Kansas Geological Survey

High Plains Aquifer Calibration Monitoring Well Program: Year 2 Progress Report

D.P. Young, R.W. Buddemeier, J.J. Butler, Jr., W. Jin, D.O. Whittemore,
E. Reboulet, and B.B. Wilson

with contributions by J. Munson (KDA-DWR)

Kansas Geological Survey Open-file Report 2008-29
December 2008

GEOHYDROLOGY

KANSAS GEOLOGICAL SURVEY
The University of Kansas

The University of Kansas, Lawrence, KS 66047 (785) 864-3965; www.kgs.ku.edu

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1. Introduction and background

The calibration monitoring (index) well program is a pilot study of an improved approach to measuring hydrologic responses at the local level. The study is being supported by the Kansas Water Office (KWO) with Water Plan funding. It is being undertaken because of the KWO's interest in and responsibility for long-term planning of the Ogallala-High Plains aquifer in western Kansas. The program is expected to make a significant contribution to understanding the aquifer dynamics at scales appropriate to the definition and management of aquifer subunits, and ultimately, providing cost-effective improvements for long-term management.

The hypotheses to be tested by this program are that

1. Properly designed, sited, and measured wells can yield water-level measurements that, supported by supplemental measurements in other wells in the vicinity, are sufficiently accurate and representative of local water-table behavior to use in intensive management programs; and
2. Consistent deviations in water levels from the behavior of a calibration well indicate aquifer heterogeneity; such results can be interpreted to refine subunit definitions and characteristics or to improve the interpretation of water-table responses over larger/other areas.

One well in each of the western Kansas GMDs is being monitored continuously over a period of ~5 years to address the following questions:

- Where, how, and at what level of confidence can high-quality measurements from a specifically designed, sited, and constructed monitoring well be combined with supplemental measurements of wells of opportunity to characterize water-level behavior over an area on the scale of an aquifer subunit?

- What can these measurements tell us about the results of the annual water-level program, and about possible opportunities for improvement?

- What can we learn about widely occurring but poorly characterized deviations from the "homogeneous aquifer" assumptions (e.g., fringe effects, variations in degree of confinement, recharge, practical saturated thickness, etc.)?

A subsidiary goal is to directly examine issues and areas of particular interest to the GMDs and the Kansas Department of Agriculture, Division of Water Resources (KDA-DWR). The rationale and conceptual framework for the program has been laid out in more detail by Young et al. (2007), available at http://www.kgs.ku.edu/HighPlains/OHP/OFR_2007_30_final.pdf.

2. General context and comparisons

This section of the report reviews some of the relevant information from Young et al. (2007), and assembles information on the regional framework and on characteristics of and comparisons between the individual well sites. Subsequent sections address each site in detail before returning to presentation of more general and project overview issues.

2.1 Water resources geography and sampling

Three index wells have been installed in the Ogallala-High Plains aquifer, one in each of the three western Kansas GMDs. The sites are located in Haskell (GMD3), Scott (GMD1), and Thomas (GMD4) counties (Figure 2.1). Wells were completed in the summer of 2007 and were instrumented with pressure transducers and data telemetry capability in August 2007 (see Young et al. [2007] for details of site selection, construction, instrumentation, well logs, etc.). All three wells, plus the nearest annual program wells and the nearby KDA-DWR study wells in Haskell County, were surveyed for elevation. Table 2.1 summarizes the identity, location, and available construction information of the wells currently included in the study. The general study site locations are indicated on Figures 2.1-2.3, and detailed local photo-maps are presented in each of the site-specific sections.

Pressure transducers were installed in each of the index wells and have been collecting hourly data for over a year. The period of record includes all of water year (WY) 2008 (Oct. 1, 2007 through Sept. 30, 2008) as well as the points of maximum drawdown in both 2007 and 2008 at the Haskell and Thomas sites, and the 2008 point of maximum drawdown at Scott. Also, the KDA-DWR has installed transducers in a number of wells surrounding the Haskell index well (Table 2.1) and is providing those data to the KGS.

In addition to Figure 2.1, Figures 2.2 and 2.3 are reproduced from Young et al. (2007) to provide an overview of how the study sites fit into the context of the average 2004-06 saturated thickness and change in saturated thickness of the High Plains aquifer since predevelopment. Table 2.2 updates these figures and assembles the site and water level data for the three study wells.

2.2 Lithology

Figure 2.4 illustrates the subsurface lithology along a cross section in the area of each of the three index well sites. Locations of the wells used in the cross section are shown in Figure 2.5. From the surface down, the Haskell site is characterized by roughly 100 ft of fine-grained, relatively impermeable sediments below the surface, an intermediate thick layer composed of mainly sand and gravel, another thick (confining) clay layer, and a relatively thin, permeable sand and gravel zone just above bedrock. Most of the thick intermediate permeable zone at the Haskell site was saturated before development of the aquifer, but has now been mostly dewatered. All the lithologic layers are laterally extensive and slope from the north to the south, as does the bedrock surface.

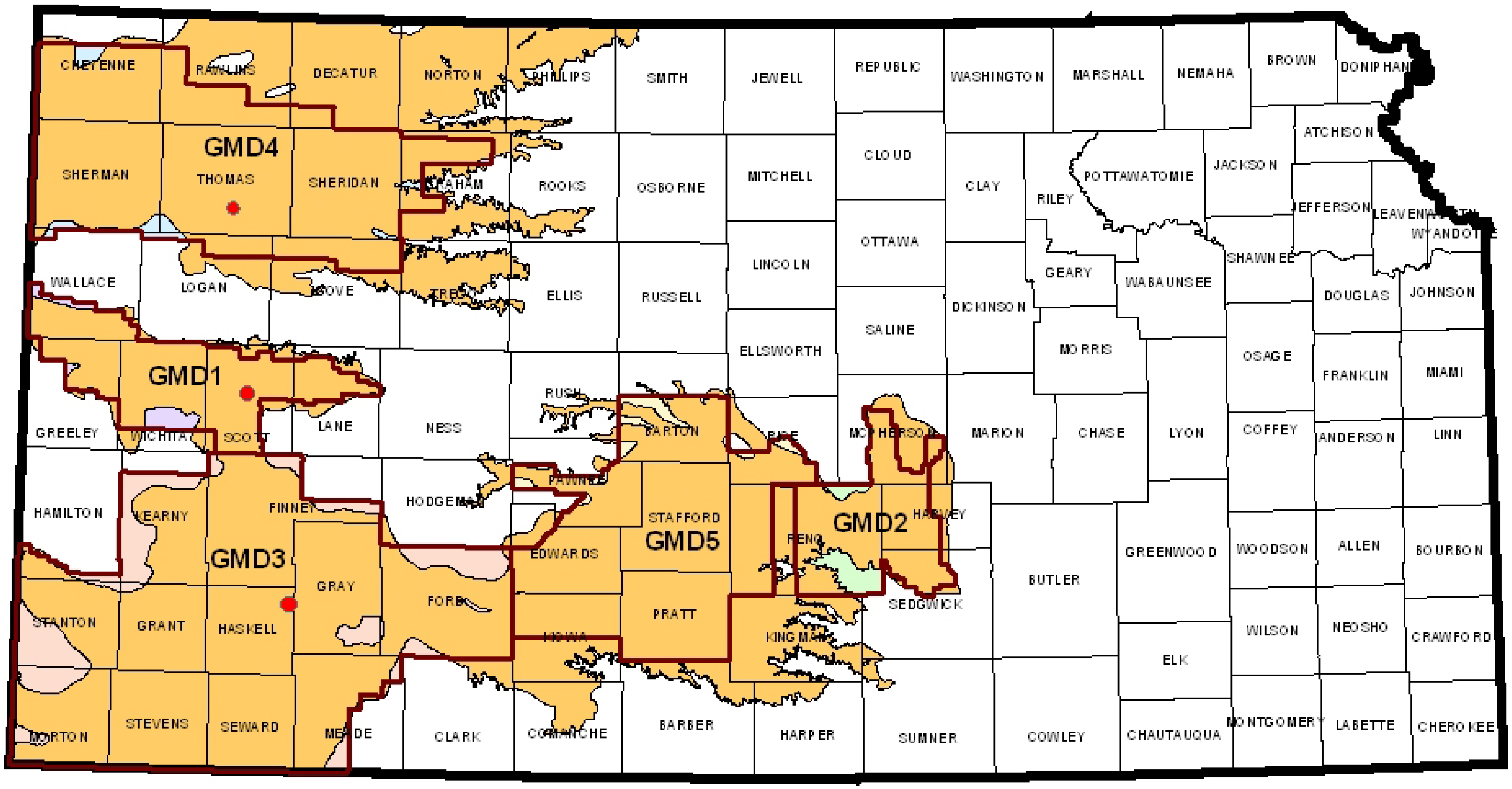

Figure 2.1. Map of Kansas showing extent of the High Plains aquifer, GMD, and county boundaries, and locations of index wells (red dots) in Thomas, Scott, and Haskell counties.

Table 2.1. Well characteristics (elevation and depth units are ft).

	LOCATION	ELEV_LS	DEPTH	SCREEN1	SCREEN2	GRAVEL_PACK	GROUT
HASKELL_INDEX	SW SE NW 36 27-31	2837.85	432	420-430		325-435	0-325
HS21	SW SE SW 24 27-31	2821.67	*383	350-380	220-280		0-20
HS22	SW SW NW 31 27-31	2893.22	250				
HS23	NE NW NW 08 27-30	2789.93	Unknown				
HS24	NW NW NW 08 27-30	2792.27	200				
HS25	SW NW NW 23 27-30	2771.18	275				
HS26	NE NW NW 17 28-30	2818.32	300				
DWR1	NE NE NW 36 27-31	2854.24	428	398-428		20-428	0-20
DWR2	SW SW SW 25 27-31	2823.98	410	370-410		20-410	0-20
DWR3	SE SW SW 25 27-31	2838.76	284	145-284			
DWR4	SE SW SW 25 27-31	2827.57	420	380-420		20-420	0-20
DWR5	NE NW NE 36 27-31	2853.43	420	380-420	240-280	20-420	0-20
DWR15	NE NE NW 36 27-31	2855.85	320	220-320			
SCOTT_INDEX	NE NE NE 01 18-33	2967.47	227	215-225		185-232	0-185
SC2	NW SW SW 03 18-33	3009.10	182				
SC3	NW NW NW 25 18-33	2974.82	180				
SC4	NW SW NE 14 17-33	3016.81	202				
SC5	NW NW NW 16 17-32	2980.82	231				
SC6	NW NW NW 27 17-32	2989.24	185				
SC7	NE NW NE 17 18-32	2974.56	135				
THOMAS_INDEX	NW NW NW 33 09-33	3187.44	286	274-284		250-284	0-250
TH2	SE NE NE 35 09-33	3145.31	244				
TH3	SW NW NW 06 10-33	3191.91	316				
TH4	NW NE NW 11 10-33	3139.87	299				
TH5	SE SW NW 12 10-34	3220.55	300				
TH6	SW SW SW 11 09-34	3179.13	257				
TH7	NE SE NE 12 09-34	3202.16	Unknown				

*Depth of replacement well added to the network in 1990. Depth of previous well was 206 ft.

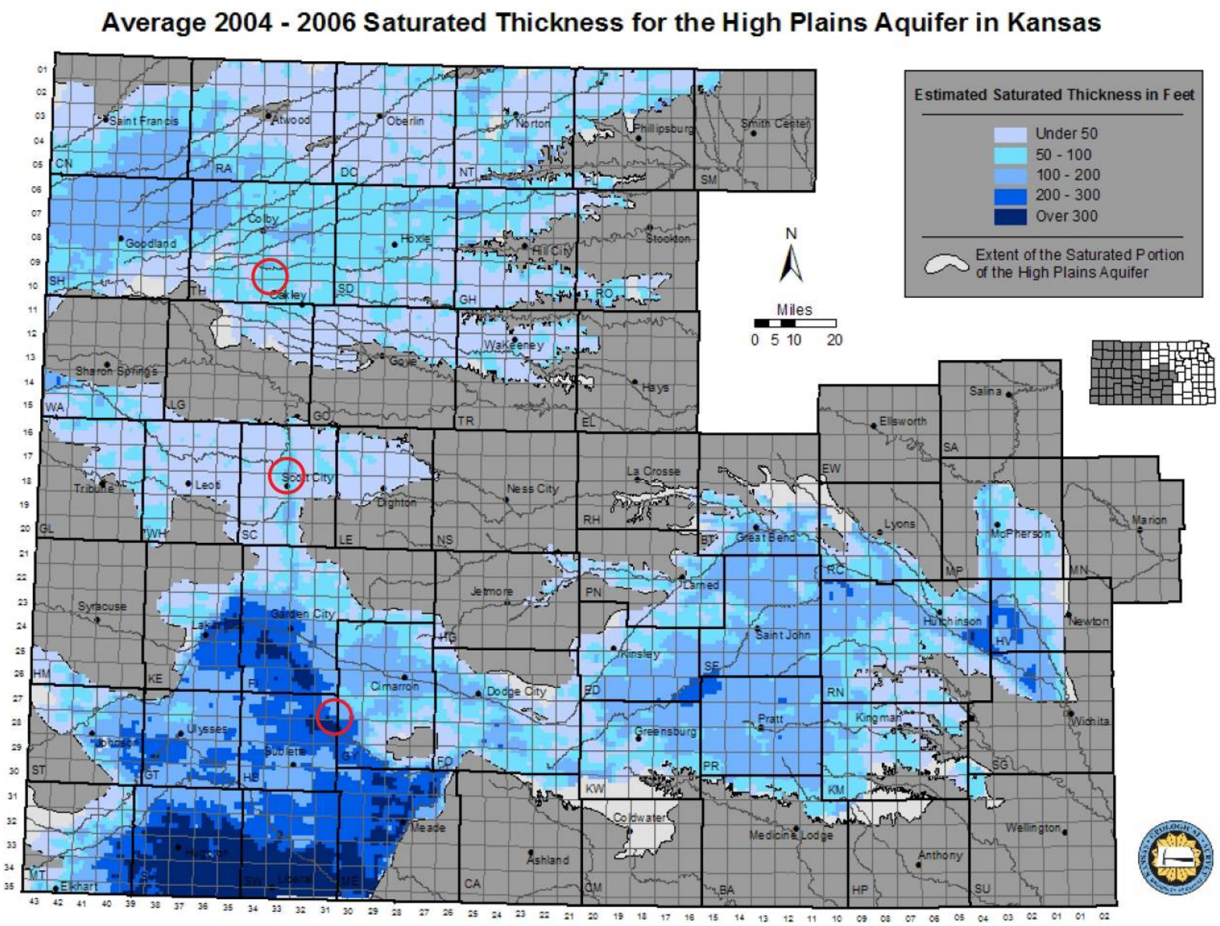

Figure 2.2. Average 2004-2006 saturated thickness for the High Plains aquifer. The red circles indicate index well locations.

Change in Saturated Thickness for the High Plains Aquifer in Kansas, Predevelopment to 2005

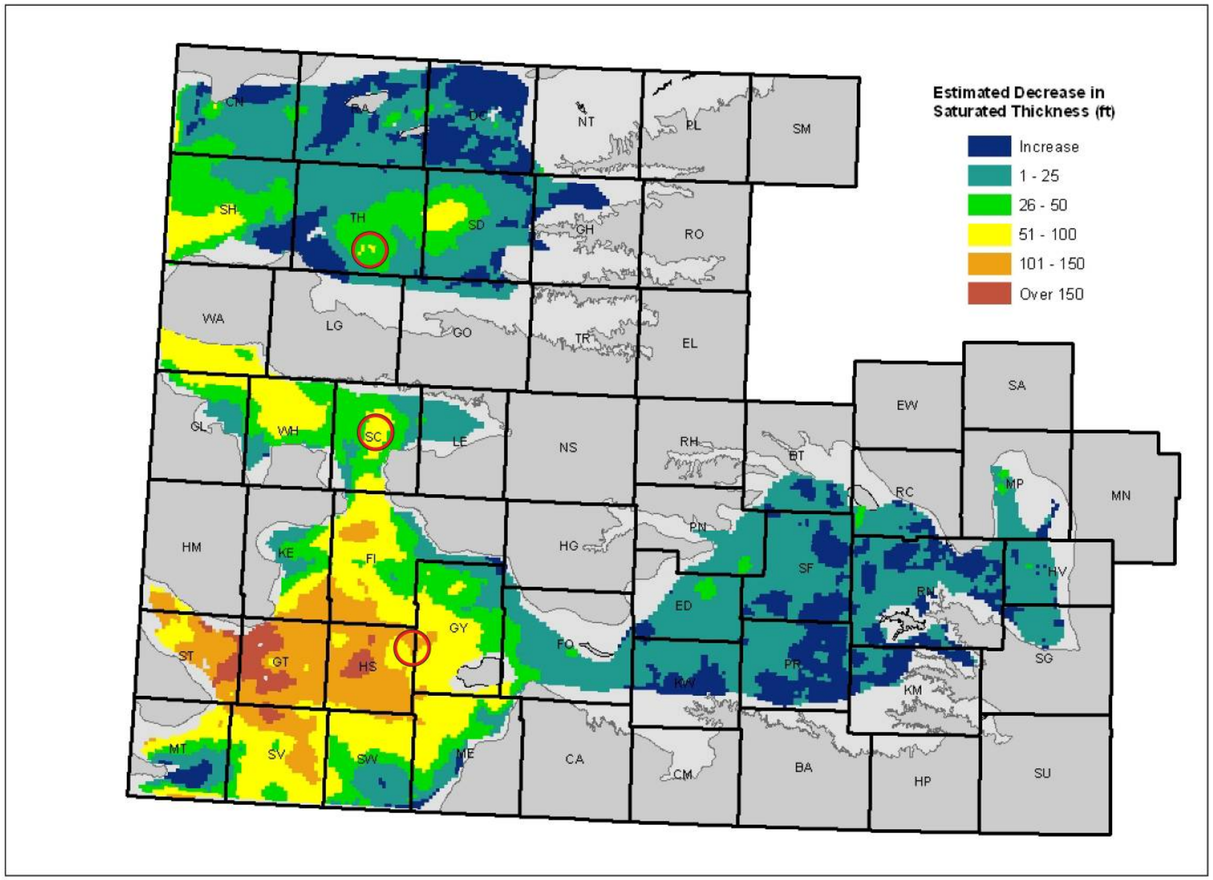

Figure 2.3. Change in saturated thickness for the High Plains aquifer, predevelopment to 2005. The red circles indicate index well locations.

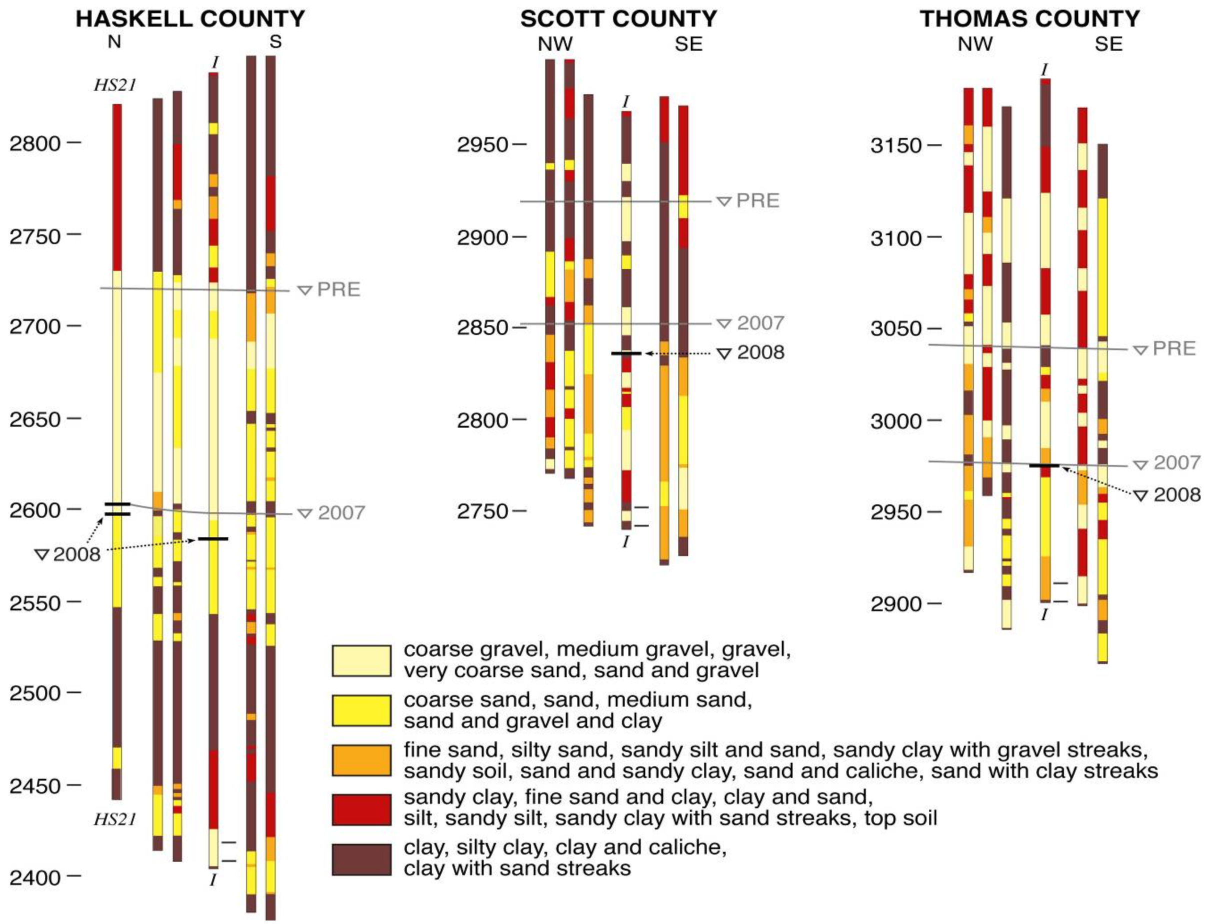

Figure 2.4. Lithologic cross sections for each well site (see Figure 2.5 for map views of the sections). The labels PRE and 2007 represent the predevelopment and January 2007 water levels interpolated from annual wells in Scott and Thomas counties. The 2008 labels represent the measured January 2008 water levels. In the Haskell section, the 2007 label represents the measured January 2007 water level in annual well HS21.

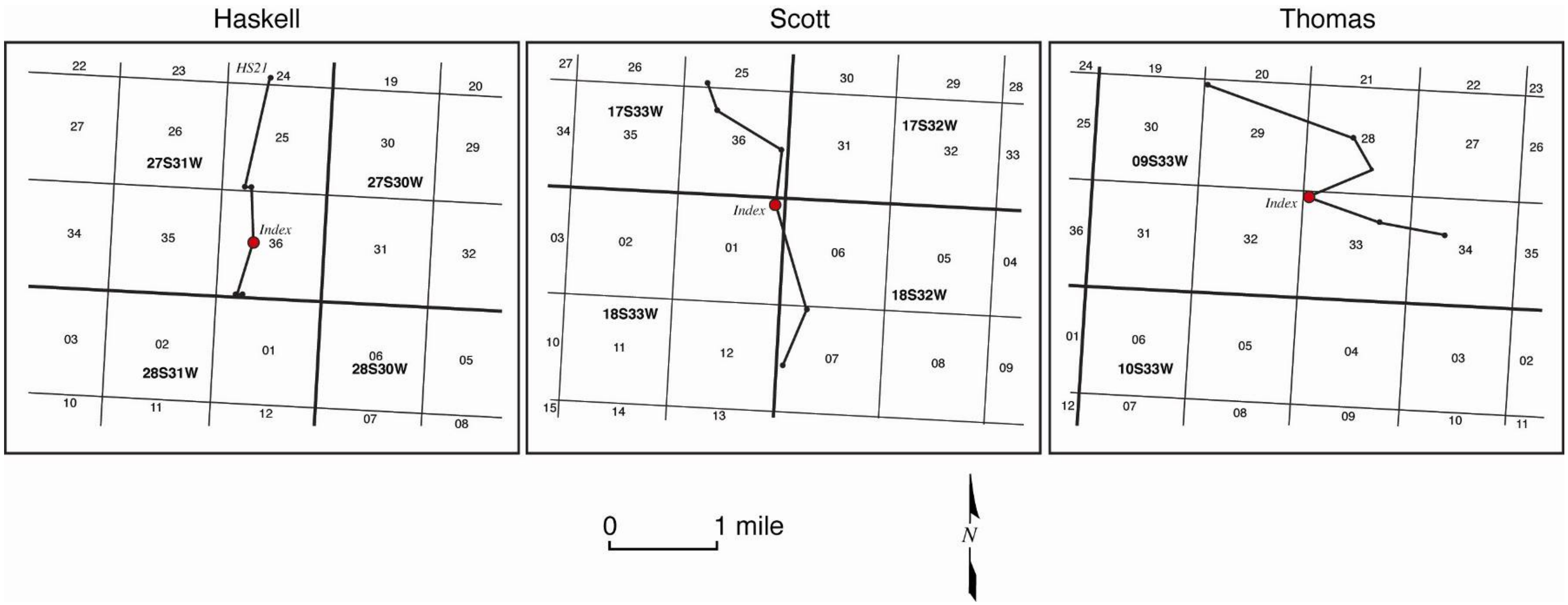

Figure 2.5. Locations of well logs used to construct the lithologic cross sections shown in Figure 2.4. The red dot indicates the index well location.

Table 2.2. Well site characteristics, including water level and total saturated thickness from January 2008.

Site	Elevation (ft)	Depth to Water (ft)	Water Level Elevation (ft)	Depth to Bedrock (ft)	Bedrock Elevation (ft)	Saturated Thickness (ft)
Haskell	2837.85	253.76	2584.10	433	2405	179
Scott	2967.47	131.82	2835.65	223	2744	91
Thomas	3187.44	212.96	2974.48	284	2903	71

The Haskell County well is screened in the relatively thin permeable zone just above bedrock. This thin confined or semi-confined zone at the base of the aquifer is increasingly used as the major water source in the area. KDA-DWR monitoring efforts are providing data from above and below the confining layer, and from some wells that are screened in both intervals.

The Haskell cross section has been modified since the previous report (Young et al., 2007) by the addition of the log of annual well HS21, which is ~1.5 miles north of the index well. Based on this addition, the aquifer layering described above appears to be continuous at least on the scale of a couple miles. Future work will continue to expand the lithologic characterization, likely in conjunction with the KGS Practical Saturated Thickness Plus (PST+) Program. The PST+ Program, which is an enhancement of the KGS' earlier PST Program, is focused on the creation of an aquifer-wide database composed of the original descriptions provided on the drillers logs, rather than interpretations of them for a particular purpose by the individual doing the data entry. The PST+ approach provides great flexibility in terms of the possible uses of the information in drillers logs and should facilitate future re-interpretations of High Plains hydrostratigraphy.

The lithology at the Scott County site is more spatially heterogeneous, and is characterized by mostly fine-grained sediments in the top half of the columns, with more permeable materials below. The remaining saturated sediments are relatively permeable and appear to be mainly unconfined.

The sediments at the Thomas County site are the most heterogeneous, in terms of lateral continuity, at the three index well locations. Individual layers and lenses are relatively thin and interspersed. The remaining saturated thickness is composed of relatively permeable sediments, and, like the Scott County site, appears to be mainly unconfined.

2.3 Rates of use and decline

Figure 2.6 illustrates the relative water use density (acre-feet per square-mile section), averaged over a 5-mile circle around the center of each section for the period 1996-2004. The pattern of water-use density has changed little in recent decades. Table 2.3 shows provisional water-use data for 2007 within both a 2-mile and a 5-mile radius centered on

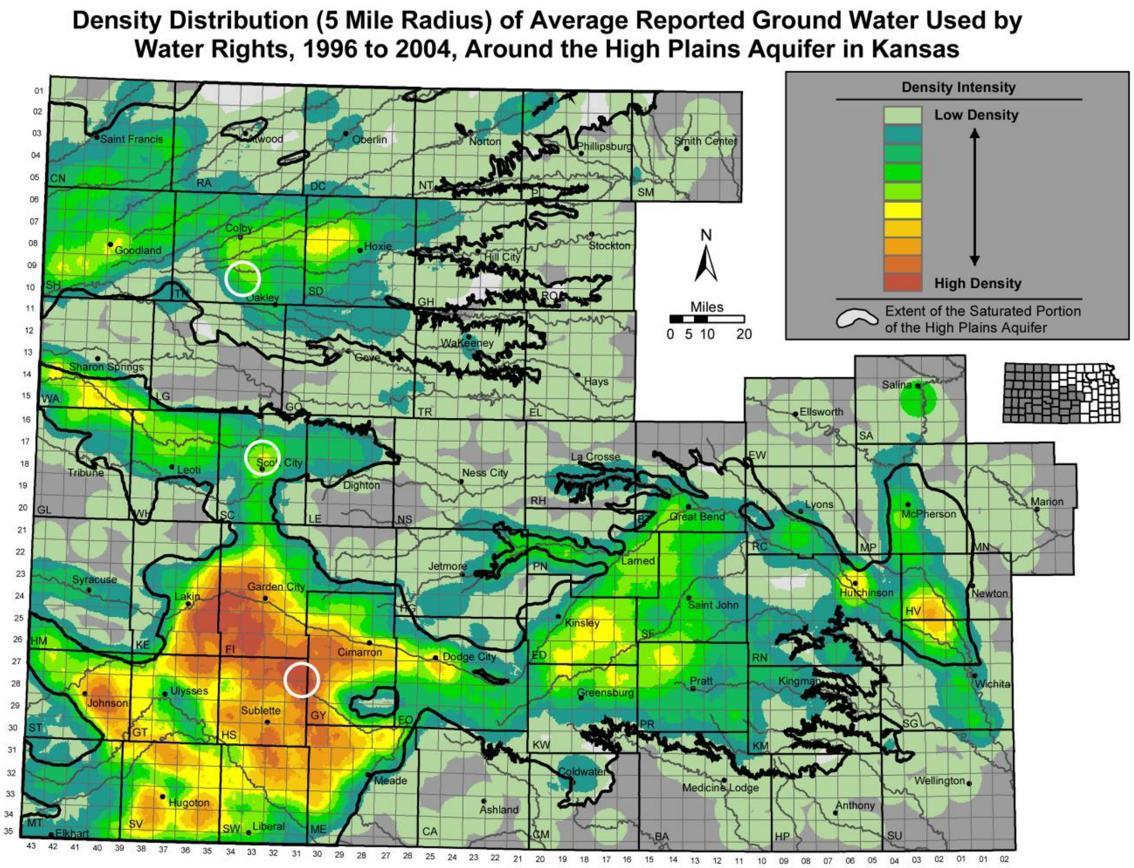

Figure 2.6. Average water use density within a circle with a 5 mile radius around the center of each section. Period of average is 1996-2004. See text and Table 2.3 for discussion of units and significance.

the index wells. Substantially more pumping occurred in the vicinity of the Haskell County index well compared with the other locations, with the least amount of water use occurring in the vicinity of the Thomas County index well.

Table 2.3. 2007 Water use within a 2-mile and 5-mile radius of index well.

	2007 WATER USE (ACRE-FT)	
Site	**2-mile radius**	**5-mile radius**
Haskell	7,593	49,184
Scott	4,132	16,982
Thomas	3,108	14,008

As water-use data become available for the areas of the study sites and for those pumping wells close enough to exert direct influences on the index wells, we will explore the relationship among pumping rates and patterns and the observed well responses, on short-term as well as annual time scales.

Figure 2.7 shows long-term hydrographs of surveyed annual network wells near each of the index wells. Locations of these wells and their relationships to other annual network wells and the index wells (which are now included in the annual network), as well as points of diversion, are shown in figures in each of the site-specific sections. The hydrographs in Figure 2.7 include only the "winter" measurements (January, or the December through March period if a January measurement was not available).

The Haskell County annual well (HS21) shows the greatest water-level decline and the greatest rate of decline, consistent with its much higher water-use density (Figure 2.6). However, the fact that the Scott County annual well (SC7) shows a lower recent rate of decline than the Thomas County annual well (TH3) in spite of the latter's lower use density is illustrative of the kinds of local characteristics for which this project is designed to provide locally applicable and cost-effective measurement and interpretive tools in support of sub-unit management.

2.4 Well measurements and water table recovery

2.4.1 Water table characterization

Water-level surfaces for January 2008 were created around each of the index sites based primarily on the annual network wells, including the index wells (January 2007 measurements were used for a few annual wells for which no 2008 measurements were available). Contour plots are presented in the site-specific sections below. The contours are interpolations based on the point measurements. Ground-water flow in the High Plains aquifer should be perpendicular or nearly so to the water-level contours, and the rate is typically faster where the contours are closer together (the slope of the water table is steeper).

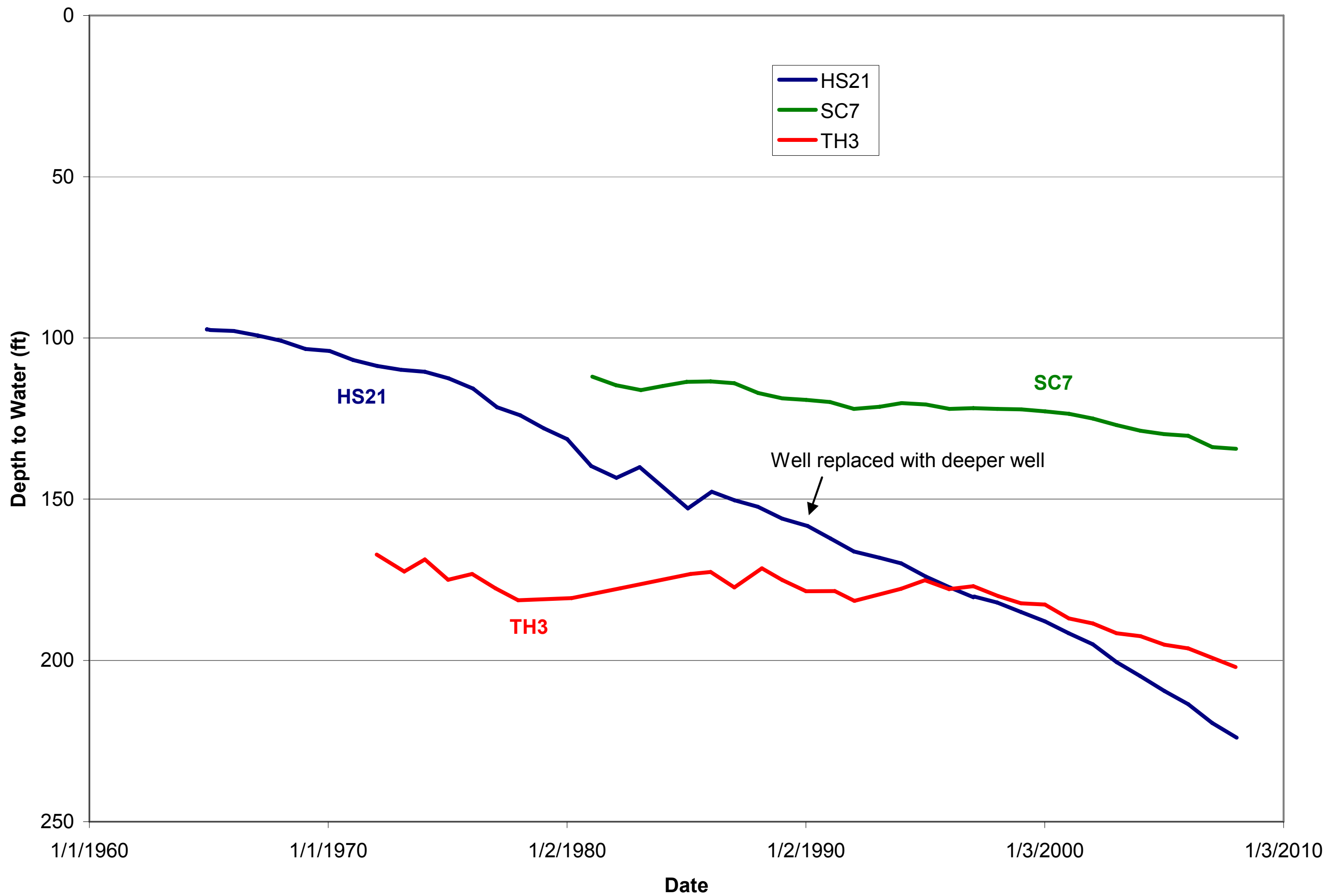

Figure 2.7. Hydrographs from annual network wells near each of the index wells.

All sites are experiencing pumping-induced perturbations of the ground-water surface. Particularly at the Haskell and Scott sites, the index wells (and our analysis of the data) have enabled us to identify substantial local depressions in the water table that were previously unrecognized in the annual measurement network program.

2.4.2 Precision and comparison of measurements

Comparison and application of water-level measurements made by tape and by transducer have focused attention on sources of uncertainty in the tape measurements, and in the interpretation of both types of data. One issue, that of incomplete recovery, is discussed in section 2.4.3.

A major issue is that of barometric-induced fluctuations in the water levels, which are superimposed on long-term average trends in elevation. These are evident in the transducer records, which show a range of variation of up to a foot centered on the mean water-level elevation. This means a potential error of up to a foot in the difference between any two tape measurements, and of $\pm$ 0.5' in the elevation of a specific point used to estimate the water-level surface. In each of the site-specific sections, the potential uncertainties from this source are identified and discussed for the transducer-equipped wells.

Because these variations result from a known and measured source (barometric pressure), they can be analyzed and corrected for. Section 6 of this report describes analyses of the atmospheric pressure effects observed in the wells, with discussion both of the uncertainty reduction issue and of a newly recognized potential for using the responses to analyze hydrogeologic characteristics and well similarities.

2.4.3 Recovery estimation

It is clear by inspection of the detailed well hydrographs produced by the transducers that water levels are still rising when the next season's pumping starts. Ideally, the most accurate and informative measurements of water level and water-level change would be based on a fully recovered well. That is not practical or possible, so we attempt to use the data available to estimate the elevation and date of recovery to an undisturbed equilibrium.

Two methods of projecting the available data to full recovery have been tested; one is simple extrapolation of an empirically fitted curve, and the other (the Horner method; Streltsova, T.D., 1988) is a technique for analysis of the recovery period following a pumping test that was developed in the petroleum industry from the Theis recovery method. Both are described in more detail in Appendix 1.

Because one method of approximation is likely to produce high estimates, and the other, low estimates, we think that approximate agreement represents a reasonable estimate of the actual recovered value, and that in any case the fully recovered water level is likely to have an elevation between the estimates produced by the two methods. In the site-specific sections below we present and compare the results of the two approaches with each other and with the measured observations.

3. Site-specific results: Haskell County

The location of the Haskell site index well in relation to existing wells in the annual network is shown in Figure 3.1. Figure 3.2 is zoomed in to show the Haskell County index well in relation to wells that the KDA-DWR is monitoring, and also points of diversion. The KDA-DWR has installed pressure transducers in many of these wells, including a barometric transducer in one well, and is providing the data to the KGS.

Characteristics of the index well, the annual wells, and the wells the KDA-DWR is monitoring around the Haskell site are provided in Table 2.1, with physical and hydrologic data in Table 2.2.

3.1 Well hydrographs - Haskell County

The Haskell site hydrology is complex, and the data records require examination at several scales. Figure 3.3 shows the hydrograph of the index well at a scale adequate to include all of the water-level variations (~125 feet). This trace is characteristic of the deep aquifer zone beneath the extensive confining layer (see Figure 2.4), because the index well is screened only in that interval and is grouted from the surface to far into the confining zone.

We have processed the transducer data from seven other wells in the vicinity that have been monitored by the KDA-DWR. There are two pairs of wells, with one deep well and one adjacent shallow well in each pair. These are DWR1 (irrigation) plus DWR15 (shallow casing), and DWR2 (irrigation) plus DWR3 (shallow casing). Figure 3.2 shows that these wells are approximately one-half mile from the index well, and the members of each pair are separated by less than an eighth of a mile. Also in the row of wells along the road are DWR4 and DWR5, both monitoring/observation wells. We also have some transducer data from HS21 (an irrigation well in the annual network), and the annual, plus supplementary tape measurements, from other surveyed annual program wells in the vicinity.

The only “shallow” wells (wells that do not penetrate the deep aquifer zone) are DWR3 and DWR15 (Table 2.1). DWR1, DWR2, and DWR4 are deep wells screened only across the deep aquifer zone. DWR5 and HS21 are deep wells with screened intervals across both the deep and shallow aquifer zones. In the following discussion, we group “deep” and “shallow” wells according to their behavior as shown by the hydrographs. DWR1, DWR2, and DWR4 behave similarly to the index well. The hydrographs of DWR5 and HS21 appear to have more features in common with DWR3 and DWR15 than with the other deep wells, however they show some intermediate signals indicative of a mix of shallow and deep ground waters.

Figure 3.1. Haskell County site area with annual water-level (WIZARD) wells (yellow crosses) and production wells (black dots).

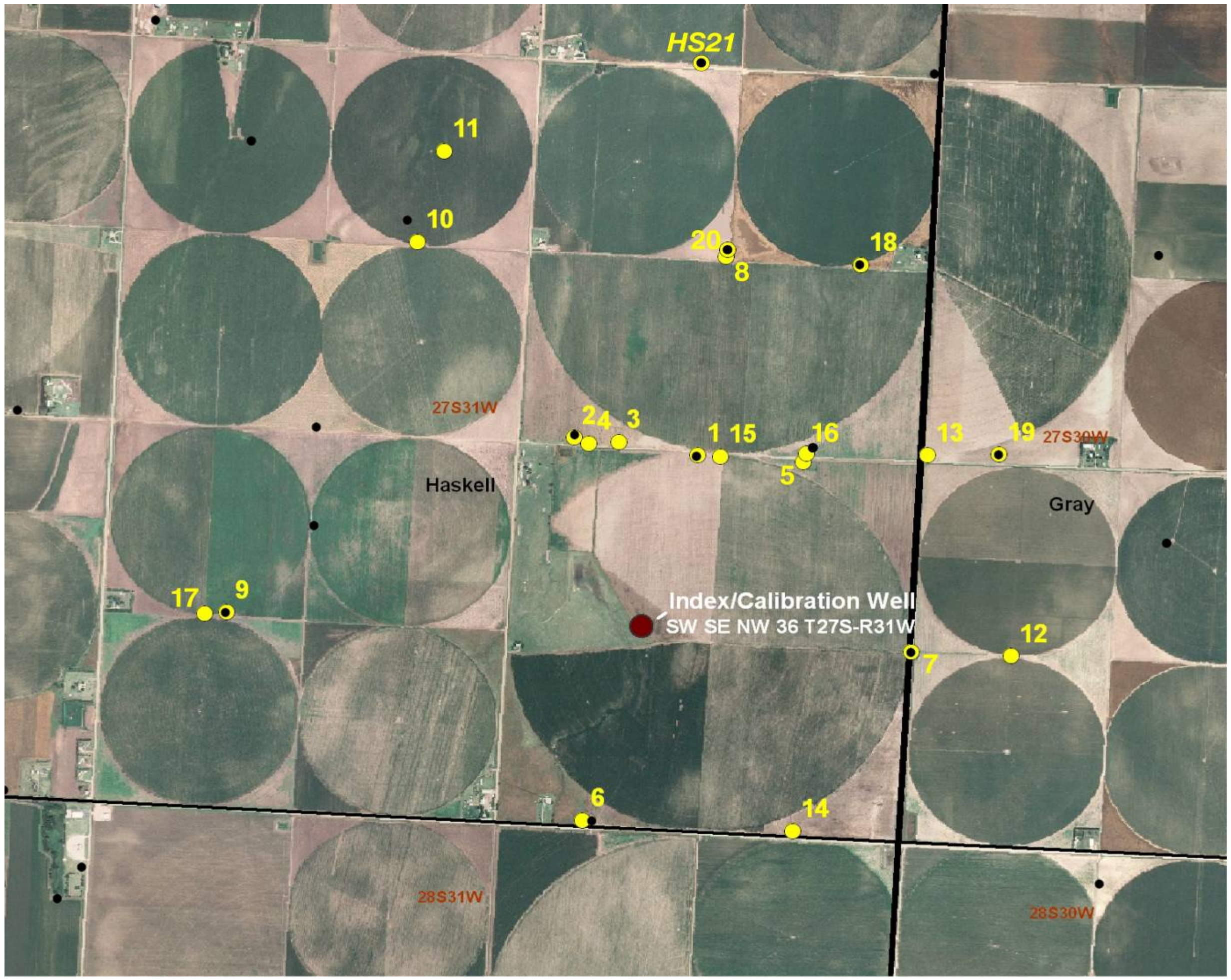

Figure 3.2. Haskell County site area showing wells that KDA-DWR is monitoring (yellow dots) and production wells (black dots).

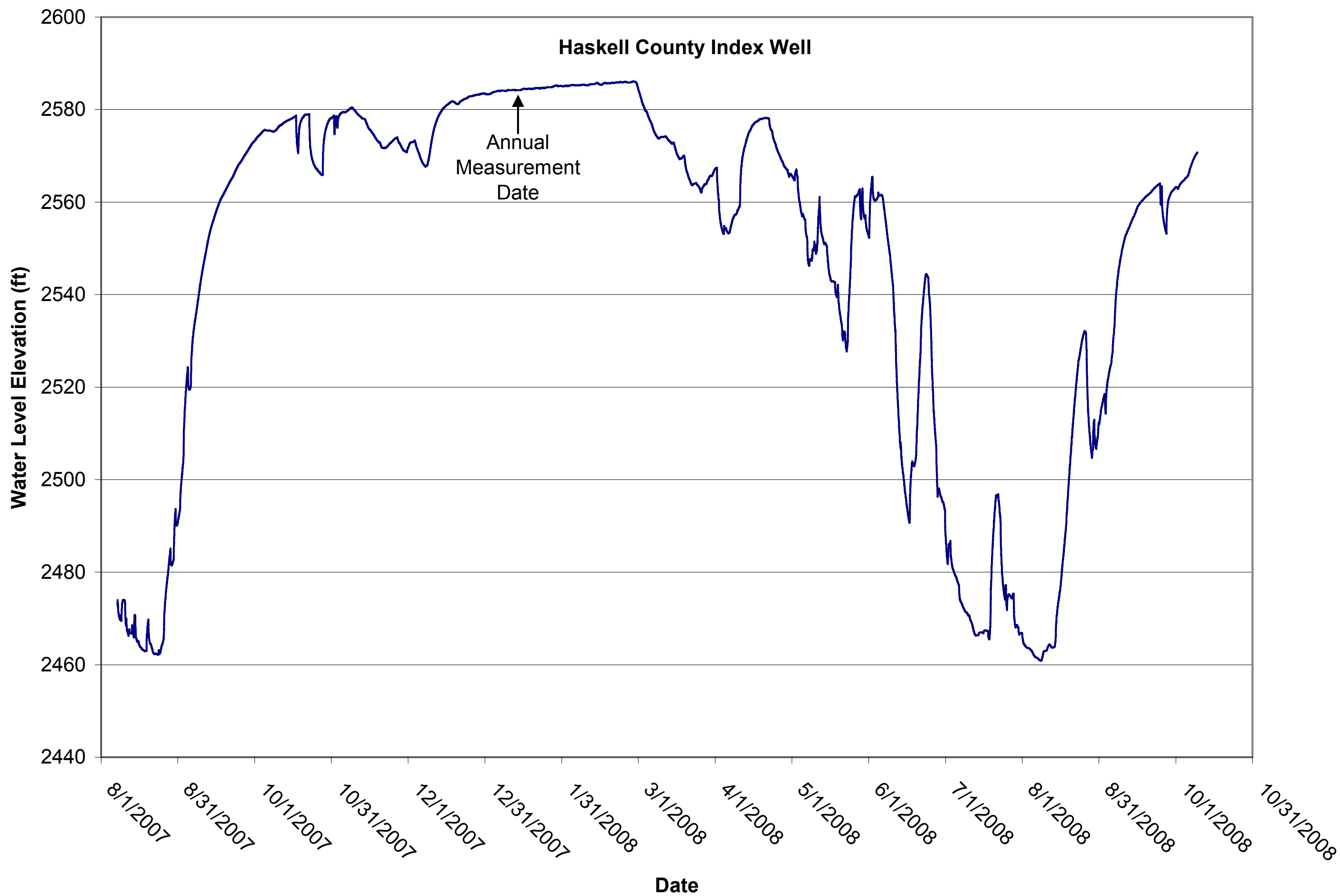

Figure 3.3. Hydrograph from Haskell County index well.

Figure 3.4 plots the hydrographs of four wells that represent responses of the deep aquifer zone – the index well, plus DWR1, DWR2, and DWR4. Also included for reference is the hydrograph from the annual program well, HS21, about 1.5 miles to the north. Except for the perturbations caused by pumping and drawdown below the transducer level in DWR1, the four deep well hydrographs are qualitatively, and in terms of the large-scale differences, quantitatively extremely similar. This provides an illustration of the concept of the index well – given a relatively few calibration measurements, the behavior of deep aquifer water levels in the three KDA-DWR wells – and therefore in the area between and around these wells – could be predicted quite confidently based on the observations in the index well. The key question that remains is how much farther the index observations can be reliably extended. At first glance, the HS21 data suggest that the indexing characteristic is lost somewhere between the deep wells and HS21. However, this is not necessarily the case because HS21 has a shallow screen as well as a deep one, and the shallow zone appears to dominate the behavior of its hydrograph.

The shallow wells display a very different pattern from DWR1, DWR2, DWR4, and the index well. Figure 3.5 shows the hydrographs of DWR3, DWR5, and DWR15, and also contains the HS21 hydrograph to facilitate comparisons with Figure 3.4. Unlike the deep wells, the shallow wells show only a total range in water elevations of about five ft over the period of record. This elevation difference is between the recovered maximum (around February 2008) and the end of the record (September-October 2008). HS21 shows frequent major pumping perturbations, but these cover a vertical range of only about 25 ft (compared to ~75 ft in DWR1), and the apparently stabilized water level at the end of the record shows an overall decline very similar to the differences seen in the shallow wells over the same period. DWR5 shows some pumping perturbations, and a total range of water elevations of about 10 ft.

3.2 Hydrogeologic implications - Haskell County

The results indicate that the Haskell site area has effectively two separate aquifer systems: a shallow phreatic layer above the low permeability zone shown in Figure 2.4, and a deep confined or semi-confined layer sampled by the deep and index wells. The data support this interpretation, which was originally proposed by Young et al. (2007) on the basis of lithology and initial water-level response observations. Irrigation wells are typically gravel-packed over all or most of their depth (and commonly screened in more than one interval), which should provide conduits for water flow and pressure equilibration between the two aquifer units. The effects of this connection are apparently very limited and/or local, as the paired wells (~1/8 mi distant from the deep wells) show essentially no shallow responses to the dramatic pressure variations at depth. The rapid recovery of HS21 to pumping and the limited pumping-induced drawdown in HS21 and DWR5 are indications that the transmissivity of the upper aquifer is considerably greater than that of the lower aquifer in the vicinity of those wells. A high transmissivity in the upper aquifer would also result in small responses in the shallow observation wells.

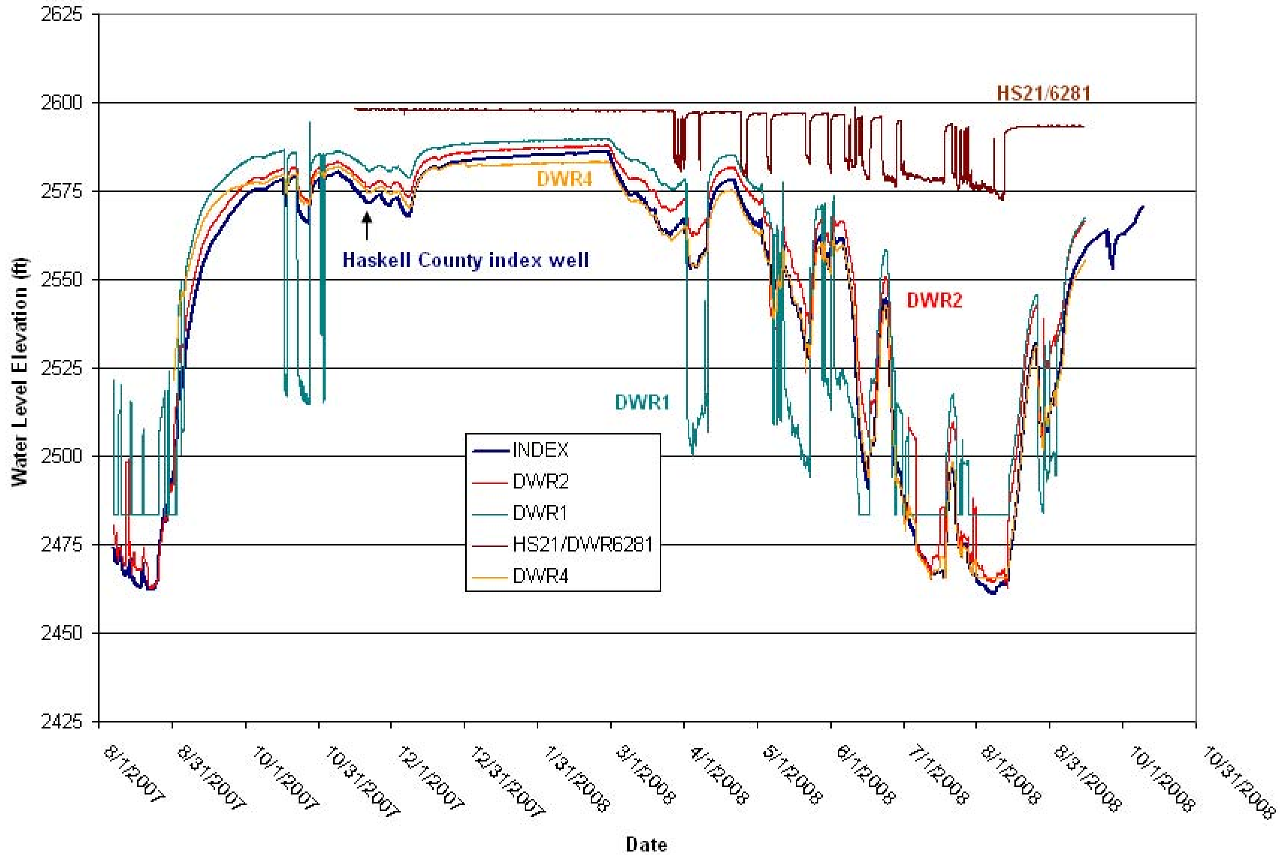

Figure 3.4. Superimposed hydrographs of the index well and deep wells DWR1, DWR2 and DWR4. DWR1 is a pumping well, and its transducer is positioned about 20 feet above the minimum water level. Also shown is the water level record from annual program well HS21, approximately 1.5 miles north of the other wells.

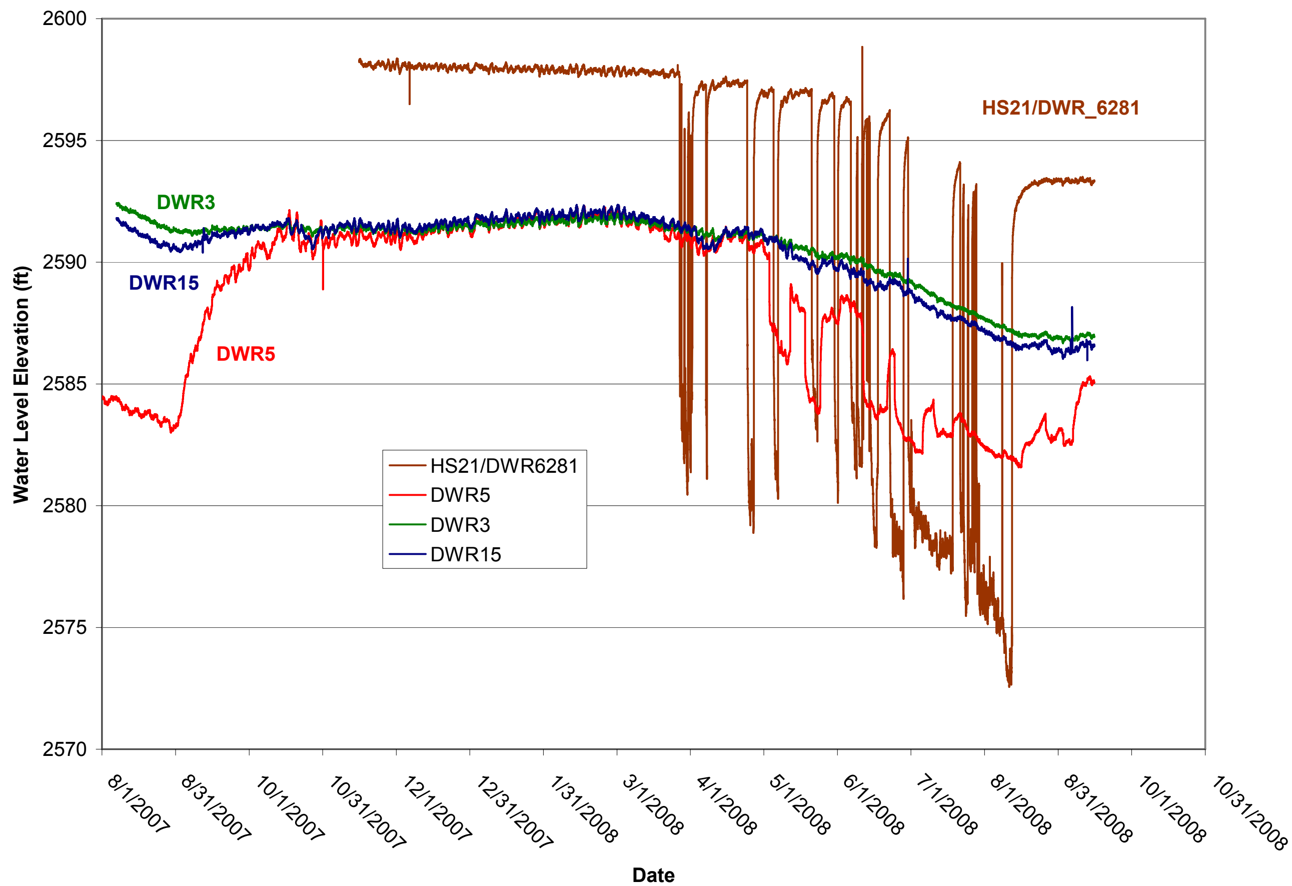

Figure 3.5. Superimposed hydrographs of shallow wells DWR3 (paired with DWR2, Figure 3.4) and DWR15 (paired with DWR1, Figure 3.4). Also shown for comparison are the hydrographs of DWR5 and of annual program well HS21, 1.5 miles to the north; DWR5 and HS21 are deep wells with both shallow and deep screened intervals (Table 2.1).

The gravel pack is the primary conduit when the well is not screened in both intervals. However, the slight and continuous water-level decline in HS21 from November 2007 through March 2008 appears indicative of flow down the well casing. HS21 is screened in both the shallow and deep intervals. Thus, HS21 is acting as an injection well to transfer water between the upper unit and the lower unit.

The January 2008 water-level surface is shown in Figure 3.6. The primary contours represent the shallow water table. These contours show what appears to be a major pumping-induced depression in the regional west-to-east sloping water table. The depression appears to be centered near the index well site, but the scarcity of water-level data prevent a more definitive characterization.

Superimposed on the primary contours is a blue-filled mini-contour plot representing the head in the deep (semi-)confined aquifer zone. These contours were based on the index well and deep wells that the KDA-DWR is monitoring. These mini-contours indicate that the deep aquifer potentiometric surface is hydrologically separate from the shallow water table. North of the index well, the deep contours indicate that the deep potentiometric surface is about ten feet lower than the shallow water table. The full-recovery elevation estimates, discussed in section 3.3 below, reduce the difference somewhat, but do not eliminate it; the data indicate a downward gradient at the site, with the shallow water levels in the vicinity of the paired wells averaging several feet higher than the head measured in the deep wells. This downward vertical gradient has substantial water-resources and management implications.

Irrigators in the vicinity of the Haskell County site have been and are commonly abandoning their shallow wells as water levels decline and drilling deeper wells to tap the deep aquifer zone. The annual wells in the area appear to measure primarily the elevation of the shallow water table, and not the deep aquifer zone that is increasingly being tapped for irrigation supplies in this area. This is to be expected for shallow wells and wells screened across both the upper and lower aquifer units. As described by Sokol (1963), the water level in a well screened in more than one aquifer is a weighted average of the water level in each aquifer, with the water level in each aquifer being weighted by the transmissivity of that aquifer. Thus, in the case of the Haskell area, where the transmissivity of the phreatic aquifer appears to be much greater than that of the deep (semi-)confined zone, the water level of a well screened in both aquifers should be similar to that in a shallow well. This is true of HS21 as well, which has been monitored for the past 18 years and extends into the deeper zone, but is screened and gravel-packed across both shallow and deep aquifer zones (Table 2.1 and Figure 2.4). The net changes and the overall elevation of the water level in HS21 are more similar to the other shallow wells than to those of the other deep wells, and although pumping responses are observed, they are not coincident with the deep well fluctuations and their absolute magnitudes are much smaller (compare figures 3.4, 3.5, and 2.4).

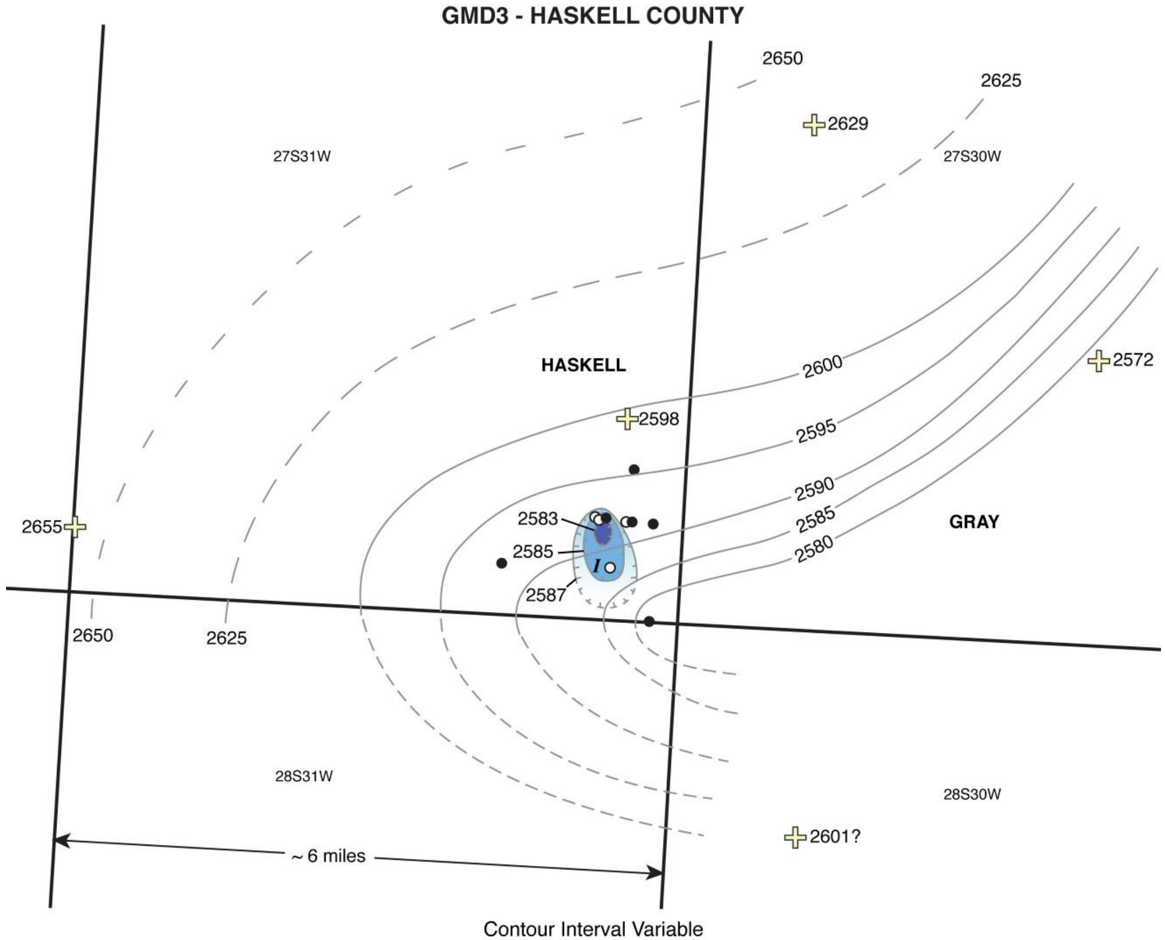

Figure 3.6. January 2008 water levels near the Haskell site. Primary contours represent the water table. Blue-filled contours represent the deep (semi-)confined potentiometric surface. Symbols: crosses = annual network wells, solid circles = shallow wells KDA-DWR is monitoring, open circles = deep wells.

3.3 Decline and recovery - Haskell County

The Haskell index well had minimum water elevations of 2462.15 ft on 8/23/07 and of 2460.84 ft on 8/8/08, so the water-level elevation at maximum drawdown at that location was 1.31 ft lower in 2008 than in 2007. The annual declines as measured by the annual program wells and tape measurements of the index well (or point estimates from the transducer records) are given in Table 3.1. In addition to the tabulated values, estimates of 2007 and 2008 maxima from the transducer records indicate an apparent total annual decline of 4.9 ft in both DWR3 and DWR15. These values are not directly comparable to the Table 3.1 values because the maximum elevations were measured in the spring instead of January.

Table 3.1. Haskell County water-level observations. Elevations and water-level changes are in ft.

Well/date	**1/2007***	**1/7/2008**	**1/10/2008**	**1/15/2008**	**4/8/2008****	**Note**	**Δ 07-08**
Index			2584.50		2557.35	Tape	na
			2584.20	2584.42	2556.89	24 hr avg	na
HS21	2602.32			2597.92	2596.73	Tape	-4.40
HS22	2656.37			2654.98		Tape	-1.39
HS23	2629.49	2629.17			2628.04		-0.32
HS25	2577.66	2571.81			2571.78	Tape	-5.85
HS26	2599.44	2600.97					+1.53

* DWR1 and DWR2 records began 4/25/07
**After the start of pumping

A summary of all water-level changes from 2007 to 2008 is provided in Appendix 2. Data indicate that the deeper wells experienced greater declines than the shallow wells. This will be explored further as more data become available.

Because the KDA-DWR transducer records cover the beginning of the 2007 pumping season, we have enough data to apply the Horner as well as the curve-fit method of recovery estimation (see section 2.4.3 and Appendix 1). We have tested two cases: (1) 6/7/07 to 8/25/07 as the pumping period and 8/26/07 to 2/28/08 as the recovery time; and (2) 11/11/07 to 12/9/07 as the pumping period and 12/10/07 to 2/28/08 as the recovery time. The long-term data set gave less credible results (improbably high recovery elevations), probably because of perturbations by fall pumping. Using the last observed pumping interval as the starting point appears to produce reasonable results (Table 3.2).

In Table 3.2, the January elevations are 24-hour transducer signal averages at the time of the annual program measurements. The last 2008 measurement (greatest observed recovery) not affected by pumping is the 2/28 24-hour average elevation. ΔJan is the difference in elevation between the January measurement and the projected fully recovered elevation; ΔLast is the elevation difference between the last observation before the beginning of the new pumping season (2/28/08 for the Haskell wells) and the full recovery estimate. Both the curve-fit and Horner techniques indicate substantial water-level changes before reaching full recovery in the deep wells after the January measurements – close to or more than 2 ft. Changes after February are less, but still substantial, and estimated equilibration times differ by more than a month. Changes in the shallow wells are smaller and their water levels equilibrate slightly earlier.

Table 3.2. Full recovery estimates, Haskell wells. Elevations are in ft.

Well	January elevation	2/28/08 elevation	Method	Recovery elevation	Recovery date	ΔJan	ΔLast
Deep							
Index	2584.2	2586.04	Curve fit	2587.00	5/9/08	2.50	0.96
	(2584.5*)		Horner	2587.40	--	3.2	1.36
DWR1	2588.66	2589.84	Curve fit	2590.43	4/17/08	1.77	0.59
			Horner	2590.50	--	1.82	0.66
DWR2	2586.36	2587.87	Curve fit	2588.21	4/6/08	1.86	0.33
			Horner	2588.75	--	2.39	0.88
Shallow							
DWR3	2591.53	2591.71	Curve fit	2591.84	3/17/08	0.31	0.13
			Horner	2591.94	--	0.41	0.16
DWR15	2591.74	2592.15	Curve fit	2592.15	4/9/08	0.41	0.00
			Horner	2592.23	--	0.49	0.08

*Tape

3.4 Haskell County site discussion

The major finding at the Haskell site is confirmation of the existence of two poorly connected aquifer units, one of them (semi-)confined. Water use has been progressively shifting to the deep aquifer unit, while it appears likely that the annual monitoring program primarily reflects water levels in the shallow aquifer because of the higher transmissivity of that aquifer. While the two aquifer zones are obviously not well connected, as seen from the major differences in hydrographs, evidence such as the general similarity of estimated recovered elevation changes in some areas and the over-winter decline in HS21 levels suggests that there is local connection between the two aquifers through well casings and gravel packs. While many questions remain about the management implications of this aquifer structure, it is clear that, as shown on Figure 2.4, only a relatively small portion of the saturated thickness is serving to transmit water to the pumping wells. The delineation of that portion of the saturated thickness is one of the goals of the KGS PST+ Program described earlier. It is also clear that the remaining resources in the deep aquifer cannot be evaluated directly from the behavior of the water table in the upper aquifer.

4. Site-specific results: Scott County

The locations of the Scott County index well, and of adjacent annual program wells and nearby points of diversion, are shown in Figure 4.1. The index well has a unique and significant position; it is the only regularly measured well in the northern portion of the Scott-Finney bedrock depression, which is the only substantial ground-water reserve left in central GMD1, and the major water supply for Scott City. The N-S depression feature can be discerned in Figure 2.2 (saturated thickness), Figure 2.3 (change in saturated thickness) and Figure 2.6 (use density), and is more extensively described by Young et al. (2007). All of the annual wells indicated in Figure 4.1 are outside of the depression in areas of low remaining saturated thickness; the index well is the only monitoring point for this water-resource feature north of Scott City.

4.1 Well hydrographs – Scott County

Figure 4.2 presents the well hydrograph for the Scott County index well. Like the Thomas County site and the shallow wells in Haskell County (but in contrast to the deep Haskell wells), the range of variation is roughly 5 ft. Although a short interval of the fall 2007 record was compromised by a pinched cable, it is clear that the major summer pumping ended in mid to late August, followed by significant autumn pumping that ended about 11/20/07. The winter recovery period ended 3/10/08 with the resumption of substantial pumping, which lasted through much of September 2008.

The Scott County well is within approximately one-half mile of three points of diversion, with others in the vicinity at an appreciably greater distance. The water level in the index well is probably most sensitive to the pumping effects of the neighboring wells. Based on estimates of prompt recovery times in the hydrograph (Figure 4.2), the water level appears to reflect the general water table when none of the neighboring wells have been operating for a week or more.

A prominent feature of the periods in the hydrograph without major pumping perturbation is the short-term variation due to atmospheric pressure effects. These are discussed in more detail in section 6 below, but they are relevant to the discussion of decline and recovery and especially to comparisons with and between the annual program wells. This variation provides a quantitative estimate of one source of uncertainty in a one-time tape measurement of water level.

The standard deviation of the water-level variation was 0.06 ft. This indicates that an accurate one-time tape measurement of water level could deviate from the 'actual' (barometrically corrected value) by as much as approximately $\pm$ 0.18 ft, but that the actual deviation measured would be < 0.06 ft approximately two-thirds of the time (the significance of the standard deviation value). This uncertainty due to barometric pressure effects is relatively small, and is comparable to the best overall precision (uncertainty) of tape water-level measurements.

Figure 4.1. Scott County site area with annual water-level (WIZARD) wells (yellow crosses) and production wells (black dots).

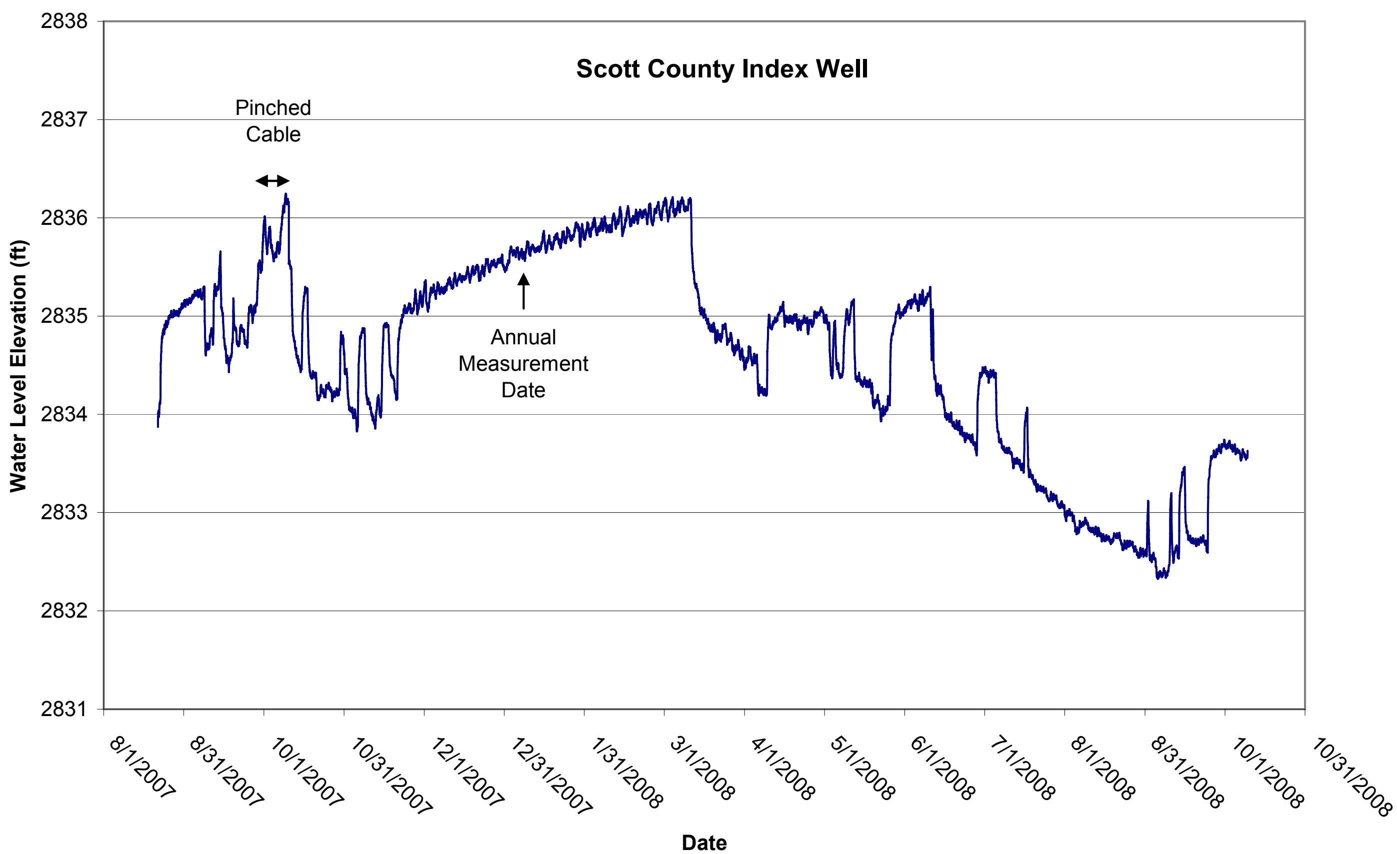

Figure 4.2. Hydrograph from Scott County index well (scaled the same as Thomas County index well hydrograph in Figure 5.2).

4.2 Hydrogeologic implications – Scott County

As discussed in Section 2.2 and shown in Figure 2.4, the three sites have different lithologic characteristics. In common with the Thomas County and shallow Haskell County wells, the Scott County site appears to function as a phreatic aquifer (in contrast to the deep Haskell zones), but with a substantially lower barometric efficiency than the Thomas County site. This is perhaps a result of the lithologic configuration in which the present water table is near the bottom of a depth interval that consists mostly of low permeability layers, but apparently does not act as a confining layer. The remaining saturated thickness appears composed primarily of higher permeability sediments (Figure 2.4).

4.3 Decline and recovery- Scott County

Because the well installation was completed after the first late-summer recovery had begun, we cannot compare the WY07 and WY08 drawdowns quantitatively. However, from the actual observations we can say that the minimum (lowest) WY07 drawdown elevation was <2833.87 ft and occurred earlier than 8/21/07. For WY08, the minimum elevation was 2832.33 ft on 9/5/08.

Table 4.1 shows the results of tape measurements in the annual program and index wells, with corresponding time-averaged transducer measurements for the dates of measurement in the index well. We will not be able to directly compare decline and recovery between the transducer measured results and the annual program results until next year, but several observations can be made from the available data (see also master table of all measured wells in Appendix 2).

Table 4.1. Scott County water-level observations. Elevations and water-level changes are in ft.

Well/date	Jan 2007	1/7/2008	1/15/2008	4/9/2008*	Note	Δ 07-08
Index	na	2835.61		2834.26	tape	
		2835.63	2835.81	2834.37	24 hr avg	
SC2	2879.14				tape	na
SC3	2847.22		2846.51		tape	-0.71
SC4	2863.31	2861.78			tape	-1.53
SC5	2831.94		2830.71	2830.52	tape	-1.23
SC6	2830.06				tape	na
SC7	2840.73	2840.18		2840.91	tape	-0.55

*After resumption of pumping on 3/10/08; see Figure 4.2

Figure 4.2 shows that the water level in the index well was still recovering and had not reached "equilibrium" when pumping resumed. The methods used to estimate recovery times and elevations are discussed in Appendix 1. Extrapolation of the "no pumping" part of the record with a 2nd order polynomial suggests equilibration the first of May at an elevation of about 2836.27 ft – roughly 0.6-0.7 ft higher than the January measurements in Table 4.1.

4.4 Scott County site discussion

From examination of the periods 8/20/07 to 10/29/07 in WY07 and through the period of record in WY08 on the hydrograph, it is clear that sustained "summer" pumping lasted longer and the initial recovery was later and less in WY08 than in WY07. We have not yet seen the extent of "fall" pumping in WY08. Based on these observations we predict that the observed recovery of the water level will be slower in WY09 (spring 09) than in WY08. Whether the recovered level (if it can be adequately estimated) will be lower should depend more on the total volume of pumping in the two years than on the relative timing.

The differences between tape water-level measurements for the wells other than the index well (Table 4.1) are outside of the range of uncertainty imposed by the barometric effects, if the other wells have responses similar to the index well (this cannot necessarily be assumed). The potential differences in degree of recovery, however, are more significant, particularly because substantial differences in pumping and in water-table recovery responses may exist between the Scott-Finney bedrock depression and the much more thinly saturated zones on either side of it.

The Scott County index well filled a hole in the annual measurement network. The well and data analysis has enabled us to identify a substantial depression in the water table centered north of Scott City, as seen in the contours in Figure 4.3 (data from the WIZARD database, some of which is included in Table 4.1). This depression is essentially coincident with the high water-use area visible on Figure 2.6. Heavy ground-water pumping to the north has apparently induced a local hydraulic gradient away (to the north) from the Scott City municipal wells. The regional hydraulic gradient is from west to east. Saturated thickness declines rapidly to the east and west of the Scott-Finney bedrock depression, in which the Scott City municipal wells and the index well are roughly centered.

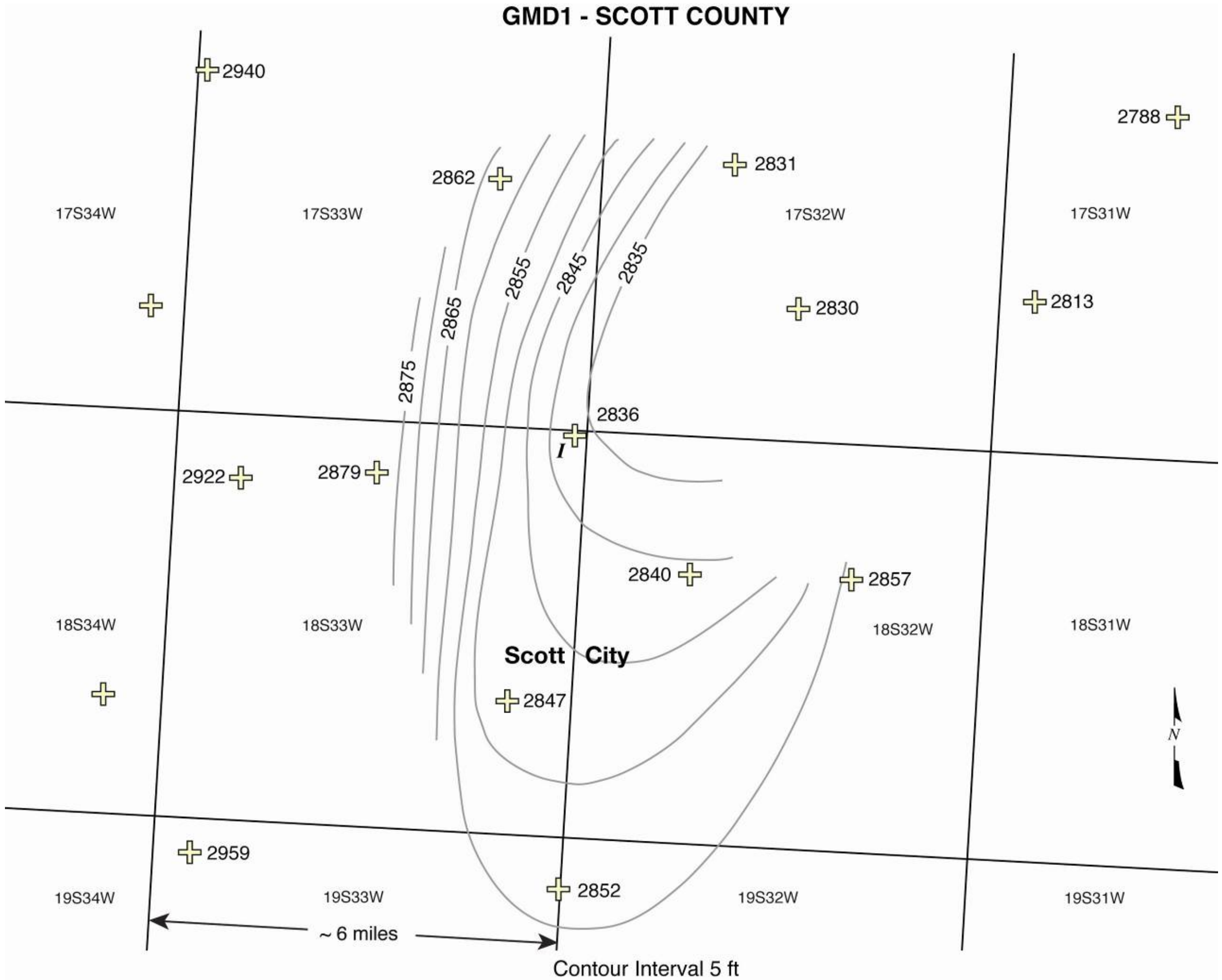

Figure 4.3. January 2008 water levels near the Scott site.

5. Site-specific results: Thomas County

The locations of the Thomas County index well, and adjacent annual program wells and nearby points of diversion, are shown in Figure 5.1. The index well is located relatively close to the edge of the aquifer (visible by the absence of points of diversion to the W and SW) and to an ephemeral stream channel (South Fork Solomon River, approximately 1.5 mi to the north). It is also in a region that has been the subject of a previous KGS water budget study carried out as support for discussions of possible locally initiated aquifer management programs.

5.1 Well hydrographs – Thomas County

Figure 5.2 displays the well hydrograph for the Thomas County index well. Like the Scott County site and the shallow wells in Haskell County (but in contrast to the deep Haskell wells), the range in the elevation variation is roughly five ft. The major summer pumping ended about the first week of September in 2007; unlike the other sites, there was apparently no substantial amount of fall pumping near the Thomas index well. Major pumping did not start in 2008 until May, but there is an apparent downward displacement of the recovery curve around 3/10/08 that suggests the possibility of earlier small pumping effects.

Short-term variation due to atmospheric pressure effects are even more evident in the hydrograph for the Thomas County index well than in the index wells discussed in the preceding sections (see Section 6 below). The variations are relevant to the discussion of decline and recovery, and especially to comparisons with and between the annual program wells because the variations due to atmospheric pressure provide a quantitative estimate of one source of uncertainty in a one-time tape measurement of water level.

5.2 Hydrogeologic implications – Thomas County

As discussed in Section 2.2 and shown in Figure 2.4, the three sites have different lithologic characteristics. In common with the Scott County and shallow Haskell County wells, the Thomas County site appears to function as a phreatic aquifer (in contrast to the deep Haskell zone), with a barometric efficiency similar to the shallow Haskell wells and greater than that for the Scott County well and the deep Haskell wells.

5.3 Decline and recovery - Thomas County

Based on analysis of water-level variations over the month of February 2008 with the recovery trend removed, the barometric-pressure head variations near the site have a maximum range of 1.11 ft and the water-level fluctuations of 0.92 ft. The corresponding standard deviations are 0.22 ft and 0.19 ft, respectively. The high barometric efficiency of this index well compared to the other wells causes greater concerns about possible effects on tape water-level measurements; in the worst case, they could be almost 0.6 ft above or below the "true" value. The water-level responses to barometric pressure changes would be in same direction in different wells, but they could vary dramatically in

Figure 5.1. Thomas County site area with annual water-level (WIZARD) wells (yellow crosses) and production wells (black dots).

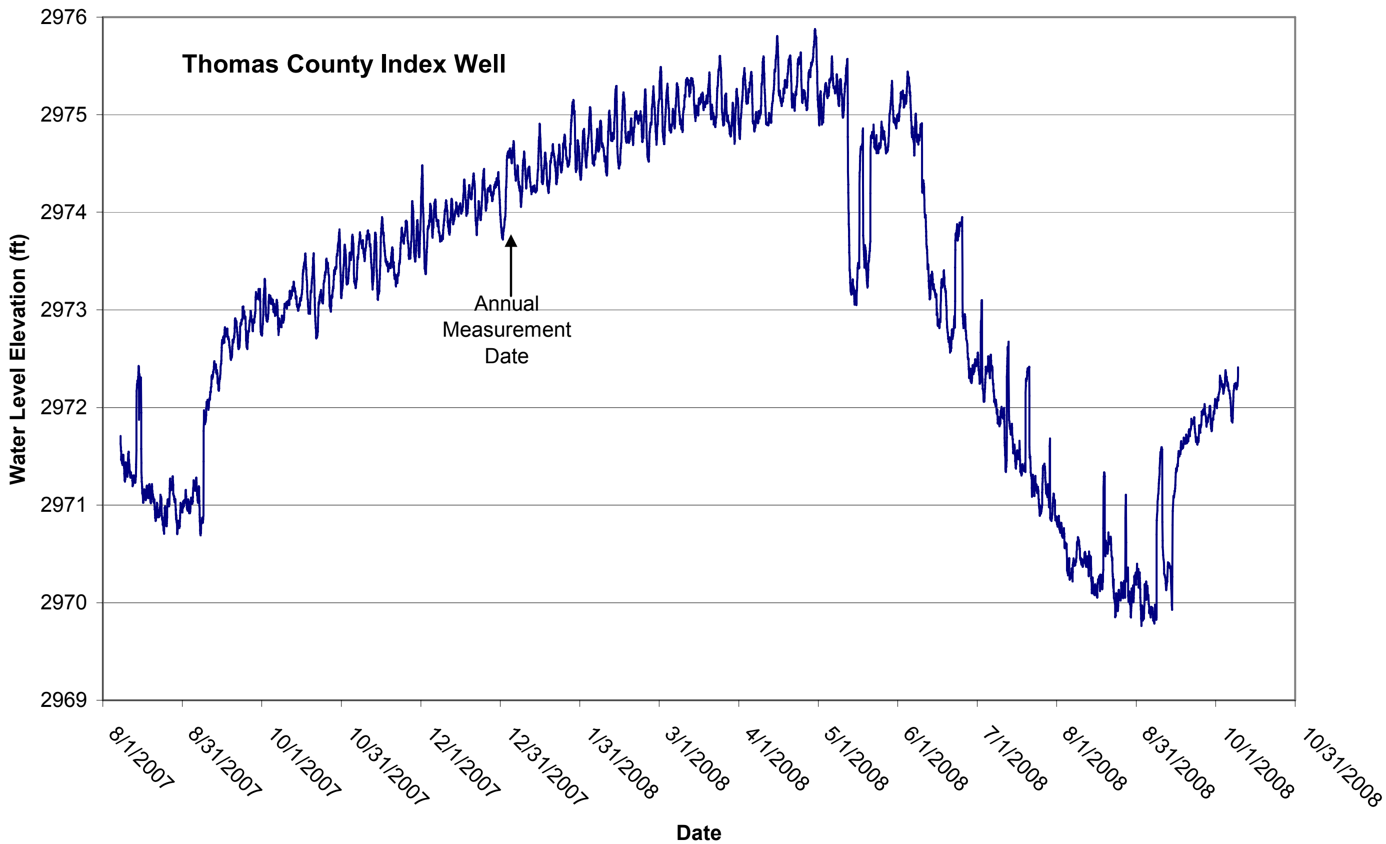

Figure 5.2. Hydrograph from Thomas County index well (scaled the same as Scott County index well hydrograph in Figure 4.2).

terms of magnitude due to different barometric efficiencies, which depend on the hydrostratigraphy in the immediate vicinity of the well and well construction. It should be possible to retroactively correct for responses to barometric pressure changes, as discussed in section 6.

Table 5.1 lists the results of tape measurements in the annual program wells, with corresponding time-averaged transducer measurements for the dates of measurement in the index well. More complete data tables are contained in Appendix 2.

Table 5.1. Thomas County water level observations. Elevations and water-level changes are in ft.

Period	**Jan – mid-March**		**After mid-March#**		**Δ_ 07-08@**
Date	**1/3**	**3/6**	**4/9**	**5/15**	
Well	**WL elev**	**WL elev**	**WL elev**	**WL elev**	
Index	2974.67 (steel tape)	2974.95 (24 hr avg)*	2975.12 (e-tape)	2973.15 (24 hr avg)*	na
"	2974.43 (e-tape)				
"	2974.59 (24 hr avg)*				
TH2	2961.21		2959.75		-2.45@
TH3	2989.87	2990.13			na
"	2990.46				
TH4	2969.34	2969.79			0.21@
TH5	3038.92	3041.86	3042.83	3042.6	-5.56@
TH7	3014.09	3014.44	3012.37	2991.96#	-2.08@

*Transducer record
Based on the hydrograph, pumping had begun; the TH7 record notes "pumping"
@ Because of heavy snow in Jan 07, wells TH2, TH4, and TH7 were measured 2/27/07, and TH5 was measured 4/2/07.

The 2007-2008 differences in the annual program measurements, described as January to January differences in the other report sections, represent an unusual opportunity here, because the 2007 measurements were delayed until late February (early April in the case of well TH5) because of heavy snow. Although well TH4 shows an unexplained rise, the other wells have apparent annual declines much greater than the recent annual average, in spite of the fact that WY08 started out with very high soil moisture because of the snowpack. This appears to be an illustration of the effects of comparing wells at different stages of recovery; the 4/2/07 water elevation of TH5 was 3044.48 ft. When this April 2007 value is compared to the 4/9/08 measurement listed in the table above, the result is a much more reasonable decline of 1.65 ft instead of 5.56 ft. The hypothesis of recovery effects can be tested when the January 09 measurements are available.

It is clear that the water level in the index well was still recovering and had not reached "equilibrium" at the point where pumping resumed. Efforts to estimate the approximate recovered level are discussed and listed in the appendices Because of the lack of data for the beginning of 2007 pumping, the Horner method could not be applied; curve fitting suggests that full recovery would have occurred around the first of August at an elevation of about 2975.7 ft.

5.4 Thomas County site discussion

In Thomas County, the index well program has helped confirm earlier results and answer some questions that arose out of the previous water-balance study KGS conducted. The previous study showed what appeared to be anomalously low water-level measurements from the well located about 2 miles southwest of the index well. However, with the addition of the index well, the elevation surveys of the surrounding annual wells, and analysis of the data, we can confirm the very steep gradient west and particularly southwest of the index well, as shown by the contours in Figure 5.3. This steep hydraulic gradient is probably a combined effect of the surface and bedrock topography and higher ground-water use density to the north and east. The regional hydraulic gradient is from west to east. Saturated thickness and water-use density both decline to the south and west of the index well area, as illustrated on figures 2.2 and 2.6.

Many of the differences between the tape water-level measurements listed in Table 5.1 are within the range of uncertainty imposed by the barometric effects, if the other wells have responses similar to the index well (which cannot necessarily be assumed). Although this is a factor to be considered because of the high barometric efficiency, the potential differences in degree of recovery are even more significant, as indicated by the outcomes of the inadvertent 'experiment' resulting from the delay of the annual 2007 measurements due to adverse weather.

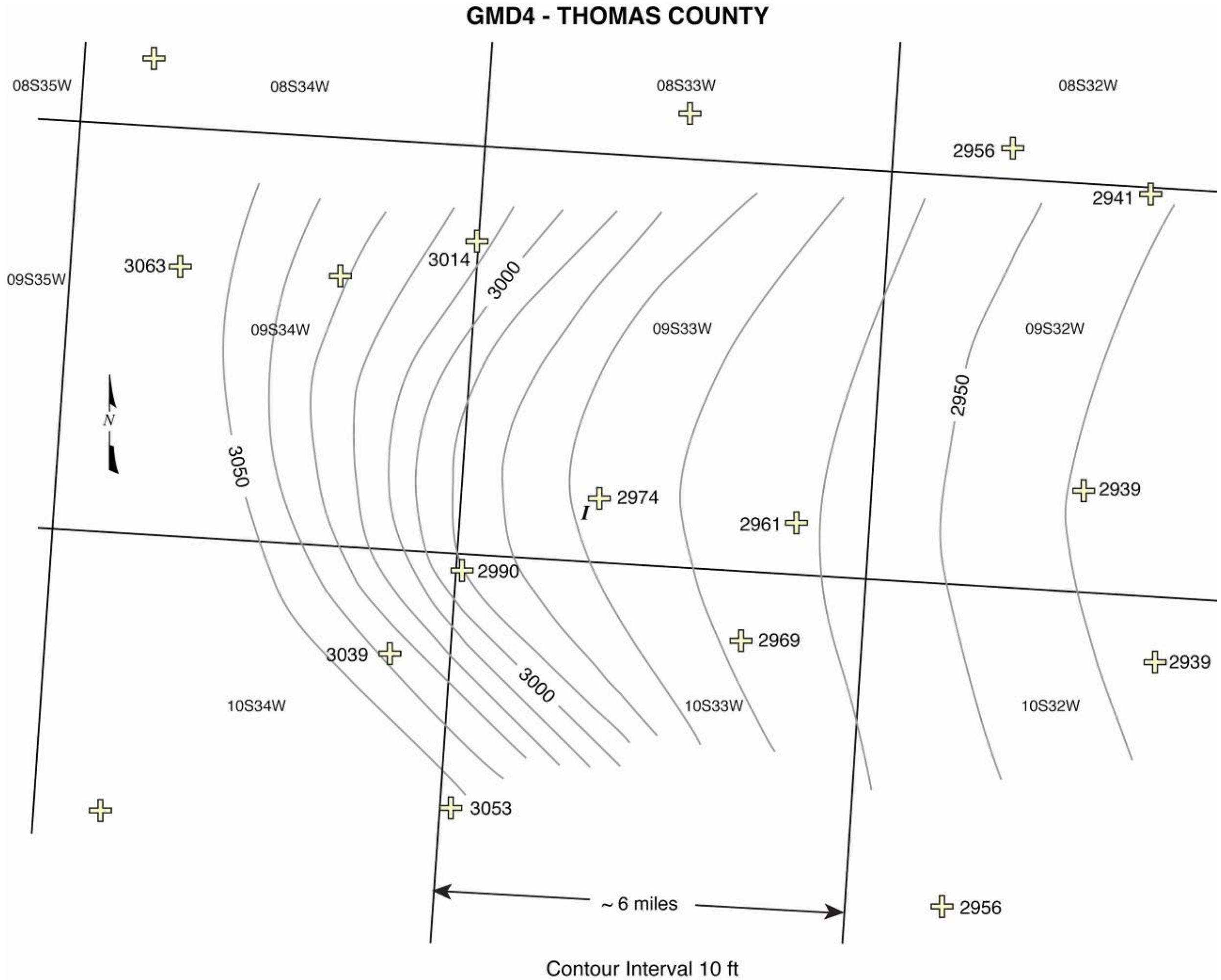

Figure 5.3. January 2008 water levels near the Thomas site.

6. Atmospheric pressure effects

6.1 Introduction

Among the motivations for the index well project was the need to improve the accuracy and precision of water-level determinations in order to evaluate the effects of special management efforts in high priority areas, and assist in identifying hydrologically useful ways to identify or define appropriate priority management units. To make a useful contribution, these improvements must be accomplished in a cost-effective and understandable fashion.

Changes in atmospheric pressure ("barometric pressure") cause changes in the elevation of water level in wells (illustrated in Figure 6.1). Because these short-term variations may be of the same magnitude as annual changes due to the amount of water in storage, they introduce considerable uncertainty into the interpretation of individual water-level measurements. At the same time, however, they create a "natural experiment" somewhat analogous to a pumping or slug test, in which the response of the water level in a well to a known pressure change can provide valuable hydrogeologic information. Box 1 summarizes some basic background information on atmospheric pressure variations.

Box 1: Atmospheric pressure represents the weight of the atmosphere above any point. At sea level, the weight of air in a vertical column with a cross-sectional area of one square foot, the atmospheric pressure, is 14.7 lbs/sq. ft. Because atmospheric pressure varies with both time and location as the atmosphere moves in response to the Earth's energy system, a defined standard atmosphere is used as a reference. Sea-level pressures can vary by $\pm$ 8-9% at the extremes, but normal weather-related fluctuations are more typically in the range of a few percent of the standard.

Atmospheric pressure is commonly measured with a barometer – a U-shaped tube partly filled with liquid and with one side open to the air and the other evacuated and sealed. The pressure on the open side is measured by how far the liquid rises into the vacuum. A standard atmosphere is the pressure exerted by a column of mercury (Hg) 760 mm (29.92 inches) in length, which is equivalent to 33.9 feet of water (the unit of interest to hydrologists). Numerous other units are also used to express gas pressures or gas pressure heads.

In addition to the use of a standard atmosphere, one other convention is important to know. Pressure declines with increasing altitude (the atmospheric pressure near the Kansas-Colorado border is about 10% lower than at sea level) but the barometric pressures in weather reports and forecasts are corrected to sea level so that values and changes will have the same general significance independent of location. In order to calculate barometric effects on water levels, we need to use the local absolute pressures rather than corrected barometric pressures.

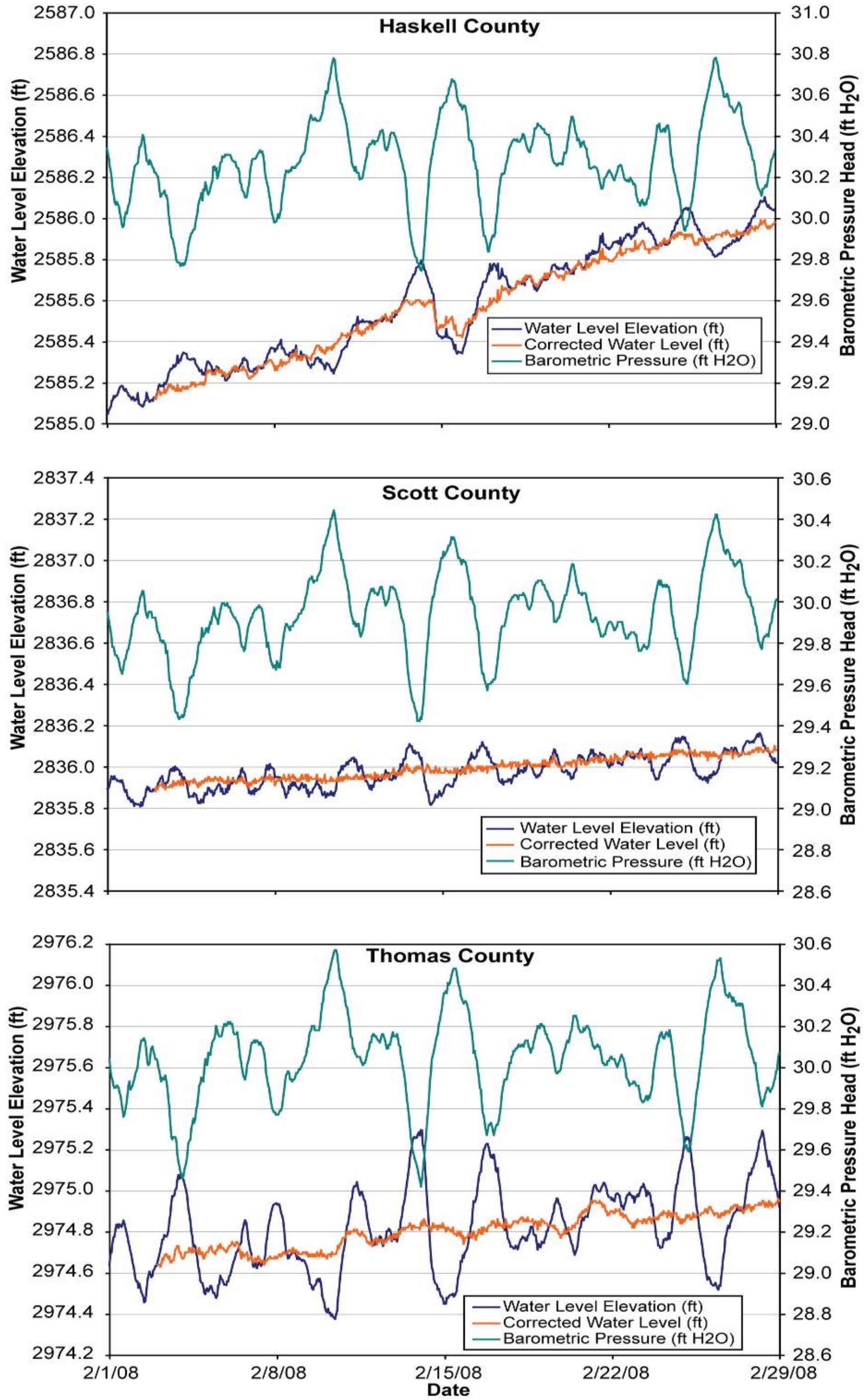

Figure 6.1. Comparison of original and corrected index well water levels with barometric pressure records Variations ranging from 1.1’ to 0.3’ are all reduced to 0.1’ or less by the corrections. In the case of Thomas and Scott counties the pressure and water level measurements were not precisely synchronized; that, plus the distances between measurements, accounts for some minor shifts.

The preliminary analyses presented in this section suggest that the effects of barometric pressure changes on water levels, a source of measurement uncertainty, can be greatly reduced by straightforward processing of water-level data, and that some short-term characterization of the wells being measured can help in the effectiveness of that processing.

In addition, the diverse natures of water-level responses in the three index wells and the KDA-DWR-monitored wells to barometric pressure changes, in combination with information available in the hydrogeologic literature (Butler et al., 2008; Spane, 2002; Toll and Rasmussen, 2007), suggest that these characteristics may be useful in assessing, or even designing, proposed management units, and can provide guidance on the useful range to which index well observations can be extrapolated.

6.2 Pressure responses and mechanisms

When atmospheric pressure changes, there is a change in the "weight" of air pressing down on the open surface of the water in a well relative to the "weight" pressing down on the water contained in the adjacent aquifer. The difference between these "weights" results in a tendency for water to move between the well and the aquifer to compensate for the pressure differential set up by the change in atmospheric pressure. Typically, the elevation of the water level in a well moves inversely to atmosphere pressure. This can be seen in Figure 6.1 in the form of very noticeable and opposite changes in the elevation of the water table when there are major atmospheric pressure changes.

The barometric efficiency is defined as the ratio of the change in water level for a given change in barometric pressure head (by convention, an increase in water level is given a positive sign while an increase in barometric pressure is given a negative sign). The barometric efficiency depends on the local hydrogeologic conditions and can vary significantly between wells in the same aquifer. This too can be seen in Figure 6.1; the primary responses in the Thomas County well are close to the value of the atmospheric pressure change, and less so at the other sites.

The pressure on the water within the aquifer is transmitted by a variety of paths, such as through the soil and aquifer materials and the pore contents (air or water). These pressure transmission pathways can be much slower than the direct action on a free water surface, so that the well water surface may "feel" a pressure change through the aquifer much later than the immediate direct effect. These time lags may vary greatly depending on factors such as depth (to both screened interval and the water table), porosity and permeability, degree of consolidation, etc. The results of such effects can also be seen in Figure 6.1, where the low-amplitude changes in water-table elevations do not correspond well with the apparently corresponding barometric pressure changes, either in magnitude or in timing. This represents the "noise level" of a large number of smaller pressure effects arriving with different lag times. The water-level responses to the larger atmospheric changes stand out above the noise, but the smaller direct responses are modified or lost in the continuum of pressure signals with various time lags.

One further feature in Figure 6.1 deserves note – at the time of comparison (February) the wells were still recovering from the previous pumping season, so the atmospheric pressure signals are superimposed on an upward trend in water elevation. This trend is an important piece of information (discussed elsewhere in this report), but for some purposes the well signal is "detrended" – that is, the upward trend in the signal is determined and mathematically removed to yield variations around a constant mean value, comparable to the atmospheric pressure variations. Estimates of barometric uncertainties in tape water level-measurements, discussed in the sections above, were obtained in this fashion.

6.3 Efficiency and lag time

The data shown in Figure 6.1 were subjected to a preliminary analysis of the magnitudes and lag times of the various identifiable pressure signals. The procedure followed is described elsewhere (Spane, 2002; Toll and Rasmussen, 2007) and will not be detailed here. Two sets of outcomes can be derived from this analysis. Figure 6.2 shows a graph of barometric efficiency as a function of lag time (time since barometric pressure change imposed) that best describes the combined signals in each of the individual index wells. Figure 6.3 compares the efficiency versus time plots for the deep wells (including the index well) at the Haskell site, and Figure 6.4 shows the Haskell site shallow well plots.

These results are exploratory; the barometric records used for the Scott and Thomas wells are only approximations of the actual pressure at the well site, and the analysis would be significantly improved (e.g., with smoother curves) if a period of record longer than a month were available for analysis. Nonetheless, some interesting and important results were obtained.

In Figure 6.2, the plots for the three wells differ in multiple ways. Consistent with the observations above, the short-term barometric efficiencies (the left hand, or short-time lag part of the graph) differ greatly; the Thomas and Scott wells show distinct peaks with the Thomas County well approaching 100% and the Scott County well about half of that. Haskell shows an essentially level response (which is consistent with its expected [semi-] confined condition). Thomas and Scott are similar in form, but the Scott trace tends to zero at the right, whereas Thomas and Haskell stabilize at a higher value.

These differences reflect the differences in the aquifer characteristics and responses at the three sites. Considerable further analysis will be required to sort out the pathways responsible for the different components, but the important point is these plots represent a "fingerprint" of the local hydrogeologic conditions affecting the well water elevation, and there is substantial distinctive variation, even between wells in generally similar formations (the Scott and Thomas sites are both phreatic aquifer wells in relatively shallow, apparently unconsolidated Ogallala deposits).

Figures 6.3 and 6.4 emphasize the potential for pattern matching by showing the similarities within the two groups of Haskell wells, and the differences between them. The shallow wells are not only similar to each other, but generally similar to the Thomas

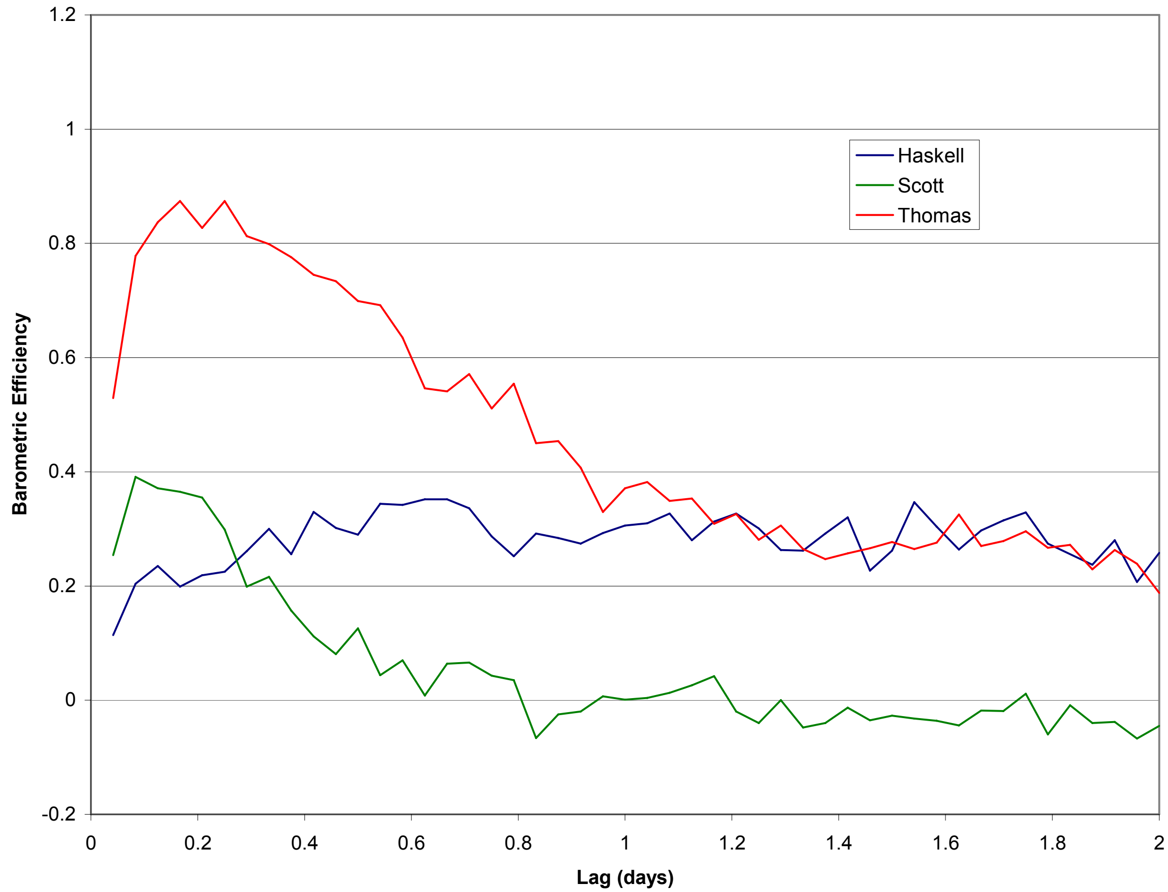

Figure 6.2. Time lag analysis for the water level response to atmospheric pressure at the three index well sites. See text for explanation.

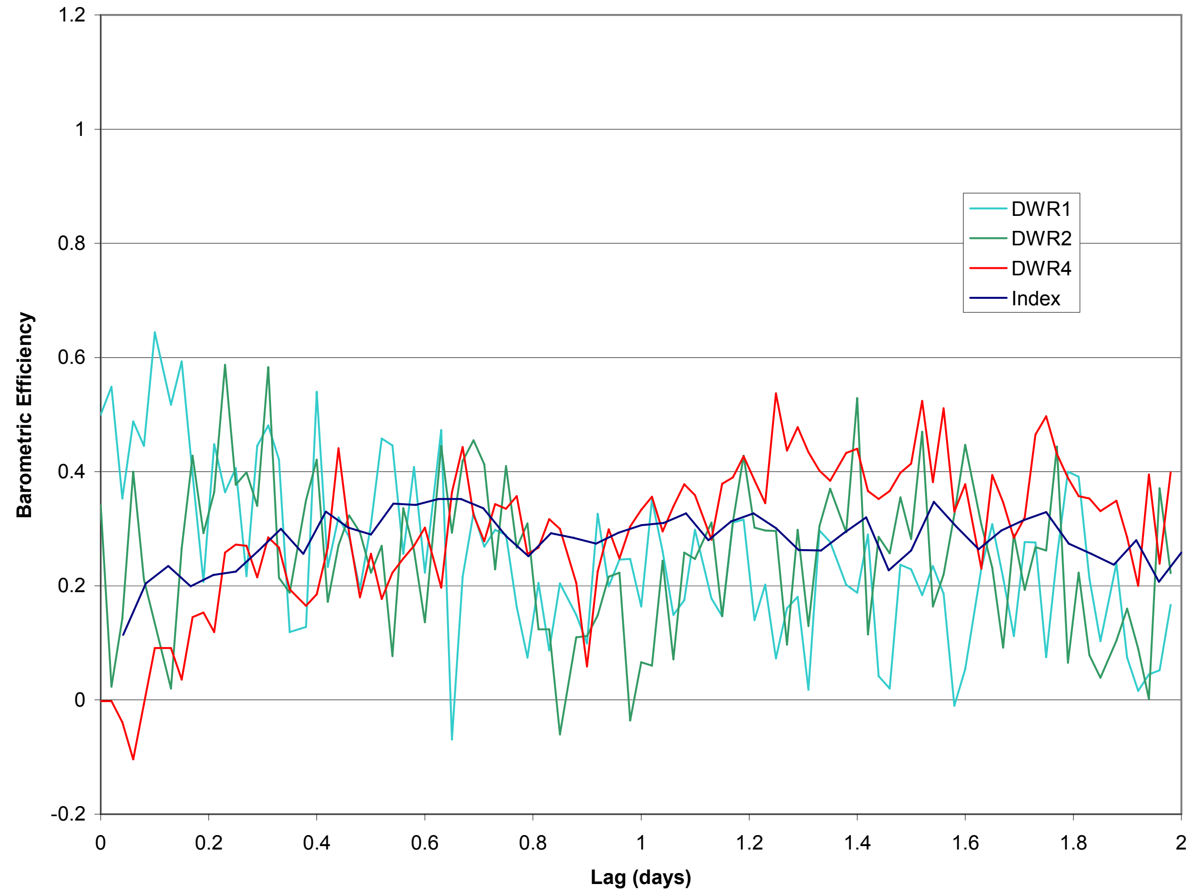

Figure 6.3. Comparison of step barometric response (efficiency time lags) in transducer-equipped wells monitoring primarily the deep (semi-) confined aquifer zone at the Haskell site.

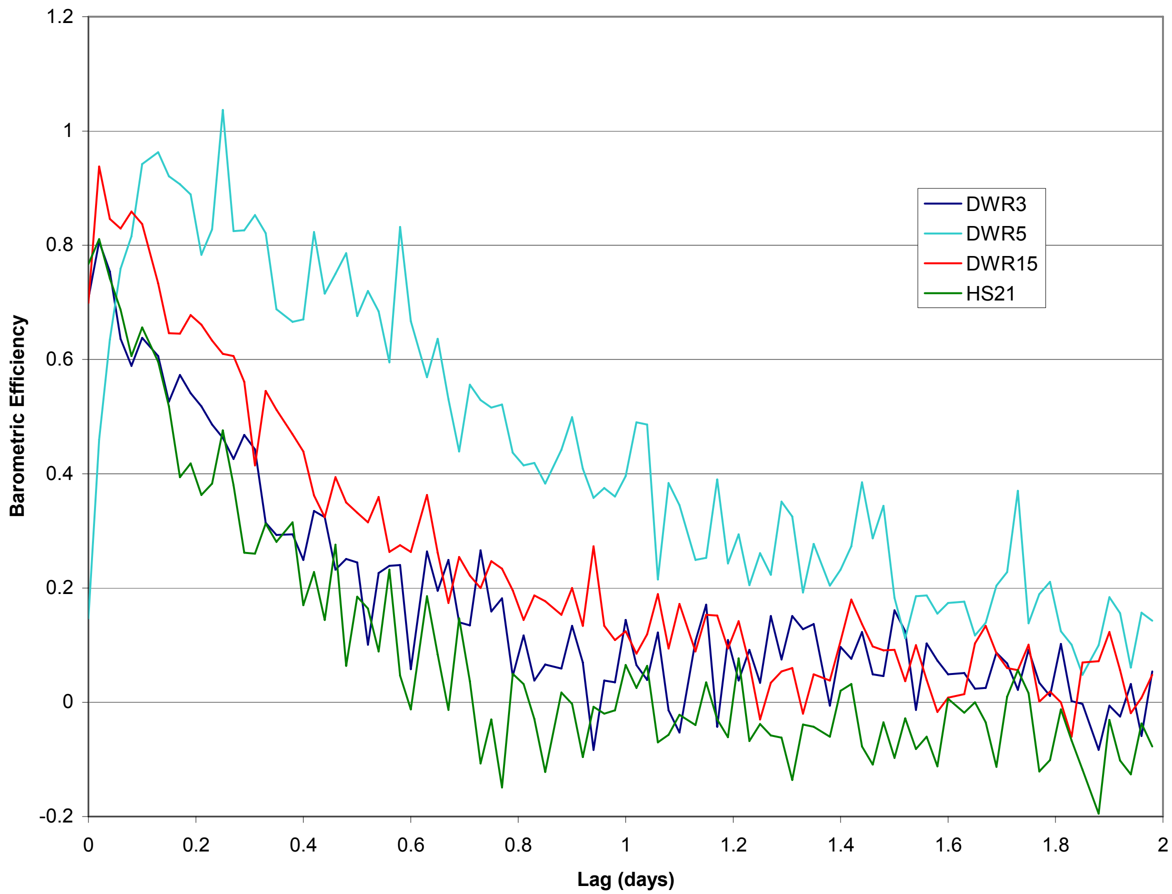

Figure 6.4. Comparison of step barometric response (efficiency time lags) in transducer-equipped wells monitoring primarily the shallow unconfined aquifer zone at the Haskell site. Note that DWR5 and HS21 are deep, with both deep and shallow screens.

County well, and with a form, but not a magnitude, qualitatively similar to the Scott County well. The deep well responses are very different from the shallow responses, and although they do not show as much internal consistency, it should be kept in mind that the index well measures only the deep aquifer response (is grouted from the surface well into the confining zone), whereas the other deep wells are gravel-packed across both aquifer zones, which may partly explain the apparent lower noise level in the index well response plot. However, the primary reason for the lower noise level in the index well response plot in comparison to the response plots for the nearby wells (Figure 6.3) is the lower sensor noise at the index well.

6.4 Signal correction

Figure 6.1 also illustrates the potential for reducing the barometric noise in the water-level signal. Here again, the result could be considerably improved by analyzing a longer time series of pressure and water-level records, but the results are significant even at this stage.

For Thomas County, the range of variation of the uncorrected signal is >0.9 ft. Correction reduces the maximum range to no more than 0.2 ft. This level of improvement in measurement precision is very significant when compared to the apparent average annual rate of decline ($\leq$ 2 ft/yr). In Scott County, the improvement is from 0.31 ft to about 0.07 ft – like Thomas County, an improvement by a factor of >4. Haskell County shows an apparent gross improvement in precision by a factor of about 2.

6.5 Implications and applications

Reduced uncertainties of water level measurements

The applications of the barometric water-level correction finding to improve the precision and accuracy of High Plains aquifer water-level measurements are straightforward and feasible. Based on Figure 6.1, the actual (uncorrected) water level will be very similar to the corrected value when the barometric pressure is close to its long-term average value. These periods would be the opportune times for tape measurements.

This selective sampling approach would be logistically difficult to include in the present annual measurement program, but would be reasonably straightforward to use for limited measurements from a GMD or KDA-DWR field office base. For the Thomas County example shown in Figure 6.1, the corrected water levels varied from -0.07 ft to +0.09 ft around the mean value for the month. Measurements made when the barometric pressure differed from its monthly mean by amounts no greater than the range of corrected water levels observed during this period could be expected to result in little or no addition to the water-level measurement uncertainty. In February, barometric pressures near the Thomas County site were within a slightly larger interval (29.95-30.15 ft H_2O) continuously during six intervals ranging from one to three days in length – time periods adequate to measure priority-unit wells under low-uncertainty conditions if barometric pressures and weather forecasts are monitored to identify the appropriate conditions.

A preferable approach would be calibration of the wells of interest by using transducers to obtain a minimum of a month's record (and preferably longer) of water-level and atmospheric-pressure fluctuations at the site during a period without pumping. Once the pressure responses are calculated, a routine could be set up to calculate the corrected water level based on the observed level and a record of the barometric pressure for some specified time period prior to the measurement.

This approach could eliminate much of the pressure response uncertainties from point measurements. It could also be useful in addressing the question of degree of recovery if a time series of point measurements were taken; their reduced uncertainty would permit extrapolation of a recovery curve with greater confidence. Although some measurement and calculation effort is required to implement this approach, it only needs to be made once per well, and it makes more efficient use of a limited number of transducers than dedicating them to individual wells. Furthermore, the results of the analyses can be used retrospectively to refine measurements made previously, and can also be used in the other application described below.

Comparison of hydrogeologic similarities and differences:

The "fingerprint" characteristics of the analytical results shown in Figures 6.2-6.4 strongly suggest that comparison of these patterns, with each other and with local knowledge of subsurface lithology, might be used to assess continuity of hydrologic conditions and similarities of wells. This could be a powerful tool in sub-unit definition and management, as it could provide a quantitative assessment of similarity with a relatively inexpensive, non-invasive measurement, and would provide direct evidence about the probable range of relevance of the observations made at a central index well. Measurement techniques are relatively simple, as the analyses require only comparisons of variations, so determinations of absolute water level are not required (although they would be useful in mapping the local water table once improved data are available).

Considerable testing will be needed to refine this approach, but that testing consists almost entirely of the measurements already identified as useful for reducing measurement uncertainty (above), and comparison of those with the results of other programs already underway (well log analysis and interpretation, and hydrologic modeling).

7. Discussion

We can start by considering two key questions derived from the hypotheses stated in Section 1 of this report:

> Can monitoring wells yield water-level measurements that, supported by supplemental measurements in other wells in the vicinity, are sufficiently accurate and representative of local water-table behavior to use in intensive management programs?
>
> Can the water-level behavior in a calibration well be a guide to interpret water-level responses in nearby wells in terms of aquifer heterogeneity and/or water use, and refine aquifer subunit definition and characterizations? If yes, can the water-level behavior in a calibration well be used to help improve the interpretation of water-level responses over larger areas?

We can give preliminary answers to these questions that are strongly positive, thanks in large measure to the collaboration with KDA-DWR at the Haskell site. Key findings and remaining questions are:

1. The Haskell index well hydrograph is an excellent match for the hydrographs of the three nearby deep wells, both qualitatively and quantitatively, over the period of record overlap. Similar levels of agreement are seen among the KDA-DWR-monitored shallow wells, although we have no equivalent index well for them. Remaining questions include: how far can these short-range agreements be assumed or extrapolated; what supplementary data are required to exploit the information with confidence; and what are the relationships with spatial and temporal patterns of water use?

2. The striking differences in water-level response, and probably in equilibrium elevation, between the Haskell deep and shallow wells provide clear confirmation of the original suggestion that there are two aquifer zones separated by a thick layer of very low permeability, and also demonstrate the reverse – that aquifer differences are detectable by appropriate monitoring techniques. Management implications are obvious not only in terms of the co-occurrence of two different, poorly connected water supplies, but also in the observation that the existing annual program wells in the area exhibit diverse responses, with most of them apparently reflecting the shallow aquifer rather than the deeper zone that is increasingly used as the major water source. Remaining questions involve the lateral extent of the two-aquifer system, the locations and effectiveness of interconnections between them, and how best to rationalize a monitoring program to serve this hydrogeologically complex area.

3. Analysis of the atmospheric pressure responses in the various transducer-equipped wells has shown that it is possible to remove or compensate for much of the short-term water-level measurement fluctuations due to barometric pressure variations. This holds out the possibility of reducing the inherent uncertainty of tape measurements by amounts of up to 0.5 ft in regions of high barometric efficiency (see Figure 6.1).

4. Patterns of time lags of various barometric components in the water-level signal have shown that there are both quantitative and qualitative differences among the wells, with systematic differences between the deep, (semi-)confined Haskell wells and the phreatic aquifer wells (Scott, Thomas, and shallow Haskell locations), and that further distinctions can be made within each of the groups. Considerable further analysis and measurement will be required to develop the possibility that barometric pressure response patterns in wells could be used as probes of the local hydrogeology, and help to diagnose the degree of similarity between wells and locations.

5. The Haskell site is unusual in both its hydrogeology and the density of data available. However, the findings there can be used to help interpret and expand the observations at the Scott and Thomas locations. We suspect that the Scott, Thomas, and shallow Haskell wells are broadly representative of a substantial majority of the High Plains well installations. This makes refined and extended analysis of their similarities and differences particularly significant.

6. In all of the phreatic wells, the pumping season drawdown was on the order of a few feet, while >100 ft of pumping-induced head change was observed in the deep (semi-)confined wells. Compared to the other wells, the Scott County well had a lower barometric efficiency, and apparently a faster recovery. Well-log analysis suggests systematic qualitative differences between the upper saturated zones in the three areas. The water-table aquifers at the Haskell and Thomas sites are believed to have no major lateral variations on a scale of miles, whereas the Scott site is in the Scott-Finney bedrock depression (close to the west side), with all of the adjacent annual program wells located in regions of shallower bedrock and much lower saturated thicknesses.

7. Supplementary tape measurements at annual program wells in the vicinity of each of the index wells produced observations generally consistent with the index well hydrographs, but did not produce quantitative confirmation of relationships that could be used to help establish the range of utility of the index wells, or to define or refine aquifer subunit boundaries. This was due in part to the number, frequency, and timing of the measurements (and hence the inability to estimate degree of recovery or similarities in response), and to uncertainties introduced by barometric effects. As indicated above, we can greatly reduce the barometric uncertainties, and, with enough observations, can make reasonable estimates of relative recovery.

More detailed understanding of all of the sites will be provided when data on two full maximum-drawdown-to-maximum-recovery cycles in all wells are available in spring 2009. Analysis of the 2007 and 2008 water use reports (in conjunction with local meter readings taken by KDA-DWR at the Haskell site) will explain some aspects of the well hydrographs in their local context; others will require additional well measurements and/or log analysis. The unplanned “experiment” of delayed 2007 annual measurements in Thomas County will make a useful contribution to the overall analysis of recovery effects and accuracy/precision of water-table elevation determinations. Feedback from managers and planners will be important in refining the questions and formulating approaches to answering them.

The experiences of the first two years indicate that advances beyond the scope of those originally envisioned can be obtained by a combination of continued observations and systematically enhanced measurement of other wells in the neighborhood of the index sites.

8. Conclusions and recommendations

The outcomes to date of the KDA-DWR collaboration demonstrate the power of multiple transducer-equipped wells in the same area. Even temporary installations could greatly facilitate the confidence in, and effectiveness of, an index well in an aquifer subunit. Interagency cooperation is strongly recommended to efficiently develop short-term datasets that can put longer term monitoring on a firm footing.

The results obtained in the preliminary analysis of atmospheric pressure and water-level responses at the index well sites suggest potential cost-effective improvements of local monitoring efforts. These include timing of point measurements to minimize uncertainty due to barometric effects, and determining the pressure response characteristics of individual wells, both for calibrating point measurements and for developing criteria for defining regions of hydrologic similarity.

We recommend:

1. During the upcoming recovery season, temporary installation of pressure transducers in other wells in the vicinity of the Scott and Thomas County index wells (with at least one atmospheric pressure measurement in the general region). This effort should start with the closest annual program wells. Since measurement periods of 1-2 months are adequate for most purposes, the equipment could be moved to other nearby wells to test ideas about hydrogeologic similarity.
2. Successive point (tape) measurements (e.g., at 2 week intervals) in wells of interest, including at least some with transducers installed. Measurements should be taken when barometric pressures show only minor deviations from mean of the preceding month. These data will provide both tests of the reduced uncertainty hypothesis outlined above when compared with the eventual pressure calibration in transducer-equipped wells, and more reliable data for identifying patterns of water-level response where transducers are not available.
3. Continued work on relating the efficiency-time lag “fingerprints” to each other and to local geohydrologic characteristics. This will be greatly facilitated by obtaining data from a local grouping of wells.

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APPENDIX 1. Full recovery estimation

One approach used is simple curve fitting of the smoothest part of the recovery curve, covering as long a time as possible, but clearly between any noticeable effects of pumping. The lengths of these periods can vary – in Water Year 2008, they were approximately three months at Haskell, four months at Scott, and close to six months at Thomas. We have tested various standard mathematical curves, and find that the simple quadratic (second order polynomial) curve is consistently the most useful. The best-fit curve is extrapolated to its maximum value, which is taken as the elevation, and the corresponding time is taken as the date of equilibrium

The second method is an analytical approach devised by Horner (Streltsova, 1988) for interpreting the data from the recovery period following a pumping test. The pressure (observed elevation of the water table, in our case) is plotted on the y-axis against the ratio of the total time (pumping plus recovery) divided by the recovery time (plotted on a log-scale x-axis) required to reach the specific water-level elevation. Ideally, this should yield a nearly straight line that can be extrapolated to a ratio value of unity, which is at the equilibrium elevation. The time of ultimate equilibration is not readily obtained by this method.

Both techniques require the analyst to select the portion of the data set to use for the extrapolation, for which there is no standard protocol. The quadratic curve reaches a maximum and turns downward, which leads to the suspicion that the values obtained may be slightly lower and earlier than the actual values. The Horner method is at its best under controlled conditions, with constant rates and locations of pumping, and no interferences with the recovery period. This is not the case in the field, and the Horner plots are decidedly non-linear. However, we find that a linear section near the end of the recovery period can be extrapolated to an apparently reasonable value of elevation. Interference by undetected pumping between the end of the pumping season and the end of the observed recovery period will result in an artificially high estimate of the equilibrium water level.

Because the probable biases of the two approaches are in different directions, approximate agreement represents a reasonable estimate of the actual recovered value, and that in any case the fully recovered water level is likely to have an elevation between the estimates produced by the two methods.

APPENDIX 2. Summary tables

Table A.2.1. Summary of water level changes from 2007 to 2008 (units are ft; negative values indicate declines).

WELL	Δ_MAX_07-08	Δ_MIN_07-08	Δ_07-08
Haskell Deep			
Haskell Index	na	-1.31	na
1	≥ -6.08	na	na
2	≥ -5.46	0.15	na
4	≥ -11.83	na	na
Haskell Shallow			
3	≥ -4.44	-4.42	na
5	≥ -4.93	-1.44	na
15	≥ -4.92	-4.42	na
HS21	na	na	-4.40
HS22	na	na	-1.39
HS23	na	na	-0.32
HS25	na	na	-5.85
HS26	na	na	1.53
Scott Index	na	na	na
SC3	na	na	-1.71
SC4	na	na	-1.53
SC5	na	na	-1.23
SC7	na	na	-0.55
Thomas Index	na	-0.93	na
TH2	na	na	-2.45
TH4	na	na	0.21
TH5	na	na	-5.56
TH7	na	na	-2.08

Δ_MAX_07-08 = difference between maximum water level elevation in WY2007 and WY2008.
Δ_MIN_07-08 = difference between minimum water-level elevation in WY2007 and WY2008.
Δ_07-08 = difference between January water-level elevation in 2007 and 2008 (except at Thomas). 2007 measurements at Thomas were later than normal due to weather (see text).

Table A.2.2. Water levels in Haskell County wells (all elevation/depth units are ft).

Well	Date	Elevation of LS	Depth to Water	WL Elevation	Δ_07-08*	Notes
HS21	1/8/2007	2821.67	219.35	2602.32		
HS21	1/15/2008	2821.67	223.95	2597.72		
HS21	4/8/2008	2821.67	224.94	2596.73		
HS21					-4.40	
HS22	1/8/2007	2893.22	236.85	2656.37		
HS22	1/15/2008	2893.22	238.24	2654.98		
HS22					-1.39	
HS23	1/8/2007	2789.93	160.44	2629.49		
HS23	1/7/2008	2789.93	160.76	2629.17		
HS23	4/8/2008	2789.93	161.89	2628.04		
HS23					-0.32	
HS25	1/8/2007	2771.18	193.52	2577.66		
HS25	1/7/2008	2771.18	199.37	2571.81		
HS25	4/8/2008	2771.18	199.40	2571.78		
HS25					-5.85	
HS26	1/8/2007	2818.32	218.88	2599.44		
HS26	1/7/2008	2818.32	217.35	2600.97		
HS26					1.53	
HS_Index	1/7/2008	2837.85	253.76	2584.10		24 hour Average
HS_Index	1/15/2008	2837.85	253.35	2584.50		Annual well survey
HS_Index	1/10/2008	2837.85	253.65	2584.20		24 hour Average
HS_Index	1/15/2008	2837.85	253.43	2584.42		24 hour Average
HS_Index	4/8/2008	2837.85	280.50	2557.35		Tape

* difference between January water-level elevation in 2007 and 2008.

Table A.2.3. Water levels in Scott County wells (all elevation/depth units are ft).

Well	Date	Elevation of LS	Depth to Water	WL Elevation	Δ_07-08*	Notes
SC3	1/10/2007	2974.82	127.60	2847.22		
SC3	1/15/2008	2974.82	128.31	2846.51		
SC3	4/9/2008	2974.82	128.09	2846.73		
SC3					-1.71	
SC4	1/11/2007	3016.81	153.50	2863.31		
SC4	1/7/2008	3016.81	155.03	2861.78		
SC4					-1.53	
SC5	1/11/2007	2980.82	148.88	2831.94		
SC5	1/15/2008	2980.82	150.11	2830.71		
SC5	4/9/2008	2980.82	150.30	2830.52		
SC5					-1.23	
SC7	1/10/2007	2974.56	133.83	2840.73		
SC7	1/7/2008	2974.56	134.38	2840.18		
SC7	4/9/2008	2974.56	133.65	2840.91		
SC7					-0.55	
SC_Index	1/7/2008	2967.47	131.86	2835.61		Annual well survey
SC_Index	1/7/2008	2967.47	130.67	2835.63		24 hour average
SC_Index	1/15/2008	2967.47	131.66	2835.81		24 hour average
SC_Index	4/9/2007	2967.47	133.21	2834.26		Tape

* difference between January water-level elevation in 2007 and 2008.

Table A.2.4. Water levels in Thomas County wells (all elevation/depth units are ft).

Well	Date	Elevation of LS	Depth to Water	WL Elevation	Δ_07-08*	Notes
TH2	2/27/2007	3145.31	181.65	2963.66		
TH2	1/3/2008	3145.31	184.1	2961.21		
TH2	4/9/2008	3145.31	185.56	2959.75		
TH2					-2.45	
TH3	1/3/2008	3191.91	202.04	2989.87		
TH3	1/3/2008	3191.91	201.45	2990.46		
TH3	3/6/2008	3191.91	201.78	2990.13		
					na	
TH4	2/27/2007	3139.87	170.74	2969.13		
TH4	1/3/2008	3139.87	170.53	2969.34		
TH4	3/6/2008	3139.87	170.08	2969.79		
TH4					0.21	
TH5	4/2/2007	3220.55	176.07	3044.48		
TH5	1/3/2008	3220.55	181.63	3038.92		
TH5	3/6/2008	3220.55	178.69	3041.86		
TH5	4/9/2008	3220.55	177.72	3042.83		
TH5	5/15/2008	3220.55	177.95	3042.6		
TH5					-5.56	
TH7	2/24/2007	3202.16	185.99	3016.17		
TH7	1/3/2008	3202.16	188.07	3014.09		
TH7	3/6/2008	3202.16	187.72	3014.44		
TH7	4/9/2008	3202.16	189.79	3012.37		
TH7	5/15/2008	3202.16	210.2	2991.96		Measured while pumping
TH7					-2.08	
TH Index	1/3/2008	3187.44	212.77	2974.67		Annual well survey
TH Index	1/3/2008	3187.44	213.01	2974.43		e-tape
TH Index	1/3/2008	3187.44	212.85	2974.59		24 hour average
TH Index	3/6/2008	3187.44	212.49	2974.95		24 hour average
TH Index	4/9/2008	3187.44	212.32	2975.12		e-tape
TH Index	5/15/2008	3187.44	214.29	2973.15		24 hour average

* difference between water-level survey elevations in 2007 and 2008.
2007 measurements were later than normal due to weather (see text).