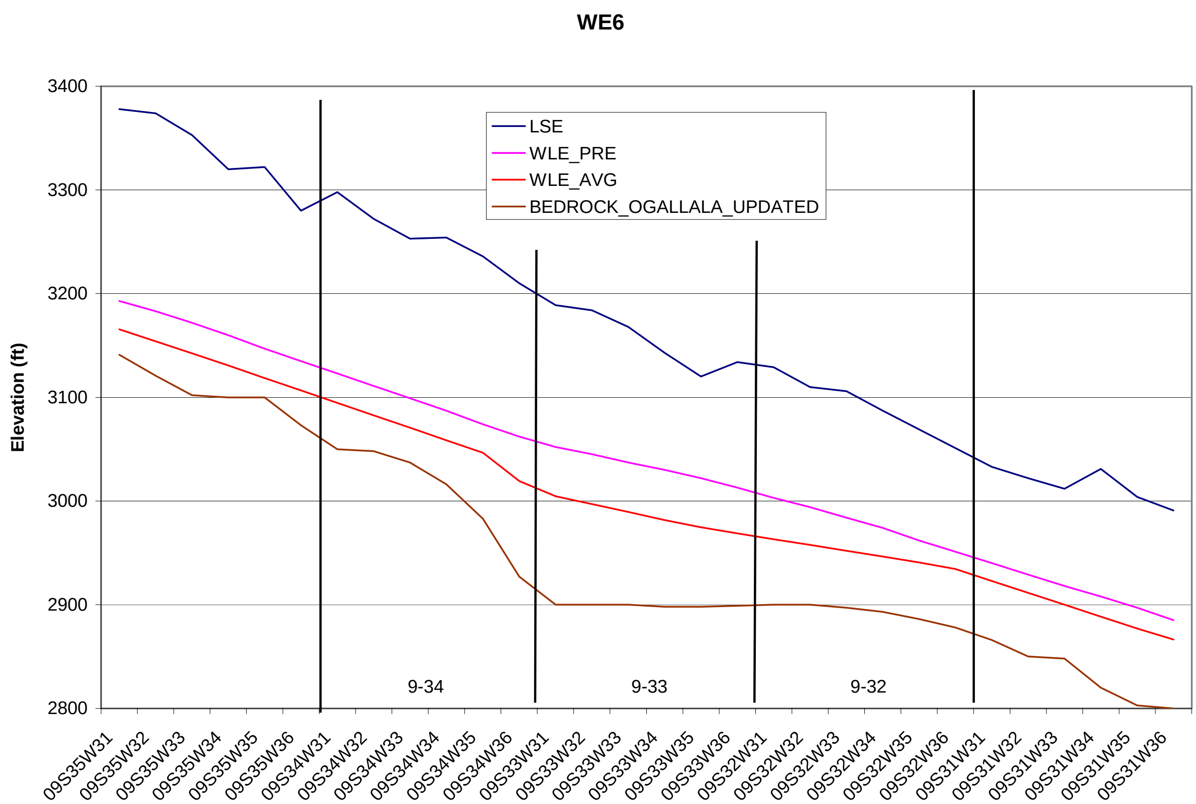


Figure D - 7: Example of west to east cross section showing elevations of land surface, predevelopment water table, average 1996-2005 water table, and bedrock surface. See Appendix D3 for the entire suite of cross section figures.

Hydraulic gradients across the west and east township boundaries were calculated primarily based on the cross sections, but also considering the point water table measurements and preliminary computer-generated contours (see example Figure D - 8; the red line is the approximate location of the cross section shown in Figure D - 7). Estimates were made for each row of sections across the west and east boundaries, and for the columns of sections across the north and south boundaries. The summary results are tabulated for the townships separately and as a group in Table D - 3.

It is important to realize that these calculations are made for a nearly recovered water table, and reflect the overall equilibrium gradient appropriate for calculating long-distance transport. When pumping occurs, local drawdown increases and re-orients short-range gradients. This will accelerate and redirect flow at the section to township scale, but is likely to have little effect at the township to county level.

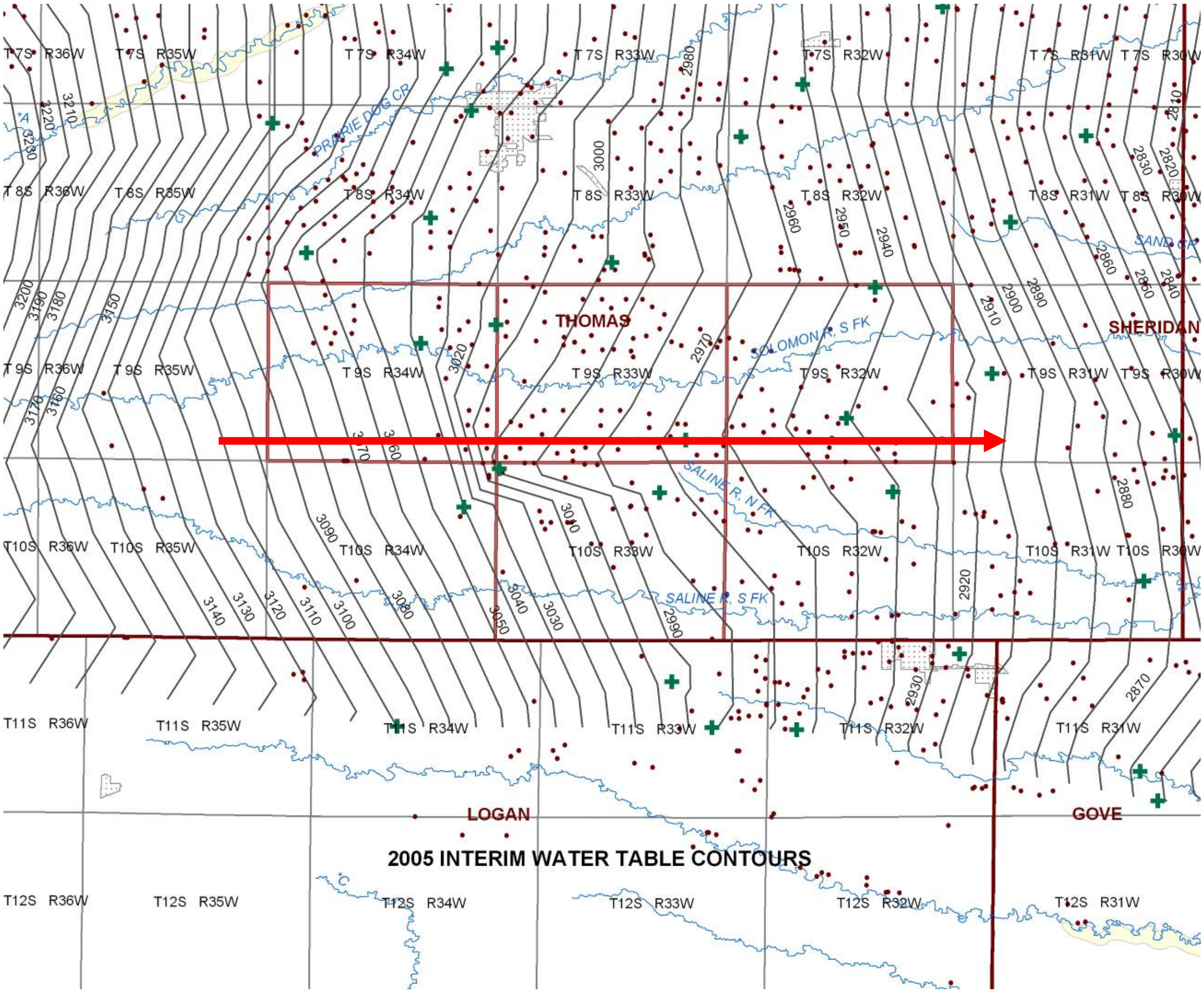


Figure D - 8: Groundwater elevation contours. Groundwater flow is perpendicular to the elevation lines, and the rate is typically faster where the contours are closer together. The red line is the approximate location of the cross section shown in Figure D - 7. Note how much influence one well can have on the shape of the contours (NW corner of 10-33).

Table D - 3: Summary of net groundwater fluxes. Positive numbers indicate a net inflow. Negative numbers indicate a net outflow. See Appendix D3 for detailed data used to produce the estimates.

	Net groundwater flux (AF/yr)
9-34	-1307
9-33	3750
9-32	-331
10-33	2135
ALL	4247

Inflows and outflows (in AF/yr) for the townships are shown schematically in Figure D - 9 below. See Appendix D3 for detailed data used to produce the estimates.

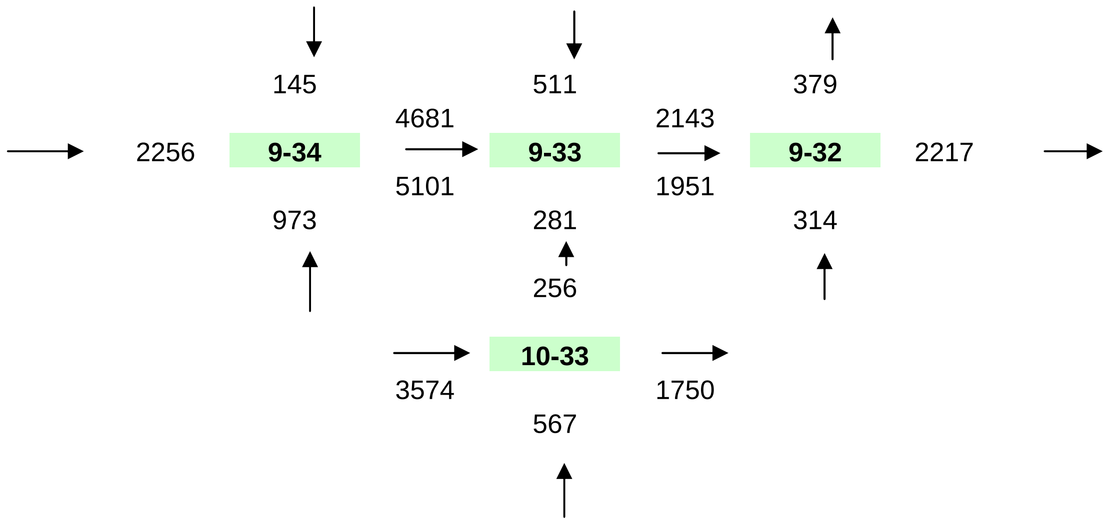


Figure D - 9: Schematic illustration of the estimated groundwater flow relations among the four Thomas County townships. The arrows with two flux values indicate the different values obtained at either side of the respective township boundary, as a result of the different hydraulic conductivities and saturated thicknesses.

Groundwater Flow Velocities

Specific discharges (Darcy velocities) and average linear velocities ("pore" velocities) were calculated at the west and east boundaries of the area using the following equations.

Specific discharge = Ki

Average linear velocity = Ki/SY, where

SY is the USGS specific yield (incorporated into the KGS section-level database).

The average linear velocity (labeled "Pore" Velocity in Table D - 4) is an estimate of how fast a particle of water will flow. Interim results in Table D - 4 indicate that groundwater flows at a rate of about 1 ft/day, a number commonly used for the High Plains aquifer. Specific discharge is a macroscopic concept to provide averaged descriptions of the pore behavior.

Table D - 4: Groundwater flow velocity estimates. The average linear velocity (labeled "Pore" Velocity in the table) is an estimate of how fast a particle of water will flow.

WEST BOUNDARY (FLOW IN)

TRS	SY	1996 Darcy Velocity (ft/d)	1996 "Pore" Velocity (ft/d)	2005 Darcy Velocity (ft/d)	2005 "Pore" Velocity (ft/d)
09S34W06	0.20	0.22	1.10	0.23	1.14
09S34W07	0.22	0.22	1.02	0.23	1.03
09S34W18	0.24	0.22	0.91	0.23	0.97
09S34W19	0.25	0.22	0.89	0.23	0.94
09S34W30	0.25	0.23	0.93	0.23	0.93
09S34W31	0.25	0.24	0.96	0.23	0.92
10S33W06	0.22	0.23	1.05	0.23	1.05
10S33W07	0.22	0.23	1.03	0.23	1.06
10S33W18	0.22	0.23	1.05	0.23	1.07
10S33W19	0.21	0.23	1.12	0.23	1.12
10S33W30	0.20	0.24	1.19	0.24	1.19
10S33W31	0.20	0.24	1.21	0.24	1.21
	AVG_NORTH		**0.97**		**0.99**
	AVG_10-33		**1.11**		**1.12**
	AVG_ALL		**1.04**		**1.05**

EAST BOUNDARY (FLOW OUT)

TRS	SY	1996 Darcy Velocity (ft/d)	1996 "Pore" Velocity (ft/d)	2005 Darcy Velocity (ft/d)	2005 "Pore" Velocity (ft/d)
09S32W01	0.20	0.14	0.71	0.14	0.68
09S32W12	0.20	0.12	0.60	0.12	0.60
09S32W13	0.17	0.12	0.71	0.12	0.71
09S32W24	0.15	0.11	0.75	0.11	0.75
09S32W25	0.14	0.10	0.71	0.10	0.71
09S32W36	0.13	0.08	0.63	0.08	0.59
10S33W01	0.16	0.09	0.57	0.09	0.53
10S33W12	0.17	0.09	0.51	0.08	0.45
10S33W13	0.18	0.09	0.49	0.07	0.41
10S33W24	0.19	0.09	0.46	0.07	0.37
10S33W25	0.18	0.09	0.48	0.08	0.44
10S33W36	0.16	0.09	0.53	0.09	0.53
	AVG_NORTH		**0.68**		**0.67**
	AVG_10-33		**0.51**		**0.46**
	AVG_ALL		**0.60**		**0.56**

Based on the values tabulated above, the long term groundwater flow in the area takes approximately 15-20 years per mile. While the effects of local pumping might speed this up slightly, we consider it very unlikely that volume of ground water underneath a township could be replaced in less than 50-60 years. This means that the first and greatest effects of either conservation or depletion will be experienced in the immediate area.

Analysis and Discussion

Because water table changes and the volume of groundwater pumped are the only two measurements we have that are directly relevant to the groundwater in storage, and because pumping, in most areas, is expected to be the largest term in the groundwater budget, it is important to determine how closely the two measures are related to each other and to precipitation, the other variable for which we have direct measurements available.

Procedural note: In the analysis we have relied heavily on, and will frequently refer to, the results of linear regression analysis (or, informally, 'correlation'). Basically, this means assuming that two variables (Y and X) are related by an equation for a straight line Y = mX +b, where m is the slope and b is the intercept of the line (with the vertical or Y axis). We then test how well this assumption is suited to our particular data, by determining not only m and b, but also a statistic known as R (the correlation coefficient). R^2 provides a measure of how well the variability in one parameter is explained by the variability in the other. A perfect match produces a value of 1.0, and a completely random relationship a value of zero.

In 'real data' determinations, and especially when environmental data of any kind are used, an R^2 value > 0.9 indicates an extremely strong relationship, 0.7-0.8 are good correlations, and values of 0.5-0.7 indicate that there probably is a relationship, but a noisy one. Still lower values may be significant, but need to be interpreted with care and caution. Even good correlations do not necessarily indicate direct relationships, however; if one variable controls another the correlation will be good, but a good correlation doesn't prove that there is a direct relationship. If two variables are well correlated, they can be independent of each other, but both dependent on a third variable (hence the saying "Correlation is not causation"). In our case, if pumping caused water level change they should be well correlated, but that could also happen if precipitation had a strong influence on both recharge and water demand. This is why we not only examine various combinations of variables, but also consider the magnitudes and the values of m and b to see if they make sense in terms of what we understand about hydrology.

Reported Use

Reported use was compared with water level change and precipitation, and precipitation and the water table variables were also compared; results are shown in Appendix D2. Initially, the section-center values obtained from TINs were used. Some degree of correlation was seen in essentially all comparisons. The strongest correlations (highest R^2 values) were between use and water table change, with weaker correlation between use and precipitation. The seasonal (March-October) precipitation value was typically better correlated than the annual.

The first group of use-change results were poorer for 10-33 than for the northern townships. We examined the relationships between the well hydrographs and the water use data for the townships (Figure D - 10abcd). There was substantial variation, both in the patterns and the magnitudes of the water table changes, and in particular well 10-33-19cbd seemed questionable. We removed it from the dataset and re-TINned the data (the new version of the dataset is identified as "v2"); the results were moderately improved for 10-33, but still not impressive as the cornerstone for the budget analysis.

In view of the variety of hydrographs seen among the wells that anchor the TINs used to determine the water levels in the four townships, we decided to experiment with an alternative approach. Rather than using the wells as geographic representatives, we tested various combinations of the wells as multiple index wells by simply averaging the water level change data and regressing that against the reported use. Optimum results were obtained with six wells each for the northern townships, and three for 10-33. All of the new correlations showed improvement over the use of the TIN values; some of them were substantial changes. The graphs of the "multiple index" approach are shown in Figure D - 11, and can be compared with the values using the TIN results, in Appendix D1. The change values in Figure D - 11 have been converted to estimated AF by multiplying the feet of change by (640 x 36) acres/township, and then by the USGS estimate of average specific yield for each township: 9-32, 17.3%; 9-33, 19.0%; 9-34, 20.9%; and 10-33, 19.1%. The plots in Appendix D1 are left in feet of change for comparison purposes.

While we cannot be sure that the absolute elevations are any better, the multiple index well average does a better job of relating the variations, and we have used those values in the rest of the analysis. Where absolute elevations are required, as in the water flux determinations described above, we have used the TINned v2 dataset.

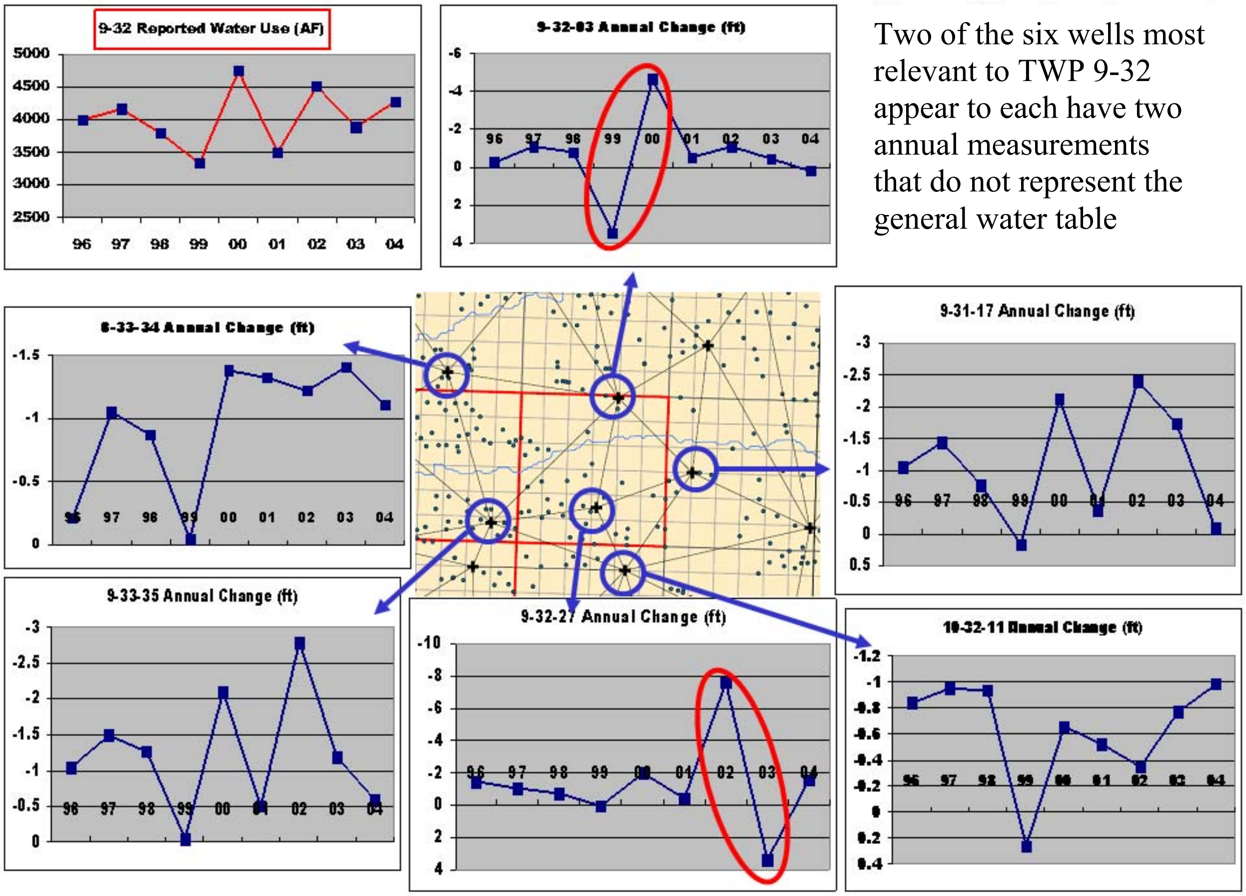


Figure D - 10a: Well hydrographs for the monitoring wells characterizing Township 9-32. The reported water use plot is in the upper left. The water level changes are plotted with increasing negative values toward the top of the plots; this is done so that variation is in the same sense as the water use plots – higher use corresponds to greater declines. Points marked in red are suspect with interannual changes of 9-12 ft. compared to the maximum range of 1.5-3 ft. for other measurements.

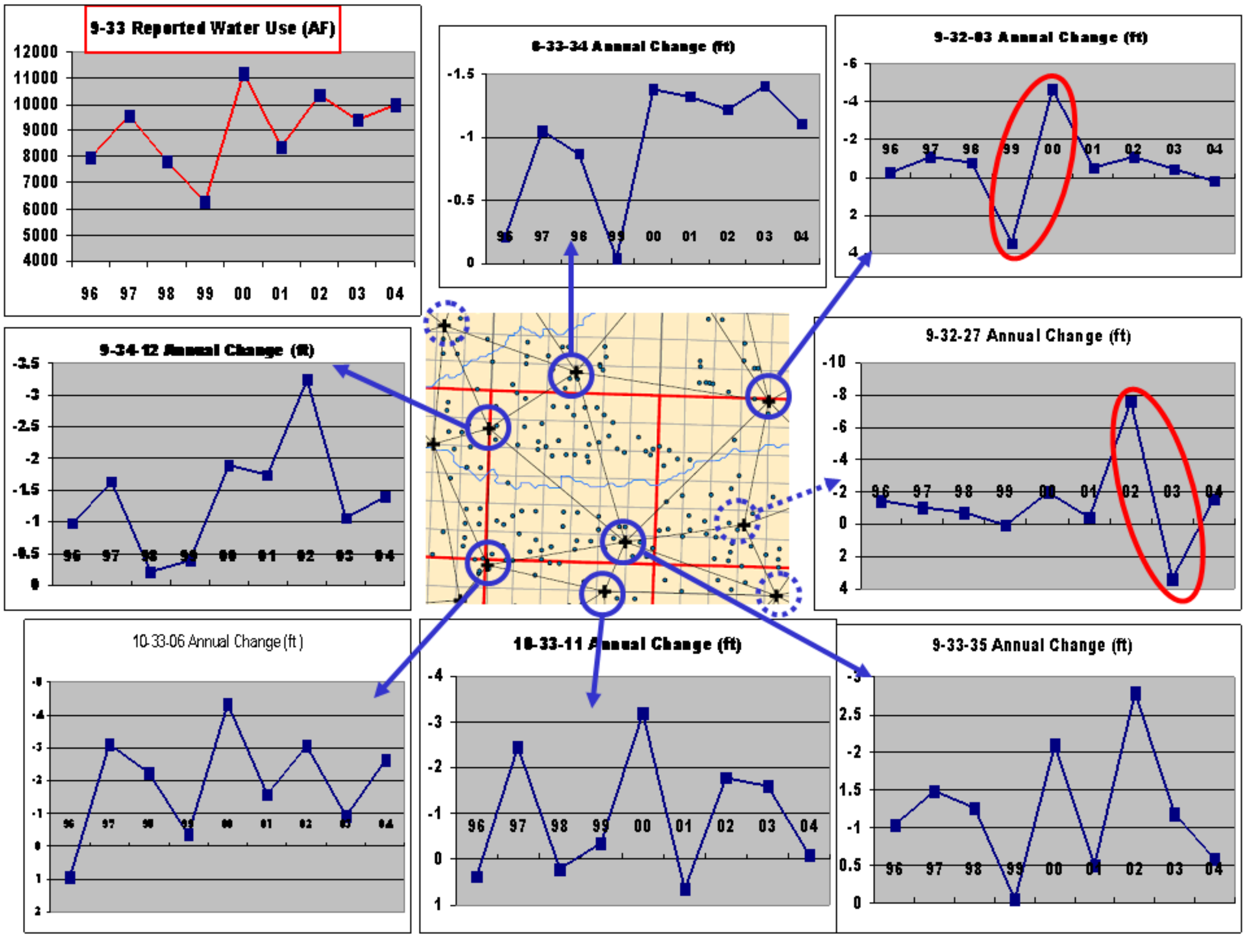


Figure D - 10b: Hydrographs and water use plots for Township 9-33, arranged as in Figure D - 10a. Wells indicated by dotted circles and arrows were not used in the subsequent stage of analysis.

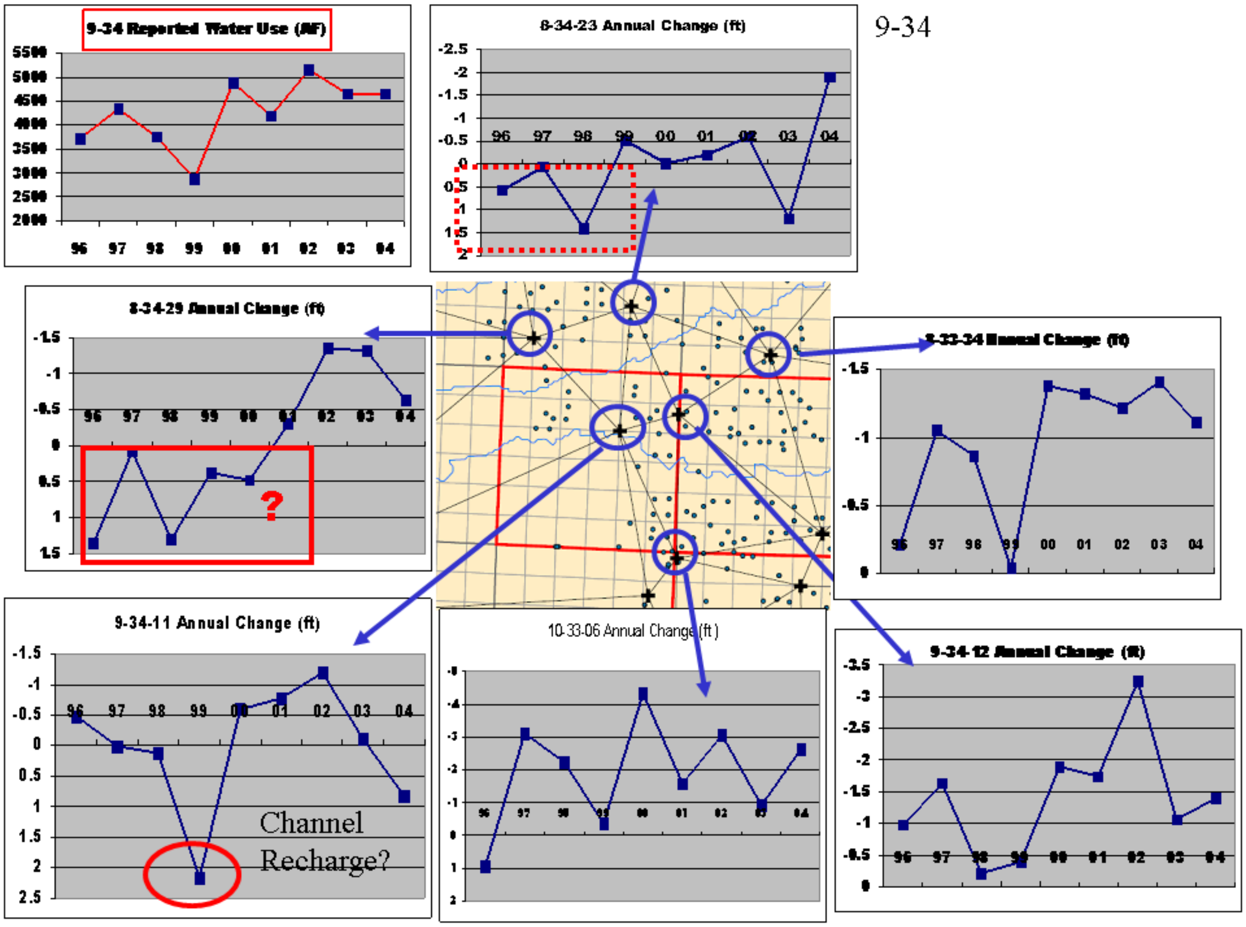


Figure D - 10c: Hydrographs and water use plots for Township 9-34. The two wells in 8-34 both showed sustained water level increases early in the period. Well 9-34-11 is the only well in this area that is located close to the river channel, so the unusual positive change in a year when most other wells were indicating some decrease needs to be considered in terms of possible enhanced recharge under the channel (see Figure D - 11 and discussion below).

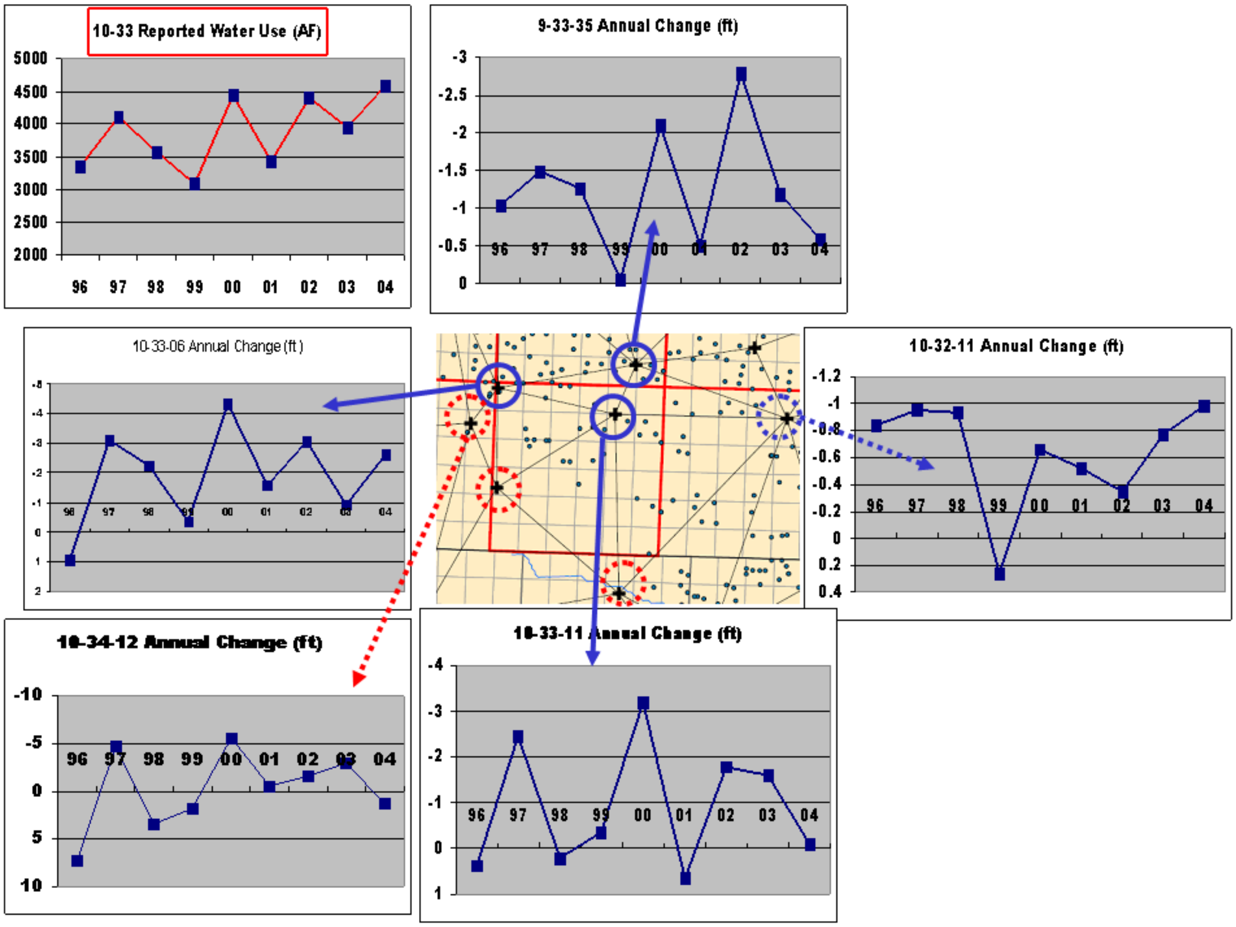


Figure D - 10d: Water use and well hydrographs for Township 10-33. Dotted circles indicate wells excluded from analysis for various reasons; for example, 10-34-12 shows changes of 9-12 ft., compared to values no larger than 3-4 ft. in other wells. Dotted circles indicate wells not used in the final average, and red indicates wells whose records showed some sort of apparent anomaly (pattern or magnitude of change).

Figure D - 11 shows that the maximum annual decline calculated in acre-feet is somewhat larger than the maximum reported use. The specific yield estimates may be inaccurate, but they are as likely to be high as low, and are probably not off by more than 10-15% in any case (which is generally less than the difference between use and change estimates). Since the data available suggest that if unmetered use reports are systematically different from metered results, they are likely to be higher, this suggests some distortion in the estimates of water table elevation. Evidence for this has already been discussed above in reference to the occurrence of unusually high annual change values. We suspect that some of these differences are due to the problem of incomplete recovery. When pumping rates are high, the well will not have returned to as close as usual to the equilibrium state, and the decline will be overestimated. If pumping rates are low or normal in the following year, recovery will be more complete and the measurement will make up the previous year's deficit and indicate lower than actual decline (or greater recovery) than is actually the case. If any of the monitoring wells are affected by off-season pumping, the difference can be even more striking.

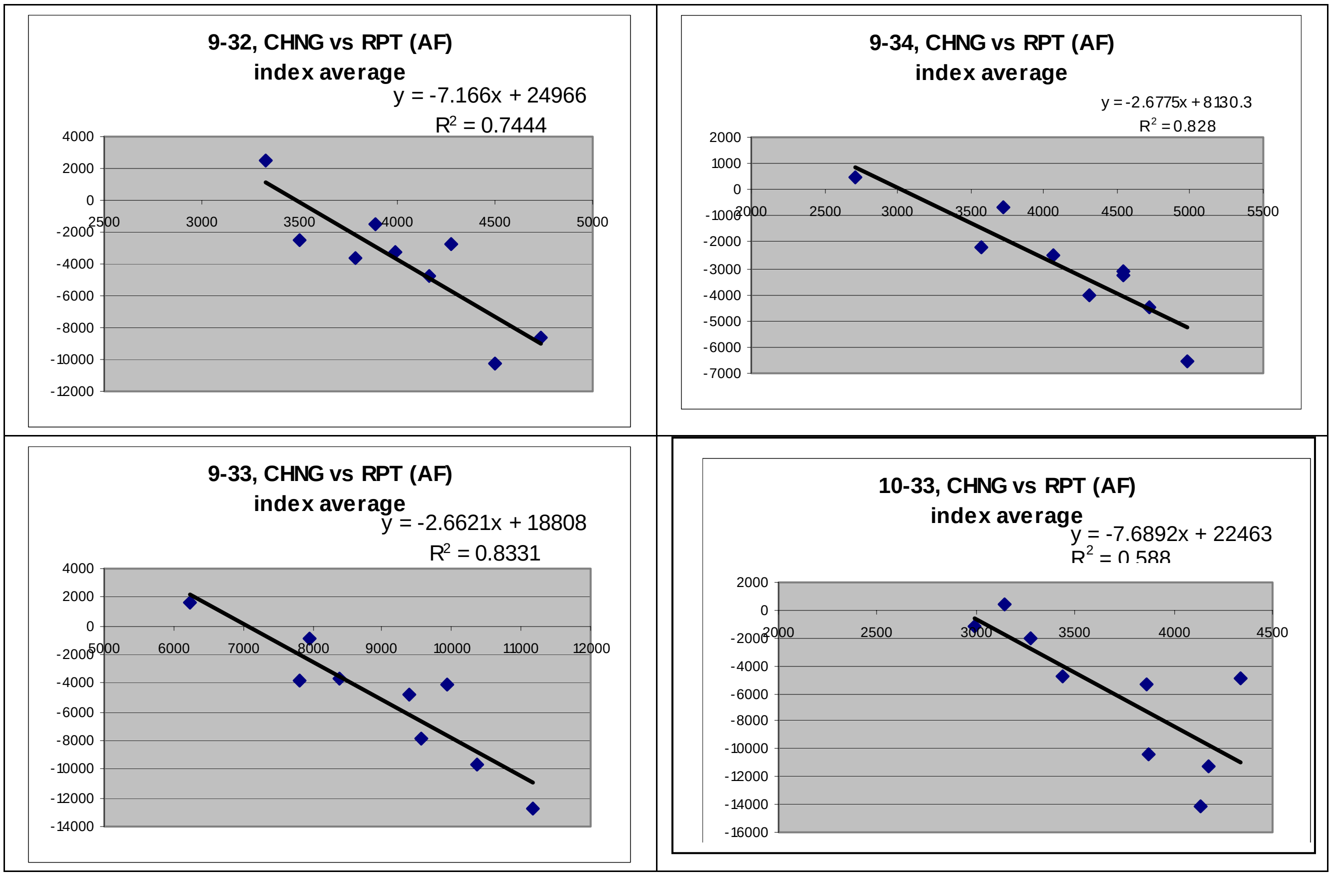


Figure D - 11: Annual change converted to estimated AF/Twp vs. reported use for each township.

The plots in Figure D - 11 reveal a number of things about the apparent water budget when examined in more detail. One obvious point is that the regression line crosses the zero-change axis at about 7000 AF for 9-33 and 3000-3500 for the other townships. This would seem to imply that this volume is the sustainable yield – with no decline when pumped at that rate. However, the regression equation shows that about 2.7 AF is lost from storage for every AF pumped from 9-33 and 9-34, and about 7.1 AF lost per AF pumped from 9-32 and 10-33. This is clearly not a realistic possibility, especially since the addition of either precipitation or lateral inflow to the system should make the ratio of storage loss to pumping <1 rather than >> 1.

Furthermore, the intercept values are the point at which the line would intercept the vertical (change) or Y axis when the reported use axis is at zero (not shown on figure). This should represent the long-term average inflow to the system (recharge plus other any other sources). If we convert these volumes back to recharge (in inches at zero pumping), the values range from 4” to 13”. However, the generally accepted long-term average value for recharge in the area is <1”. Even with a generous allowance for enhanced recharge and lateral groundwater flow, the slope and intercept values from the regression equation do not appear hydrologically reasonable.

A further point of interest is that 9-33, with about twice the pumping of the other townships, shows about twice the apparent sustainability – presumably because more pumping produces more signal distortion and less complete recovery in the water table response. However, there is also another difference between 9-33 and the other townships, in that 9-33 has pumping distributed rather uniformly, while the others all have significant areas with little or no pumping, as shown in Figure D - 12. This may be introducing some systematic differences because of our choice of treating all of the townships as township units, without considering the actual active area for water use. This will be discussed in more detail later when we consider the combined budget.

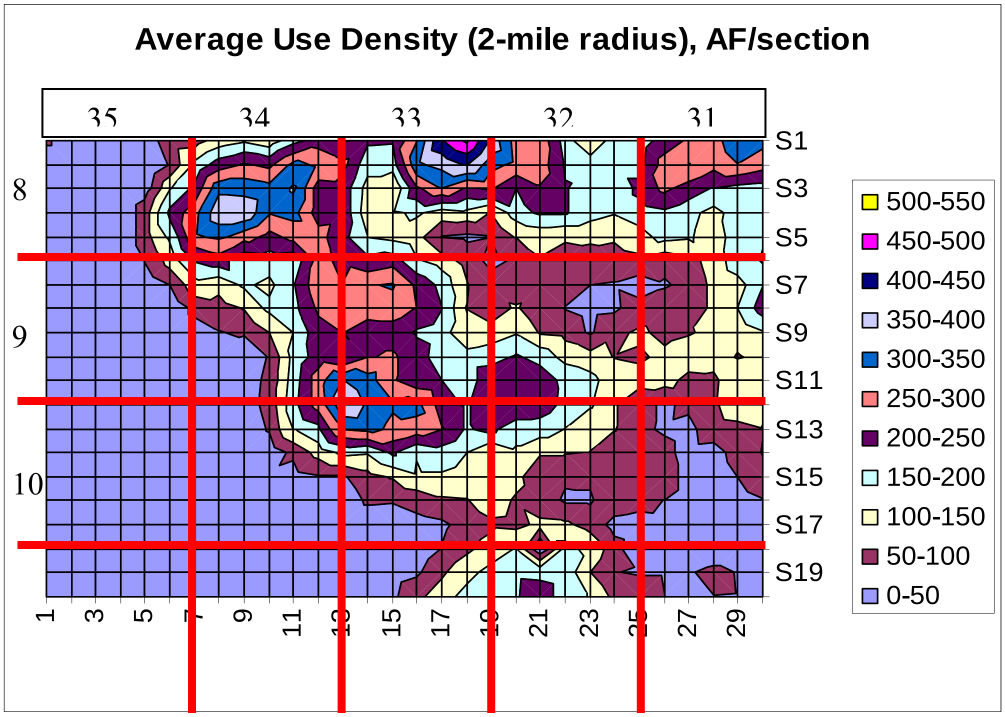


Figure D - 12: Average 2-mile use density, AF/section. Areas less than ~ 50AF/section experience little or no direct pumping stress, and may respond differently from the pumped areas.

Recharge and Other Factors

Recharge is the term used to describe the addition of groundwater to a specific aquifer body from some other compartment (we do not use it to describe lateral flow within the same aquifer unit). The most common and usually the largest recharge component is usually rain or surface water that percolates through the soil and eventually reaches the groundwater. Figure D - 13 illustrates some of the factors affecting the amount of recharge.

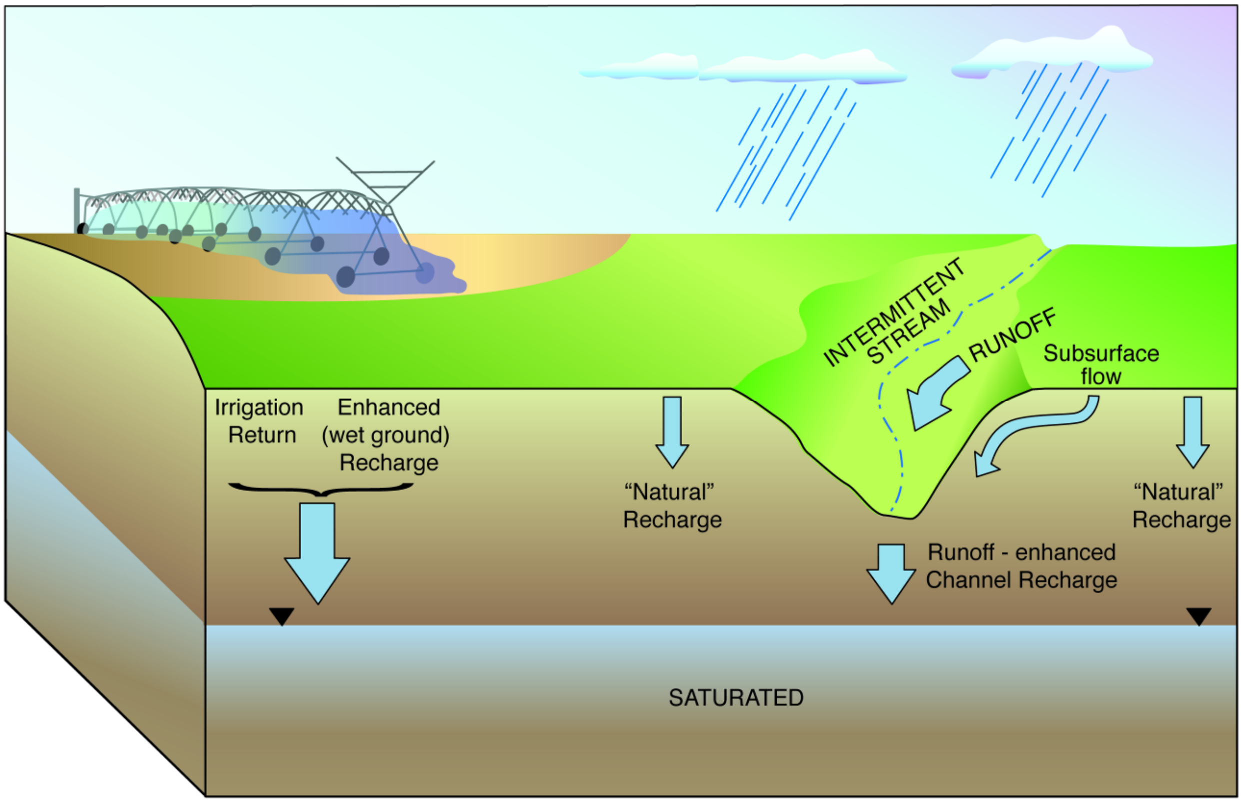


Figure D - 13: Aspects of groundwater recharge. See text for discussion.

One component not shown in Figure D - 13 but illustrated in Figure D - 2 is addition of water due to upward seepage from underlying geologic units. Hecox (2003) estimated from his model studies of GMD 4 that about 10% of recent recharge might be due to this process over the entire region. Because recharge is one of the smaller components of the water budget and 10% of it is a very small component we are not specifically considering that source.

Regional recharge estimates are typically based on a very large scale water budget of the sort we are attempting locally; the estimates we have available are those based on a USGS study that estimated the average natural recharge rate in most of western Kansas as about 0.5” per year. This would reflect the portion labeled natural recharge in Figure D - 13. Also natural, but locally much larger, can be recharge beneath stream channels, especially if the water table is well below the surface (a “losing stream”). Even if there is seldom flow in the channel, the natural depression can act as a collector of water that flows over the surface or (more slowly) laterally through the shallow soil layers.

Once the landscape is modified by cultivation, construction, etc., patterns and mechanisms of recharge may change. Irrigation in particular is an important factor because not only can some of the applied water return to the aquifer, but keeping the ground close to field capacity (the water content at which drainage occurs) makes it more likely that precipitation falling on the moist soil will generate recharge. Both of these provide enhancements to the natural recharge.

Most of the water (>90%) that arrives as precipitation returns to the atmosphere as evapotranspiration. In western Kansas, runoff (surface flow) rarely moves much water for long distances, except in extremely heavy storms or wet years. Wet periods in general are the major source of groundwater recharge; during dry or normal years relatively little water may penetrate below the rooting zone. However, when there is a thick unsaturated zone, water may take years to decades to make the trip between surface and water table, so it is mostly the major events and channel recharge that generate prompt responses of the water table.

The various components of recharge, and their spatial and temporal distributions, are difficult to measure and challenging to estimate. Recharge is often the adjustment term used to close budgets in which the other quantities are reasonably well known. In the estimates that follow we use the USGS recharge estimates, averaged at the township level. As a long-term average these would probably be low numbers since they do not take account of the human enhancements, but it is not clear how well they represent the time period considered.

Water Budget

In order to estimate the combined water balance of the four townships, we used the reported water use, the USGS recharge values, and the USGS specific yield estimates (for converting water heights (thicknesses) or volumes to groundwater heights (thicknesses) or volumes). We calculated the groundwater flux values at all four boundaries of each township, using the equations and methods described above, the USGS hydraulic conductivity values, and water table elevations derived from the v2 version of the updated section-level database. We derived three versions of the water level change data: one based on the TIN process and the section level database, another using the values obtained by averaging the records of the wells that provided (as a group average) the best correlation with water use (see Figure D-10 above), and a third that adjusted the second to reflect the fraction of the area of each township with an average annual 2-mile use density > 50 AF/section (in this case the same adjustment was made to the recharge values).

We used average values over the 9-year period to reduce the uncertainties and variability associated with individual years. The results are presented in Table D - 5, where the first block of numbers represents the water balance for each township and the total for each of the three methods of calculating change. The second block breaks down the details of the overall net groundwater flow numbers for each side of each township, and the third block presents the component data used in the calculations.

We have not presented some of the efforts to examine individual years, but we found that averaging the data to produce one budget was not only more efficient but much more credible in terms of results than producing budgets from the individual year data and averaging those. These findings, as well as the observation that a better balance can be achieved at the four-township level than for the individual townships, underscore the points made in the beginning: the annual monitoring program is most reliably used over time scales of decades and spatial scales >township; and more, better, and different data are needed for local understanding on an annual basis.

Before discussing the implications of these findings for management and conservation, we need to point out that the analysis used the change data that we identified above as "inflated" relative to the actual withdrawals (slope, or ratio of CHNG/RPT >>1). This is one of the primary arguments for the averaging process – although the individual annual change values plotted (Figure D - 11) might be extremely divergent from a prediction based on use, the longer-term average values presented in Table D - 5 are relatively well-behaved in terms of hydrologic expectations – the change values are similar in magnitude but generally somewhat smaller than the reported use values. The averaging process eliminates the extreme values without greatly affecting the signal of the long-term trend.

Table D - 5: Summary of average budget term estimates for the period 1996-2004, calculated by: (1) using as water table changes the average of the wells best correlated with use (Figure D - 10); (2) the TIN method applied to the database; and (3) as in (1), but with the recharge and change values adjusted to reflect only the area of the township with used density >50 AF/section-year.

	1. Multiple Index Well Average					**2. TIN v2 Average CHNG**					**3. Area-Adjusted Index Well Values**				
Twp	***9-34***	***9-33***	***9-32***	***10-33***	***ALL***	***9-34***	***9-33***	***9-32***	***10-33***	***ALL***	***9-34***	***9-33***	***9-32***	***10-33***	***ALL***
Use Report (AF)	**-4481**	**-8986**	**-4243**	**-3823**	**-21533**	**-4481**	**-8986**	**-4243**	**-3823**	**-21533**	**-4481**	**-8986**	**-4243**	**-3823**	**-21533**
CHNG (AF)	**4417**	**6639**	**2532**	**1534**	**15122**	**4185**	**5516**	**4623**	**2288**	**16612**	**3799**	**6639**	**2000**	**1212**	**13650**
RCHG (AF)	**960**	**1018**	**1114**	**979**	**4071**	**960**	**1018**	**1114**	**979**	**8142**	**826**	**1018**	**880**	**773**	**3497**
Flow (Total, AF)	**-1307**	**3750**	**-331**	**2135**	**4247**	**-1307**	**3750**	**-331**	**2135**	**4247**	**-1307**	**3750**	**-331**	**2135**	**4247**
Net	**-59**	**2428**	**-704**	**954**	**2619**	**-643**	**1298**	**1163**	**1579**	**5304**	**-1164**	**2421**	**-1694**	**297**	**-139**
Flow (+ in, - out)															
N	**145**	**511**	**-379**	**-256/ -281**		At left	At left	At left	At left			At left	At left	At left	
S	**973**	**256/ 281**	**314**	**567**		At left	At left	At left	At left			At left	At left	At left	
E	**-4681/ -5101**	**-2143/ -1951**	**-2217**	**-1750**		At left	At left	At left	At left			At left	At left	At left	
W	**2256**	**4681/ 5101**	**2143/ 1951**	**3574**		At left	At left	At left	At left			At left	At left	At left	
UD >50 fraction	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**.86**	**1**	**.79**	**.79**	**.86**
AvgCHNG (ft)	**-0.92**	**-1.51**	**-0.99**	**-0.35**		**-1.05**	**-1.26**	**-0.96**	**-0.52**						
RECH (in)	0.5	0.53 ±0.03	0.58 ±0.02	0.51 ±0.01		At left	At left	At left	At left		At left	At left	At left	At left	
SY (%)	20.9 ±3.3	19.0 ±1.8	17.3 ±2.5	19.1 ±1.7		At left	At left	At left	At left		At left	At left	At left	At left	
HC (ft/day)	101.1 ±1.6	98.6 ±3.3	88.2 ±7.5	89.4 ±9.5		At left	At left	At left	At left		At left	At left	At left	At left	

If we have considered all the factors and the budget numbers are correct, the residuals in the "Net" row should be zero. This appears not to be the case, although the residuals are generally substantially smaller than the reported use term, and appreciably smaller than the change term – the two parameters for which we have actual data. For the four townships taken together as a system (ALL), the third option (area corrected multiple index wells) appears best, with the uncorrected multiple index well approach better than the TIN-based values. However, when uncertainty is considered, all of the budgets are effectively "balanced." Table D - 6 shows the propagation of uncertainty through the calculations for the TIN v2 result on the basis of two assumptions: the input data have an uncertainty of either ± 10% or ± 20%. The first is unrealistically optimistic; the second somewhat more realistic but still optimistic.

Table D - 6: Uncertainties in net water balance for the TIN v2case (see Table D - 5) with two assumptions about the uncertainty of the input data.

Township	9-34	9-33	9-32	10-33	ALL
Net water in/out (AF)	**-643**	**1298**	**1163**	**1579**	**5304**
Std. dev. 10% input	**637**	**1131**	**649**	**528**	**2919**
Std. dev. 20% input	**1275**	**2262**	**1297**	**1056**	**5838**

At ± 20% uncertainty in the input data, the one standard deviation uncertainty for the total budget and three of the four individual townships is >100% -- we simply cannot say that these values are different from zero. At an unrealistically precise 10% input uncertainty, the net uncertainty for two of the townships is close to 100 %, and for the total, >50%.

Conservation and Management Implications

In spite of the high levels of uncertainty, some important conclusions can be reached about the prospects for useful conservation programs in the area. One of the most important points is that a significant fraction of the water being pumped comes from recharge and lateral inflow rather than from groundwater storage (that is, decline). Based on Table D - 5, we estimate this percentage as 30% for case 1, 23% for case 2 and 37% for case 3. We use the middle value for an example.

If only 70% of the water pumped on average results directly in water table decline, a cutback of pumping by 10% could yield up to a 14% decrease in the rate of water table decline if the inflow and recharge were not significantly reduced. Changes in irrigation would have essentially no effect on recharge from rainfall or runoff (channel recharge) or in upward flow from the bedrock, and a 10% change would have only minor effects on the irrigation-enhanced component of recharge. Similarly, we estimate that enhancement of groundwater flow during the pumping season would amount to something like a 10%

change for a few months a year, so a fractional reduction in this would not be a major factor.

To the extent that we can draw guidance from the water balance calculations, it appears that the four townships in question are in a position to leverage conservation measures by reducing groundwater declines by significantly more than the reduction in volume pumped. The long-term groundwater pore velocities calculated above indicate that the savings will have a primarily local effect for a period of at least several decades, so will not be quickly lost to outflow. These same results apply to inflowing water too, however, indicating that the rate at which pumped water is replenished is essentially as slow as the rate at which conserved water is lost.

A significant factor in this high-leverage situation appears to be the large area of thin, undeveloped aquifer to the west and south of the study region. It is probable that these areas are functioning as recharge collectors, supporting the continued down-gradient flow of groundwater at near-predevelopment rates, rather than being depleted as would be the case if the area were developed to the same extent as the four townships. This supplies water that is estimated to be a net positive (in greater than out) contribution of 2437 AF/yr for the four townships as a system.

Reducing Uncertainties: Data Needs

The somewhat positive findings outlined above are obviously approximate, and the data used to arrive at them will not be adequate to monitor the effect of any conservation programs on the time and space scales of interest. What is needed, and what are the chances of reducing some of the uncertainties?

Water use reports are probably near ± 20% in accuracy, and may be substantially better in terms of precision. Improvement is possible and desirable, but would not address the dominant uncertainties.

Recharge estimates can be improved, but the only component conveniently subject to direct measurement on a routine basis is channel recharge – continuous or more frequent measurements of wells near the base of the major stream channels, coordinated with local rainfall and runoff or flow observations. Other aspects of recharge estimation can probably be improved by models using data on soil types, ground cover, irrigated acreage, etc.

Change in groundwater storage has two components:
Change in water table elevation is one of the biggest issues, and data on that can be very substantially improved by

1. *Measuring more wells more often* (e.g., continuously or monthly) and with particular attention to local conditions (e.g, current or recent pumping, etc.).

2. *Selecting wells to monitor* based on their suitability as areal indicators (the index well approach) or as anchor points for the TIN process (the geographic sample approach).
3. *Surveying elevations* of wells needed to link neighboring observations or determine the absolute elevation (see 'later flow' below).
4. *Improving 3-dimensional estimates of specific yield* – which can be done by the Practical Saturated Thickness estimation technique.

<u>Lateral groundwater flow estimations</u> can be improved by two actions:

1. *Improved determination of the head gradient* near and across the boundaries of the area of interest. This will require both additional measurement points (which can be simple and relatively inexpensive piezometers) and elevation surveys. Some of the measurements need to be in the upgradient source area, since the present water level measurement program is likely to systematically underestimate water table elevations in unpumped areas (see Figure D - 14 below).
2. *Estimates of the distribution of hydraulic conductivity* (or actual flow) can be improved to some extent by relatively simple methods (for example, using the Practical Saturated Thickness determination process to assign approximate or relative values to the strata identified.

The measures outlined above would in some cases improve our knowledge of the water balance rather promptly, but the major effect would be felt after a few years of data collection with a consistent system set up for the purpose at hand and designed and measured at appropriate scales. The results will gradually permit us to calibrate on the basis of field observations some of the parameters we cannot measure directly.

Once a larger inventory of better-qualified data is in, groundwater modeling at the local scale can be useful in developing plans and testing hypotheses. At present, regional scale models will not have the database or resolution to make accurate determinations in transitional areas with limited data, and attempts to model at the local scale will suffer from the same problems of data assessment and availability described in this report.

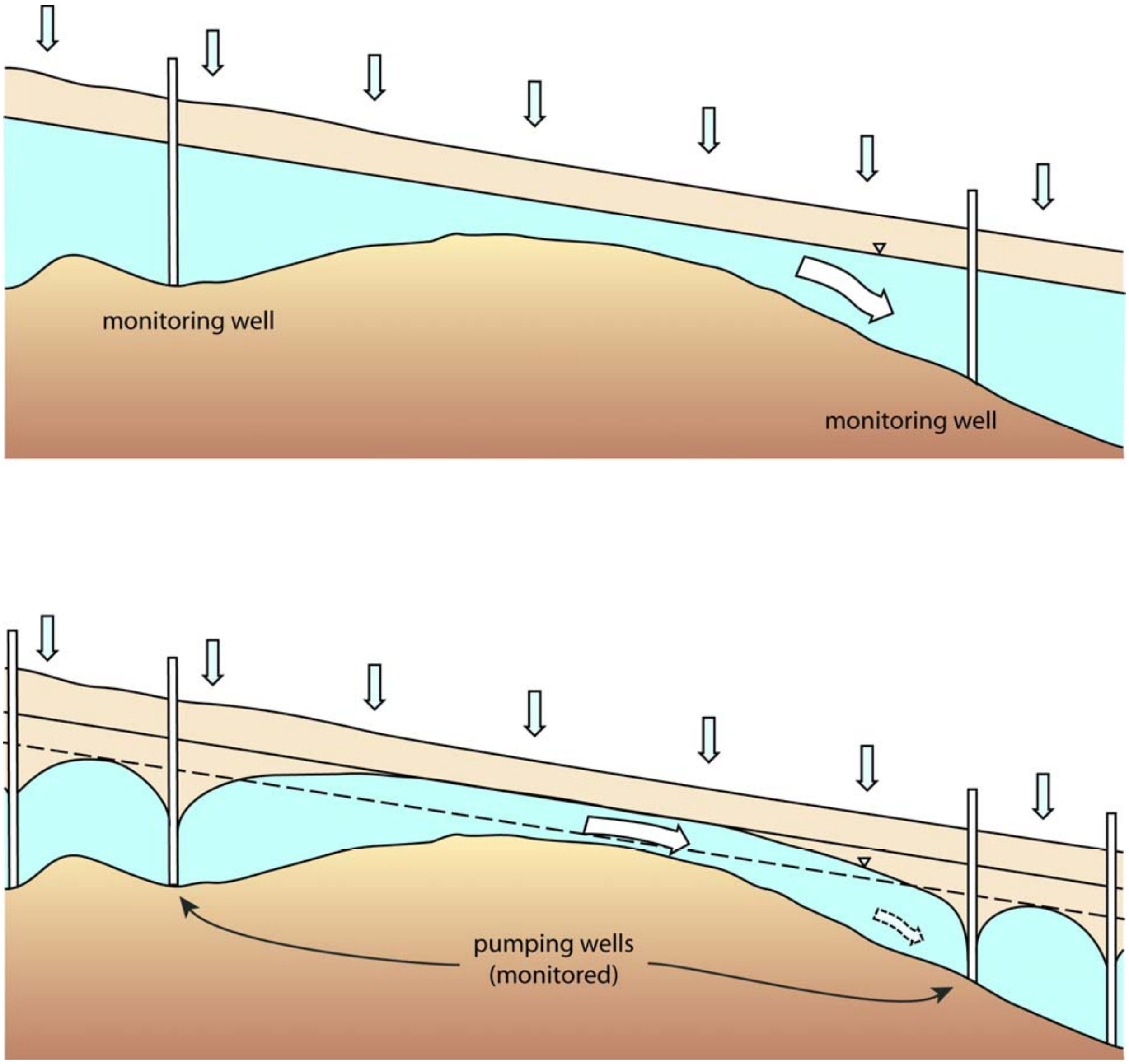


Figure D - 14: Monitoring water-level change in undeveloped areas – the upper figure shows the natural gradient across regions of the aquifer with variable saturated thickness. The areas of greater saturated thickness are developed; the others are not (lower picture). Because water levels are preferentially monitored where there are wells and pumping, post-development observations imply a uniform reduction in water table elevation. However, the undeveloped area has its water table supported by local recharge, and now becomes a source area, with water table elevations higher than estimated from the monitoring wells.

Summary and Conclusions

The available information suggests that four-township region in southern Thomas County has a significant amount of net groundwater inflow that enhances local recharge and provides 'leverage' that increases the effectiveness of local groundwater conservation measures in reducing declines.

This condition appears to be the result of their location adjacent to thin, undeveloped areas of the aquifer that are funneling additional recharge into the region.

The movement of groundwater places limits on the rate at which the upgradient water is supplied, but also ensures that any conservation benefits will remain beneath the four townships for a substantial period of time.

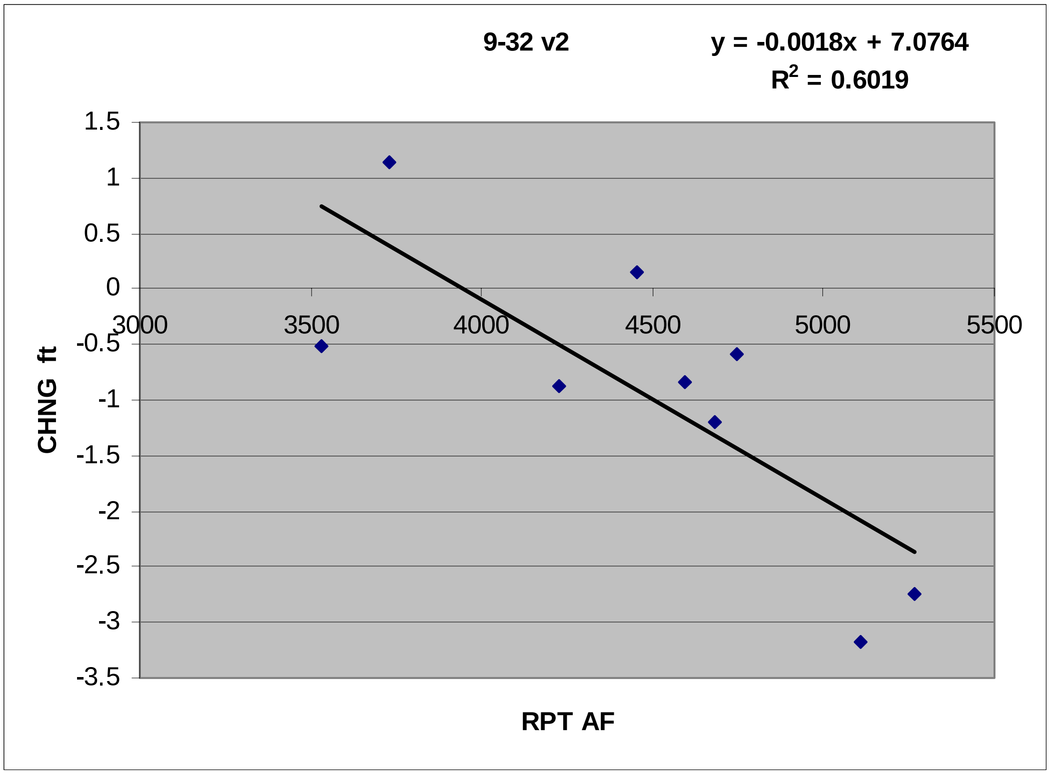
The details of the water balance are uncertain because data on water levels and other conditions in the region of interest are inadequate in both quantity and quality for application at the time and space scales of concern.

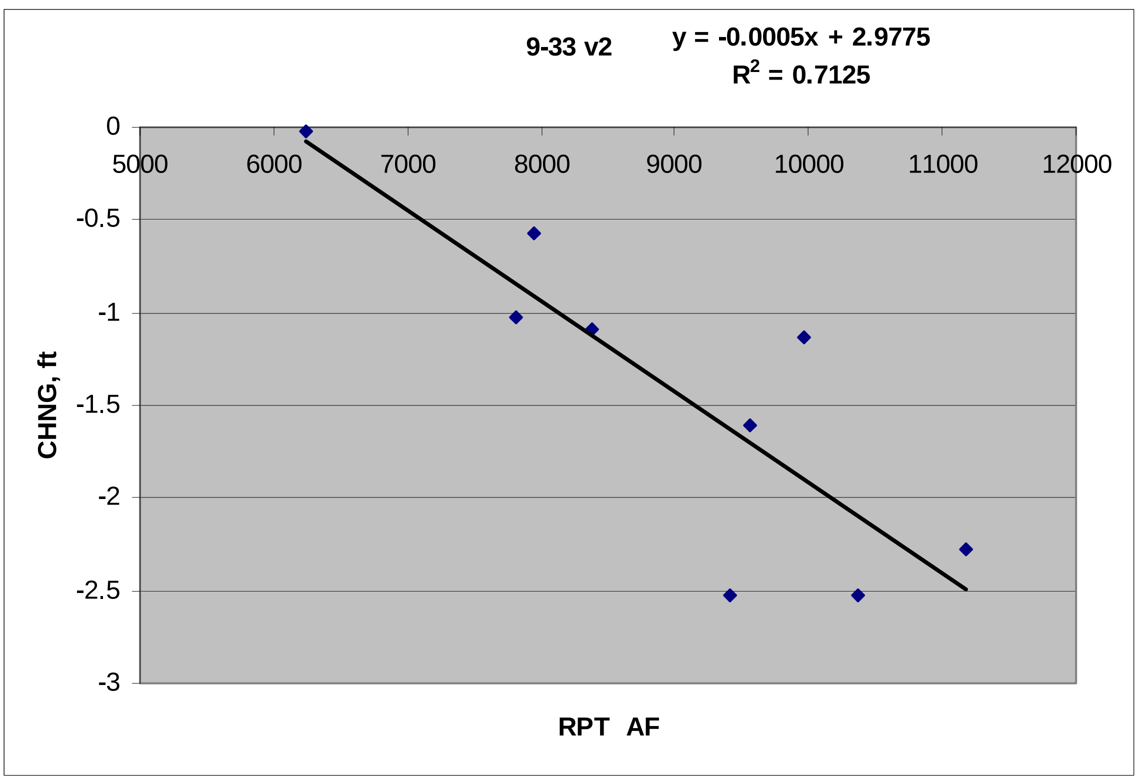
A greatly improved data collection program to support management and assessment can be put in place with a combination of one-time measurements and improvement with expanded ongoing monitoring activities.

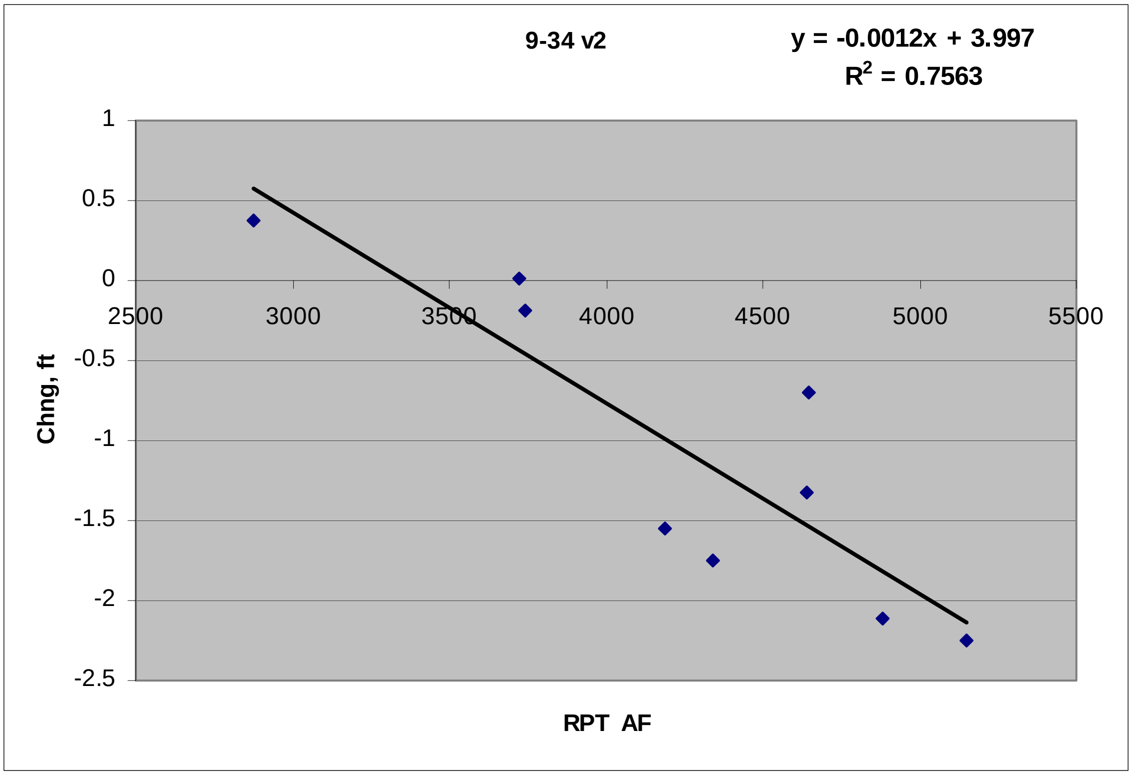
Reference

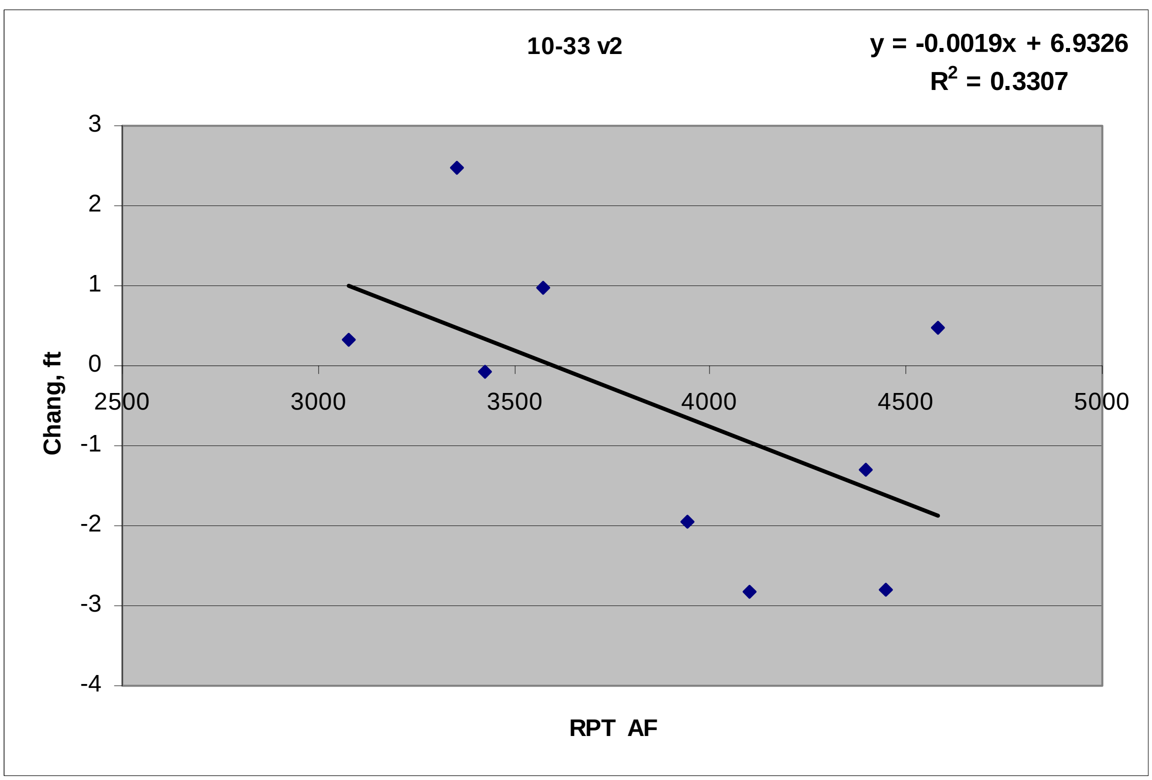
Hecox, G.R. 2003. GIS integration and error analysis for hydrogeologic evaluations. Unpubl. Ph.D. Dissertation, Department of Geology, University of Kansas, Lawrence, KS, 519p. Available as KGS Open-file Report 2003-53.

Appendix D-1 – v2 (Geographic Sample) Change vs. Use Regressions



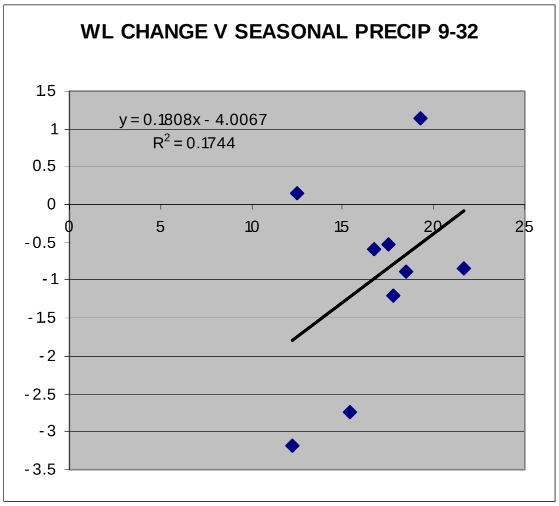


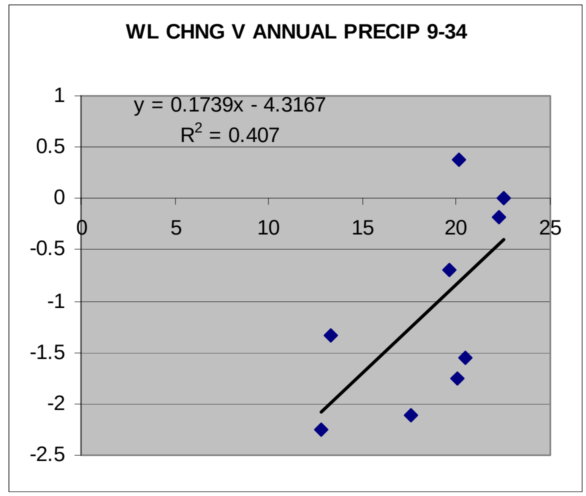

9-34 v2
y = -0.0012x + 3.997
R2 = 0.7563
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
2500
3000
3500
4000
4500
5000
5500
Chng, ft
RPT AF

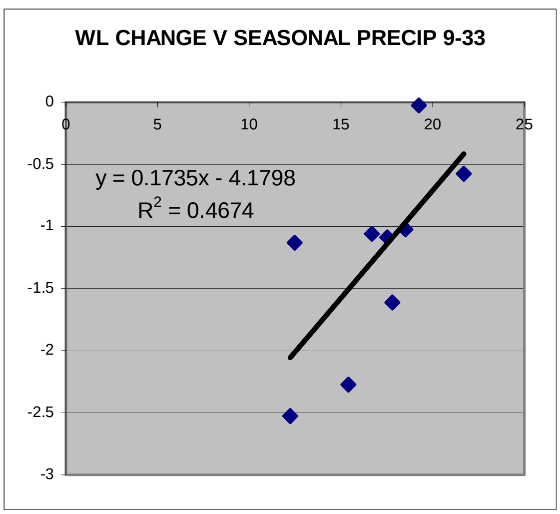

10-33 v2
y = -0.0019x + 6.9326
R2 = 0.3307
3
2
1
0
-1
-2
-3
-4
2500
3000
3500
4000
4500
5000
Chang, ft
RPT AF

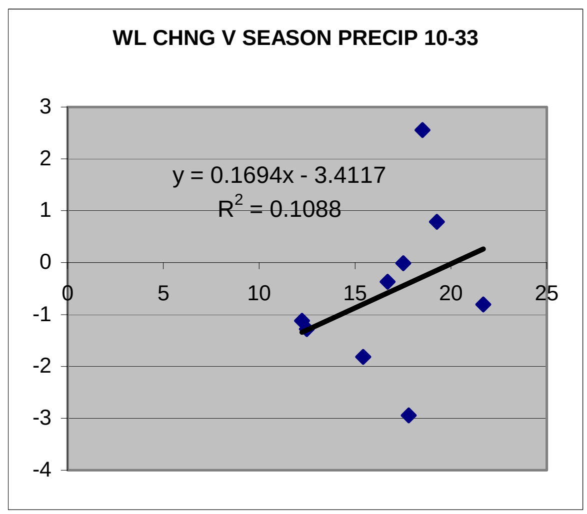
Appendix D 2

Water table elevation changes (TIN, data version 2) as a function of seasonal precipitation. Seasonal precipitation consistently gave slightly higher R^2 values than did annual. However, the R^2 values are generally poor, and the predominance of negative change values means that precipitation, which by itself should have a zero or positive effect on water level, is superimposed on the much stronger effect of decrease due to pumping.

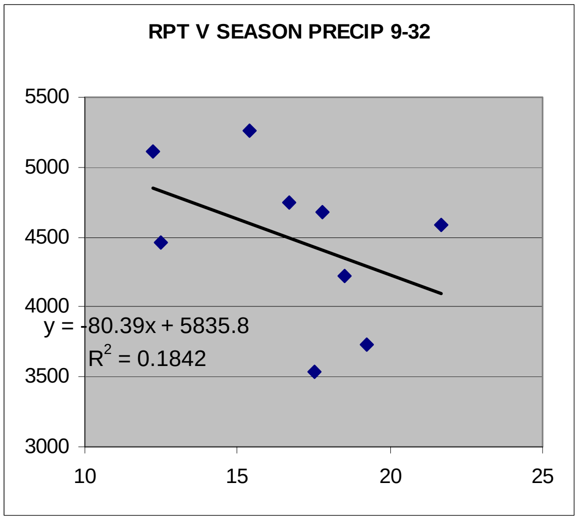


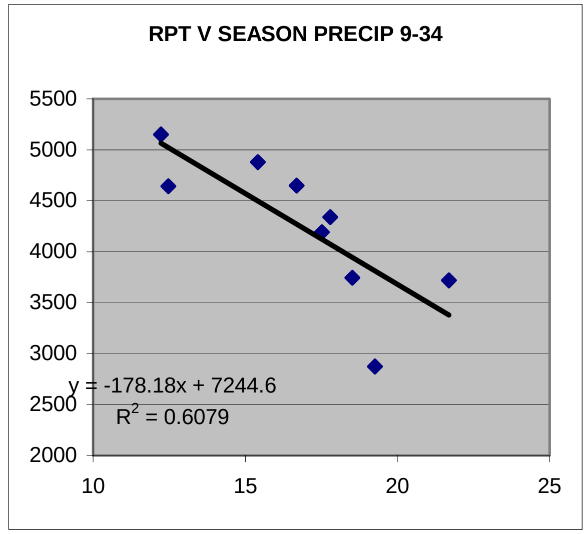


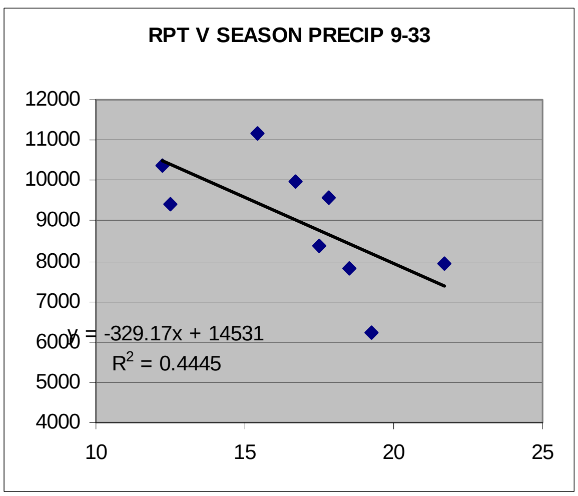


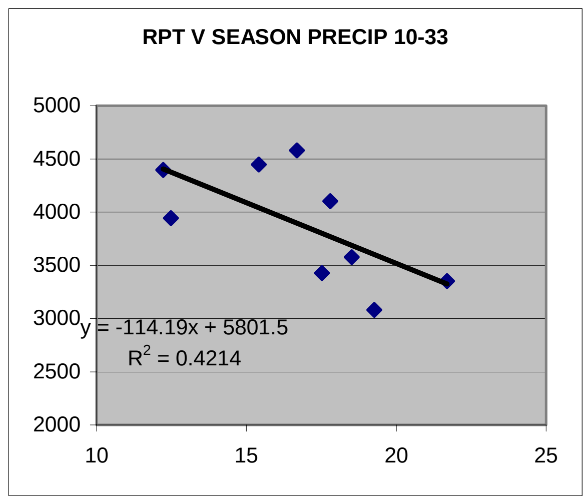


Reported use vs seasonal precipitation, by year and by township. R^2 values are better than with annual precipitation, but note how much the relationship would be affected if a few of the highest or lowest values on either axis were dropped from the analysis.









Appendix D-3

<u>Contents</u>

Detailed data used in groundwater flow estimates
West-East Cross Sections
North-South Cross Sections

1996 WEST BOUNDARY (FLOW IN)

TRS	ST96_V2	K (ft/d)	i	Q (ft3/d)	Q (af/yr)
09S34W06	29.3	106	0.002083	34172	286
09S34W07	35.4	105	0.00214	41992	352
09S34W18	39.6	104	0.002102	45681	383
09S34W19	43.8	103	0.002159	51408	431
09S34W30	45.8	102	0.002273	56088	470
09S34W31	47.1	101	0.002367	59493	499
10S33W06	97.2	100	0.002311	118633	994
10S33W07	71.1	100	0.002273	85344	715
10S33W18	51.8	100	0.002311	63231	530
10S33W19	37.4	99	0.002367	46224	387
10S33W30	41.5	99	0.002405	52195	437
10S33W31	36.7	99	0.002443	46856	393
		Q_IN_SUM	**NORTH**	**288833**	**2420**
		Q_IN_SUM	**10-33**	**412482**	**3456**
		Q_IN_SUM	**ALL**	**701315**	**5876**

1996 EAST BOUNDARY (FLOW OUT)

TRS	ST96_V2	K (ft/d)	i	Q (ft3/d)	Q (af/yr)
09S32W01	76.3	96	0.001477	57141	479
09S32W12	87.6	94	0.001269	55184	462
09S32W13	89.0	92	0.001307	56493	473
09S32W24	84.3	89	0.001269	50243	421
09S32W25	77.3	83	0.001193	40403	339
09S32W36	59.9	72	0.001136	25867	217
10S33W01	77.5	85	0.00108	37537	315
10S33W12	83.0	81	0.00108	38308	321
10S33W13	84.4	78	0.001136	39488	331
10S33W24	75.8	75	0.001174	35254	295
10S33W25	79.2	71	0.001212	35995	302
10S33W36	85.6	67	0.001269	38431	322
		Q_OUT_SUM	**NORTH**	**285331**	**2391**

	Q_OUT_SUM	**10-33**	**225012**	**1885**
	Q_OUT_SUM	**ALL**	**510344**	**4276**
	IN MINUS OUT	**NORTH**	**3501**	**29**
	IN MINUS OUT	**10-33**	**187469**	**1571**
	IN MINUS OUT	**ALL**	**190971**	**1600**

2005 WEST BOUNDARY (FLOW IN)

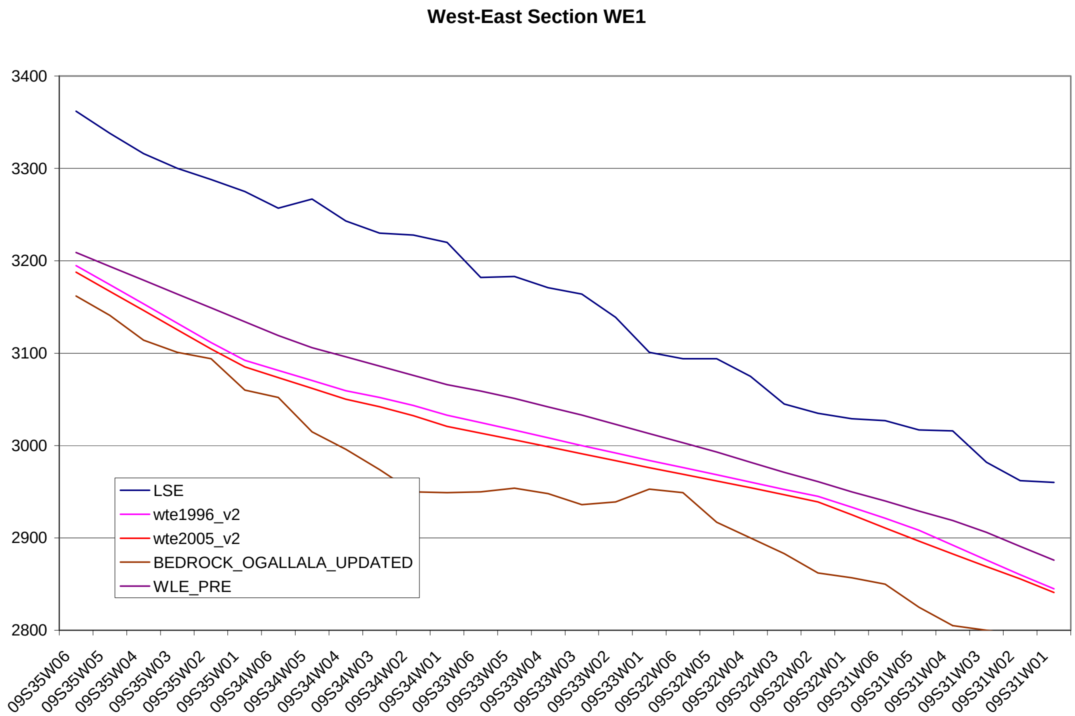
TRS	ST05_V2	K (ft/d)	i	Q (ft3/d)	Q(af/yr)
09S34W06	21.5	106	0.002159	26017	218
09S34W07	27.1	105	0.002159	32384	271
09S34W18	30.7	104	0.002235	37648	315
09S34W19	34.3	103	0.002273	42438	356
09S34W30	37.5	102	0.002273	45853	384
09S34W31	40.4	101	0.002273	48977	410
10S33W06	83.6	100	0.002311	102030	855
10S33W07	68.0	100	0.00233	83632	701
10S33W18	50.0	100	0.002348	61952	519
10S33W19	36.5	99	0.002367	45143	378
10S33W30	41.4	99	0.002405	52101	437
10S33W31	37.4	99	0.002443	47780	400
		Q_IN_SUM	**NORTH**	**233316**	**1955**
		Q_IN_SUM	**10-33**	**392638**	**3290**
		Q_IN_SUM	**ALL**	**625954**	**5245**

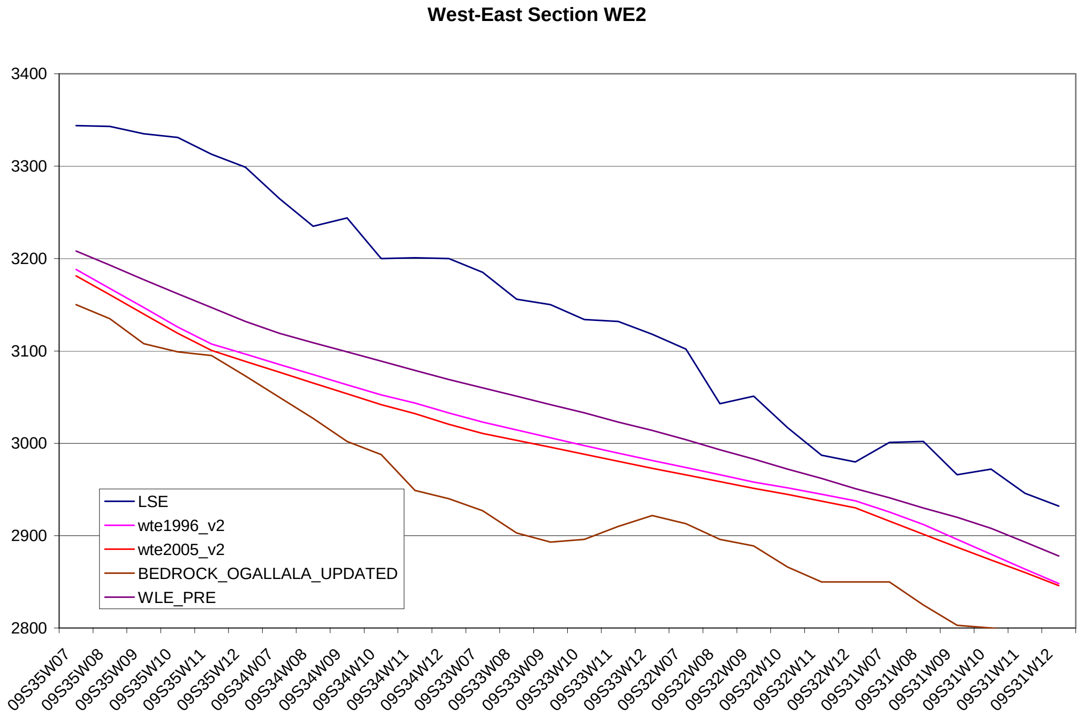
2005 EAST BOUNDARY (FLOW OUT)

TRS	ST05_V2	K (ft/d)	i	Q (ft3/d)	Q(af/yr)
09S32W01	68.0	96	0.00142	48965	410
09S32W12	80.1	94	0.001269	50431	423
09S32W13	80.1	92	0.001307	50826	426
09S32W24	73.9	89	0.001269	44069	369
09S32W25	68.3	83	0.001193	35720	299
09S32W36	52.7	72	0.001061	21257	178
10S33W01	68.9	85	0.001004	31022	260
10S33W12	75.8	81	0.000947	30701	257
10S33W13	78.4	78	0.000947	30568	256
10S33W24	71.0	75	0.000947	26621	223
10S33W25	75.6	71	0.001117	31648	265
10S33W36	83.1	67	0.001269	37311	313
		Q_OUT_SUM	**NORTH**	**251268**	**2105**
		Q_OUT_SUM	**10-33**	**187871**	**1574**

Q_OUT_SUM	**ALL**	**439139**	**3680**
IN MINUS OUT	**NORTH**	**-17952**	**-150**
IN MINUS OUT	**10-33**	**204767**	**1716**
IN MINUS OUT	**ALL**	**186815**	**1565**

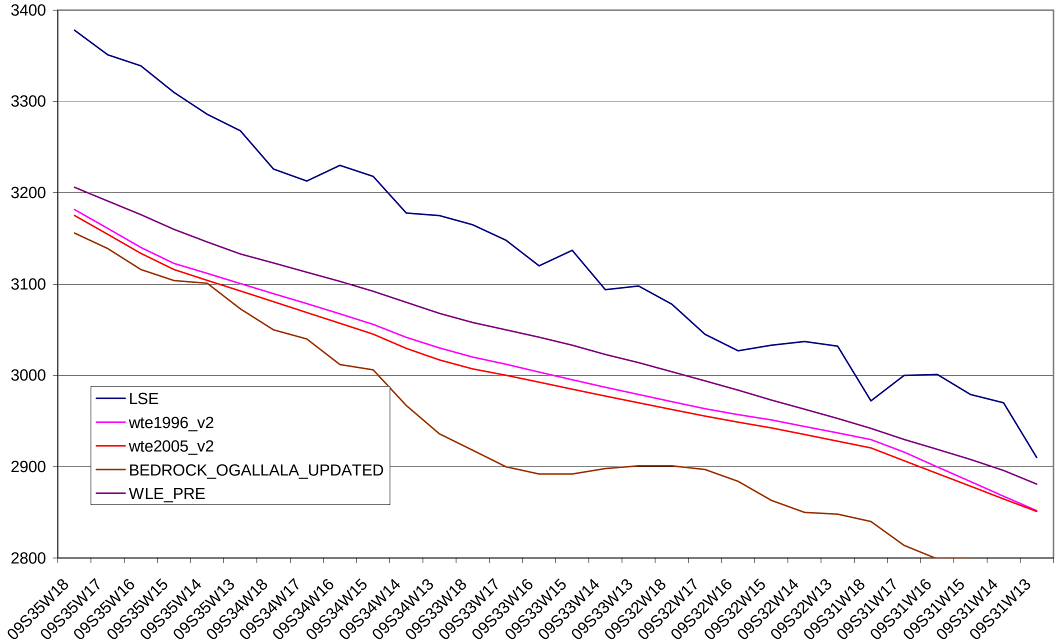
- **West-East Cross sections labeled from north to south. For example Section WE1 is across the northernmost row of sections, and WE12 is across the southernmost.**



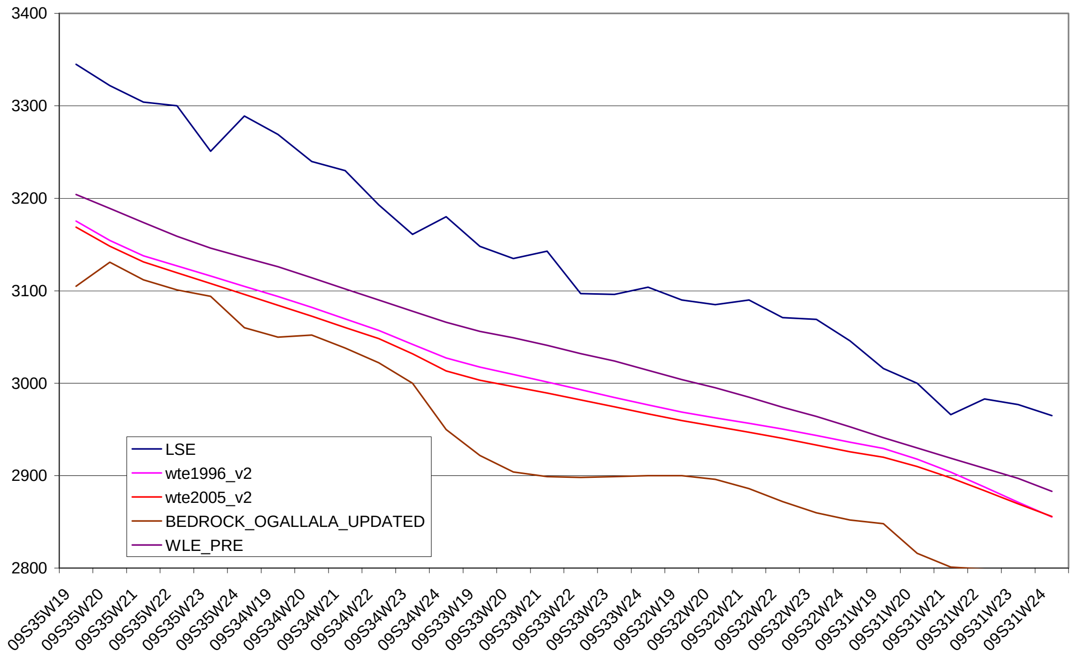


West-East Section WE2
3400
3300
3200
3100
3000
2900
2800
LSE
wte1996_v2
wte2005_v2
BEDROCK_OGALLALA_UPDATED
WLE_PRE
09S35W07
09S35W08
09S35W09
09S35W10
09S35W11
09S35W12
09S34W07
09S34W08
09S34W09
09S34W10
09S34W11
09S34W12
09S33W07
09S33W08
09S33W09
09S33W10
09S33W11
09S33W12
09S32W07
09S32W08
09S32W09
09S32W10
09S32W11
09S32W12
09S31W07
09S31W08
09S31W09
09S31W10
09S31W11
09S31W12

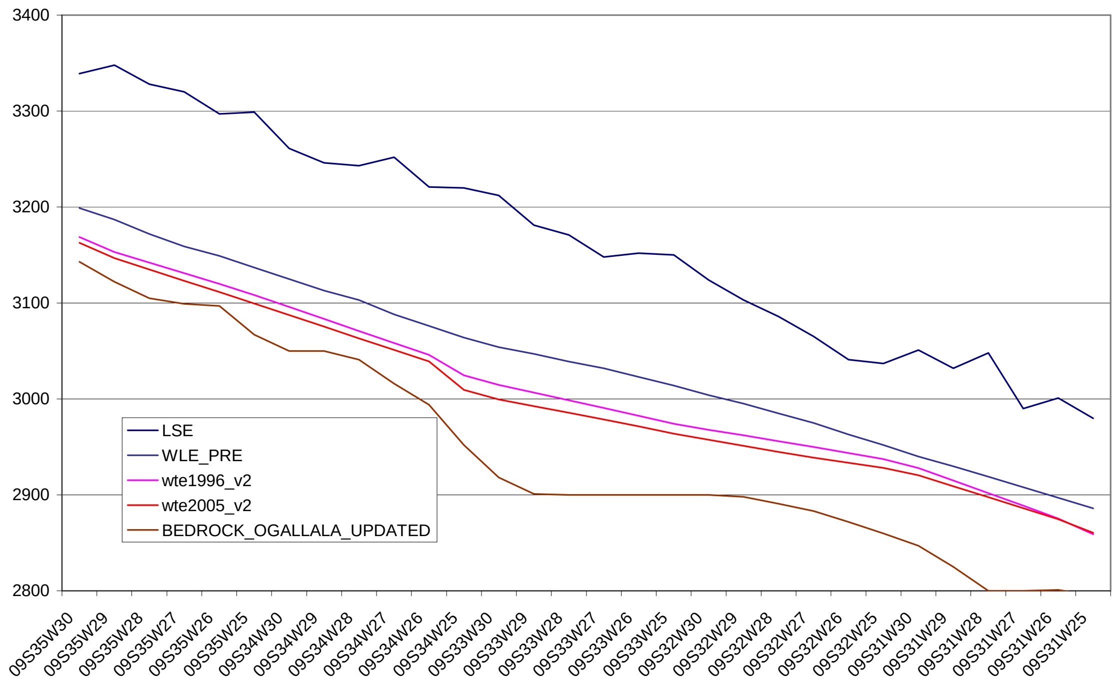
West-East Section WE3



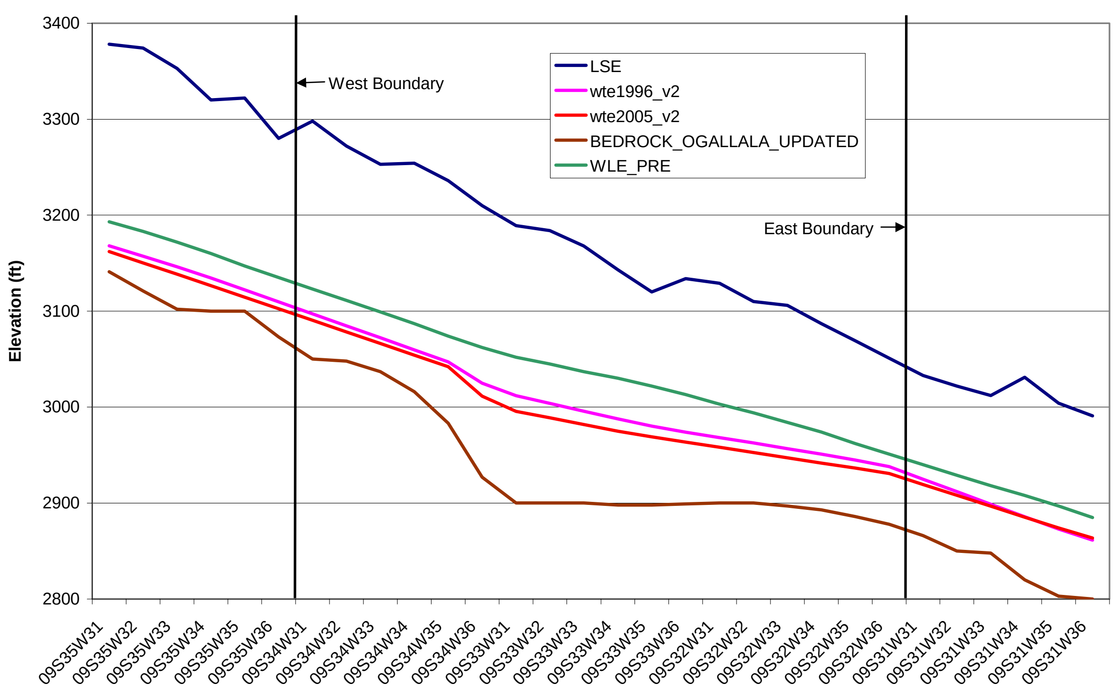
West-East Section WE4



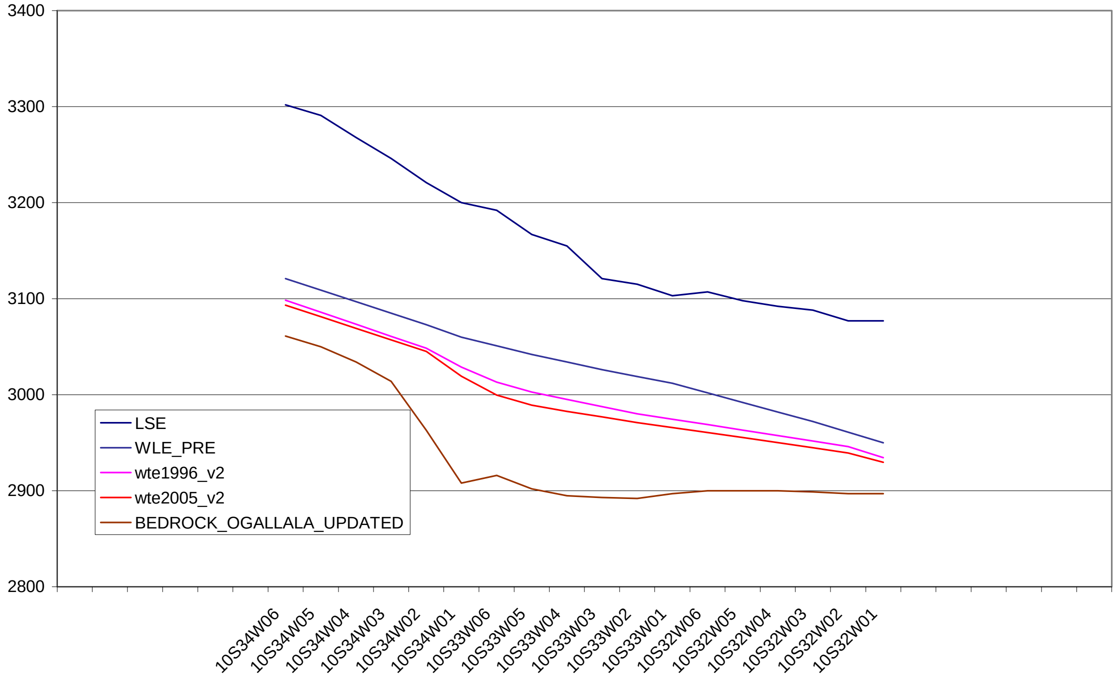
West-East Section WE5



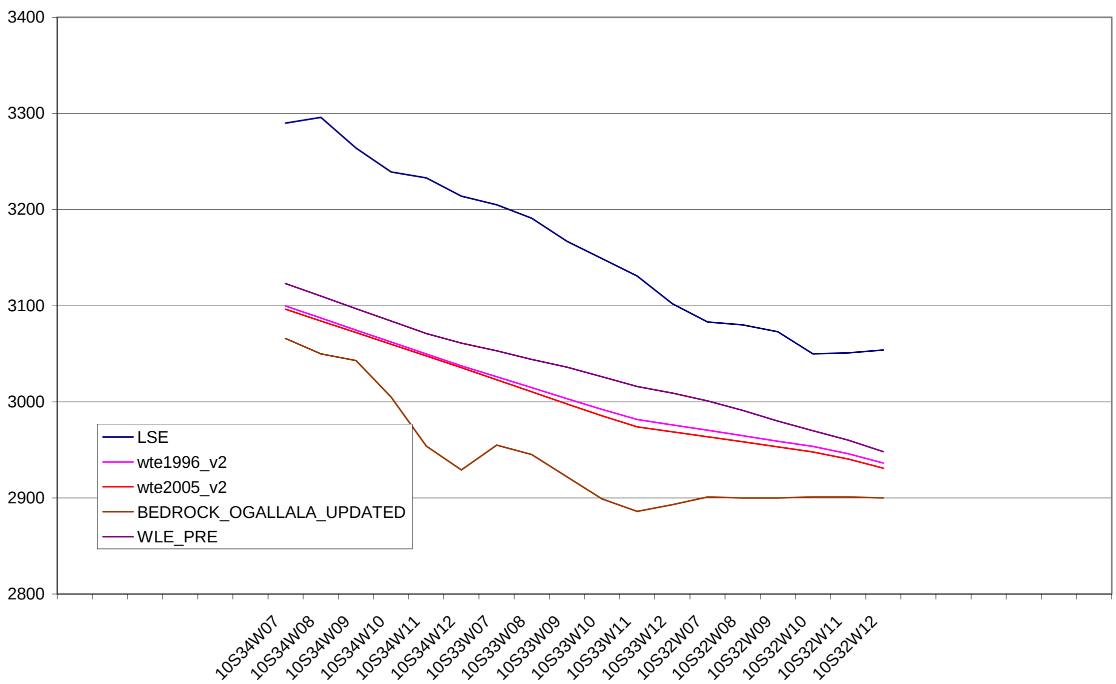
West-East Section WE6



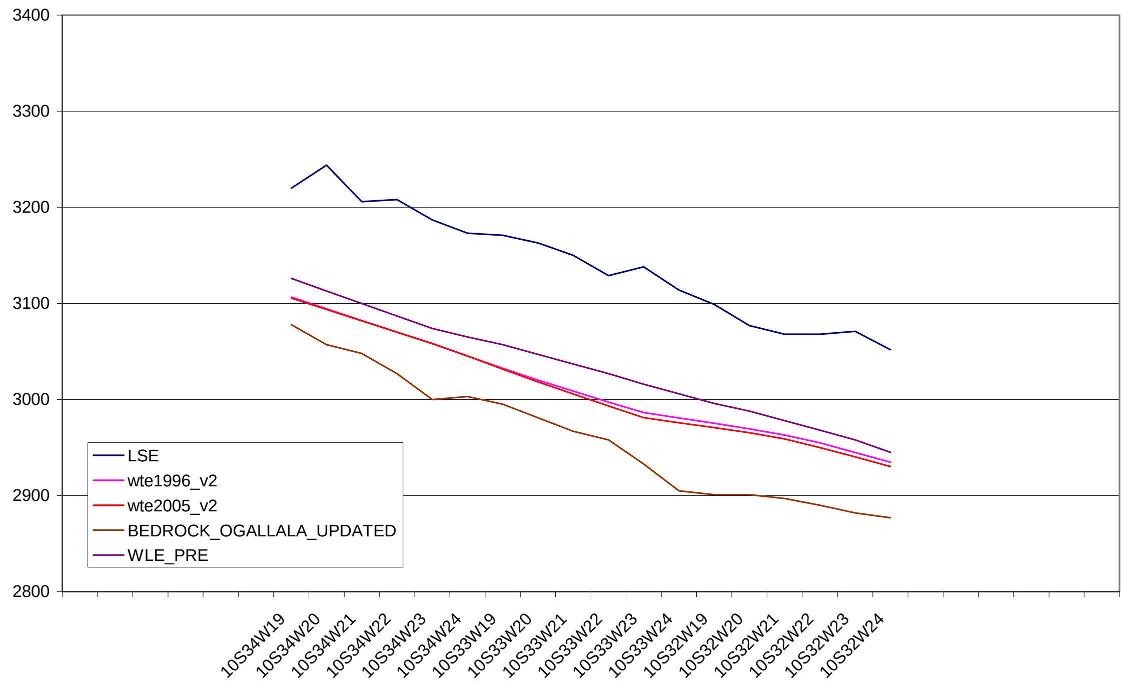
West-East Section WE7



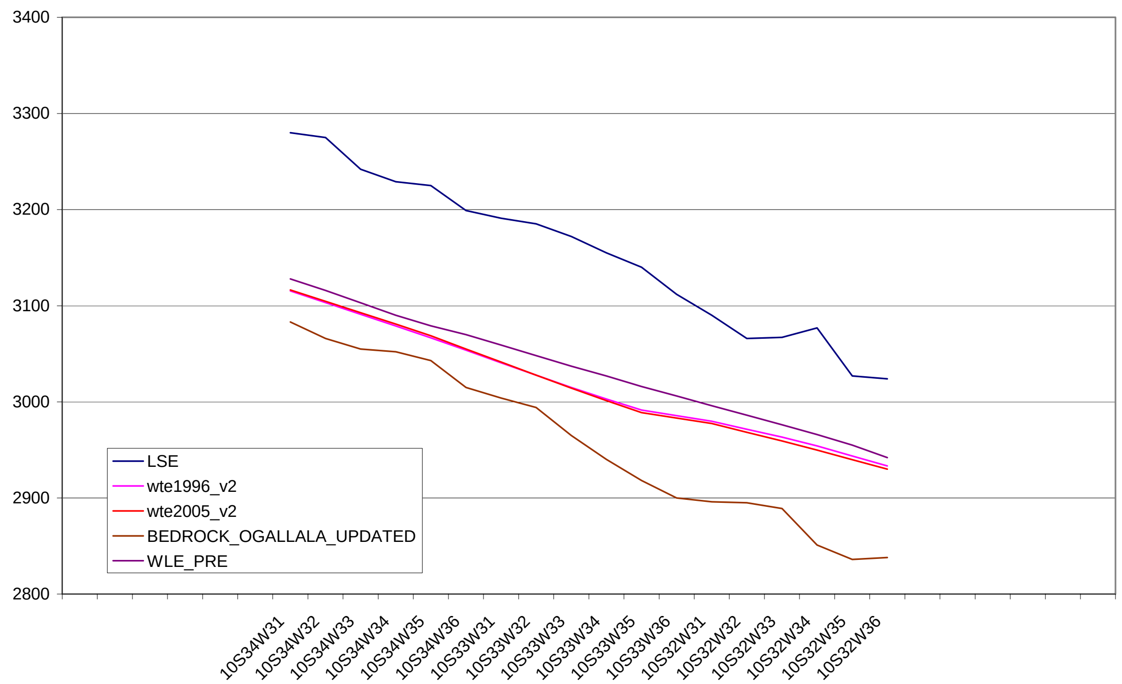
West-East Section WE8



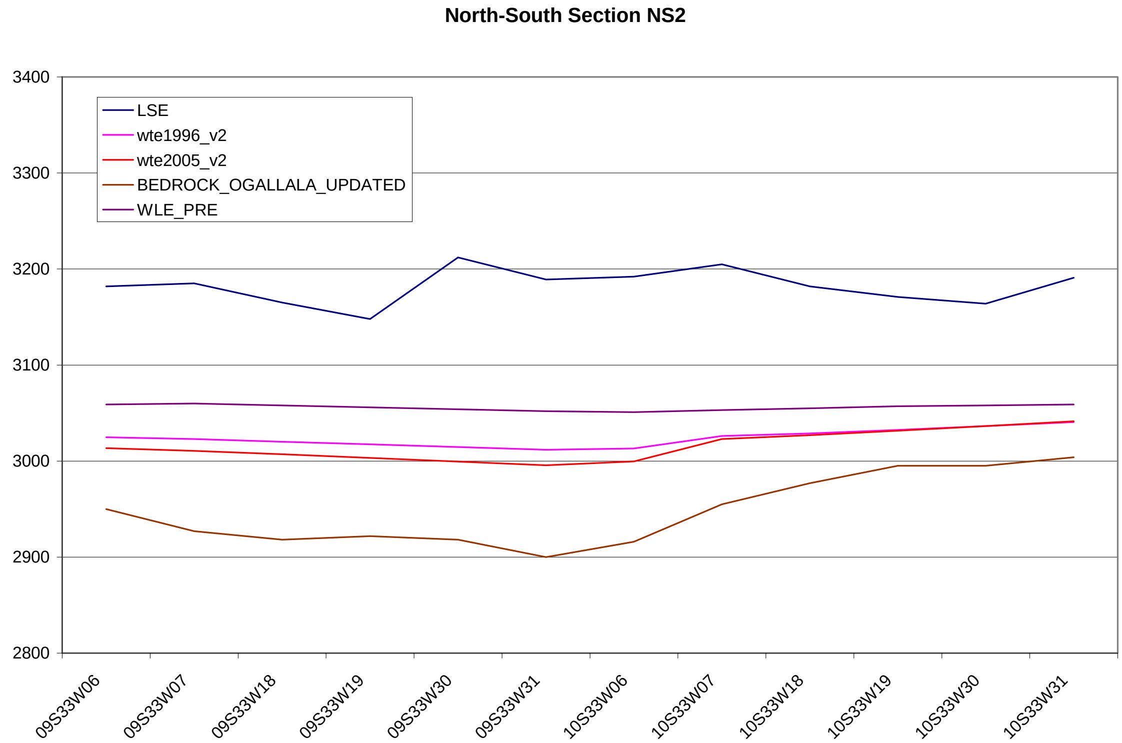
West-East Section WE10

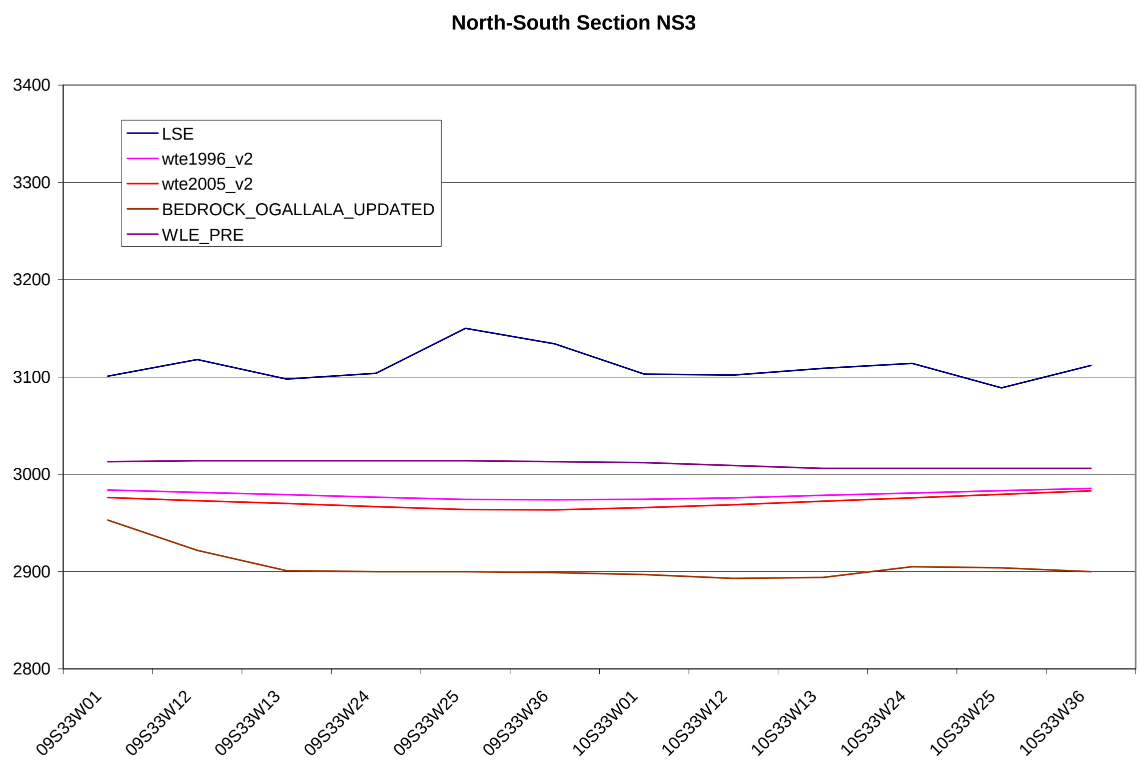


West-East Section WE12

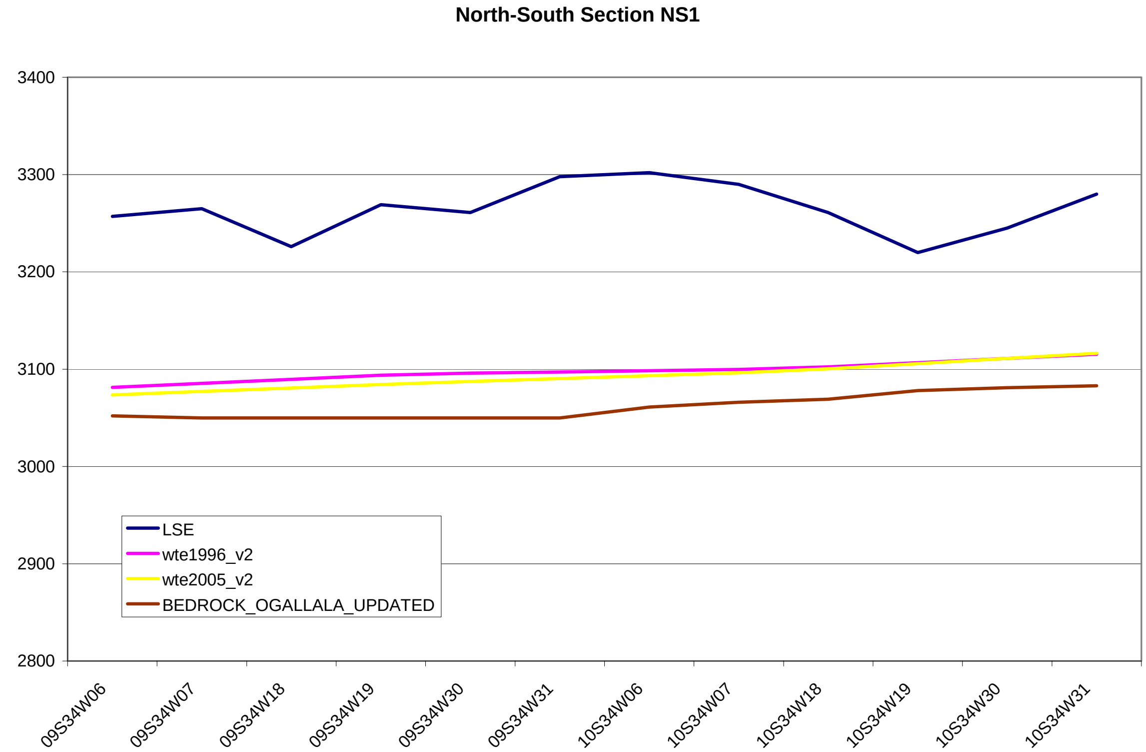


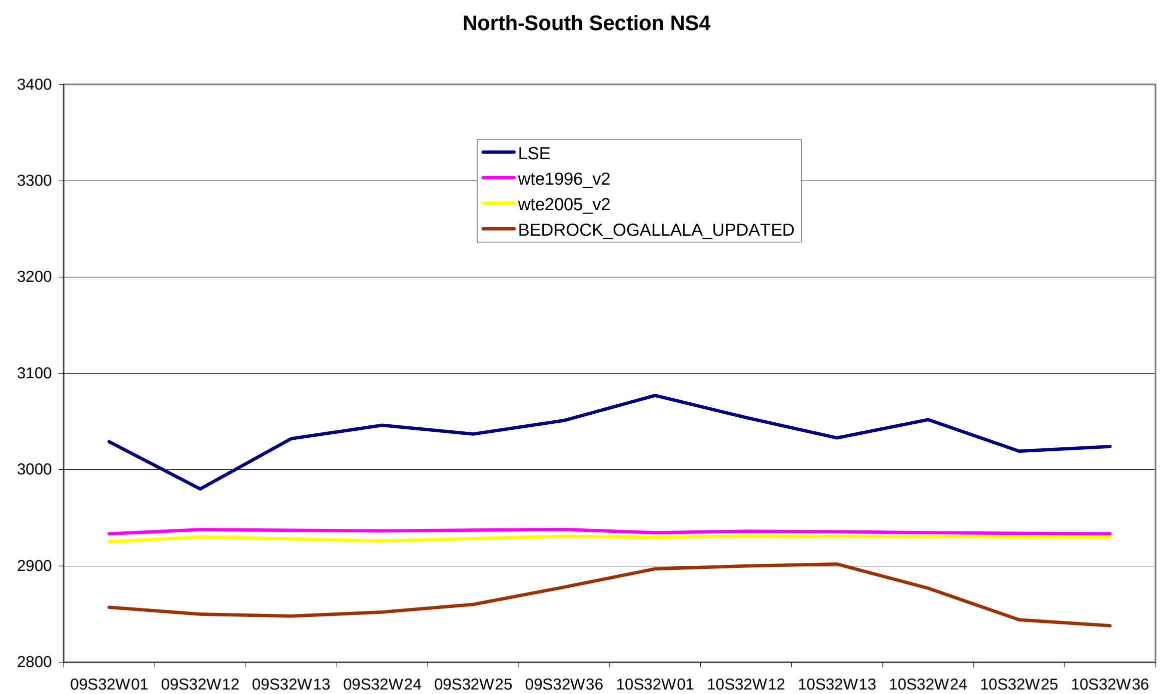
- **North-South Cross Sections. NS2 is across the west side of range 33; NS3 is across the east side of range 33.**





NS1 (west boundary) and NS4 (east boundary) – need to add WLE_PRE etc.





Appendix E: New Insights From Well Responses to Fluctuations In Barometric Pressure

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Accepted by *Ground Water*

Original Submission: November 2009
Revised Submission: August 2010
Accepted for Publication: September 2010

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ABSTRACT

Hydrologists have long recognized that changes in barometric pressure can produce changes in water levels in wells. The barometric response function (BRF) has proven to be an effective means to characterize this relationship; we show here how it can also be utilized to glean valuable insights into semi-confined aquifer systems. The form of the BRF indicates the degree of aquifer confinement, while a comparison of BRFs between wells sheds light on hydrostratigraphic continuity. A new approach for estimating hydraulic properties of aquitards from BRFs has been developed and verified. The BRF is not an invariant characteristic of a well; in unconfined or semi-confined aquifers, it can change with conditions in the vadose zone. Field data from a long-term research site demonstrate the hydrostratigraphic insights that can be gained from monitoring water levels and barometric pressure. Such insights should be of value for a wide range of practical applications.

INTRODUCTION

For more than three centuries, scientists have known that changes in barometric pressure can produce changes in water levels in wells (Pascal, 1973). Although the phenomenon has long been recognized, the underlying mechanisms have only been clarified much more recently (Jacob, 1940; Weeks, 1979; van der Kamp and Gale, 1983; Rojstaczer, 1988; Spane, 2002). For a confined aquifer, a change in the barometric pressure load on the land surface is transmitted downward, grain to grain, near instantaneously to the interface between the confining unit and the aquifer. Part of the load is then borne by the pore water and part is borne by the aquifer framework (Figure

22B in Ferris et al. [1962]). In contrast, the entire load is borne by the water column in a well open to the atmosphere. The resulting pressure difference induces water flow between the aquifer and the well, leading to the commonly observed inverse relationship between barometric pressure and water level (Figure 1). The magnitude of the water-level change primarily depends on how the load is shared between the pore water and the aquifer framework, although the properties of the aquifer and overlying units, and the characteristics of the well (e.g., well diameter and degree of well development) can also play important roles. A different mechanism controls water-level responses in an unconfined aquifer. In that case, access to the free water surface minimizes pore-pressure changes produced by the grain-to-grain transmission of the surface load; the primary control on responses is the downward propagation of air pressure through the pores of the vadose zone (Figure 22A in Ferris et al. [1962]). For shallow water tables, this propagation can occur so quickly that the pressure difference between the well and the aquifer is negligible and, as a result, there is virtually no flow between the two. If the propagation is delayed, due to the depth to water and/or conditions in the vadose zone, the inverse relationship of Figure 1 is observed (Weeks, 1979; Hare and Morse, 1997; Spane, 2002).

Hydrologists have traditionally characterized the relationship between barometric pressure and water level using the ratio of the change in water level to the change in barometric pressure head, which is termed the barometric efficiency (BE) and, by sign convention, varies between zero and one (Jacob, 1940). In a confined aquifer, a BE value near zero indicates that most of the load is borne by the pore water, while a value near one indicates most is borne by the aquifer framework. Although BE has proven to be an effective means of characterizing the short-term response of a well to a change in barometric pressure, the barometric response function (BRF) is a more effective means for characterizing the longer-term response (Rasmussen and Crawford, 1997; Spane, 2002). The BRF, which can be determined through a regression convolution procedure (Furbish, 1991; Rasmussen and Crawford, 1997; Toll and Rasmussen, 2007), characterizes the water-level response over time to a step change in barometric pressure, essentially BE as a function of time since the imposed load. The BRF has been successfully used to remove the effect of barometric-pressure changes on water levels (Toll and Rasmussen, 2007), a critical step, for example, in the interpretation of pumping tests when drawdown is small (Batu, 1998). Rasmussen and Crawford (1997) and Spane (2002) discuss the impact of well conditions and site hydrogeology on BRFs and propose characteristic BRF forms for certain hydrogeologic settings (confined and deep unconfined aquifers). Spane (2002) reviews a number of time- (e.g., Toll and Rasmussen, 2007) and frequency- (e.g., Quilty and Roeloffs, 1991) domain approaches that have been proposed for removing the effect of barometric-pressure changes from water-level data series and concludes that the BRF (a time-domain method) is particularly effective for this purpose.

Water-level responses to fluctuations in barometric pressure have also been used to estimate subsurface properties. Specific storage can be determined from BE if estimates of aquifer porosity and pore-water compressibility are available (Jacob, 1940; Batu, 1998). Time- and frequency-domain methods, often in a type-curve format, have been developed for determining hydraulic properties from water-level responses to barometric-pressure changes (e.g., Weeks, 1978; Rojstaczer, 1988; Rojstaczer and Riley, 1990;

Evans et al., 1991; Furbish, 1991). These methods, however, have yet to be widely adopted.

The purpose of this paper is to extend the earlier work to show how the BRF can be utilized to glean further hydrogeologic insights. Our primary emphasis is on gaining insights into the low permeability unit (henceforth, aquitard) that overlies a semi-confined aquifer. Given the utility of the BRF for removing the impact of barometric-pressure changes from water-level data, we also explore its value for estimating subsurface properties. We propose a new approach for estimating aquitard hydraulic conductivity (*K*) by fitting theoretical responses to field-determined BRFs. We demonstrate these concepts using field data from a long-term research site and discuss how the BRF can also be used to gain insights into conditions in unconfined aquifers and, potentially, the vadose zone. Although BE is considered an invariant parameter of a well, we show that a BRF can change as a function of conditions in the vadose zone.

Field Site Overview

The field component of this study took place at the Larned Research Site (LRS; 38.2° N latitude, 99.0° W longitude) of the Kansas Geological Survey (Figure 2a). The primary focus here is on three LRS wells (LWC2, LEA5, and LEC2 in Figure 2a; all 0.102-m inner diameter) screened in the semi-confined High Plains aquifer (interval A in Figure 2b), with a secondary focus on adjacent wells screened at the bottom of the unconfined Arkansas River alluvial aquifer (interval B in Figure 2b). Each well has an integrated pressure-transducer and datalogger unit submerged in the water column (miniTroll, In-Situ, Inc.); pressure readings are taken every 15 minutes. Gauge (relative to atmospheric pressure) and absolute pressure transducers were used in this work; Price (2009) describes how both types of transducers can be utilized for assessing water-level responses to barometric-pressure changes. Atmospheric pressure is recorded with on-site barometers at the top of wells (baroTroll, In-Situ, Inc.) and at a weather station (Onset Computing Corp.); readings are also taken every 15 minutes. Groundwater in the vicinity of the LRS is primarily used for irrigation, so the vast majority of pumping is during the growing season (mid-March to mid-October). In most years, water levels recover from seasonal pumping by mid-December (Figure 3). The Arkansas River, which was flowing at the time of the photograph in Figure 2a, is intermittent at the LRS and had little to no flow for the period of the analyses discussed here. Note that all of the LRS wells in the semi-confined High Plains aquifer display a pronounced water-level response to changes in barometric pressure (e.g., Figure 1). Small responses (a few mm or less) to precipitation loading (e.g., Rasmussen and Mote, 2007) have been observed, but had no influence on the analyses. Water-level responses to stream-stage loading (e.g., Boutt, 2010) have also been observed, but were negligible during the period of the analyses.

Methodology

BRFs were determined from the LRS water-level and barometric-pressure data using the regression convolution approach of Furbish (1991) and Rasmussen and Crawford (1997). This approach, which has been implemented in a spreadsheet format (e.g., Halford, 2006; Toll and Rasmussen 2007), assumes that temporal changes in a detrended (removal of linear trend in this work) time series of water levels (equally spaced in time) can be represented as

$$\Delta W(t) = \sum_{i=0}^{m} \alpha_i \Delta B(t - i\Delta t) + \sum_{i=0}^{n} \beta_i \Delta E(t - i\Delta t) \quad \textbf{(1)}$$

where $\Delta W(t)$ is the change in detrended water-level elevation [L] between time t and the previous time when a measurement was taken (t-Δt); $\Delta B(t$-$i\Delta t)$ and $\Delta E(t$-$i\Delta t)$ are the changes in the detrended barometric-pressure head [L] and earth-tide gravity potential [LT^{-2}], respectively, between time t-$i\Delta t$ and the previous time when a measurement was taken [t-(i+1)Δt]; α_i and β_i are the unit (impulse) barometric-pressure and earth-tide response functions at lag i, respectively; m is the maximum time lag for the barometric pressure response; n is the maximum time lag for the earth tide response; and Δt is the time between adjacent measurements. The underlying assumption of this implementation of the BRF approach is that $\Delta W(t)$ is only a function of changes in barometric pressure and the earth-tide gravity potential, i.e. the impact of other mechanisms on water levels is negligible or can be removed by detrending the water-level data. This assumption appears quite reasonable for systems such as the High Plains aquifer in western Kansas where recharge is very small and pumping is seasonal in nature. The earth-tide gravity potentials for the LRS are obtained with TSOFT, which generates synthetic earth tide records for a given location (Van Camp and Vauterin, 2005). Earth tides do have a small effect on water levels at the LRS, so they are incorporated in the analysis following the approach outlined in Toll and Rasmussen (2007). The focus of this paper, however, is on the much larger fluctuations induced by changes in barometric pressure and the insights that can be derived from them.

Ordinary least-squares linear regression is used to estimate α_i and β_i, and the barometric response function for lag j, A_j, is obtained by summing the α_i terms up to that lag:

$$A_j = \sum_{i=0}^{j} \alpha_i \qquad \textbf{(2)}$$

with the standard error given as

$$\hat{\sigma}_{A_j} = \sqrt{\sum_{i=0}^{j} \sum_{k=0}^{j} C_{i,k}} \qquad \textbf{(3)}$$

where C is the variance-covariance matrix for the α_i estimates (e.g., Abraham and Ledolter, 1983). A small BE and finite transducer resolution can result in occasions when $\Delta W(t)$ is incorrectly truncated to zero. In order to reduce such truncation errors, the above approach can be extended to incorporate water-level and barometric-pressure changes over multiples of Δt.

We have developed theoretical BRFs for an aquifer system similar to that of Figure 2b using a semi-analytical solution for a 1-D vertical representation of a two-layer (aquitard and aquifer – see vertical bar on Figure 2b) configuration. The governing equations, which are based on the development of van der Kamp and Gale (1983), are

$$\frac{\partial h_1}{\partial t} - \gamma_1 h_0 \delta(t) = D_1 \frac{\partial^2 h_1}{\partial z^2} \qquad \textbf{(4a)}$$

$$\frac{\partial h_2}{\partial t} - \gamma_2 h_0 \delta(t) = D_2 \frac{\partial^2 h_2}{\partial z^2} \qquad \textbf{(4b)}$$

where h_0 is the change in barometric pressure head at the land surface [L], $\delta(t)$ is the delta function [T^{-1}], and h_i, D_i, and γ_i are head deviation from static [L], hydraulic diffusivity [L^2T^{-1}], and loading efficiency (1-BE) [-] for the aquitard (1) and aquifer (2), respectively, and z is depth (0 at aquifer-aquitard interface and increases downward). The hydraulic diffusivity is the ratio of hydraulic conductivity (K_i, [LT^{-1}]) over specific storage (S_{si}, [L^{-1}]). The loading efficiency term ($\gamma_i h_0 \delta(t)$) represents the pressurization of the pore water via the near-instantaneous grain-to-grain transmission downward of the surface load. Groundwater flow is primarily driven by the boundary condition at the top of the aquitard, which is a function of the pressure propagation through the pores of the overlying vadose zone and unconfined aquifer.

The initial condition for the system is static heads in the aquifer and aquitard (i.e., h_i is zero); the boundary conditions are a constant head at the top of the aquitard (produced by the propagation of a step change in barometric pressure head to the bottom of the overlying unconfined aquifer), zero flow at the bottom of the aquifer, and continuity of head and flow at the aquitard-aquifer interface.

A solution for the governing equations, (4a)-(4b), and auxiliary conditions is obtained using standard integral-transform techniques. The system of equations is transformed into Laplace space and solved to yield the transform-space solution:

$$\overline{h}_i(z,p) = \frac{h_0}{p} f_i(z,p) \qquad \textbf{(5a)}$$

where $\overline{h}_i$ is the Laplace transform of h_i, p is the Laplace-transform variable,

$$f_1(z,p) = \frac{\left(\frac{h_{UB}}{h_0} - \gamma_1\right) K_r \sqrt{\frac{D_2}{D_1}} \operatorname{sech}\left(\sqrt{\frac{p}{D_1}} l\right) - (\gamma_1 - \gamma_2) \tanh\left(\sqrt{\frac{p}{D_1}} l\right) \tanh\left(\sqrt{\frac{p}{D_2}} a\right)}{K_r \sqrt{\frac{D_2}{D_1}} + \tanh\left(\sqrt{\frac{p}{D_1}} l\right) \tanh\left(\sqrt{\frac{p}{D_2}} a\right)} \cosh\left(\sqrt{\frac{p}{D_1}} z\right)$$

$$- \frac{\left(\frac{h_{UB}}{h_0} - \gamma_1\right) \operatorname{sech}\left(\sqrt{\frac{p}{D_1}} l\right) + (\gamma_1 - \gamma_2)}{K_r \sqrt{\frac{D_2}{D_1}} + \tanh\left(\sqrt{\frac{p}{D_1}} l\right) \tanh\left(\sqrt{\frac{p}{D_2}} a\right)} \tanh\left(\sqrt{\frac{p}{D_2}} a\right) \sinh\left(\sqrt{\frac{p}{D_1}} z\right) + \gamma_1 \quad \textbf{(5b)}$$

for the aquitard ($-l \le z \le 0$),

$$f_2(z,p) = \frac{\left(\frac{h_{UB}}{h_0} - \gamma_1\right) \operatorname{sech}\left(\sqrt{\frac{p}{D_1}} l\right) + (\gamma_1 - \gamma_2)}{1 + \frac{1}{K_r} \sqrt{\frac{D_1}{D_2}} \tanh\left(\sqrt{\frac{p}{D_1}} l\right) \tanh\left(\sqrt{\frac{p}{D_2}} a\right)} \frac{\cosh\left[\sqrt{\frac{p}{D_2}} (z - a)\right]}{\cosh\left(\sqrt{\frac{p}{D_2}} a\right)} + \gamma_2 \quad \textbf{(5c)}$$

for the aquifer ($0 \le z \le a$), K_r is K_1/K_2, h_{UB} is the constant head at the top of the aquitard, a is aquifer thickness, and l is aquitard thickness. The derivation of equation (5a) is given in the Appendix.

The real-space form of equation (5a) is generated using the inversion algorithm of Stehfest (1970). The expression for the head in the semi-confined aquifer is

$$h_2(z,t) \approx h_0 \sum_{n=1}^{N} \frac{V_n}{n} f_2\left(z, \frac{\ln 2}{t} n\right) \quad \textbf{(6)}$$

where V_n is the coefficient for the Laplace inversion and N is the number of terms in the Stehfest summation (14 for this work). The barometric response function for a well in the semi-confined aquifer is

$$A(z,t) = 1 - \frac{h_2(z,t)}{h_0} \approx 1 - \sum_{n=1}^{N} \frac{V_n}{n} f_2\left(z, \frac{\ln 2}{t} n\right) \quad \textbf{(7)}$$

Equation (7) assumes a constant head (h_{UB}) at the top of the aquitard. Temporal variations in that head can be readily incorporated using superposition (convolution) procedures (e.g., Olsthoorn, 2008) as shown in the Appendix. Although wellbore storage is ignored in this development because of the rapid (relative to the typical Δt used in practice) response of wells in aquifers of moderate to high *K*, the solution can be extended to incorporate wellbore storage following Furbish (1991) and Spane (2002). Similarly, the solution can be extended to incorporate the vadose zone following Weeks (1979) and others.

Application

The regression convolution approach was applied to data from three LRS wells (LWC2, LEA5, and LEC2 – Figure 2a) and the site reference barometer (adjacent to LEC2). Winter 2003-04 (henceforth, winter 2004) data were used because there was virtually no pumping then and well responses appeared to be representative of typical conditions observed in LRS High Plains aquifer wells (Figure 3). The winter 2004 BRFs (Figure 4) have three important characteristics. First, the agreement between the BRFs from the different wells is quite striking, despite the wells being separated by over 680 m, indicating that the character of the aquifer-aquitard system is not changing substantially between the wells. Second, the short-term (one-hour) response is typical of what would be expected in a confined aquifer in which most of the load is borne by the pore water (BE≈0.08), consistent with the near-surface, unconsolidated nature of the aquifer (e.g., Rasmussen and Mote, 2007). Third, the longer-term (one-day) response is typical of what would be expected in a semi-confined (leaky) aquifer where water movement through the aquitard equilibrates heads, consistent with the results of a four-day pumping test at the LRS in which drawdown stabilized as a result of leakage (Butler et al., 2004). The BRFs of wells screened at the bottom of the unconfined aquifer (interval B of Figure 2b) were zero for this time period (winter 2004 curve of Figure 5), indicating that barometric-pressure changes propagated rapidly through the pores of the vadose zone and the unconfined aquifer. The rapid propagation across the unconfined aquifer (BRFs from LRS wells screened at the water table and those screened at the bottom of the unconfined aquifer always coincide) indicates that the apparent clay layers in the unconfined aquifer shown in the EC log of Figure 2b are not laterally extensive enough to affect the hydraulic connection between the top and bottom of that aquifer for the temporal resolution (Δt = 15 min) of this analysis.

The BRFs presented in Figure 4 suggest the possibility of acquiring information about the aquitard from these functions. Theoretical response functions were computed using equation (7) and fit to the field-determined BRFs to estimate the properties of the aquifer-aquitard system. Conditions at the top of the aquitard, which are required for the response function calculation, were obtained from wells screened at the bottom of the unconfined aquifer (interval B of Figure 2b). For winter 2004, the BRFs for those wells were essentially zero for all lags beyond the zero lag (winter 2004 curve of Figure 5). Using that condition at the aquitard top, an aquifer loading efficiency (1-BE) of 0.92, and an estimate of aquifer diffusivity (2.9×10^{6} $m^{2}d^{-1}$) based on previous estimates of aquifer K (88 md^{-1}) and S_s (3.0×10^{-5} m^{-1}) obtained from the four-day LRS pumping test (Butler et al., 2004), we fit a theoretical response function to the winter 2004 BRF for well LEA5

(Figure 6). The fit, which was based on the first half-day of the BRF because additional mechanisms appear to be affecting the BRF at larger times, yielded estimates of the aquitard diffusivity (D_1 =1.7 × 10^2 m^2d^{-1}), the aquitard loading efficiency (γ_1 = 0.97), and the ratio between the aquifer and aquitard hydraulic conductivity (K_r = 1.8 × 10^{-5}). Using the K_2 estimate from the LRS pumping test, an aquitard K of 1.6 × 10^{-3} md^{-1}, which is within 25% of the pumping-test value (2.1 × 10^{-3} md^{-1}), is calculated from the K_r estimate, demonstrating the similarity of the K_r ratios obtained with the different approaches. Note that an estimate of aquifer diffusivity is required for the parameter estimation procedure because of the high degree of correlation between K_r and D_2. In the absence of the pumping-test information that was available at the LRS, the aquifer diffusivity could be estimated using the aquifer K from a slug test and the aquifer S_s determined from the BE. In this example, the target for comparison was the aquitard K from the LRS pumping test, so the aquifer K and S_s values from that same pumping test were used for the diffusivity estimate. Isotropy in aquifer hydraulic conductivity was assumed for the calculation of K_1. This assumption should be reasonable in unconsolidated aquifers with a hydrostratigraphic framework similar to that at the LRS (Figure 2b).

A check on the parameters calculated from the BRF fit was performed by using the same parameters to generate a theoretical response function to compare with the field-determined BRF for winter 2008; this time was chosen because it followed an extended period of recharge (Figure 3). Although intuitively one might expect the BRF to be a characteristic function of a well, our results show otherwise. The BRF for well LEA5 in winter 2008 (Figure 6) is distinctly different from the 2004 BRF because of differing conditions at the top of the aquitard (bottom of the unconfined aquifer). In winter 2008, the wells screened at the bottom of the unconfined aquifer display a barometric response (e.g., winter 2008 BRF in Figure 5), indicating that the propagation of air pressure through the vadose zone was affected by a change of conditions in that zone (e.g., perched water table or layer of frozen soil). This difference in barometric responses at the bottom of the unconfined aquifer between 2004 and 2008 is analogous to the difference reported by Hare and Morse (1997) between a well below a low permeability landfill cap and one adjacent to the cap. Moreover, the 2008 response in the unconfined aquifer cannot be matched with the one-dimensional, uniform vadose zone solution of Weeks (1979), indicating that the response must be a product of complicated flow paths or other phenomena. Using the parameters determined from the 2004 fit and the upper boundary condition based on the 2008 data (i.e. the winter 2008 BRF of Figure 5), we generated the 2008 theoretical response function for well LEA5 shown in Figure 6. The agreement with the 2008 field-determined BRF is quite good, although no curve fitting was involved, and can be considered a strong verification of the parameters calculated from the 2004 analysis.

Discussions and Conclusions

This work demonstrates the utility of the barometric response function (BRF) for gaining insights into site hydrostratigraphy. In semi-confined aquifers, the form of the BRF indicates the degree of aquifer confinement and can be exploited to estimate aquitard properties using the approach developed here. A comparison of BRFs between wells can shed light on aquitard continuity. However, the generality of the conclusions that can be drawn from this comparison depends on the BRF averaging (support) volume, which is the subject of ongoing work. In unconfined aquifers, the similarity of BRFs from wells screened at the water table and those at the base of the aquifer indicate that low-*K* layers within the aquifer are not laterally extensive enough to affect the hydraulic connection across the aquifer for the temporal resolution of this analysis. Differences between such BRFs could potentially be exploited to estimate the vertical *K* of an unconfined aquifer in a manner analogous to the frequency-domain approach of Rojstaczer and Riley (1990).

This work appears to be the first to show that BRFs are not necessarily an invariant characteristic of a well. The form of a BRF can depend on the nature of the pressure propagation through the vadose zone, even for wells in a semi-confined aquifer (Figure 6). This dependence on the vadose zone presents the opportunity to glean insights into changes in vadose-zone conditions, a subject of ongoing work. Spane (2002) and others have speculated that the barometric response of wells in unconfined aquifers could vary as a function of vadose-zone conditions. This work confirms that speculation and demonstrates that a similar dependence is found in semi-confined aquifers (Figures 5-6).

The barometric response function is a promising tool for gaining important insights through monitoring of water levels and barometric pressure. In this study, we demonstrated that BRFs can provide reasonable estimates of aquitard properties as well as valuable information about other aspects of site hydrostratigraphy. They thus can often be a cost-effective alternative/supplement to a conventional pumping test. Similarly, BRFs should be a useful tool for initial screening of potential shallow target zones for CO_2 sequestration and, more generally, for monitoring changes in formation and fluid properties (e.g., porosity and fluid compressibility) in the course of sequestration activities. Although we demonstrated the approach in a system in which the strong seasonality of pumping facilitated data processing, it is also applicable in aquifers that are pumped more continuously, although more involved processing is required to remove the impact of other mechanisms. Finally, we must emphasize that the approach for estimation of aquitard properties described here is best implemented with a well in the overlying aquifer. In the absence of such a well, considerable error may be introduced into the parameter estimates through uncertainty about head conditions at the top of the aquitard. This uncertainty can be particularly large at sites with thick vadose zones.

ACKNOWLEDGMENTS

This paper greatly benefited from reviews provided by Todd Rasmussen, Garth van der Kamp, Frank Spane, Geoff Bohling, Peter Dietrich, and an anonymous reviewer. GAM was a 2008 participant in the Applied Geohydrology Summer Research Assistantship program of the Kansas Geological Survey. This program is open to students at any university with an interest in learning more about recent developments in hydrogeological field methods.

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APPENDIX E1

Solution Derivation

The Laplace-space expressions for the governing equations ([4a-b]) are

$$p\bar{h}_1 - \gamma_1 h_0 = D_1 \frac{d^2\bar{h}_1}{dz^2} \tag{A1a}$$

$$p\bar{h}_2 - \gamma_2 h_0 = D_2 \frac{d^2\bar{h}_2}{dz^2} \tag{A1b}$$

with the notation defined in the main text following equation (5).

The Laplace-space expressions for the boundary conditions are

$$\bar{h}_1(-l, p) = \frac{h_{UB}}{p} \quad \text{for the constant-head condition } (h_{UB}) \text{ at the aquitard top} \tag{A2}$$

$$\frac{d\bar{h}_2(a, p)}{dz} = 0 \quad \text{for the no-flow condition at the bottom of the aquifer} \tag{A3}$$

and

$$\bar{h}_1(0, p) = \bar{h}_2(0, p) \tag{A4}$$

and

$$K_1 \frac{d\bar{h}_1(0, p)}{dz} = K_2 \frac{d\bar{h}_2(0, p)}{dz} \tag{A5}$$

for continuity of head and flow, respectively, at the aquifer-aquitard interface.

The general solution to (A1) is

$$\bar{h}_1(z,p) = A_1(p)\cosh\left(\sqrt{\frac{p}{D_1}}z\right) + B_1(p)\sinh\left(\sqrt{\frac{p}{D_1}}z\right) + \frac{\gamma_1 h_0}{p} \quad \textbf{(A6a)}$$

$$\bar{h}_2(z,p) = A_2(p)\cosh\left(\sqrt{\frac{p}{D_2}}z\right) + B_2(p)\sinh\left(\sqrt{\frac{p}{D_2}}z\right) + \frac{\gamma_2 h_0}{p} \quad \textbf{(A6b)}$$

where A_i and B_i are functions of p that are determined from the boundary conditions.

Using the boundary conditions of (A2)-(A5) and the D_i and K_r notation defined after equation (5), expressions for A_1, A_2, B_1, and B_2 can be written as follows:

$$A_1(p) = \frac{h_0}{p}\frac{\left(\frac{h_{UB}}{h_0} - \gamma_1\right)K_r\sqrt{\frac{D_2}{D_1}}\operatorname{sech}\left(\sqrt{\frac{p}{D_1}}l\right) - (\gamma_1 - \gamma_2)\tanh\left(\sqrt{\frac{p}{D_1}}l\right)\tanh\left(\sqrt{\frac{p}{D_2}}a\right)}{K_r\sqrt{\frac{D_2}{D_1}} + \tanh\left(\sqrt{\frac{p}{D_1}}l\right)\tanh\left(\sqrt{\frac{p}{D_2}}a\right)} \quad \textbf{(A7)}$$

$$A_2(p) = \frac{h_0}{p}\frac{\left(\frac{h_{UB}}{h_0} - \gamma_1\right)\operatorname{sech}\left(\sqrt{\frac{p}{D_1}}l\right) + (\gamma_1 - \gamma_2)}{1 + \frac{1}{K_r}\sqrt{\frac{D_1}{D_2}}\tanh\left(\sqrt{\frac{p}{D_1}}l\right)\tanh\left(\sqrt{\frac{p}{D_2}}a\right)} \quad \textbf{(A8)}$$

$$B_1(p) = -\frac{A_2(p)}{K_r}\tanh\left(\sqrt{\frac{p}{D_2}}a\right)\sqrt{\frac{D_1}{D_2}} \quad \textbf{(A9)}$$

$$B_2(p) = -A_2(p)\tanh\left(\sqrt{\frac{p}{D_2}}a\right) \quad \textbf{(A10)}$$

Substituting (A7)-(A10) into (A6) and simplifying yields the Laplace-space solution of equation (5a) in the main text.

Convolution Expression

Temporal variations in the head at the top of the aquitard (h_{UB}) can be incorporated using a standard convolution approach (e.g., Olsthoorn, 2008). In order to demonstrate the approach for the head in the semi-confined aquifer (h_2), equation (5c) can be rewritten as

$$f_2(z,p) = F(z,p) + \frac{h_{UB}}{h_0} G(z,p) \quad \textbf{(A11a)}$$

where

$$F(z,p) = -\frac{\gamma_1 \operatorname{sech}\left(\sqrt{\frac{p}{D_1}}l\right) + (\gamma_2 - \gamma_1)}{1 + \frac{1}{K_r}\sqrt{\frac{D_1}{D_2}} \tanh\left(\sqrt{\frac{p}{D_1}}l\right) \tanh\left(\sqrt{\frac{p}{D_2}}a\right)} \frac{\cosh\left[\sqrt{\frac{p}{D_2}}(z-a)\right]}{\cosh\left(\sqrt{\frac{p}{D_2}}a\right)} + \gamma_2 \quad \textbf{(A11b)}$$

and

$$G(z,p) = \frac{\operatorname{sech}\left(\sqrt{\frac{p}{D_1}}l\right)}{1 + \frac{1}{K_r}\sqrt{\frac{D_1}{D_2}} \tanh\left(\sqrt{\frac{p}{D_1}}l\right) \tanh\left(\sqrt{\frac{p}{D_2}}a\right)} \frac{\cosh\left[\sqrt{\frac{p}{D_2}}(z-a)\right]}{\cosh\left(\sqrt{\frac{p}{D_2}}a\right)} \quad \textbf{(A11c)}$$

The F function quantifies the dissipation of the pressure in the aquitard-aquifer system produced by the barometric surface loading, while the G term quantifies the head change produced by the boundary condition at the aquitard top. Only the G term is involved in the convolution.

The infinite series expression for the convolution in real space is

$$A(z,t) \approx A(z,k\Delta t) = 1 - \left[\begin{array}{l} \sum_{n=1}^{N} \frac{V_n}{n} F\left(z, \frac{\ln 2}{k\Delta t} n\right) + \frac{h_{UB}(0)}{h_0} \sum_{n=1}^{N} \frac{V_n}{n} G\left(z, \frac{\ln 2}{k\Delta t} n\right) + \\ \sum_{i=1}^{k-1} \frac{\Delta h_{UBi}}{h_0} \sum_{n=1}^{N} \frac{V_n}{n} G\left(z, \frac{\ln 2}{(k-i)\Delta t} n\right) \end{array} \right] \quad \textbf{(A12)}$$

where $t=k\Delta t$, $h_{UB}(0)$ is the head at the top of the aquitard at $t=0$,

$$\Delta h_{UBi} = h_{UB}(i\Delta t) - h_{UB}(i\Delta t - \Delta t)$$

is the change in head at the aquitard top over one time interval Δt.

FIGURES

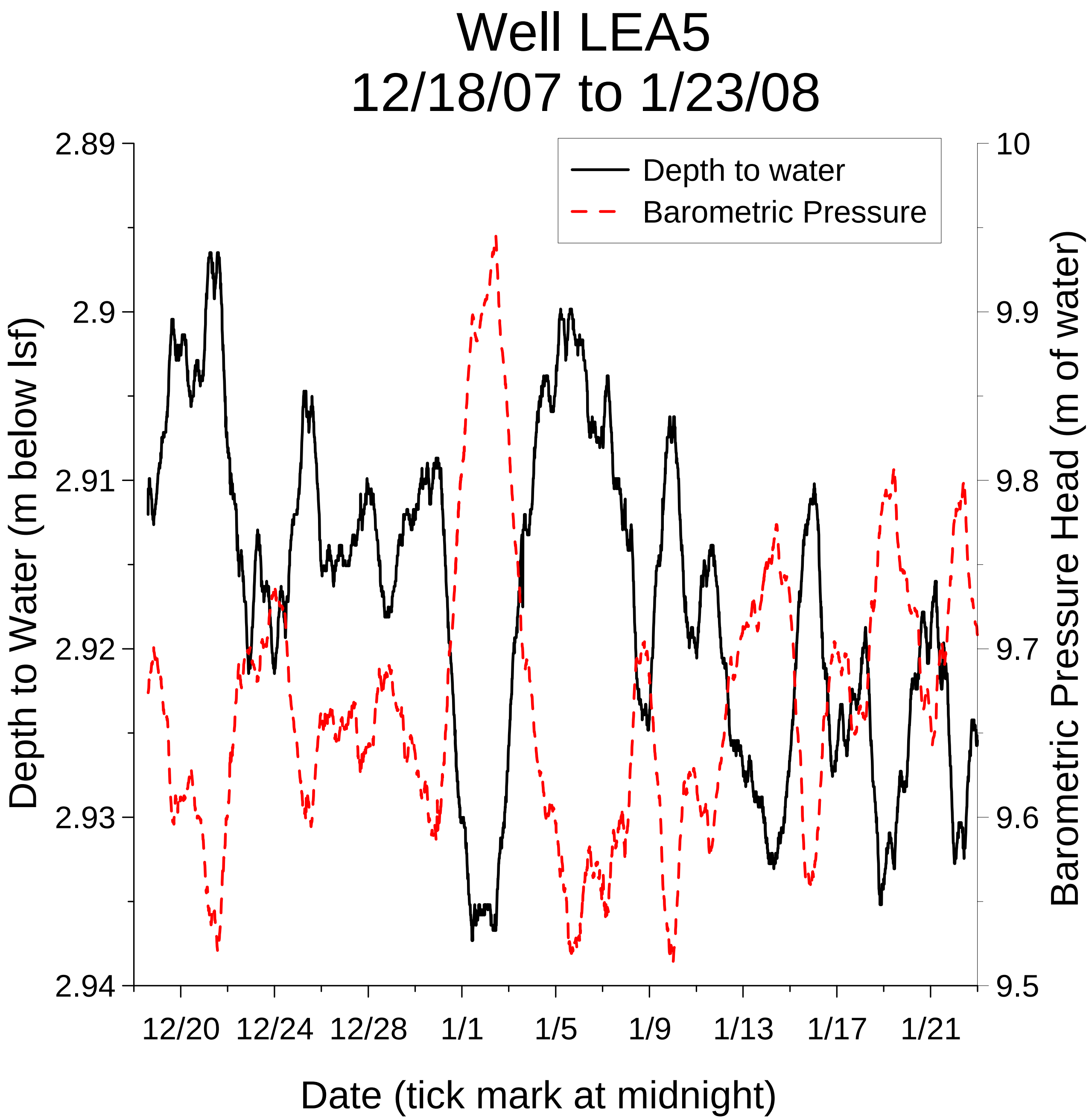
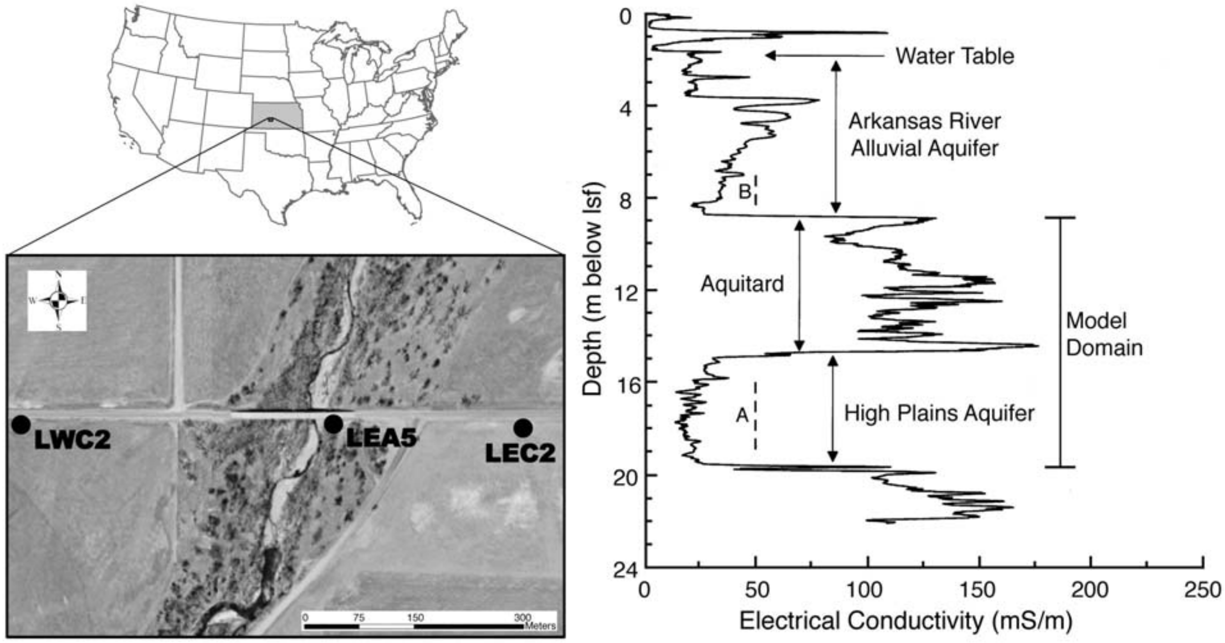


Figure 1 – Depth to water from land surface and barometric pressure head for well LEA5 at the Larned Research Site for a period in the winter of 2007-08. Depth to water is plotted increasing downward to display the inverse relationship between water level and barometric pressure; spans of the left and right y-axes differ by a factor of ten.



a) b)

Figure 2 – a) Location map and aerial photo of the Larned Research Site (LRS). Aerial photo (year 2000) only shows wells discussed in paper, watercourse in photo is the Arkansas River; b) High-resolution direct-push electrical conductivity (EC) log from near the center of the LRS riparian zone. Wells in the High Plains aquifer are screened across the interval marked A, while adjacent wells in the lower portion of the Arkansas River alluvial aquifer are screened across the interval marked B. At this site, high EC values indicate clays and low values indicate sands and gravels. Bar on right side shows the vertical extent of the model discussed in the text.

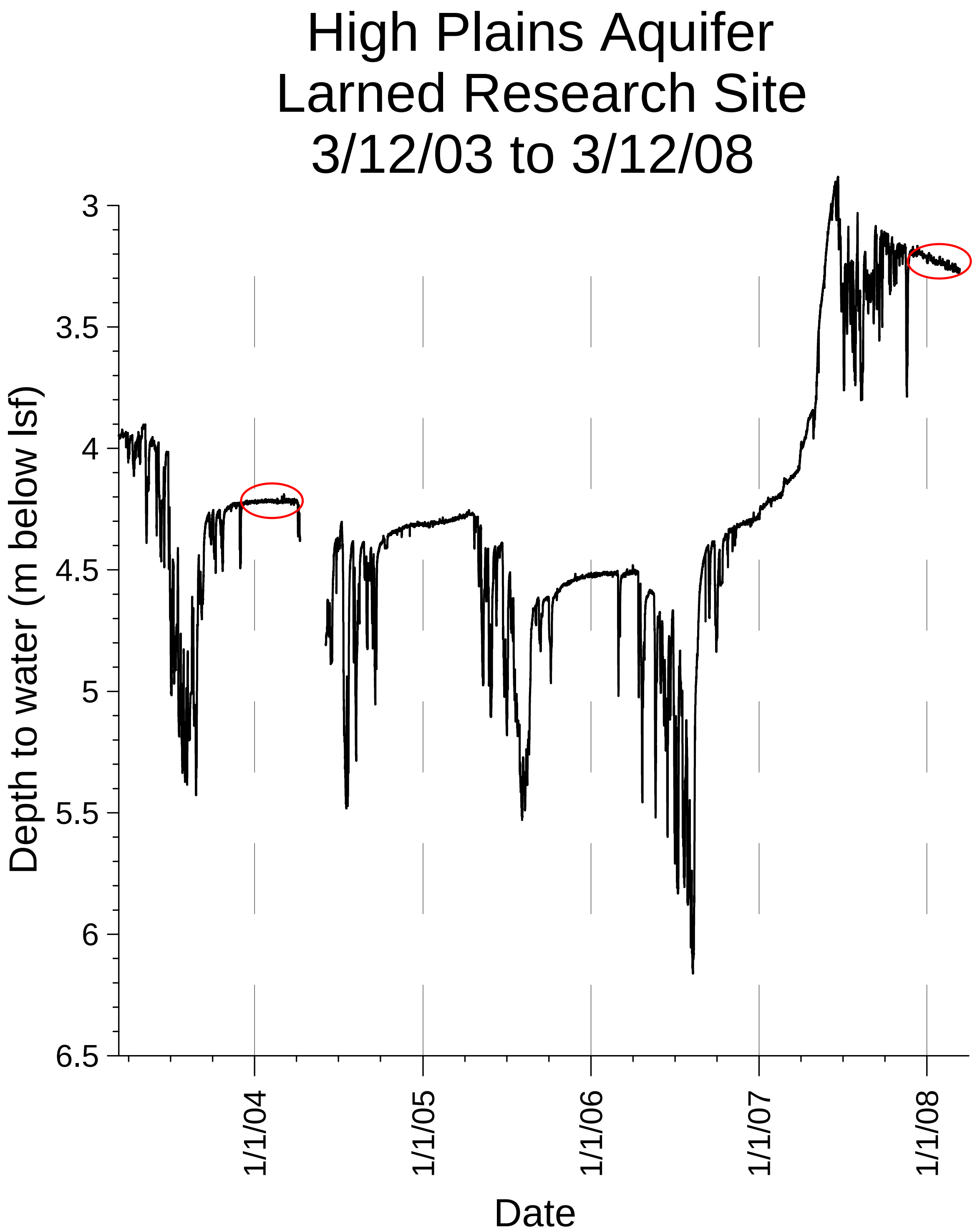


Figure 3 – Depth to water versus time plot for LRS well LEC2 (see aerial photo in Figure 2a for location); well LEC2 has the most continuous record for this period of the three wells shown in Figure 2a. The ovals indicate the time intervals used for the analyses discussed in this paper. Note the pronounced seasonality of groundwater pumping in the vicinity of the LRS and the period of significant recharge beginning in the latter half of 2006.

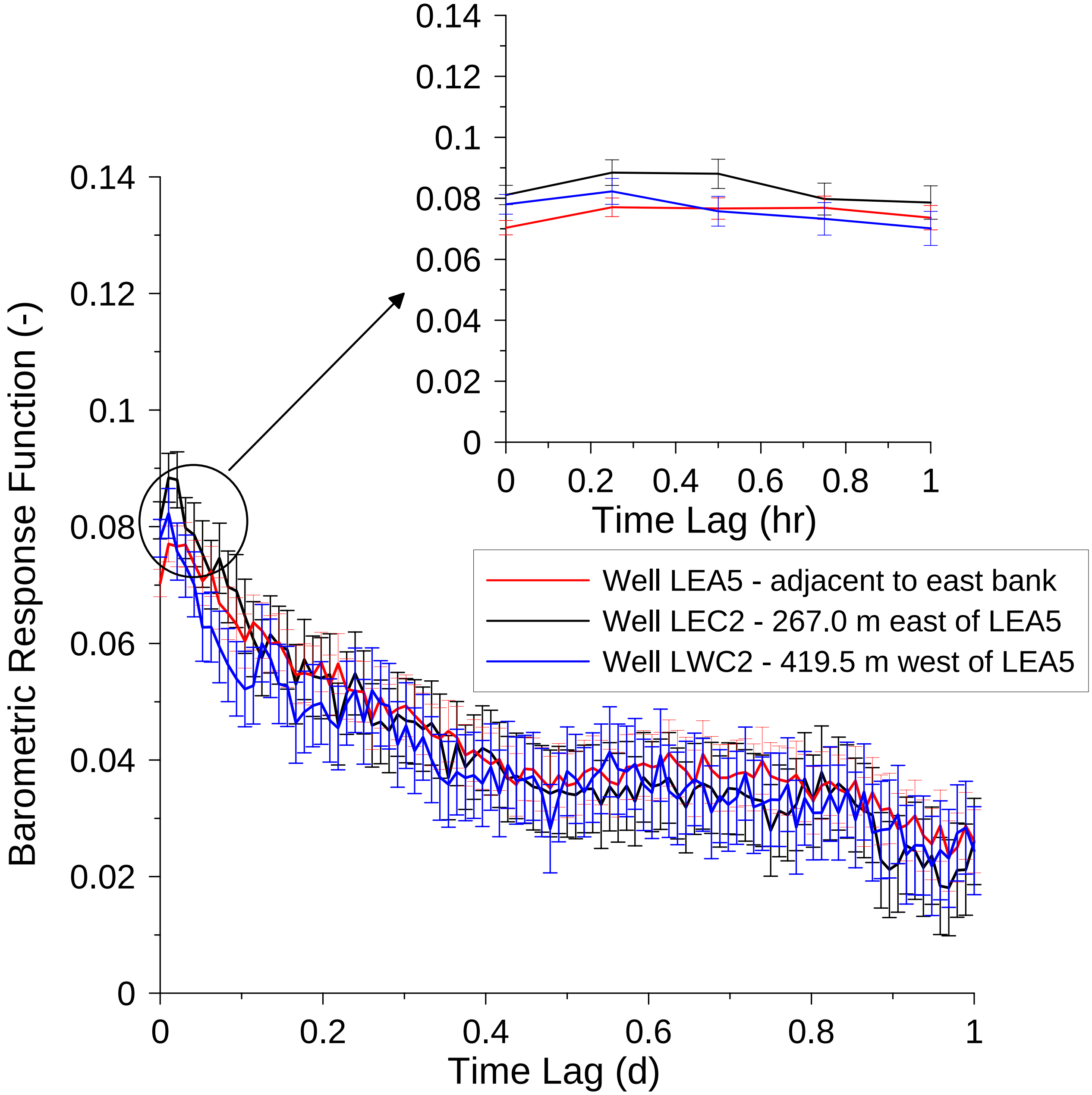


Figure 4 - One-day and one-hour (inset) barometric response functions (BRFs) for three LRS wells in the High Plains aquifer in the winter of 2004. BRFs for winter 2005 and 2006 are similar in form. Agreement between the BRFs from these wells was observed in all years since monitoring began (2001 or 2002). Error bars indicate one standard error about the estimated functions; linear trend removed from data series prior to BRF calculation.

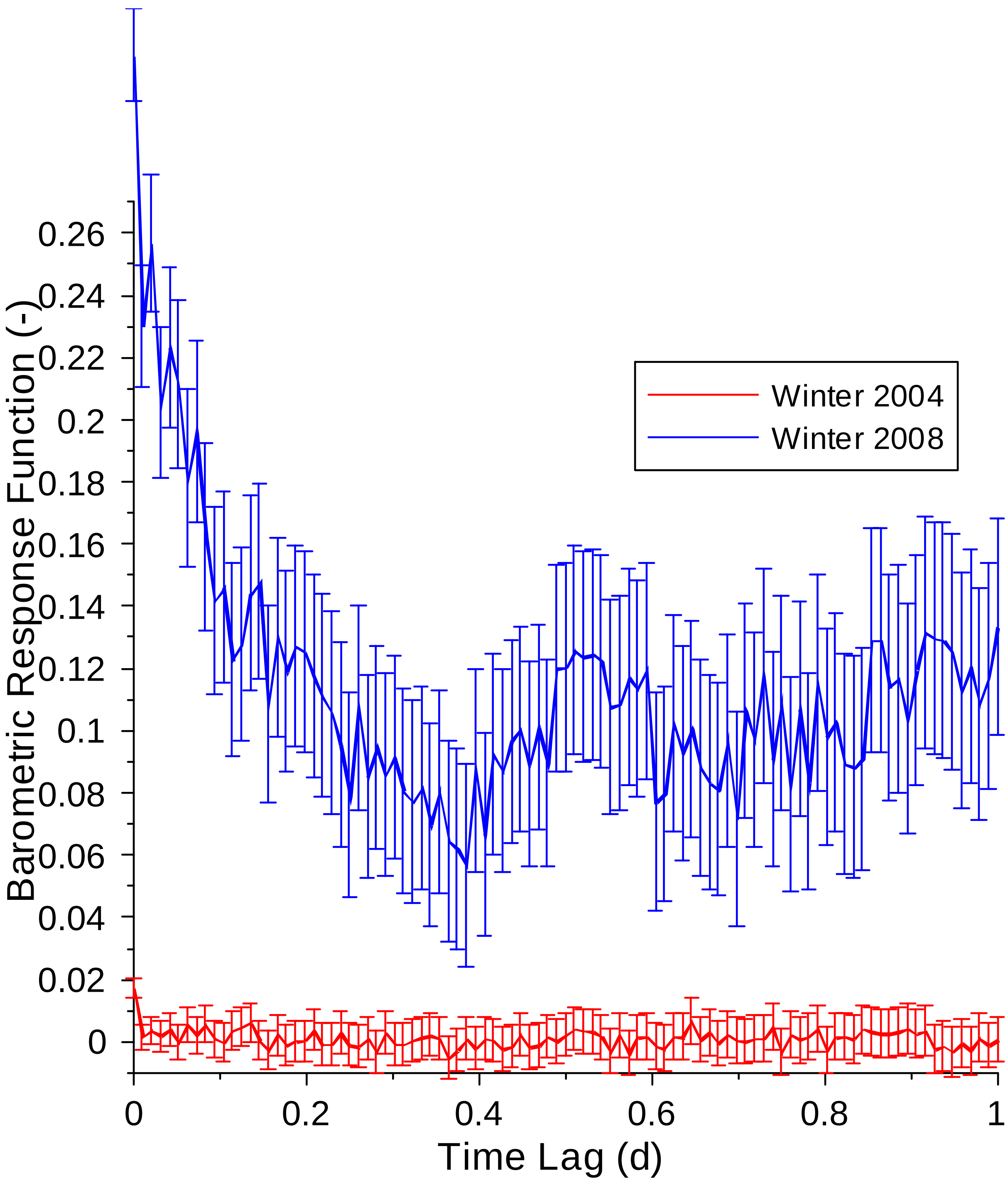


Figure 5 - One-day barometric response functions for well LEA4 for winters 2004 and 2008; well LEA4 is adjacent to well LEA5 and screened across interval B of Figure 2b. Linear trend removed from the data series prior to BRF calculation.

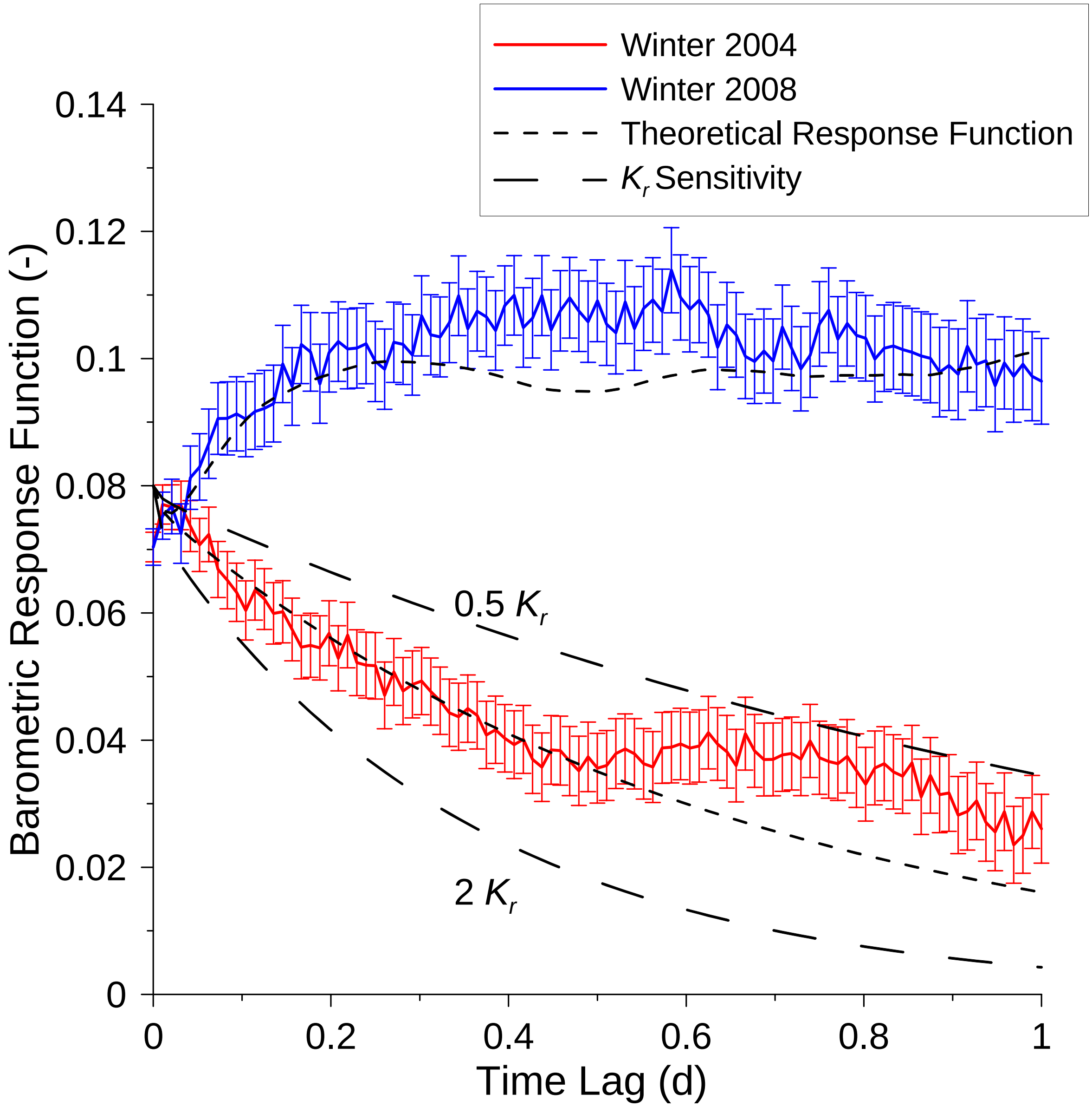


Figure 6 - One-day barometric response functions for well LEA5 for winters 2004 and 2008, and the best-fit theoretical response function for the winter 2004 data. Hydraulic parameters from the winter 2004 fit were used to generate the winter 2008 theoretical response function. Estimated parameters were obtained from the first half-day of the 2004 BRF: $K_r = 1.8 \times 10^{-5}$ [-], $D_1 = 1.7 \times 10^2$ m^{2}d^{-1}, and $\gamma_1 = 0.97$ [-]. The aquifer loading efficiency (γ_2), the aquifer diffusivity (D_2), and the ratio of aquitard thickness to aquifer thickness were fixed at 0.92 [-], 2.9×10^6 m^{2}d^{-1}, and 1.0, respectively. Similar results were obtained for the other High Plains aquifer wells. The sensitivity of the response functions to K_r is shown for variations of a factor of two about the 2004 theoretical response function; similar variations in D_1 produced plots that were barely distinguishable from the response function, indicating the much smaller sensitivity to that parameter for these conditions (i.e. aquifer and aquitard characteristics). Linear trend removed from the data series prior to BRF calculation. Span of y-axis is half that of Figure 5.