Kansas Geological Survey

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

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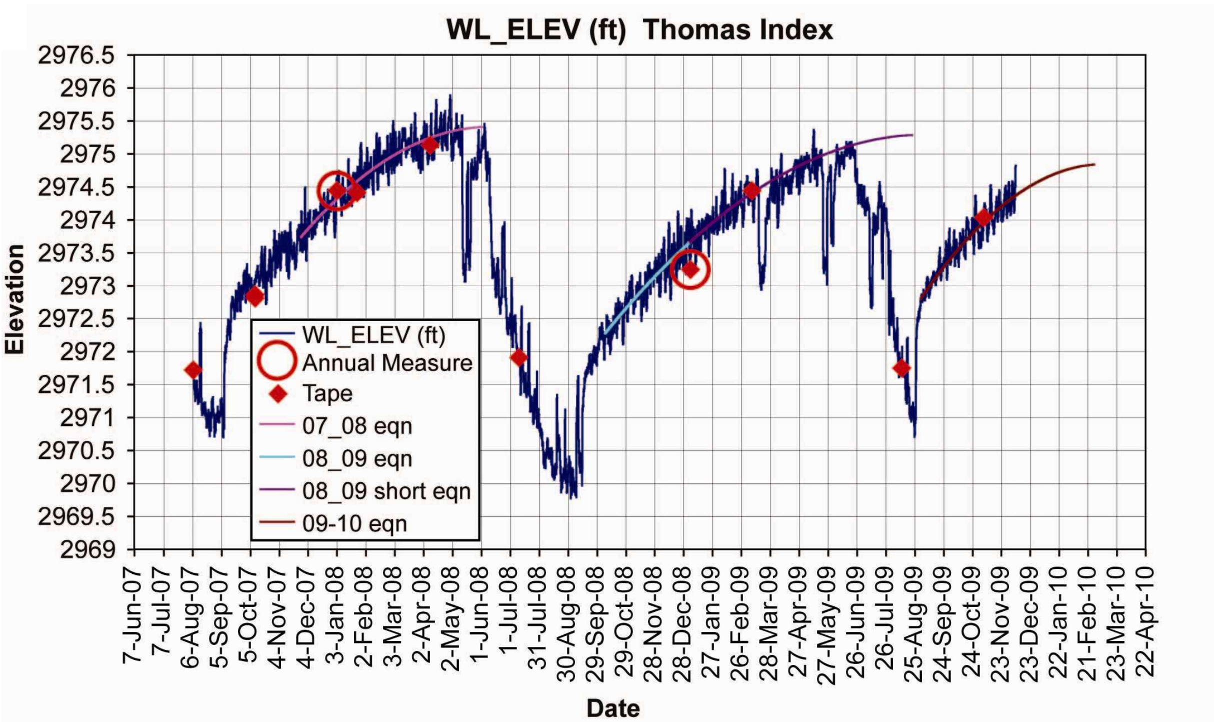
Kansas Geological Survey Open-File Report,
March 2010



Kansas Geological Survey Open-file Report No. 2010-3

GEOHYDROLOGY

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1. Introduction and background

The calibration monitoring (index) well program is a pilot study to develop improved approaches for measuring hydrologic responses at the local (section to township) scale. The study is supported by the Kansas Water Office (KWO) with Water Plan funding. It is being undertaken because of KWO's interest in and responsibility for long-term planning of the Ogallala-High Plains aquifer 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) 4, 3, and 1.

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 use patterns need to be evaluated promptly and accurately. The project has therefore focused on identifying and reducing the uncertainties and inaccuracies involved in producing quantitative estimates of year-to-year changes in water-level, in order to support managers in identifying the impacts of water-use changes as rapidly as possible.

Now concluding its third year, the program has taken significant steps toward achieving the goals of understanding and measuring aquifer dynamics at scales appropriate to the definition and management of aquifer subunits, and, ultimately, providing cost-effective methods for assessing the impact of long-term management strategies. This annual report of progress summarizes not just findings, but also the current state of knowledge and interpretation, and the needs, plans, and opportunities for further study.

More detailed information on the design and inception of the project is available from the previous annual reports, Young et al. 2007 (http://www.kgs.ku.edu/HighPlains/OHP/OFR_2007_30_final.pdf) and Young et al. 2008 (http://www.kgs.ku.edu/HighPlains/OHP/OFR_2008_29.pdf); see also http://www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml for detailed descriptions of the wells and access to the telemetered water-level data. The overall experimental design and the current field sites are described in section 2. Section 3 of this report addresses the issues and findings to date concerning the measurement of groundwater levels and the accurate determination of water-level elevation changes. Section 4 summarizes the progress made toward applying the findings to monitoring and management at the aquifer subunit scale, and outlines remaining needs and work plans. Section 5 presents an overall summary of findings and directions. The appendices to the report contain more extensive and detailed data and background information: Appendix A.1 has a complete compilation of available data on the characteristics of all wells involved in the study; A.2 presents precipitation data for the three counties involved; A.3 supplies recent water use data in the vicinity of the index wells; and A.4 presents hydrographs and Barometric Efficiency Function plots for all transducer-monitored wells at the Haskell site. Appendices B and C present methods and background information relating to well recovery analysis and barometric correction.

2. Setting and overall 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, which were 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. Site characteristics are described and discussed in more detail in previous publications and in subsequent sections of this report; here we briefly introduce the sites and their characteristics.

Figure 2-1 shows the general location of the sites; all three are located in areas of substantial groundwater depletion – the predevelopment saturated thickness has been reduced by a third to over half. Figure 2-2 provides more detailed information on saturated thickness and recent water-level declines in the general vicinity of each monitoring well and Table 2.1 provides well construction details and water use data. The Thomas and Scott county 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 Thomas County site has been the subject of previous water budget analyses and is of additional interest because of the presence of stream channels that may influence recharge and the proximity of the site to the edge of the productive portion of the Ogallala aquifer. The Scott County site is the only well that directly monitors the level of the northern portion of the Scott-Finney depression, where the aquifer is the major water supply for Scott City. In addition, the county has also recently been the target 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 will be necessary for relating aquifer lithology to well response characteristics. Both the Scott and Thomas sites are assumed to represent phreatic (water-table, or unconfined) aquifer conditions, while the Haskell site represents confined aquifer conditions.

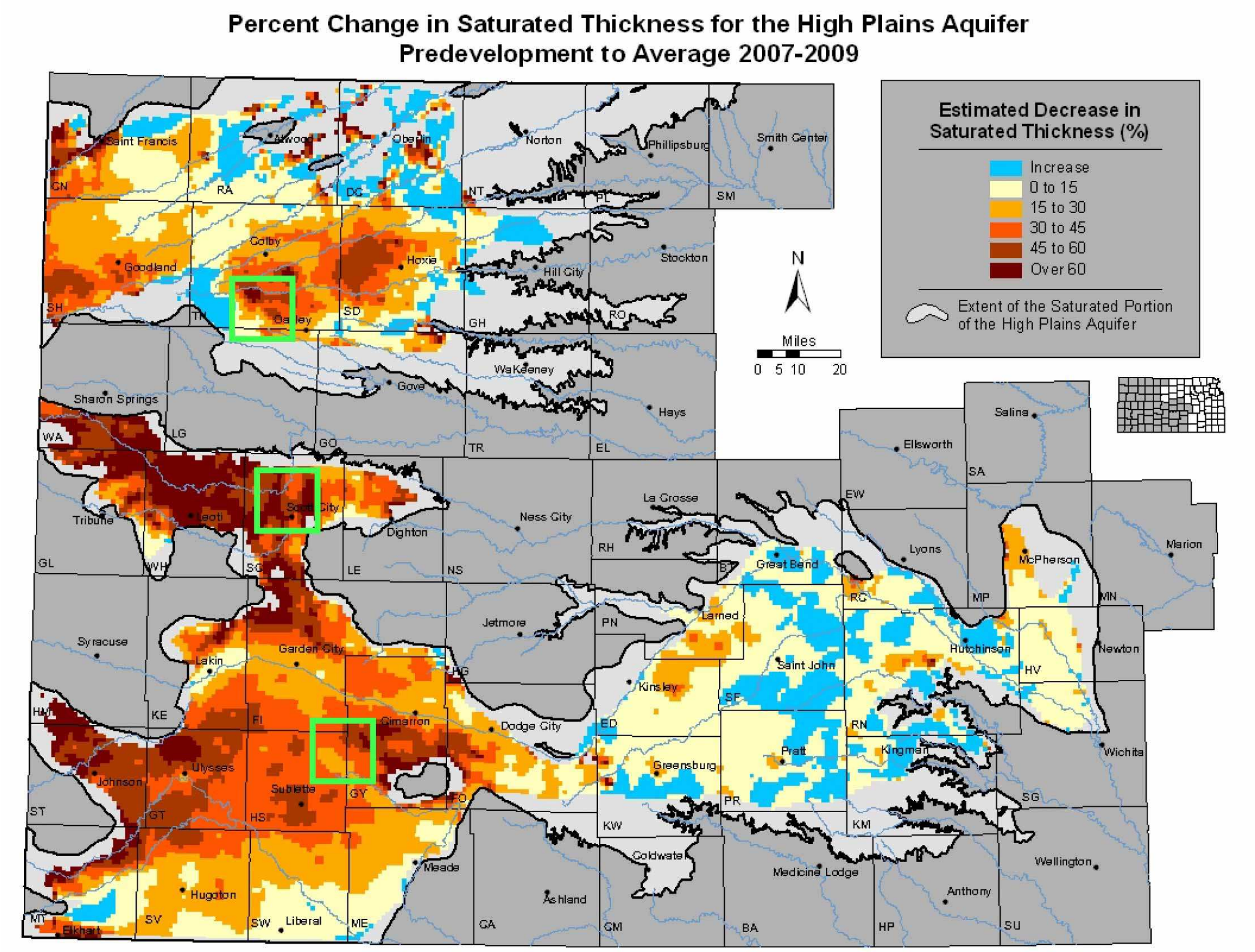
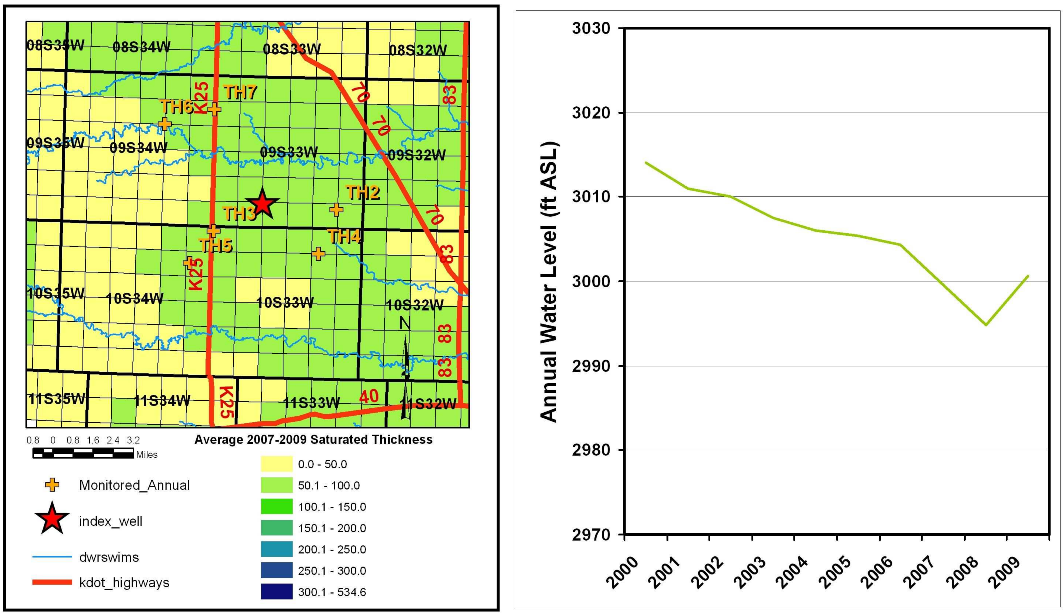
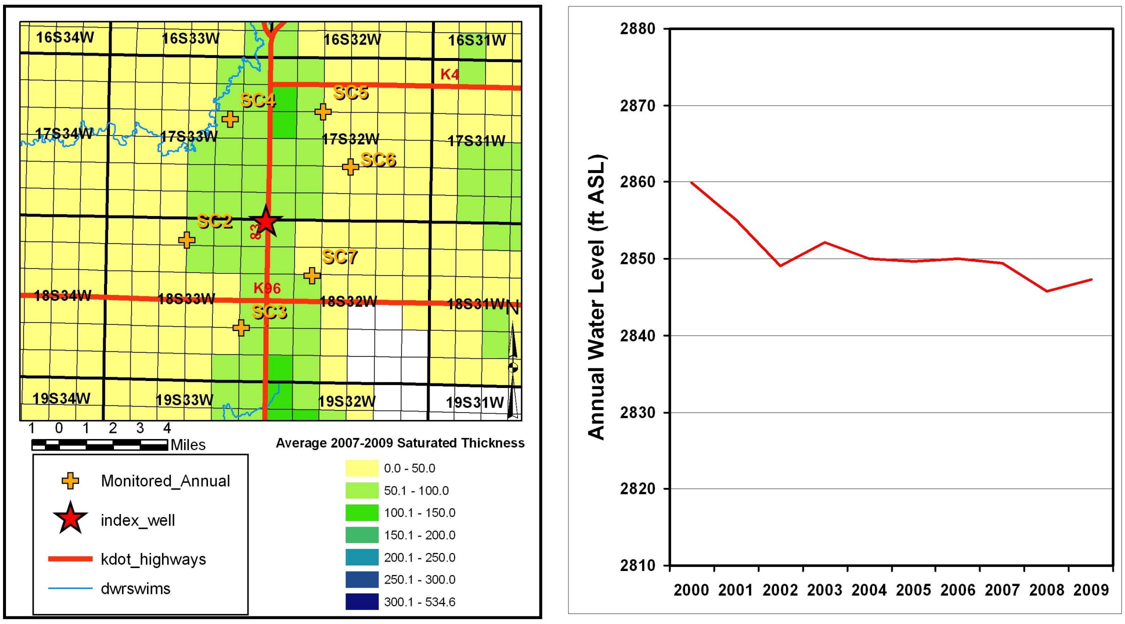


Figure 2-1: The western (Ogallala) portion of the High Plains aquifer, with aquifer and county boundaries shown. The colored pixels represent one section (1 sq. mi.), coded to show the degree of groundwater depletion from the beginning of large-scale development to the average of conditions in 2007-2009. The three outlined areas are the calibration well study sites, shown in greater detail in Figures 2-2 through 2-5, and described in the text and Table 2-1.



a)Thomas County Site



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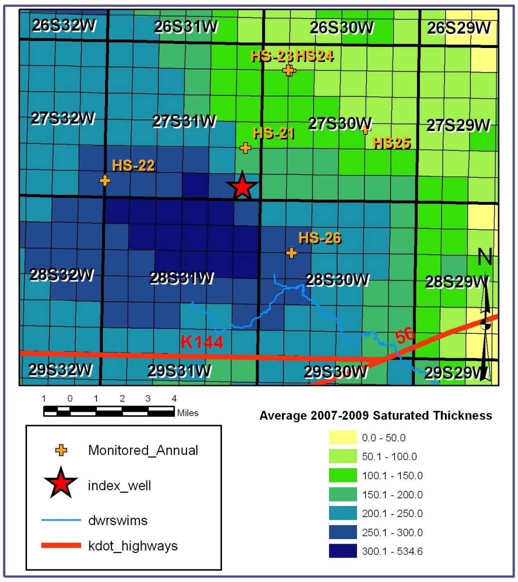
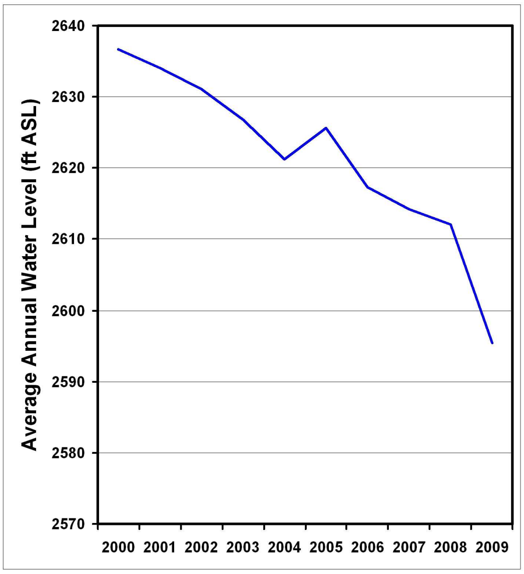




c) Haskell County Site

Figure 2-2: Expanded views of the of the outlined site areas in Figure 2-1. The colored pixels (legal sections) show the total saturated thickness (ST) of the aquifer, averaged over 2007-2009, and the hydrographs are approximate traces of water-level change, averaged over the annual program wells closest to the index site. The ST at the Thomas and Scott county sites is at the lower end of thicknesses usable for extensive irrigation; the Haskell county site is in area of somewhat greater ST, but with high lateral variation and rapid decline.

Figure 2-3 is an overview of the Thomas County site at a scale that shows the surrounding network of annual program wells, as well as the index and other observation wells, and water rights within the area. Figure 2-4 provides a similar view of the Scott County site, which is slightly more than two miles north of the city limits of Scott City, and three miles north of the intersection of highways K96 and US83.

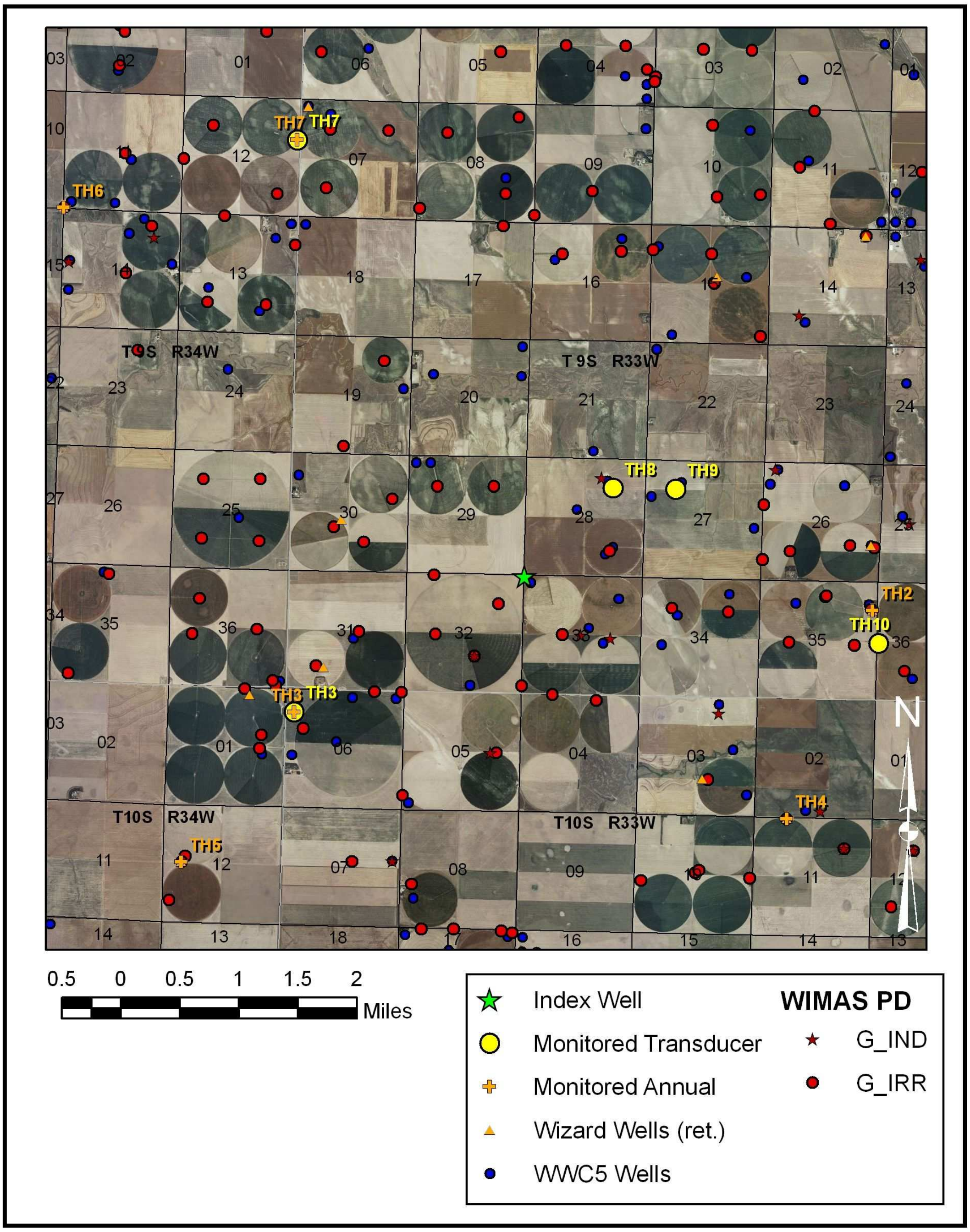


Figure 2-3: Thomas County site, showing surrounding annual wells, water rights, the index well, and other wells that have recently been or will soon be equipped with transducers. Data from the additional transducers will be used to determine exactly how well the index well represents behavior of the larger area. Note that the South Fork Solomon River flows E-W just N of the index well.

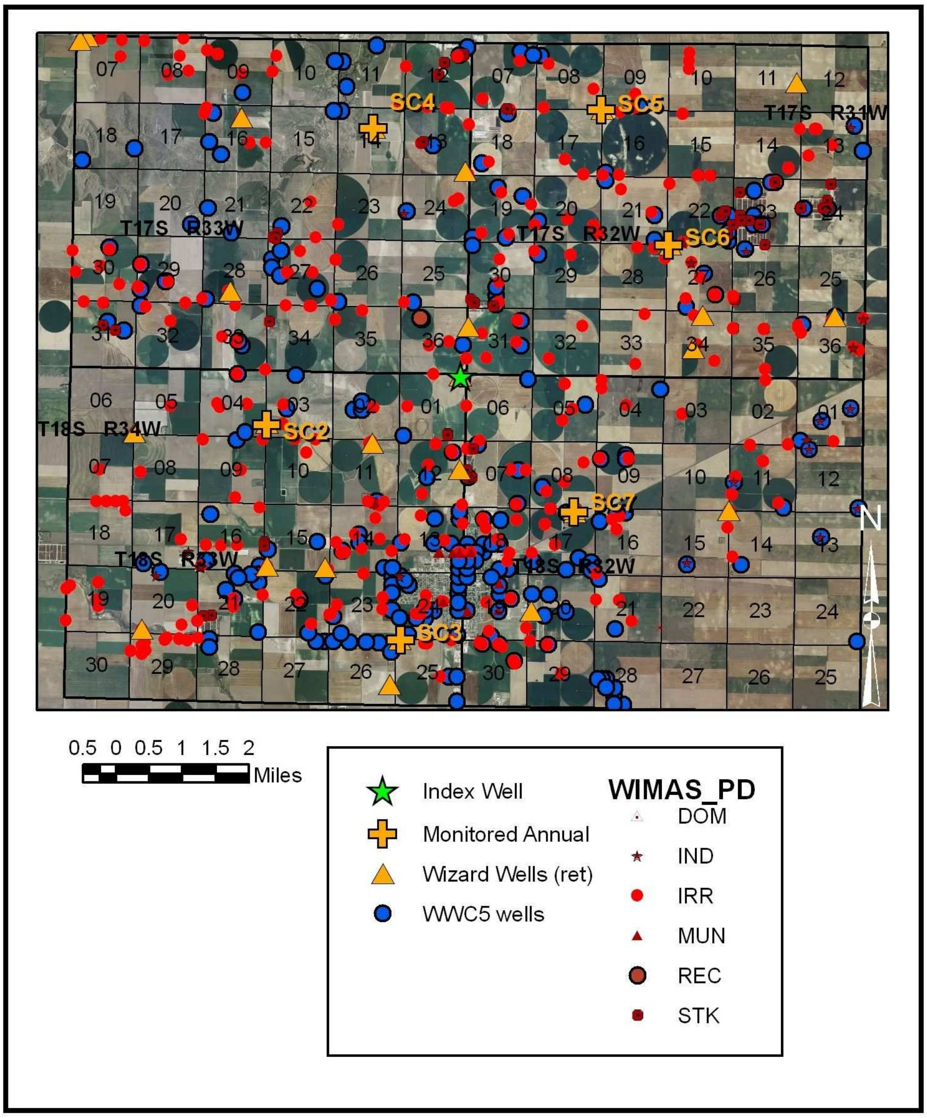
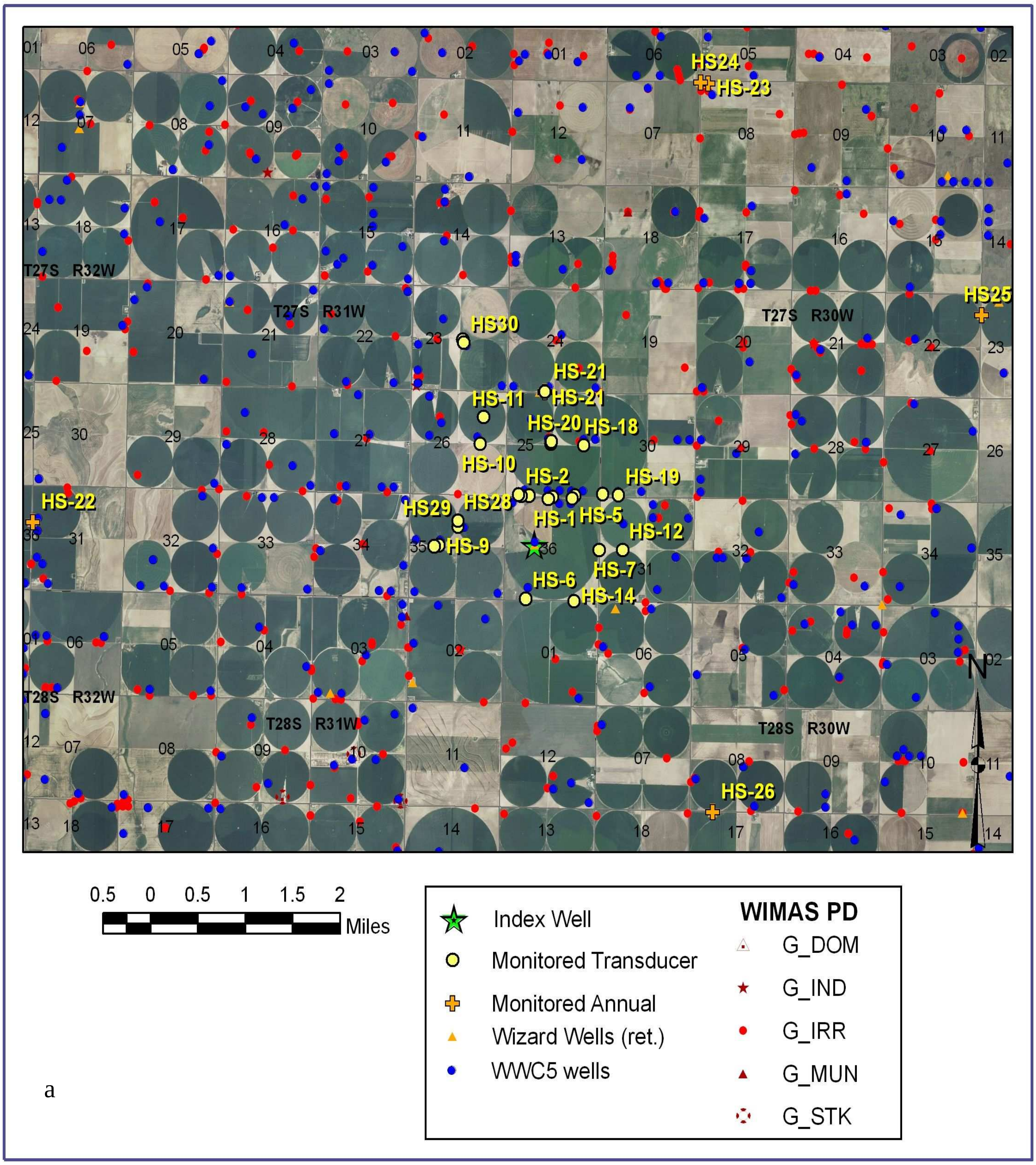


Figure 2-4: Scott County site, showing points of groundwater diversion and the network of annual wells around the site, as well as Scott City. The aquifer region monitored by the index well supplies municipal water for the city.

The Haskell County site (Figure 2-5) represents the most complex set of conditions. It is located over a rather steeply sloping section of bedrock, along a gradient in both water use and water availability. Although the saturated thickness is large, the thickness of intervals that readily yield water to wells is much less. Probably as a result, well yields have deteriorated and an impairment complaint (since withdrawn) was recently filed. It appears that there is a two-aquifer system: 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 wells in both aquifer zones in the vicinity.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Index Well
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Monitored Annual
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WWC5 wells
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G_DOM
G_IND
G_IRR
G_MUN
G_STK
a

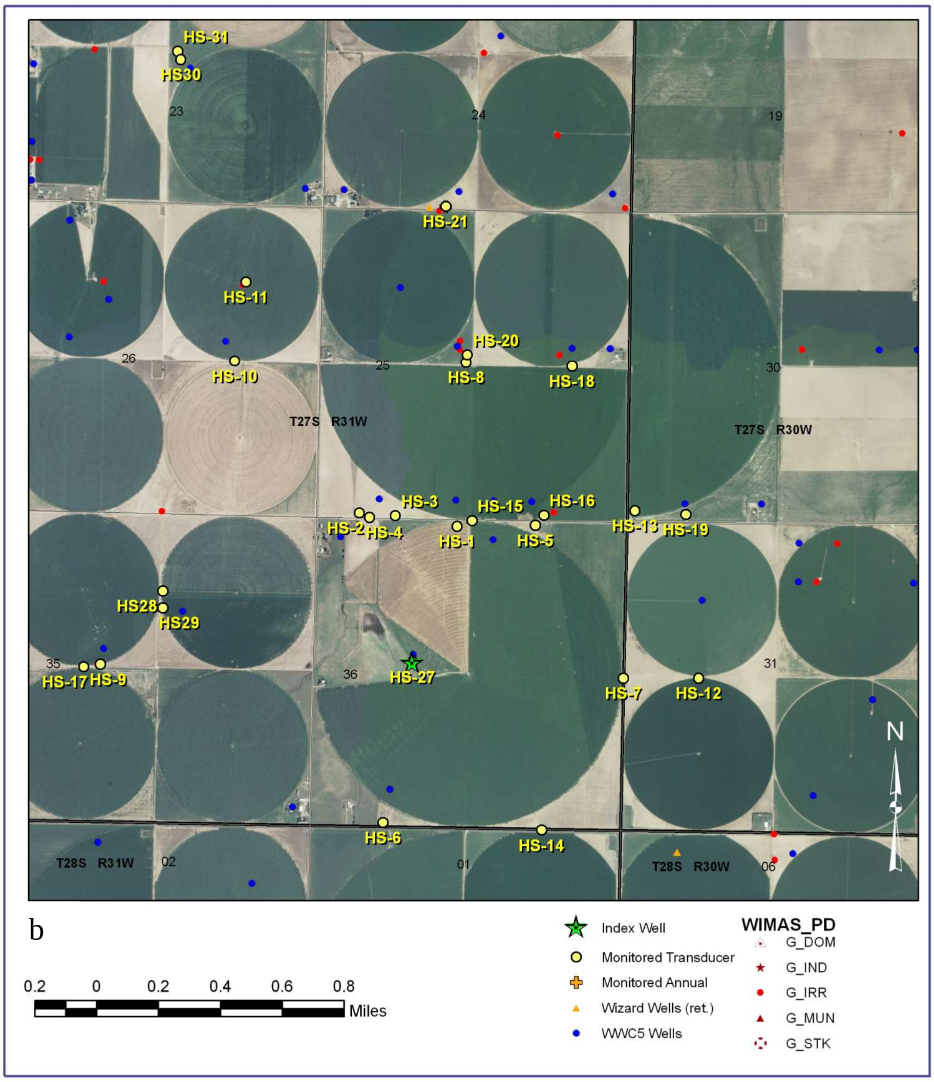


Figure 2-5: (a) Haskell County site, showing the index well, adjacent monitoring wells, and water rights. (b) Area of concentrated KDA-DWR studies. Most of the marked wells are equipped with transducers; see text for discussion and Appendix B for hydrograph traces.

Table 2.1: Characteristics of the index well sites.

Site	2009 WL elev. (ft)[a]	2009 Saturated thickness (ft)	Bedrock depth (estimated ft below lsf)	Screened interval (ft below lsf)	2008 Water Use (AF)		
					1-mi circle	2-mi circle	5-mi circle
Haskell	2580.4	175.4	433	420-430	1825	9932	54612
Scott	2834.2	90.2	223	215-225	933	4059	16767
Thomas	2973.2	70.2	284	274-284	879	2686	13541

[a] from Table 3.1

The original experimental design envisioned use of the index wells to anchor and calibrate the tape 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. The findings discussed below led to the realization that more extensive calibration was necessary to develop a suitable measurement protocol. Two experimental pathways are being pursued to achieve this.

The Haskell site, with numerous other wells instrumented by KDA-DWR (see section 4 and Appendices A.1.1 and A.4), provides one opportunity for more extensive comparisons over a relatively short distance. These comparisons are being pursued, and initial results are presented in this report. 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 as a single phreatic aquifer.

In order to complement the local site comparisons at the Haskell site, the Thomas County site study area has been expanded. With the collaboration of KDA-DWR and GMD4, five additional wells (two of which are annual program wells) have been equipped with transducers, and a sixth has been identified and will be equipped when weather and personnel availability permit.

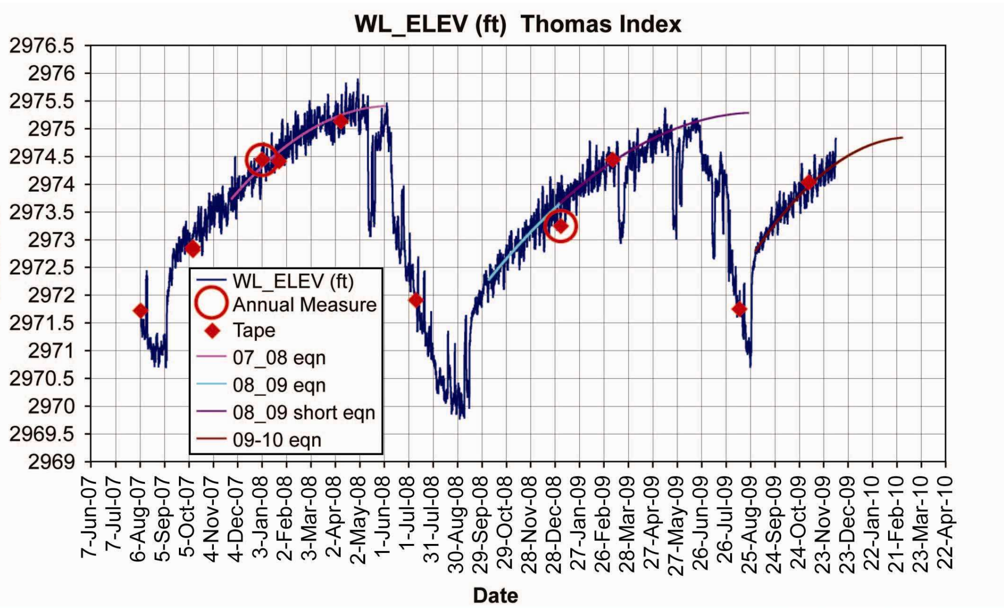
3. Accuracy and precision of water-level determination

One major goal of the project is to use the results of the continuously monitored wells to assess the accuracy and precision of tape water-level measurements, such as those collected in the annual water-level program. This has largely been achieved in terms of diagnosis. Additional work, however, is needed to continue to refine understanding and, especially, to develop techniques to reduce problems with records based on tape measurements and to increase confidence in the conclusions based on transducer records.

Buddemeier et al. (2002) documented three major sources of inaccuracy in tape measurements in addition to the inherent uncertainty in the actual measurement: incomplete recovery, barometric effects, and interference from nearby pumping wells. All three are readily observed in a transducer record. This section of the report documents these effects, explains their nature and magnitude, and presents summary comments on mitigation or correction and needed further work. In the discussions that follow, we take an uncertainty of one tenth of a foot (0.1 ft) as both the measurement precision achievable by a careful and experienced operator using a steel tape, and the accuracy and precision desired to evaluate management strategies. At 15% specific yield, a change of 0.1 ft represents about 10 AF per sq. mi. This is 3-4% of the annual pumping volume in the vicinity of the Scott and Thomas sites (Table 2.1), so determinations of water-level change based on measurements with this accuracy and precision have the potential to detect changes in the amount of water pumped on the order of 10% in a single year, and smaller changes over the course of a few years.

Figure 3-1 shows the complete hydrographs for the three index wells. Since the Haskell well has a much larger range of water-level variation than the others due to its confined aquifer response characteristics, an additional plot is included to show the upper parts of the Haskell hydrograph at a scale somewhat similar to those used in the Scott and Thomas hydrographs. In addition to the hourly transducer records, these plots show the tape measurements made at each well (red diamonds), with the annual program tape measurements circled. Smooth curves overlain on and extending past the recovering portion of the hydrograph show the current best estimate of extrapolation to the approximate equilibrium (fully recovered) water level. Hydrographs for the other (KDA-DWR) wells at the Haskell site are presented in Appendic A.4.

a



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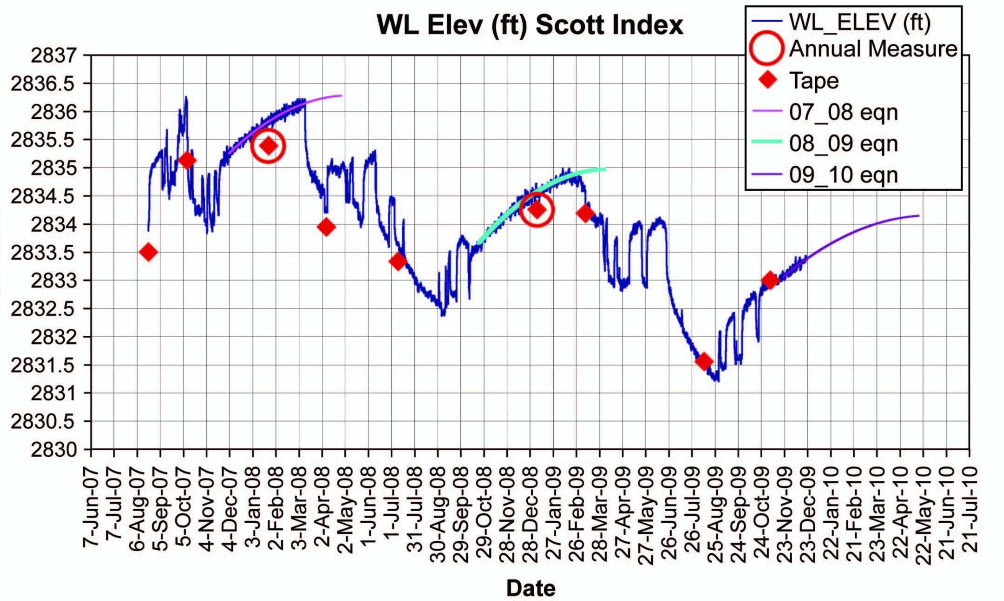


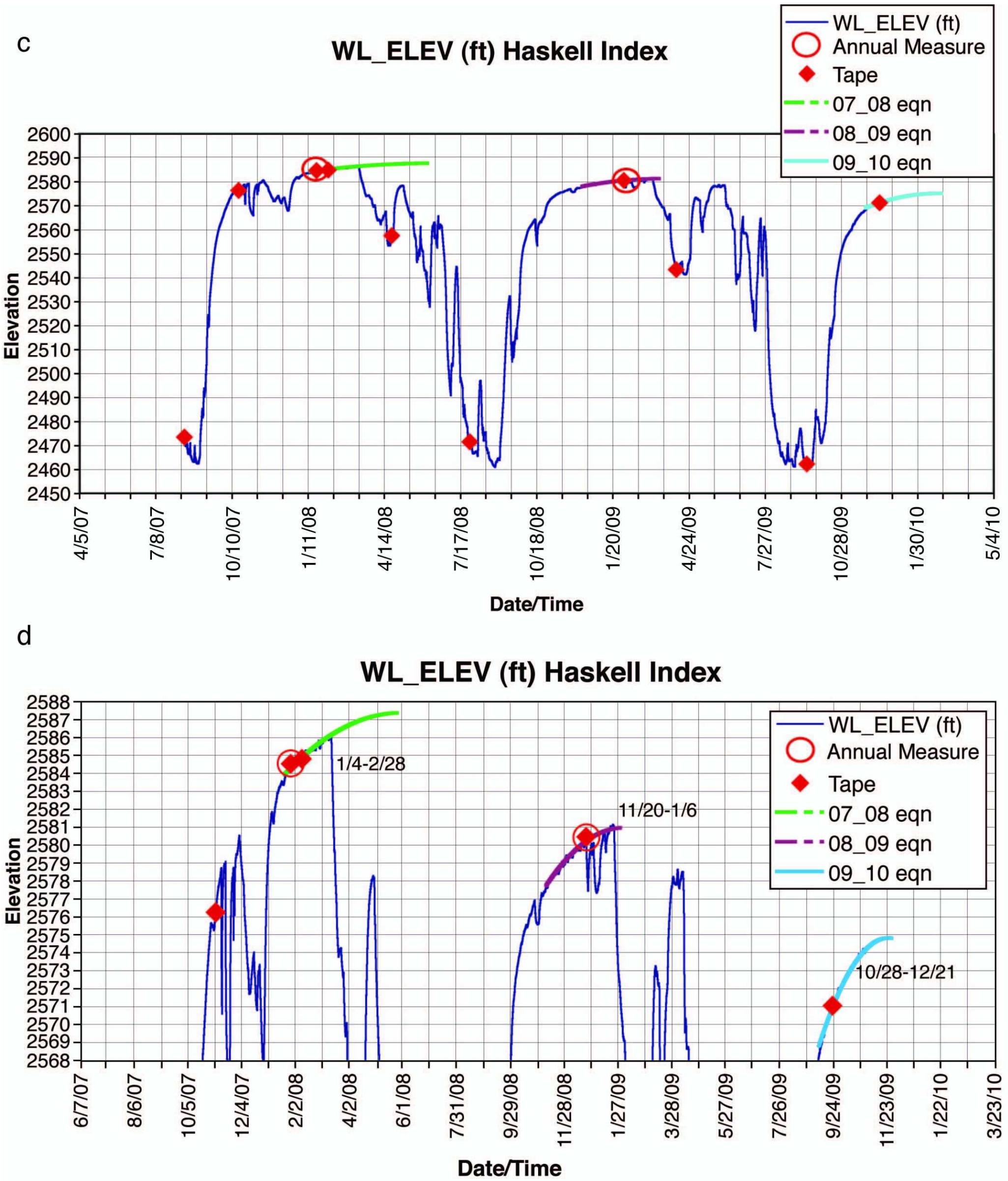


Figure 3-1: Index well hydrographs. In all cases the blue lines represent the transducer output converted to water-level (WL), red diamonds are tape measurements, and circled diamonds are annual water-level measurements. Overlays ('eqn') are plots of best-fit quadratic equations used to estimate the time and level of complete recovery. (a) Thomas County – high barometric efficiency, low annual decline ($\leq$ 0.5 ft); (b) Scott County -- intermediate barometric efficiency, higher annual decline (> 1.0 ft); (c) Haskell County full scale --lower barometric efficiency, high annual decline (~5 ft); (d) Expanded view of Haskell County recovery.

3.1 Incomplete recovery

Accurate measurement of change in water level requires that the water level be at equilibrium (full recovery) when measured. Substantial year-to-year variations in the timing and amount of pumping make it impossible to identify a reproducible point in the recovery process other than full recovery. “Full recovery” on a local level means that the water level is essentially stable for periods of several weeks to months. At a time scale of years, there may still be equilibration between different regions of the aquifer, but this will be slow and can be ignored for the purposes of assessment at the scale of townships.

Figure 3-1 shows that all of the hydrograph curves were still rising not only when the annual tape measurement was taken, but also as much as a few months later when the next season’s pumping began. In order to determine the full recovery level, it is desirable to extrapolate the water-level trend to an elevation estimated to be within 0.1 ft of equilibrium. To accomplish this, we must be able to identify the central trend through the “noise” of barometric responses, which is substantial in Thomas County, and moderate to low in Scott and Haskell counties, respectively.

Barometric responses and corrections are discussed in detail in section 3.3; for the purposes of this section, we simply note that it is possible to correct the transducer record to remove most of the barometric-induced fluctuations in water levels.

Barometric correction, although desirable, is not essential to the extrapolation if a long enough record undisturbed by pumping is available. Initial results suggest that at least a month, and preferably longer, is needed to be able to make the assumption that the barometric variations essentially average out. After experimenting with various approaches, we currently use an empirical approach based on fitting the recovery curve with a second-order polynomial (quadratic) equation. The results of this approach are the overlain lines in the curves in Figure 3-1; they show the length of the curve fitted and the duration and final elevation of the extrapolation to approximate equilibrium. For the 2008-2009 Thomas County recovery, two different extrapolations were tested, one over the 4.5 months preceding the onset of the next season’s pumping and another over the final 3 months of the recovery period. The two extrapolations agreed well on the final elevation (within 0.04 ft), and were within 2.5 weeks in terms of the predicted recovery date.

It is easy to see that the extrapolated endpoints are at very different elevations from the annual measurements or the highest average observed recovery, and that they occur at very different times of year in different two years and wells. Table 3.1 summarizes the comparison between the extrapolated estimates and the annual program measurements.

Table 3.1: Comparison of annual water-level change determined by annual tape measurement and by transducer extrapolation.

	Haskell		Scott		Thomas	
	Annual Tape	Index extrap	Annual Tape	Index extrap	Annual Tape	Index extrap
2008	2584.50	2587.30	2835.29	2836.27	2974.430	2975.40
2009	2580.43	2580.89	2834.23	2834.95	2973.235	2975.28
08-09 Δ	-4.07	-6.41	-1.06	-1.23	-1.19	-0.12
2010		*2574.75*		*2834.14*		*2974.83*
09-10 Δ		*-6.14*		*-0.81*		*-0.45*

Although we cannot yet put an exact value on the confidence limits of the extrapolated determinations, they are undoubtedly much more accurate and representative than the annual tape measurements. Table 3.1 shows that the annual tape measurements in 2008 and 2009 underestimate the groundwater decline between the two years at the Haskell site by >2 ft, overestimate the decline at the Thomas site by >1 ft, and are in good agreement at the Scott site. These differences, which are more than a factor of ten greater than the target uncertainty of 0.1 ft at two of the wells, clearly show that incomplete recovery is a major factor in water-level determinations, and must be accounted for to approach the accuracy and precision needed for enhanced management.

In Appendix B, we discuss our work on various methods to estimate the equilibrium water level and the results of a field comparison of those methods at the Larned Research Site (Pawnee County) where water levels recover to equilibrium each year; that work is ongoing. Calculations of the equilibrium water levels at the index well sites that are tabulated in Appendix B (Table B.3-1) differ from those in Table 3.1, typically by a few tenths of a foot. The two sets of extrapolations were deliberately done independently by different analysts to test reproducibility and 'operator effects' in our present approach. We consider the agreement encouraging, but are seeking to improve it further.

Steps that can be taken to improve the quality of tape water-level measurements are discussed in section 3.4, and additional information on extrapolation-based recovery curves may be found in Appendix B.

3.2 Pumping Interference

Water-level drawdown caused by pumping also occurs in the wells used for water-level measurement that are adjacent to the pumping well. The magnitude of the effect depends on the rate and duration of the pumping, the distance between the wells, and the local aquifer characteristics. The annual program measurements are taken in winter under the assumption that there will be no irrigation pumping at that time.

Buddemeier et al. (2002) calculated that approximately 25% of the area within the High Plains GMDs is within the zone of influence of a well with a non-irrigation water right (industrial, municipal, stock, or domestic). Non-irrigation wells are more likely to be pumped year-round, and therefore to affect the quality and consistency of winter measurements. In addition, it is commonly observed that irrigation wells may be pumped during the winter for maintenance and testing, or for pre-irrigation (soil-moisture build-up).

The hydrographs in Figure 3-1 show the various types of pumping effects. The large trough from spring to fall represents the irrigation season in which many wells with high pumping rates are operating. The abrupt upward and downward spikes within the trough represent nearby wells turning off and on during the irrigation season. However, there are also spikes in the hydrographs outside of the irrigation season that can be attributed to pumping. For example, in the Thomas well record, the downward spikes in late March and late May 2009 are clearly brief periods of pumping-induced drawdown before the start of the general irrigation season. However, it is less certain that hydrograph spikes at other times represent pumping interference. These non-irrigation season spikes can, however, impact extrapolations to full recovery. For example, the 2009 Thomas well extrapolation curve, fitted to a period up to mid-January, shows a reasonably good fit with the data until the March spike occurs; thereafter, the extrapolated line is significantly above the data-defined curve. Such disturbances result in an offset in the recovery curve. A "new" curve (i.e. curve after the March spike) may be used for the extrapolated determination of equilibrium if a long enough record is available, but errors are likely if the "new" and "old" sections are treated as a single data set.

Another factor of importance is the variability of pumping interference effects between years. For example, at the Haskell site in 2007 there was significant pumping until mid- to late December, and pumping resumed in late February 2008. Pumping essentially ended around mid-October in 2008 (although there may have been some limited pumping in November) and resumed by mid-February 2009. However, there was apparently no pumping after mid-September in 2009. These differences not only call into question any generalizations about the non-pumping period, but also make it difficult to extrapolate from similar time periods or recovery stages in different years.

A possible approach to estimating the periods of irrigation pumping during a year is to use an indicator of climate for sub-regions or subunits around water-level measurement wells. Examples of climatic indicators are the Palmer drought index, the crop moisture index, and the Eagleman aridity index. The first two indices are routinely calculated and maps displaying the indices are generated by the National Weather Service. However, these climatic indices are determined for climatic divisions, of which there are nine in Kansas. The area of a climatic division is much too large to be of use in estimating climatic characteristics for a subunit around a measurement well. Although the first two drought indices could be calculated for smaller areas, the amount of sub-regional data needed would be substantial. The Eagleman aridity index (AI) (Eagleman, 1971, 1976) can be computed for a subunit area given temperature, precipitation, and relative humidity, assuming some soil moisture characteristics for the area. The AI has been shown to have a statistically significant correlation with local variations in ground-water salinity for selected aquifers for which recharge is an important factor in diluting mineral intrusion (Whittemore et al., 1989). The use of the AI as a climatic indicator for estimating the start and end of the irrigation pumping season, as well as characterizing possible changes in the intensity of pumping periods during the irrigation season will be examined for applicability to characterizing pumping interference effects. Section 4.4 further discusses the role of precipitation and/or the water balance in causing or characterizing variability in pumping.

If high-frequency water-level and barometric-pressure measurements are available, the water-level record can be tested for interference effects by examining the correlation between barometric-pressure and water-level data. Intervals of low correlation could be attributable to pumping interferences. Also, possible effects on extrapolated equilibrium water-level estimates can be assessed empirically by comparing results obtained using different record lengths or data segments in the extrapolation procedure.

3.3 Barometric effects

3.3.1 Magnitude and temporal-spatial distribution

The factors causing changes in atmospheric pressure are widely understood, but the magnitude of those changes and their effects on water levels in wells are not as commonly understood. The average atmospheric pressure, compared to a vacuum, is equivalent to that of the pressure exerted by a column of water about 30 ft high. Thus, a few percent change in atmospheric pressure is equivalent to a change of a foot or more in the height of the water column.

Figure 3-2a shows the patterns of variation in atmospheric pressure measured by transducers, placed just below land surface inside the well casings, at the three index well sites, expressed in units of feet of water. The pressure patterns are very similar, but the values are offset because one of the major factors controlling atmospheric pressure is elevation. If corrected for elevation or expressed as deviations from a mean value, pressure changes across western Kansas generally match up within a few hours and a few hundredths of a foot of water as shown in Figure 3-2b (Scott County pressure record lags the Thomas County record slightly [< 1 hr] while the Haskell County pressure record lags the Thomas County record by 3-4 hrs). The similarity between the plots on Figure 3-2b indicates that a sparse network of barometers (one per county to one per several counties) across the High Plains aquifer should, when combined with elevation data, provide a reasonable estimate of barometric pressure at any particular well. As will be discussed later, this has very significant ramifications for assessing the impact of barometric pressure on annual water-level measurements. Note that during this one-month period, atmospheric pressure changed as rapidly as a foot of water in little more than 24 hours and the maximum pressure range was close to 1.4 ft of water.

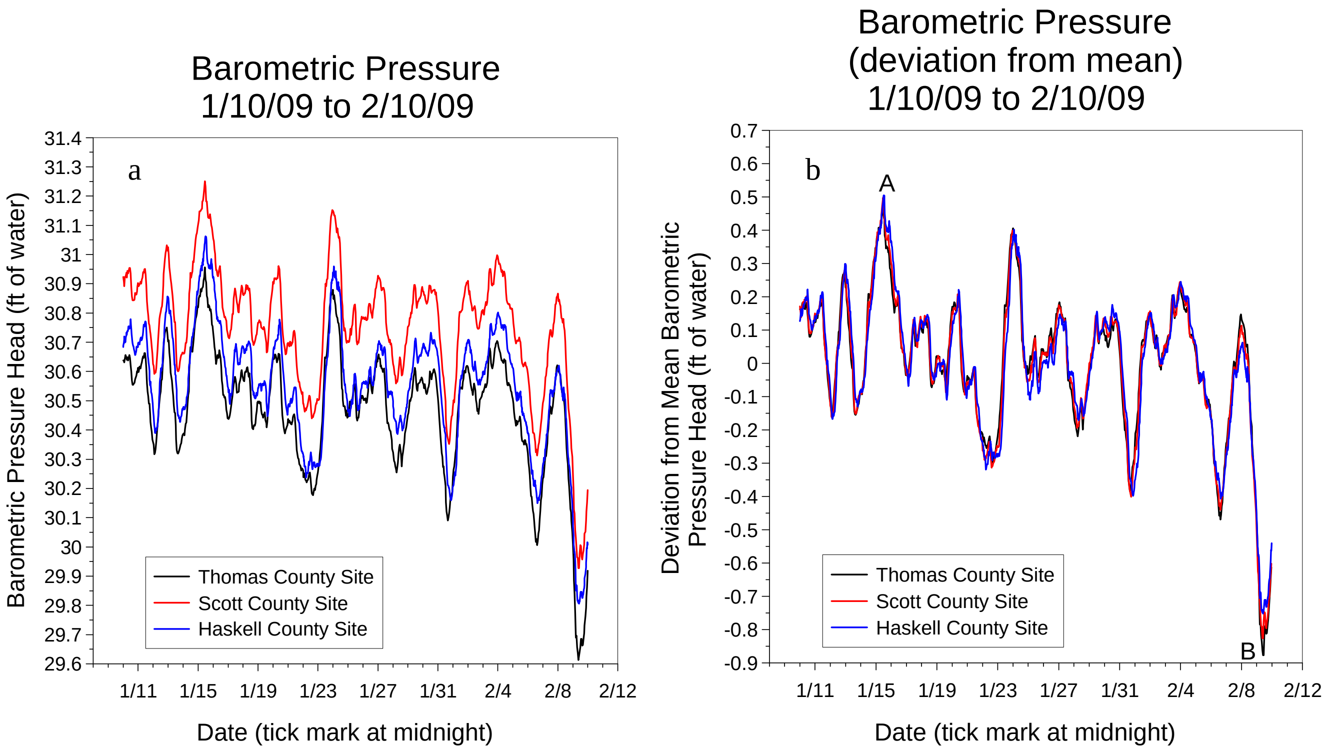


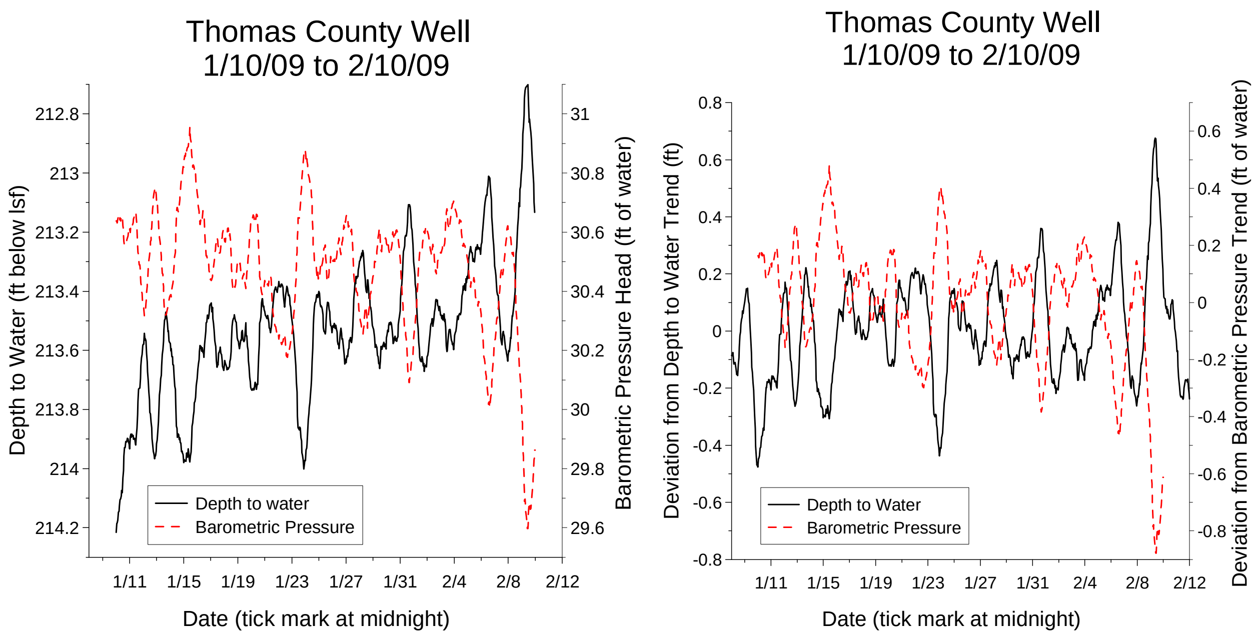
Figure 3.2 – a) Barometric pressure versus time at the three index wells for mid-winter 2009; b) Barometric pressure at the three index wells, expressed as a deviation from the mean pressure at each site, for mid-winter 2009. A and B indicate time of highest and lowest barometric pressure, respectively, in this data record.

3.3.2 Well responses

Changes in barometric pressure can produce changes in water levels in wells. Figure 3-3a shows the relationship between barometric pressure and depth to water at the Thomas County well. Figure 3-3b, which is a plot of detrended depth to water (long-term trend mathematically removed, average of the deviation from the trend is zero) and the deviation from the mean barometric pressure for this period, more clearly depicts the commonly observed inverse relationship between depth to water and barometric pressure. Rising atmospheric pressure forces water levels down, while water levels rise when pressure falls.

The magnitude of the water-level change produced by a certain change in barometric pressure is heavily dependent on site conditions. At the Thomas County well, the magnitude of the water-level change is approximately 96% of the magnitude of the barometric-pressure change. The magnitude of the water-level change is approximately 40% of the barometric-pressure change at the Scott County well, while approximately 30% at the Haskell well. These percentages mean that atmospheric pressure fluctuations can potentially impose water-level changes that significantly exceed our target level of about 0.1 ft. For example, assume that the water level is being measured for the annual measurement program in a well with the characteristics of the Thomas County well. In the first year, the January annual water-level measurement is taken when the barometric pressure is at point B on Figure 3-2b, whereas the next year the annual January measurement is taken when the barometric pressure is at point A on Figure 3-2b. In that scenario, even if the water level had not actually changed between years, there would be an apparent 1.39 ft decline because of atmospheric pressure fluctuations. Clearly, the possible impact of barometric pressure fluctuations must be considered in the interpretation of the annual water-level measurements. Fortunately, we have found that that can be done with a sparse network of barometers coupled with an understanding of the range of water-level responses that can be produced by barometric pressure fluctuations.

Although barometric fluctuations are easily measured and water levels can be corrected for the effects, the process is not simple, for reasons evident in Figure 3-3 and explained below. There is generally a lag (of variable duration) between the peak in barometric pressure and the corresponding water-level peak, and although the major features of the patterns are similar, there is a good deal of distortion in detail. This is because of the complexity of the pathways by which the barometric pressure signal is transmitted to the groundwater.



a) *b)*

Figure 3.3 – a) Depth to water and barometric pressure plot for mid-winter 2009 at the Thomas County index well. Note that the water level continued to recover over this period; b) Detrended depth to water and barometric pressure plot.

3.3.3 Explanation for well responses

Barometric pressure changes induce water-level changes in wells because they set up a pressure gradient between the well and the formation that causes water to flow between the two. Barometric pressure changes are imposed directly on the top of the water column in a well, causing an immediate pressure change in the water in the screened interval of that well. However, barometric pressures changes are not imposed directly on the water in the pores of the formation. Those changes impact pore water pressures via two mechanisms: surface loading and the downward transmission of air pressure through the vadose zone. The surface loading effect is analogous to placing a heavy load on the roof of a building – that load is immediately transmitted through the framework of the building. In the case of the High Plains aquifer, that framework consists of unconsolidated sediments. If that framework bears the entire load, there is no change in pore water pressures and, therefore, a large pressure difference between the water in the well (on which the full change is imposed) and the pore water, producing water flow between the two and a relatively large change in water level in the well. If the framework is somewhat compressible, such as would be expected in an unconsolidated formation, the surface load is shared between the framework and the pore water, i.e. the pore water is pressurized to bear part of the load. This sharing of the load results in a smaller pressure difference between the well and the formation and smaller changes in well water level. This mechanism is causing the modest barometric response in the Haskell County well.

The surface loading effect is primarily seen in confined aquifers, such as the lower aquifer zone at the Haskell site, because the water table serves as a “relief valve” for the pore waters in an unconfined aquifer. In an unconfined aquifer, the primary mechanism is the downward transmission of the air pressure change to the water table. If the water table is deep, considerable time may be required for the air pressure change to propagate to it. In that case, the initial response in the well is similar to that of the framework taking the entire load in a confined aquifer, i.e. the pore water pressures do not change. This mechanism causes the large barometric response in the Thomas County well. Eventually, the air pressure change, or a significant component of it, reaches the water table and pressurizes the pore waters. In shallower water tables, the downward transmission occurs more rapidly, so the response is more modest, as at the Scott County well. In the case of a water table very close to the surface, the wells will often not exhibit a barometric-pressure-induced fluctuation because the barometric change is imposed on the well and the water table at essentially the same time (very rapid transmission through the thin vadose zone). Thus, a range of water-level responses can be expected depending on the nature of the hydrogeologic setting and the well construction. Some settings of relevance to the High Plains aquifer are illustrated in Figure 3-4.

The response of a well to a change in barometric pressure can reveal important additional information about the hydrogeologic setting. In the following section, we describe our approach for analyzing this relationship to glean further insights about the index wells.

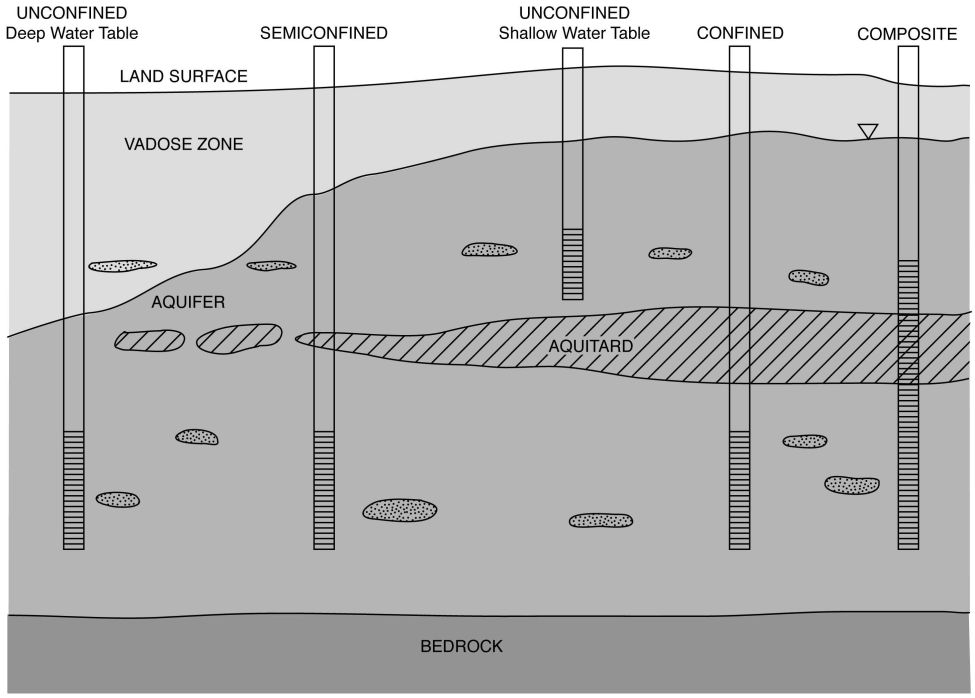


Figure 3-4 – Schematic of well settings relevant to barometric responses. The positions of the well screens and the water table, relative to the surface, and the nature and thickness of the various geologic strata, control the speed and efficiency with which atmospheric pressure changes are transmitted to the water table.

3.3.4 Barometric efficiency functions and the index wells

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 0 and 1 (Jacob, 1940). A BE value near 1 indicates that the pore water within the formation has been virtually unaffected by the barometric pressure changes, while a value near 0 indicates the pore water pressure changes in a manner very similar to barometric pressure. Although the barometric efficiency 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 and gaining important information about site conditions (Rasmussen and Crawford, 1997; Spane, 2002). As explained in the Year Two Report, the BRF, which can be determined through a regression deconvolution procedure (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 annual water-level measurements as described previously. Given the relationship between the BRF and BE, we have renamed the barometric response function as the barometric efficiency function (BEF) for the purposes of this report. Progress was made this year in refining methods for using the BEFs to correct water-level measurements (See Appendix C). In the following paragraphs, we describe the BEFs determined for each index well.

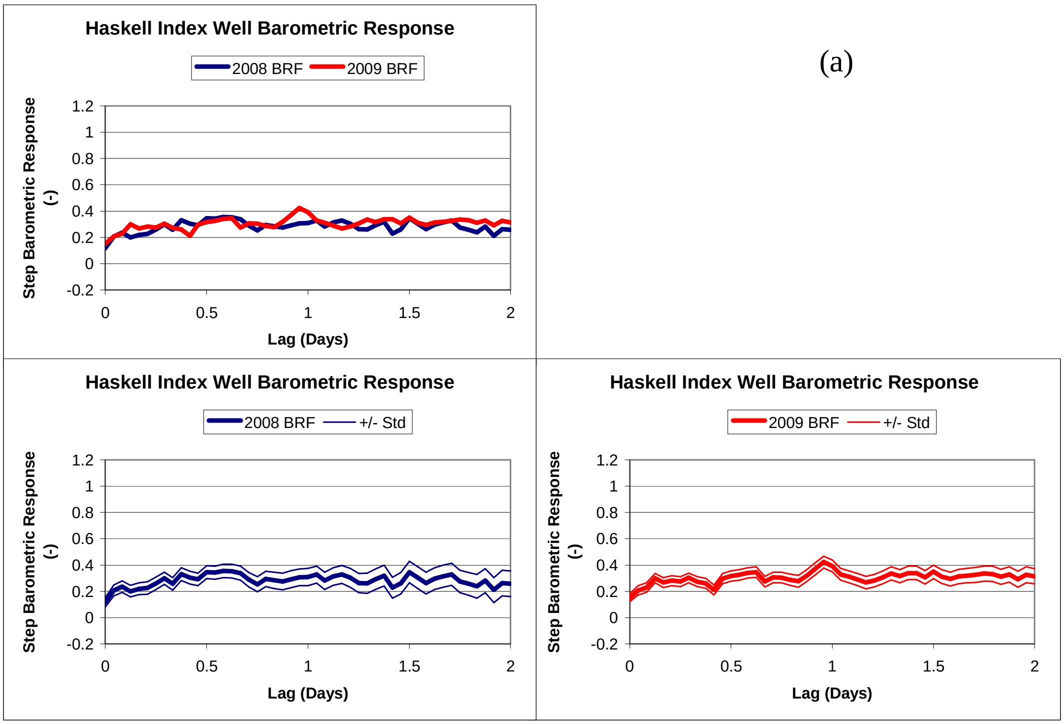
An analysis of the relationship between water levels and fluctuations in barometric pressure was carried out for the winter period of 2008-2009, which, for the purposes of the analysis, was defined as 1/4/2009-3/9/2009 for the Thomas County well, 1/6/2009-2/16/2009 for the Scott County well, and 11/25/2008-1/6/2009 for the Haskell County well. These specific intervals were chosen for the analysis because no pumping appears to have occurred in the vicinity of the wells and the recovery trends were approximately linear during these intervals. As explained in the Year Two Report, linear recovery trends enable the well records to be "detrended" in a straightforward manner and facilitate the analysis of the relationship between water levels and fluctuations in barometric pressure. The results of a similar analysis were presented in the Year Two Report for these same wells using one month of data from the 2007-2008 winter period. For each well, the plots of the 2007-2008 and 2008-2009 barometric efficiency versus lag time (time since change in barometric pressure) are essentially the same (Figure 3-5). However, the longer periods (two to three months) used for the 2008-2009 analysis resulted in improved estimates of the barometric response, as evidenced by the much reduced widths of the error bars for the 2008-2009 analysis plots.

As discussed in the Year Two Report, the barometric response functions for the three wells differ in multiple ways, reflecting the differences in the aquifer characteristics and responses at the three sites. A brief summary of these differences is presented here.

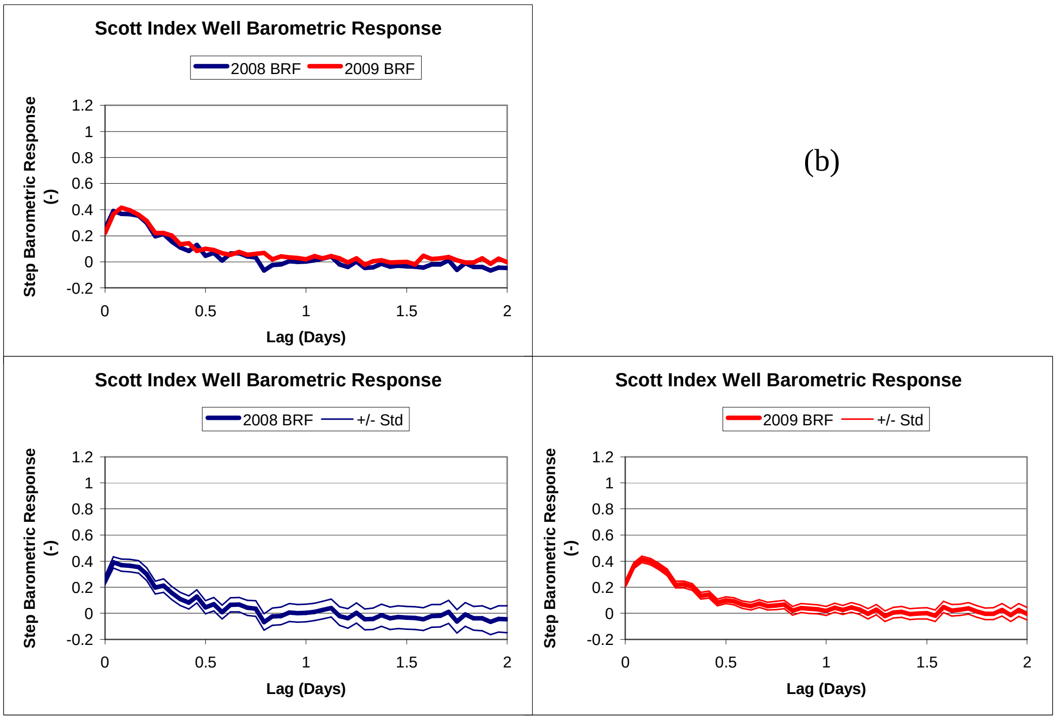
The Haskell County well barometric response function (Figure 3-5a) rises up to a value near 0.3 and then is essentially level through the two-day lag period. This response is consistent with a semi-confined aquifer overlain by an aquitard of relatively low permeability. As part of work complementary to this project, the KGS has developed an approach for estimating aquitard permeability from barometric response functions in semi-confined aquifers (Butler et al., in review).

The Scott County well barometric response function (Figure 3-5b) rapidly rises up to a value of 0.4 and then falls back to zero. This response is consistent with a phreatic (unconfined) aquifer with an overlying vadose zone that acts to slow somewhat the downward transmission of the barometric pressure change. Thus, it takes close to two-thirds of a day for the full extent of the imposed barometric pressure change to reach the water table.

The Thomas County well barometric response function (Figure 3-5c) rapidly rises up to a value of over 0.9 and then diminishes. This response is consistent with an unconfined aquifer overlain by a thick vadose zone that acts to significantly slow the downward transmission of the barometric pressure change. In this case, it takes over five days for the full extent of the imposed barometric pressure change to reach the water table. The January 2008 depths to water for the Scott and Thomas counties wells were approximately 132 ft and 213 ft, respectively (Year Two Report). The greater depth to water for the Thomas County well is undoubtedly one of the primary reasons for the longer period that is required for the full extent of the barometric pressure change to reach the water table at that well, as discussed in the previous section.



(a)



(b)

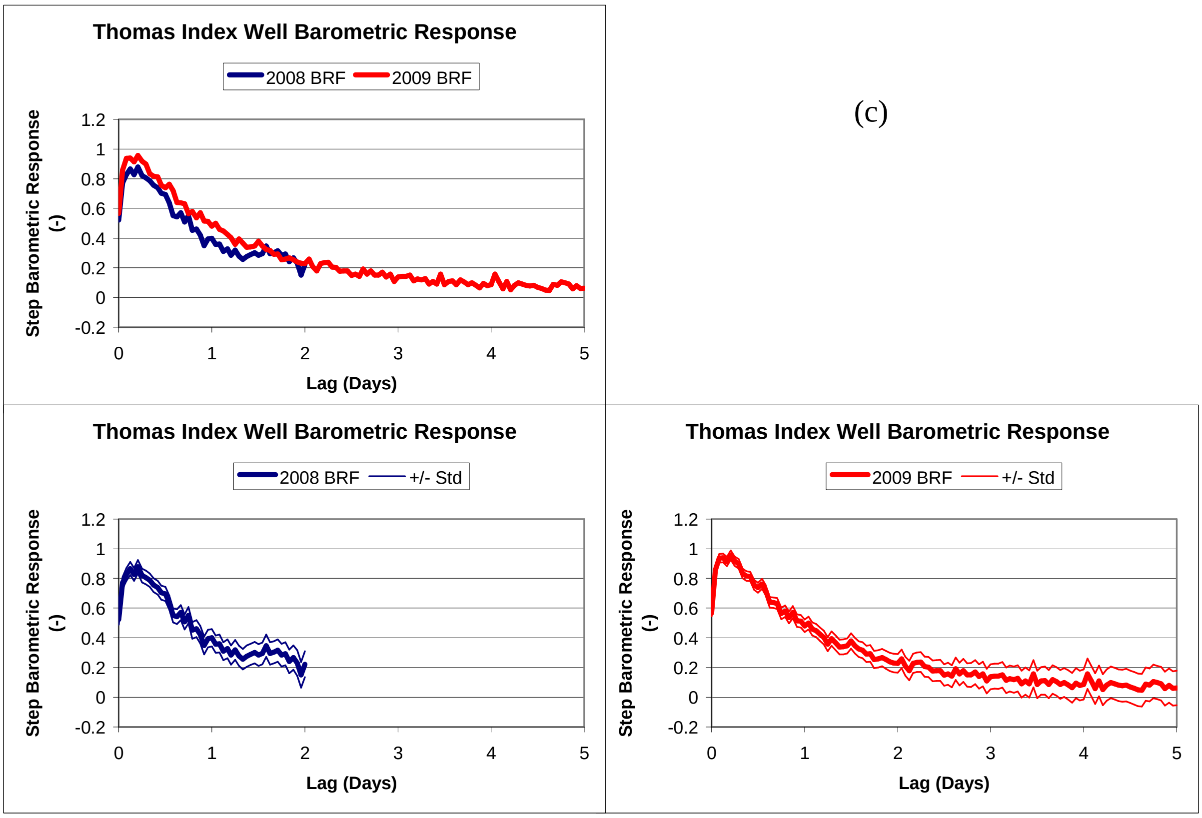
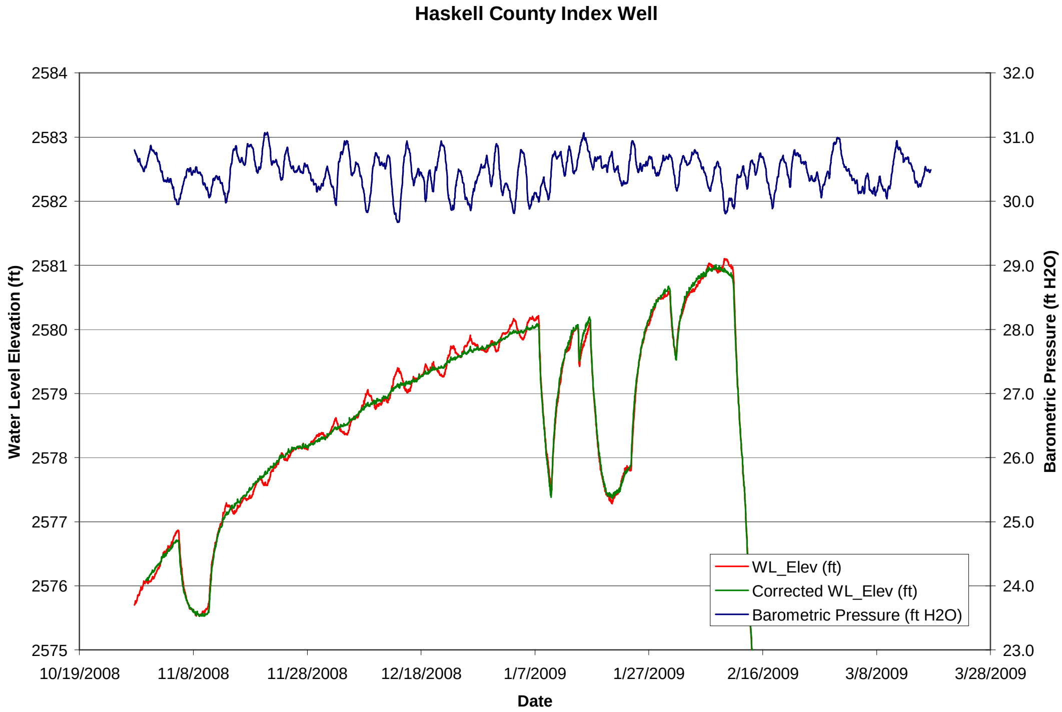


Figure 3-5. Barometric responses of the three index wells. The upper left plot displays the two barometric efficiency functions calculated for the winter 2008 and 2009 analysis periods. The lower two plots display the individual winter 2008 and 2009 functions with the calculated error bars. BEF plots for the other transducer-equipped wells at the Haskell site are shown in Appendix A.4.

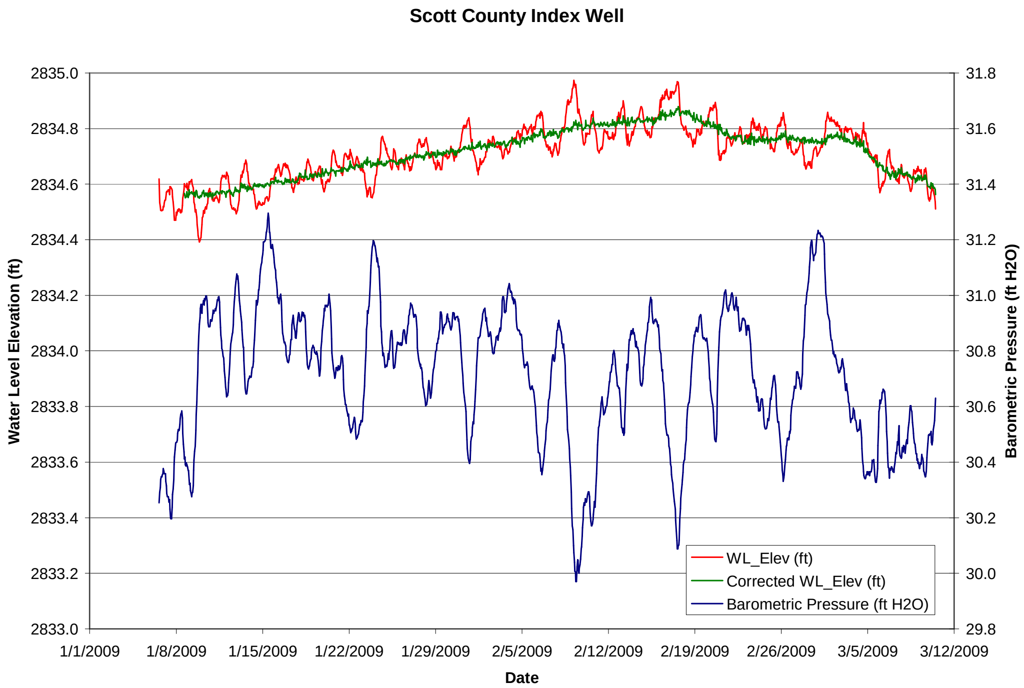
3.3.5 Water-level correction

As shown earlier, barometric pressure fluctuations can introduce “noise” into the water-level measurement, which can potentially lead to misinterpretations of the actual yearly change in water levels. As shown in the Year Two Report, that noise can be largely removed by correcting the water-level observations using the estimated barometric efficiency functions. Figure 3.6 illustrates the reduction of barometric noise in water-level signals that can be achieved through this correction using modifications to the correction procedure developed in year three and described in Appendix C



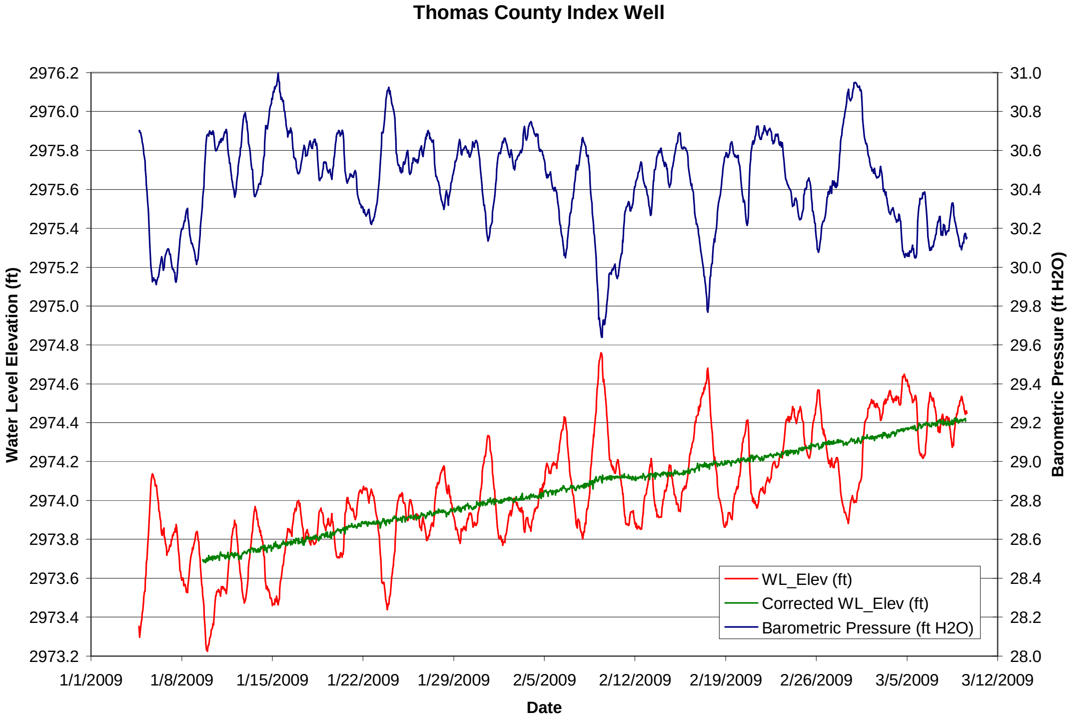
Haskell County Index Well
Water Level Elevation (ft)
Barometric Pressure (ft H2O)
2584
2583
2582
2581
2580
2579
2578
2577
2576
2575
32.0
31.0
30.0
29.0
28.0
27.0
26.0
25.0
24.0
23.0
10/19/2008
11/8/2008
11/28/2008
12/18/2008
1/7/2009
1/27/2009
2/16/2009
3/8/2009
3/28/2009
Date
WL_Elev (ft)
Corrected WL_Elev (ft)
Barometric Pressure (ft H2O)

(a)



Scott County Index Well
Water Level Elevation (ft)
Barometric Pressure (ft H2O)
2835.0
2834.8
2834.6
2834.4
2834.2
2834.0
2833.8
2833.6
2833.4
2833.2
2833.0
31.8
31.6
31.4
31.2
31.0
30.8
30.6
30.4
30.2
30.0
29.8
1/1/2009
1/8/2009
1/15/2009
1/22/2009
1/29/2009
2/5/2009
2/12/2009
2/19/2009
2/26/2009
3/5/2009
3/12/2009
Date
WL_Elev (ft)
Corrected WL_Elev (ft)
Barometric Pressure (ft H2O)

(b)



(c)

Figure 3-6. Water-level corrections for barometric effects on the three index wells: (a) Haskell County; (b) Scott County; (c) Thomas County. The correction is applied once the time since the start of the data record exceeds the maximum lag time for the barometric efficiency function for that well (two days for the Haskell County and Scott County wells, and five days for the Thomas County well).

3.4 Measurement of water levels and changes: Summary and interim conclusions

The preceding parts of this section have shown, using the index well hydrographs and their comparison with tape water-level measurements, that each of the individual measurement perturbations is capable of introducing errors ranging from a substantial fraction of a foot to several feet in the determination of water levels and year-to-year changes. The three sources of error – incomplete water-level recovery, nearby pumping, and atmospheric pressure variations – are completely independent, and therefore must be controlled, corrected, or compensated for individually.

Tape water-level measurements, unsupported by other data or types of measurements, cannot be expected to approach the accuracy or precision in measurements (~ ± 0.1 ft or at least a very few tenths of a foot) of changes in equilibrium water-levels needed to evaluate the effectiveness of special management approaches on time scales of one to a few years. However, this does not mean that tape measurements cannot be useful as part of a monitoring system that also addresses the issues raised here.

The evidence to date indicates that transducer water-level determinations made several times per day have the potential to provide the needed accuracy and precision, if the appropriate corrections (e.g., barometric) and extrapolations (e.g., full recovery elevation) can be made.

- The fully equilibrated elevation value of the recovered water table can be estimated from a transducer (or other quasi-continuous water-level) record that includes periods of a month or more unaffected by recent nearby pumping. The presently used means of extrapolating the recovery curve yields encouraging results, and efforts to develop still better approaches are in progress. In addition, it may be possible to identify sites where pumping-induced drawdown is minimal and the water table remains close to a local equilibrium value (e.g, see hydrographs for wells HS 8, 10, 13, 14, and 20 in Appendix A).
- Atmospheric pressure fluctuations can be removed from the record using the hydrograph and the corresponding barometric pressure record, provided both have adequate temporal resolution (ideally 1-3 hours). The BEF of a given well is unlikely to change rapidly, so once it has been carefully determined using transducers, the result can be applied to corrections of, for example, tape-based measurements. Barometric pressure variations are sufficiently consistent on a regional (e.g., county-scale) basis that a relatively few stations can serve the needs for barometer records over a large area.
- Transient pumping disturbances can be identified from transducer water-level measurements, from simple methods of logging times of well operation (e.g., pipe temperature records), or by information sharing among local operators and managers.

These issues are discussed further in the following section, in the context of applying calibration well monitoring technology to areas such as aquifer subunits.

4. Application of calibration measurements to an extended area

<u>4.1 Introduction</u>

Anticipating that the calibration (or index) well approach will be useful for some kinds of enhanced monitoring and/or management, this section addresses the basic question of how to move from an index well water-level record to acceptably accurate inferences about aquifer behavior over a larger area. As with the water-level measurement itself, some aspects of answers to this critical question are still under investigation.

4.2 Basic principles

When a volume of water is pumped from an aquifer, the water table is lowered in response. A change in pumping should therefore be directly related to a change in water level. However, a number of factors that can influence changes in water level must be considered, so there are challenges to be overcome in interpreting water-level changes in addition to those of making an accurate measurement.

First, the change in water level reflects the net change in volume (ΔV):

$$\Delta V = \text{pumping} + \text{outflow} - \text{inflow} - \text{recharge},$$

where outflow and inflow refer to groundwater movement out of and into the area, respectively. Although pumping is usually the largest term in the equation, interpreting changes in water level requires some knowledge or assumptions about the other factors.

Second, aquifer characteristics, specifically the transmissivity (layer permeability multiplied by layer thickness) and the specific yield (the fraction of the aquifer volume that consists of drainable pore space), influence each component of the above equation. These characteristics vary both horizontally and vertically. Figure 4-1 shows interpretations of drillers' logs for the areas around the three index wells, with the descriptions of the cuttings grouped into five classes, ranked in order of magnitude of permeability (light colors high, dark low). These figures can be used to illustrate the concept underlying the Practical Saturated Thickness Plus (PST+) Project, which is directed at providing an estimate of the thickness of the aquifer intervals that readily yield water to a pumping well. Note that the PST+ results can also be used to provide estimates of specific yield of the material in the vicinity of the water table.

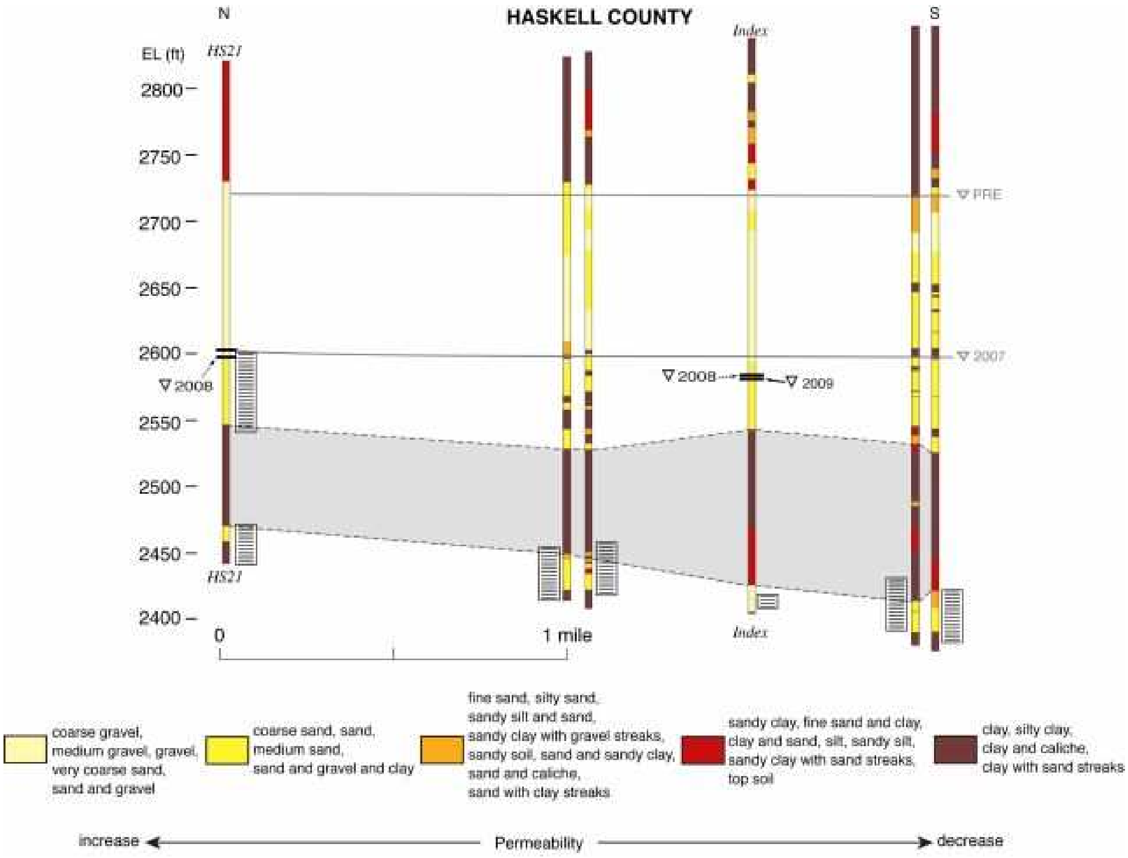
4.3 Lithologic effects

If P_1 is the permeability of the most permeable layer of aquifer material (light yellow in Figure 4-1) determined from the lithology in the driller's log, P_2 is the permeability of the next most permeable layer, and so on down to P_5, the least permeable (dark brown) layer, we can construct an estimate of the effective transmissivity of the aquifer by summing the transmissivities (permeability times thickness) of each layer. We can then create an estimate of the equivalent thickness of high transmissivity material by dividing the effective transmissivity by the estimated permeability (hydraulic conductivity) of the most permeable layer. That equivalent thickness has been termed the practical saturated thickness (PST) in previous work. That terminology will be used here although the practical transmissive thickness would perhaps be a more accurate characterization. Table 4.1 compares the measured saturated thickness (ST) and estimated PST values for the three index wells.

Table 4.1 Index well saturated thickness and practical saturated thickness.

Site	2009 ST (ft)	Estimated PST (ft)	Notes
Haskell	175.4	63	Lower permeable unit confined by $\geq$ 50 ft of continuous clay layer
Scott	90.2	54.8	Thick layer of low-K material near surface but has no impact on PST estimate because present water table much deeper
Thomas	70.2	49.9	Numerous thin layers; nothing apparently laterally or vertically continuous

The transmissivity of the aquifer will have a strong influence on the rates of drawdown and recovery; whereas the specific yield of the sediments in the vicinity of the water table can have a strong influence on the water-level decline per volume of extracted water. Thus, the detailed water-level responses shown in Figure 3-1 will be, in part, determined by where the water table is with respect to the different types of strata illustrated in Figure 4-1.



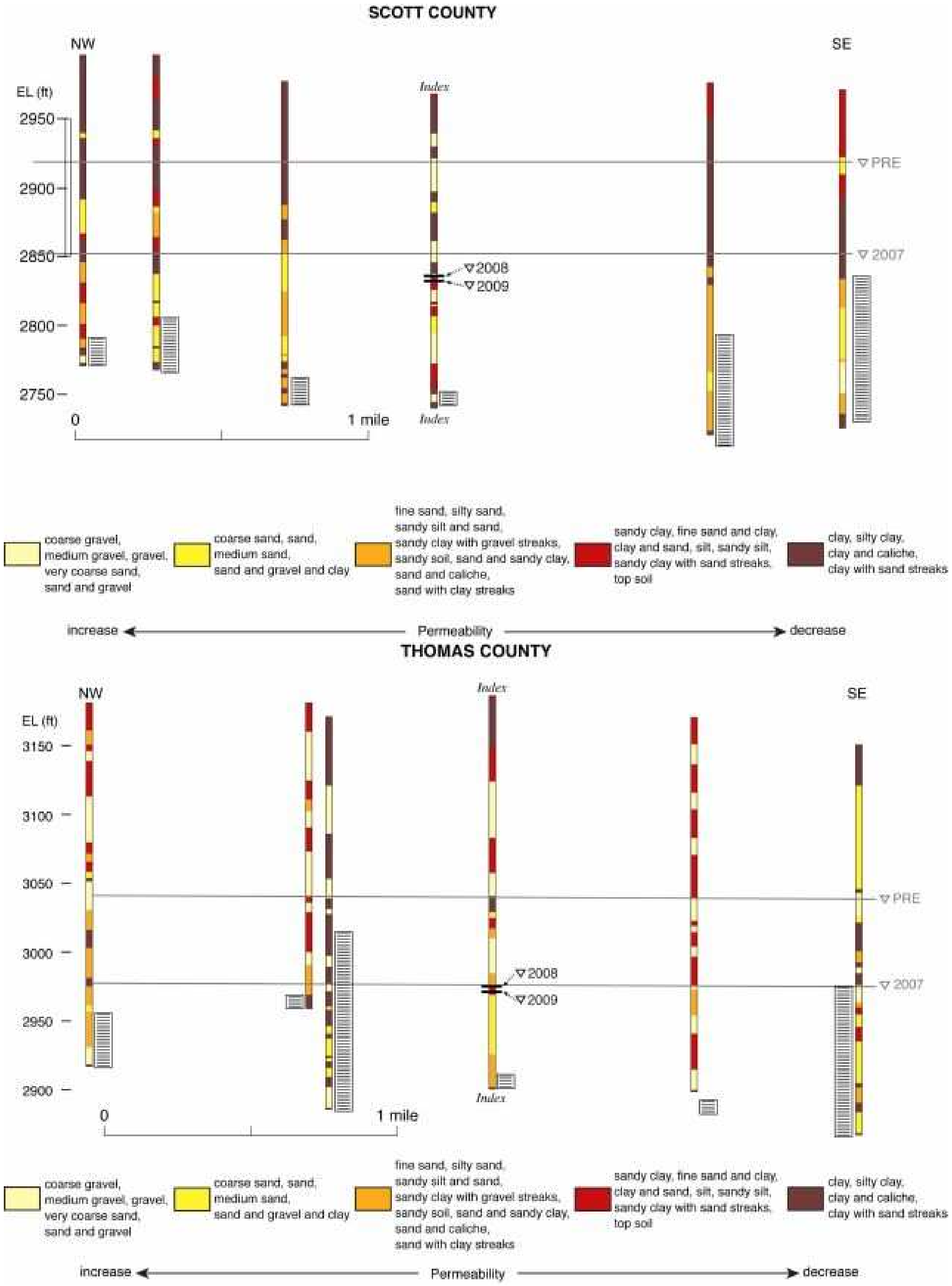


Figure 4.1: Aquifer lithology based on drillers' logs for the (a) Haskell, (b) Scott, and (c) Thomas county sites. Patterns show the general similarities within sites at the scale of the transects, and the differences between sites.

4.4 Hydrologic similarity

For one or a few detailed water-level records to be useful in describing and predicting the behavior of an area with dimensions of many miles, the area needs to be reasonably homogeneous. The logs illustrated in Figure 4-1 suggest that the three index well sites are generally hydrogeologically similar over distances of one to a few miles. In most areas of the state with significant pumping, usually enough WWC5 records exist on file to at least screen for major discontinuities. However, direct comparison of responses to pumping and/or precipitation are even more relevant, since the water-level response to groundwater extraction is typically what is being measured and managed.

Appendix A.3 contains tables of total reported use summed within concentric circles (1, 2, 3, 4, 5 mile radius) around each index well. These results show that the ratios of AF pumped in the successive circles at a given site are generally very close to the ratio of the geometric areas of the circles. This suggests that out to at least a 4-mile radius circle (8 mile diameter, or greater than a township area) the use density or stress on the aquifer is relatively even across that area.

The Haskell County site, with a large number of wells being concurrently monitored by KDA-DWR, provides a good location for a preliminary evaluation of subunit characterization approaches. We have at least one year (2008) for which we have both water use reports and transducer-based water-level changes for most of the wells, and for some of the DWR wells, reasonable estimates to the 2007 water-level decline can also be made. These data can be used to make well-to-well comparisons within an area. This analysis, which requires generating recovery level estimates for the available wells in each year, is summarized by the results for maximum seasonal drawdown, water-level elevation at equilibrium, and annual decline given in Table 4-2, and shows encouraging consistency in terms of responses and estimated water-level declines.

Figure 4-2 shows estimated local water-table contours at the Haskell site, superimposed on regional water-level contours generated from the annual well network. Figure 4-3 shows regional water-table contours at a larger scale and the elevation of the bedrock surface. The three years shown in Figure 4-2 (2007, 4-2a; 2008, 4-2b; 2009: 4.2c) exhibit consistent general trends, but high spatial and temporal variability. Since this is presumably the result of dealing with two different, poorly-interconnected aquifer units subject to pumping stresses that vary in time and space, we have estimated contours by drawing 5 ft elevation contours that contain as many of the wells with values inside that interval as possible, and within which all of the outlier elevation values are lower than the interval values.

This procedure produces reasonable and consistently varying contours (Figure 4-2); significantly, all of the outliers (lower water-table elevations) are wells identified as “deep” – that is, penetrating the lower aquifer unit. The local contours show elevations at least 5 ft lower than the regional contours; because the local values are at estimated full recovery and the annual program measurements are probably not, the actual difference may be even greater. The amount by which the outlier wells are below their contour interval varies from about 3 ft in 2007 to almost 10 ft in 2008. We suspect this is the result of differential pumping in the two aquifers, and delayed re-equilibration, through well bores and casings, as well as the low-permeability confining layer. However, at this point we cannot rule out the possibility of a systematic head difference of up to a few feet between the two aquifers.

It is also noteworthy that the local head gradient seems to differ from that of the regional water table, with a stronger southward component. We think this is at least partly due to the local effects of the steep southwestward slope of the bedrock surface in this area. These deviations in both elevation and gradient from the predictions of the annual monitoring program further indicate the importance of accurate, dedicated monitoring at the subunit scale.

Table 4.2: Seasonal drawdown, water-level elevations, and water-level changes at and near the Haskell site.

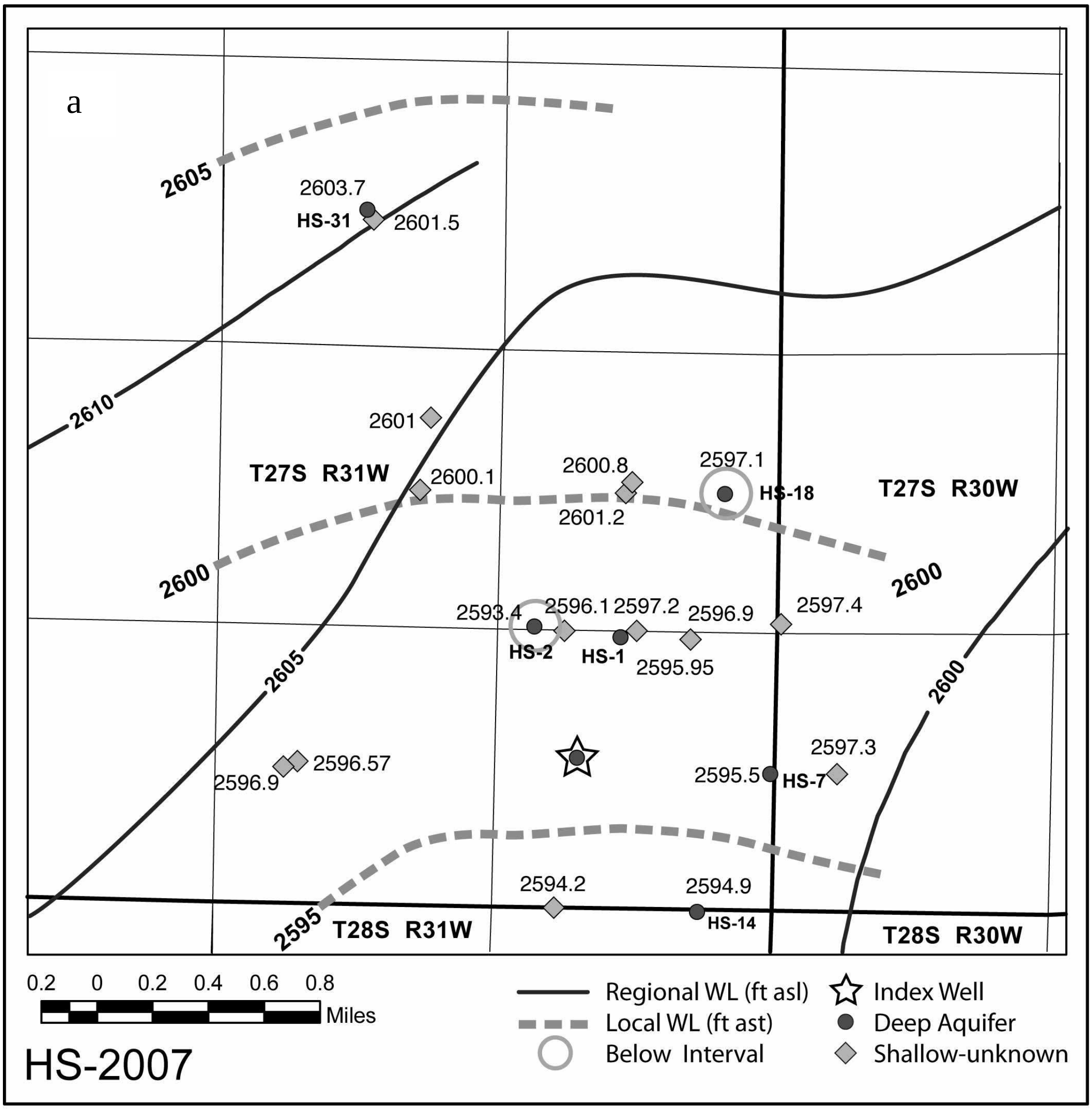
Well # HS-	**Well Type**	**Deep/ Shallow**	**Meas[a]**	**Draw-down, ft**	**WL Elev (ft)[b]**	**WL elev (ft)**	**WL elev (ft)**	**Δ (ft) 07-08[b]**	**Δ(ft) 08-09**
					2007	**2008**	**2009**		
1	Irrig.	D	X-x	>115	2595.95	2589.92	2584.64	-6.03	-5.28
2	Irrig.	D	X-x	~25	2593.4	2588.27	2583.82	-5.13	-4.45
3	casing	S	X-p	~5	2596.1	2591.2	2587.2	-4.9	-4
4	obs.	D	X-x	~115		2583.59	2579.84		-3.75
5	obs.	S	X-x	10-13	2596.9	2592.32	2588.67	-4.58	-3.65
6	obs.	S?	X-x	12-14	2594.2	2589.13	2584.67	-5.07	-4.46
7	Irrig.	D	X-x	>60	2595.5	2590.91	2586.51	-4.59	-4.4
8	obs.	S	X-p	7-8	2601.2	2597	2592.9	-4.2	-4.1
9	Irrig.	S?	X-x	20-25	2596.57	2591	2587.15	-5.57	-3.85
10	casing	S	X-p	4-5	2600.1	2595.3	2591	-4.8	-4.3
11	Irrig.	D?	X-p	12-15	2601	2596.5	2592.3	-4.5	-4.2
12	casing	?	X-x	5-6	2597.3	2593		-4.3	
13	casing	S	X-p	3-5	2597.4	2593.1	2590.8	-4.3	-2.3
14	Irrig.	D	X-p	~5	2594.9	2589.7	2586	-5.2	-3.7
15	casing	S	X-x	~7	2597.2	2592.17		-5.03	
16	Irrig.	D							
17	casing	?	X-x	1-7	2596.9	2591.4	2590.56	-5.5	-0.84
18	Irrig.	D	X-x	>100	2597.1	2592.8	2586.67	-4.3	-6.13
19	Irrig.	D							
20	Irrig.	S	X-p	20	2600.8	2596.5	2592.3	-4.3	-4.2
21	Irrig.	*S*	*X-p*	*22*		*2597.5*	*2592.9*		*-4.6*
“	“ “	*S*	*T (Jan)*	*“*		*2597.72*	*2593.15*		*-4.57*
22		*?*	*T (Jan)*		*2604.95*	*2600.35*	*2595.78*	*-4.6*	*-4.57*
23	*Irrig.*	*S?*	*T (Jan)*		*2657.67*	*2656.28*	*-*	*-1.39*	
24		*?*	*T (Jan)*		*2629.79*	*2629.47*	*2624.93*	*-0.32*	*-4.54*
25		*S*	*T (Jan)*		*-*	*-*	*-*		
26		*?*	*T (Jan)*		*2578.86*	*2573.01*	*2565.93*	*-5.85*	*-7.08*
27	*monitor*	*D*	*T (Jan)*	*~120*		*2584.50*	*2580.43*		*-4.07*

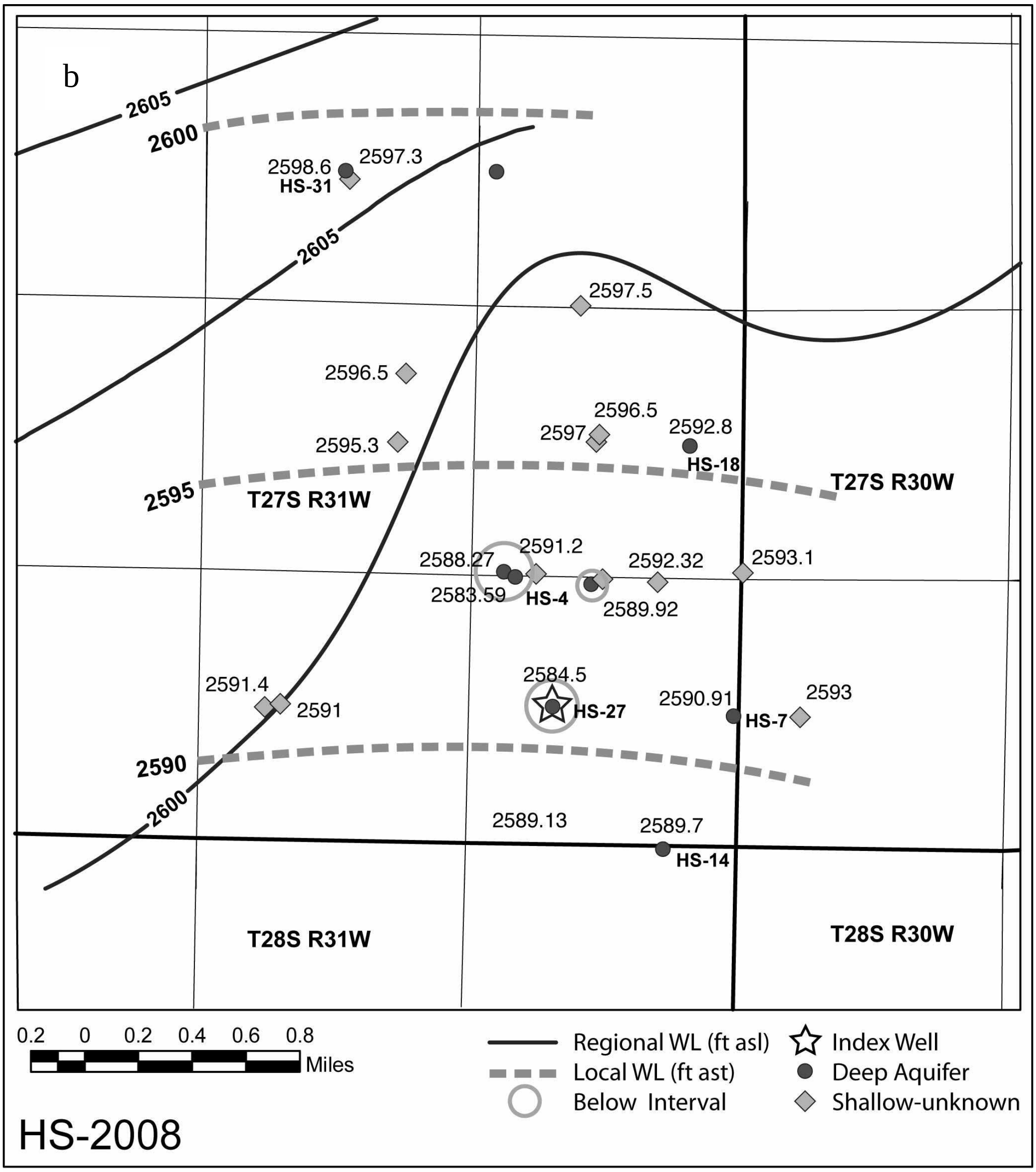
“	*” “*	*D*	*X-x*	*“*		*2587.31*	*2580.91*		*-6.4*
28		?		~2?					
29		(NEW)S	X-p	~55			2583.5		
30		?	X-p	~65	2601.5	2597.3	2593.3	-4.2	-4
31		(NEW)D	X-p	0-5	2603.7	2598.6	2598.6	-5.1	0

a. X = transducer, T = tape, x = extrapolated to recovery; p = picked from trace.
b. 2007 elevations were estimated from the highest recorded early value for those wells with transducer records beginning in May, 2007. These should be treated as minimum estimates; actual recovered elevations could have been higher.

Irrig = a well actually pumped
Casing = a formerly pumped well
Obs = irrigation type well installed by DWR
Monitor = designed monitoring well

☐


a
2605
2603.7
HS-31
2601.5
2610
2601
T27S R31W
2600.1
2600.8
2601.2
2597.1
HS-18
T27S R30W
2600
2600
2593.4
2596.1
2597.2
2596.9
2597.4
HS-2
HS-1
2595.95
2605
2600
2597.3
2596.57
2596.9
2595.5
HS-7
2594.2
2594.9
HS-14
2595
T28S R31W
T28S R30W
0.2 0 0.2 0.4 0.6 0.8
Miles
HS-2007
Regional WL (ft asl)
Local WL (ft ast)
Below Interval
Index Well
Deep Aquifer
Shallow-unknown


b
2605
2600
2598.6
2597.3
HS-31
2605
2597.5
2596.5
2596.5
2597
2592.8
2595.3
HS-18
2595
T27S R31W
T27S R30W
2591.2
2588.27
2592.32
2593.1
2583.59
HS-4
2589.92
2584.5
2591.4
2590.91
2593
2591
HS-27
HS-7
2590
2600
2589.13
2589.7
HS-14
T28S R31W
T28S R30W
0.2 0 0.2 0.4 0.6 0.8
Miles
Regional WL (ft asl)
Local WL (ft ast)
Below Interval
Index Well
Deep Aquifer
Shallow-unknown
HS-2008

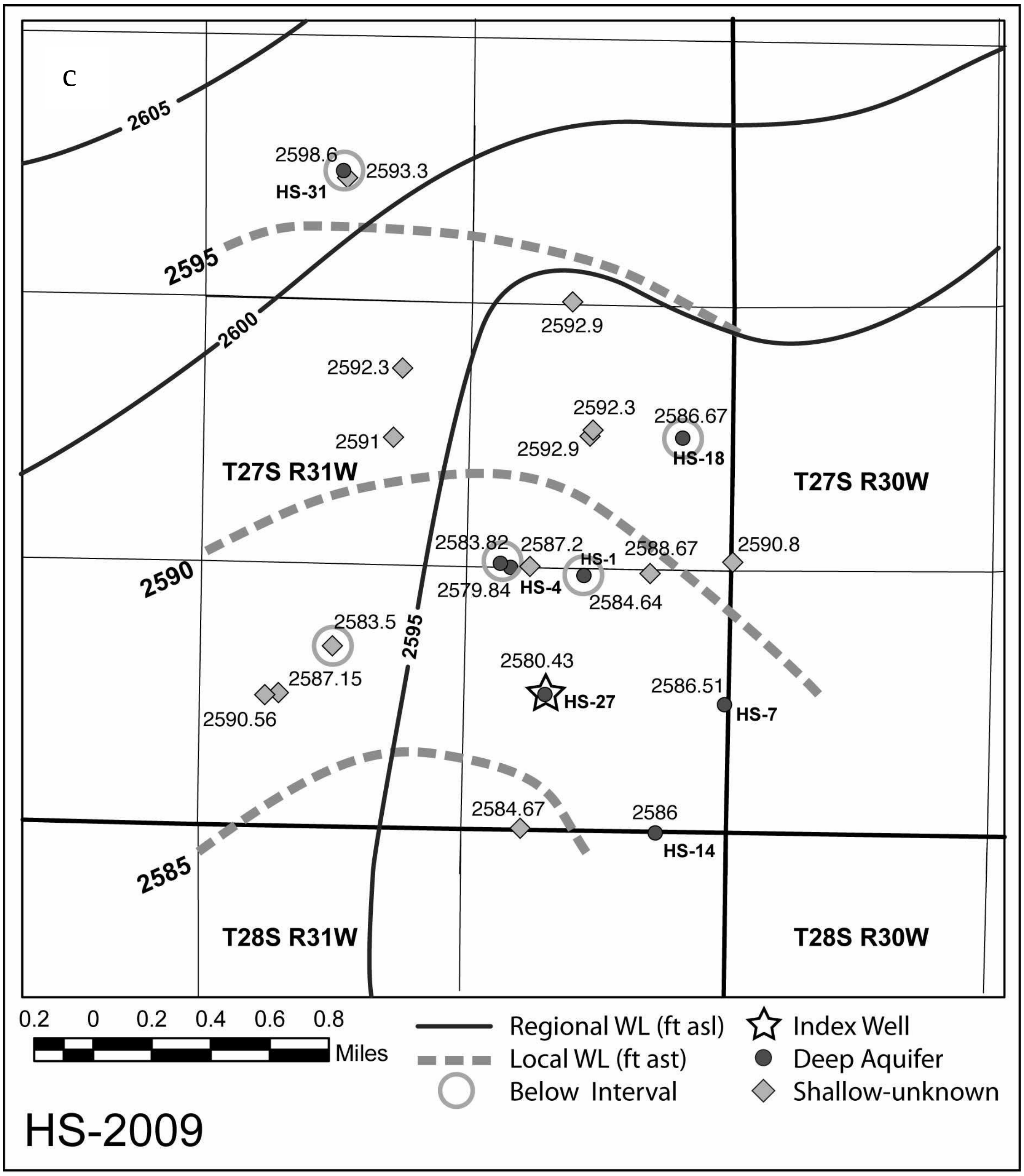


Figure 4-2 Local and regional water-table contours, Haskell Site. (a) 2007 (b) 2008 (c) 2009. See text for explanation of contouring technique and explanation of low elevation outliers. Note that "Local" contours are from estimates of equilibrium water levels while "Regional" contours are from annual program measurements.

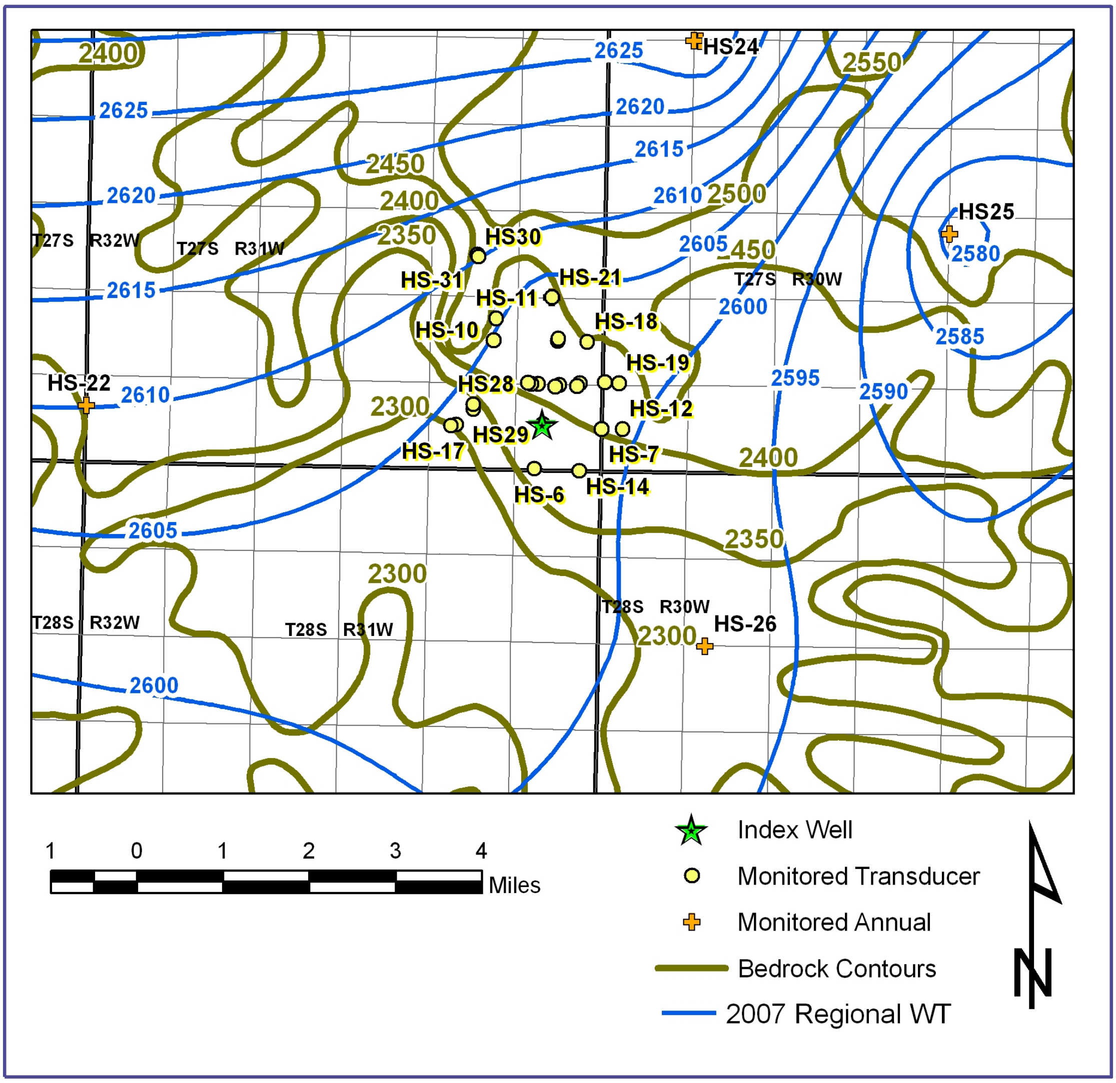


Figure 4-3 Regional bedrock and water-table contours, Haskell Site. Note that the SSE-trending bedrock gradient is generally a good match for the local water-table gradient in Figure 2-2, but agrees less well with the regional water-table gradient.

Table 4-3 compares the relationship between the volume of water pumped from the 2-mile circle around each well and the decline observed in that well. The practical specific yield (PSY) is estimated from the ratio of the water use over the volume of dewatered aquifer within that 2-mi. circle. Typical specific yields for the High Plains aquifer average around 0.15 (15%) with a range from about 0.1 to 0.2 for productive formations. The fact that the calculated PSY values are close to this range suggests that most of the water withdrawn is the result of the local aquifer being dewatered; a much larger value indicates that lateral inflow is making a significant contribution to water-level responses. Note that the comparisons are on an arbitrary scale; use of a 1.8 rather than a 2-mile circle for the water-use calculation would center the distribution of estimated PSY values on the expected range for the High Plains aquifer. Also, care must be used in interpreting the PSY values in their current form because the volume of dewatered aquifer is based solely on the drawdown at the well in question. Thus, if the drawdown at the well is much lower than at the surrounding wells in that 2-mile circle, the PSY calculation will yield a physically implausible value (e.g., HS-17 (2008) and HS-24 (2007) in Table 4.3).

Table 4.3: Water-level decline – water use relationships near the Haskell site.
PSY = Practical (field-estimated) specific yield[a]

Well # HS-	**Well Type**	**Deep/ Shallow**	**Δ (f) 07-08[b]**	**Δ(f) 08-09**	**07 Water Use (AF)**	**08 Water Use (AF)**	**2007 PSY**	**2008 PSY**
1		D	-6.03	-5.28	8756.78	8406.61	0.181	0.198
2		D	-5.13	-4.45	8723.78	8431.61	0.211	0.236
3		S	-4.9	-4	8443.78	8147.61	0.214	0.253
4		D		-3.75				
5		S	-4.58	-3.65				
6			-5.07	-4.46	8397.86	8179.64	0.206	0.228
7			-4.59	-4.4	7378.93	7313.22	0.200	0.207
8		S	-4.2	-4.1	6816.2	7163.61	0.202	0.217
9			-5.57	-3.85	10468.46	10793.43	0.234	0.349
10		S	-4.8	-4.3				
11		D?	-4.5	-4.2	8104.91	7946.61	0.224	0.235
12			-4.3		7380.58	7319.37	0.213	
13		S	-4.3	-2.3	6374.29	6431.4	0.184	0.348
14		D	-5.2	-3.7	8287.79	7822.5	0.198	0.263
15		S	-5.03					
16					7313.85	7466.19		
17			-5.5	-0.84	10462.46	10462.72	0.237	1.549
18			-4.3	-6.13	6998.14	7264.19	0.202	0.147
19								
20		S	-4.3	-4.2				
21	annual	S		-4.6	6423.2	6772.61		
“	“ “	S			6423.2	6772.61		
22	annual		*-4.6*	*-4.57*	6673.11	6539.71	0.180	0.178
23	annual		*-1.39*		1668.94	2049	0.149	
24	annual		*-0.32*	*-4.54*	6066.12	6721.46	2.357	0.184
25	annual							
26	annual		-5.85	-7.08	6072.16	5828.96	0.129	0.102
27	Index	D		*-4.07*				
“	” “	D		-6.4				
28								
29		(NEW)						
30			-4.2	-4				
31		(NEW)	-5.1	0	8130.44	7821.54	0.198	

a. Based on decline at the specific well and water use in a 2-mi circle around the well.
b. 2007 elevations were estimated from the highest recorded early value for those wells with transducer records beginning in May, 2007. These should be treated as minimum estimates; actual recovered elevations could have been higher.

For the PSY estimates in Table 4-2 to be reasonable, accurate water levels are required. Since we have only two to three years of such data, examining similarity over time, as well as space, requires a different approach. For this purpose, we can use the annual program data if we only look at the general trend in water level over a period of 5-10 years. Figure 4-4 illustrates such an approach. The plots show the annual water use within a 2-mile circle around each of the study wells at the Haskell site (Figure 2-5). In both graphs, the bold red line represents the index well and the bold blue line is the average of all the graphed 2-mile circle values. Figure 4-4a also shows the average water-level trend (bold light blue line) as determined by combining the measurements from all of the annual wells shown in Figure 2-5, and Figure 4-4b shows the annual growing season (March-September) precipitation for the county (bold green line).

The individual well water use patterns are generally very similar, with only a few outliers. Furthermore, the average behavior is tracked very closely by conditions at the index well. Although year-to-year variations in usage remain very similar, the overall usage trend is downward over the 20-year period, declining from an average of about 11,000 AF to around 7,500 AF. The usage decline tracks the water-level decline over the first ten years, but since about 2000, the water level has been dropping much more rapidly.

The outliers that fall below the family of curves for the closely spaced wells are instructive: these (HS 23 and a well midway between the index well and HS 23) are wells to the northeast of the cluster of study wells. That is in the direction of rising bedrock elevation and decreasing water availability likely due to a decrease in saturated thickness (see Figure 2-2).

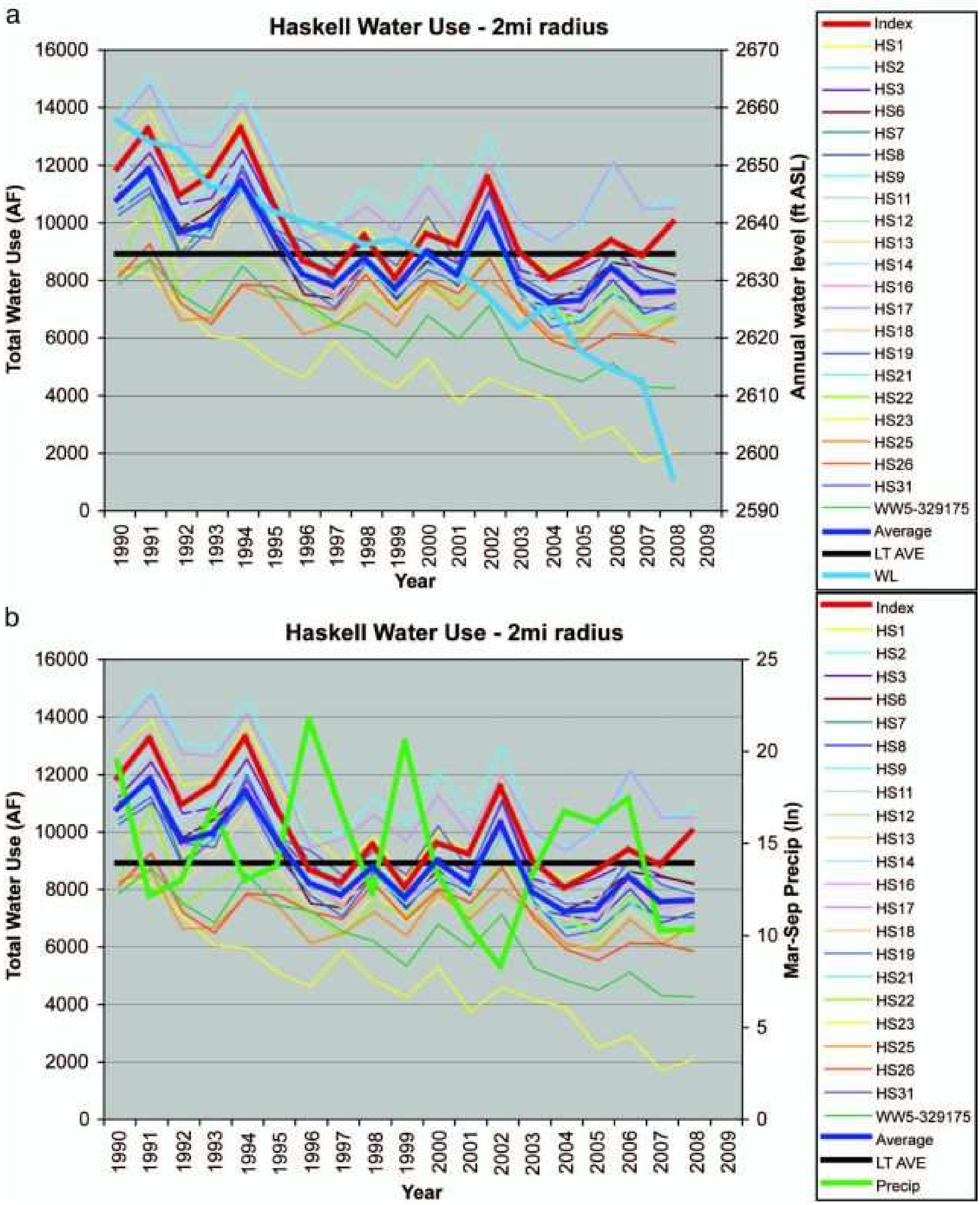


Figure 4.4 Plots of the total water used (AF) within a 2-mi circle around each of the identified Haskell site wells in each year. The bold dark blue line is the average over all values and the bold red line shows the value for the index well. (a) Regional average of

the water-level change, determined from the surrounding annual monitoring wells, is shown by the bold light blue line. (b) The bold green line shows the growing season (Mar-Sep) precipitation for each year.

Figure 4-4 illustrates a probable explanation for much of the pattern of use variation; the high usage years generally correspond to drier times, whereas high rainfall is associated with lower use. This is a reasonable expectation, since the crop's moisture source is the combination of precipitation and irrigation water. As we attempt to analyze smaller-scale effects with higher precision, it will be necessary to develop some criteria for deciding whether or not groundwater recharge is also affecting water levels, in addition to variations in pumping.

4.5 Potential implementation strategies

The index wells yield a wealth of information, but require investment in well construction (the major cost) and instrumentation. The optimum way to gain the benefits of such information in a cost-effective fashion will vary with the nature of the problem being addressed, the local hydrogeology and water use patterns, and local approaches to management and oversight. Two end-member cases can be identified.

- A situation in which stakeholders can agree to use one individual monitoring well as a benchmark for evaluating conditions and programs. In some areas this might be even more economical if a suitable existing "well of opportunity" can be identified instead of drilling a new one. This approach can be expected to work where the hydrogeology can be shown to be consistent over the area of interest, water users are experiencing the same kinds of conditions and problems, and relationships are generally amicable.
- The opposite end of the spectrum might be a network of designed monitoring wells, spaced at 2-4 mile intervals. This would be expensive, probably justifiable only where stakes are high and relations adversarial.

However, a wide range of options exist between the two cases described above. A middle-ground approach might be to install a central index well and acquire several transducer-logger units. These additional units could be rotated around to characterize other supplemental wells of opportunity in terms of their barometric responses and recovery behaviors. Suitable wells could then be incorporated into the local "network" with either carefully made and corrected tape measurements, or longer-term installation of the transducers.

5. Summary, conclusions and plans

In the course of three years, the index well project has installed, equipped, and monitored water levels in three observation wells (in Haskell, Scott, and Thomas counties), and has cooperated with KDA-DWR in monitoring and analysis of numerous others (in Haskell and, more recently, Thomas counties). Observation and analysis have led to several significant conclusions with regard to the measurement and use of water-level elevation changes as components of a groundwater management system. These findings are being developed into tools and protocols to improve the quality and sensitivity of water-level measurements.

The parameter of interest is the estimated elevation of the fully recovered water table. To determine the effects of changes in pumping with reasonable confidence and on a time scale of one to two years, water-level measurements with accuracy and precision of at least a few tenths of a foot (preferably 0.1 ft) are required.

One-time measurements of water level, such as the typical tape measurement for the annual program, are subject to errors from three major sources (in addition to the inherent accuracy and precision of the measurement itself). These are: barometric pressure fluctuations, pumping interferences, and incomplete recovery from the drawdown of the previous pumping season. Barometric pressure can fluctuate around its mean value by a range that is the equivalent >1.0 ft of water, whereas transducer hydrographs show that the other two sources can induce errors of up to several feet. Uncertainties of these magnitudes help explain why the annual water-level program is generally viewed as useful for discerning trends over fairly large spatial (> township) and temporal (at least 5-10 year) scales. In the absence of calibration or corrections based on additional data or knowledge, tape water-level measurements cannot be used to reliably determine management effects on an annual scale. The ultimate potential utility of tape measurements depends on the nature of well responses, water use patterns, and the amount and type of supporting information available in a given area, but are unlikely to be effective for the accurate representation of local conditions.

Techniques for the correction and/or avoidance of these errors have been identified and are being developed into tools (calculational tools, protocols, and design principles) for application to subunit management. The progress that was made in the third year of the program on the correction of errors introduced by barometric pressure fluctuations is particularly noteworthy.

The influence of aquifer lithology and precipitation on water use and water-level responses is under active investigation to provide a comprehensive understanding of water-level variations and responses to pumping.

The multi-well Haskell site is being used to explore issues of similarity, differences, and prediction over a limited local area. Because this site involves both a shallow unconfined aquifer unit and a deep confined unit, observations at the Thomas site (unconfined aquifer only) are being expanded to provide similar information in a more typical High Plains locale.

In summary, major conclusions and findings of the project to date are:

- In addition to withdrawal and recharge of water, well water levels are influenced by barometric pressure, the degree of recovery toward hydrostatic equilibrium, and pumping of other wells in the vicinity. All of these can potentially introduce water-level errors or uncertainties on the order of feet.

- Barometric pressure and incomplete recovery effects can be corrected, and the nature of the effects provides additional information about characteristics of the well and the aquifer.

- One-time tape measurements of water level are particularly vulnerable to errors, and water-table changes based on widely-spaced annual measurements are unlikely to accurately represent local (e.g., subunit) conditions.

- A calibrated budgetary approach involving accurately determined water-table changes, water use, and precipitation or an appropriate water availability index appears to have strong potential for predicting and monitoring the effects of management on groundwater resources.

Major activities and objectives for 2010 will include:

- Refinement of barometric response interpretations and completion of development and dissemination of correction tools and methods.
- Further research on optimizing techniques of extrapolation to fully recovered water-levels.
- Characterization and response analysis at both the Haskell and expanded Thomas sites.
- Evaluation of the potential effects of lithologic variations and precipitation on the relationships between water use and water-level change.
- Initial development of (draft) comprehensive guidelines for monitoring and interpreting water-level change over an enhanced management aquifer subunit.

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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.

2009 Annual Index Well Project report appendices

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- **A.3.1 Comparative data on circles used to evaluate water use**
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Appendix A: Data and Calculations

A.1 Well Characteristics

The following tables contain the assembled information about all of the wells used or expected to be used in the study.

A.1.1 Haskell County: Wells HS1 through HS31, 20 unique data columns

Table A.1.1-1. Well identification data for wells referred to in the Index Well Study, Haskell Co.

SITE_ID	LEGAL	Well Type	USGS_ID	OTHER IDENTIFIER	Water Right	WWC5
HS1	NE NE NW 36 27-31	Irrigation		HS3 new, 8157	8157	385288
HS2	SW SW SW 25 27-31	Irrigation		25275 new	25275 - 00	385642
HS3	SE SW SW 25 27-31	Irrigation (ret?)		25275 old casing	25275 - 00	28165
HS4	SE SW SW 25 27-31	Monitoring		25275 observation we	25275 - 00	390016
HS5	NE NW NE 36 27-31	Monitoring		10467 observation we		389767
HS6	SE SW SW 36 27-31	Monitoring		8157s observation we		389768
HS7	SE SE NE 36 27-31or NE NE SE 36 27-31	Irrigation		11750		320718
HS8	SE SE NW 25 27-31	Monitoring		18715 observation we		395017

SITE_ID	LEGAL	Well Type	USGS_ID	OTHER IDENTIFIER	Water Right	WWC5
HS9	SW SE NW 35 27-31	Irrigation		19542	19542	363947
HS10	SE SW NE 26 27-31	Irrigation (ret?)		1207 old casing	1207	28170
HS11	NE SW NE 26 27-31 or NW SE NE 26 27-31	Irrigation		1207 new		396941
HS12	SE SW NW 31 27-30	Irrigation (ret?)		11750 old casing		
HS13	SE SE SE 25 27-31/SW SW SW 30 27-30	Irrigation (ret?)		10035 old casing		
HS14	SE SW SE 36 27-31	Irrigation (ret?)		8157s old casing		341913
HS15	NE NE NW 36 27-31	Irrigation (ret?)		HS3 old casing, 8157		
HS16	SE SW SE 25 27-31	Irrigation		10467		28168
HS17	SE SW NW 35 27-31			19542 old casing		
HS18	SW SE NE 25 27-31	Irrigation		19032		304615
HS19	SE SW SW 30 27-30	Irrigation		10035		319354
HS20	SE SE NW 25 27-31	Irrigation		18715		28166
HS21	SW SE SW 24 27-31	Irrigation	374044100395001	6281	6281 - 00	28160

SITE_ID	LEGAL	Well Type	USGS_ID	OTHER IDENTIFIER	Water Right	WWC5
HS22	SW SW NW 31 27-31		373929100453601			
HS23	NE NW NW 08 27-30	Irrigation	374319100375801		GY 025	114859
HS24	NW NW NW 08 27-30		374317100375501			
HS25	SW NW NW 23 27-30		374125100344101			
HS26	NE NW NW 17 28-30		373709100374701			
HS27	SW SE NW 36 27-31	Monitoring	373925100395301	Index Well		406332
HS28	NW SW NE 35 27-31			**21985** or 21985 new		
HS29	NW SW NE 35 27-31	Irrigation		21985 or **21985 new**		416154
HS30	NW NW SE 23 27-31			cas16212		
HS31	NW NW SE 23 27-31	Irrigation		16212		302391

Table A.1.1-2. Well construction data for wells referred to in the Index Well Study, Haskell Co. Elevations, depths, and screened intervals are in ft.

SITE_ID	SURF ELEV	EOH DEPTH	EOH ELEV	WELL DEPTH	ELEV DEPTH	SCREENED INTERVAL	ELEVATION SCREENED INTERVAL	Gravel Pack	Casing Dia.	BH Dia.
HS1	2854.24	435	2419.24	428	2426.24	398-418, 418-428	2456-2426	20-428'	16"	
HS2	2823.98	420	2403.98	410	2413.98	370-390, 390-410	2454-2414	20-410		
HS3	2838.76	340	2498.76	284	2554.76	145-284'	2694-2555	10-284'	16"	28"
HS4	2827.57	420	2407.57	420	2407.57	380-400,400-420	2448-2408	20-420		
HS5	2853.43	420	2433.43	420	2433.43	240-280'	2613-2573	20-420'	2"	
HS6	2846.74	465	2381.74	465	2381.74	425-445, 445-465	2422-2382	20-465		
HS7	2845.99	435	2410.99	430	2415.99	411-531'	2435-2315	20-411'	16"	
HS8	2828.66	320	2508.66	305	2523.66	240-300'	2589-2529	20-305'	2"	
HS9	2847.17	405	2442.17	398	2449.17	318-338, 358-378, 378-398	2529-2509, 2489-2449	20-398'	16"	
HS10	2822.94	300	2522.94	255	2567.94	195-255'	2628-2568		16"	26"
HS11	2817.54	425	2392.54	420	2397.54	250-420'	2568-2398	20-420'	16"	
HS12	2848.75			?						

SITE_ID	SURF ELEV	EOH DEPTH	EOH ELEV	WELL DEPTH	ELEV DEPTH	SCREENED INTERVAL	ELEVATION SCREENED INTERVAL	Gravel Pack	Casing Dia.	BH Dia.
HS13	2848.74			?						
HS14	2845.63	461	2384.63	455	2390.63	415-435', 435-455'	2431-2391	20-455'	16"	
HS15	2855.85			?						
HS16	2854.25	506	2348.25	411	2443.25	256-306', 326-336', 371-411'	2598-2548, 2528-2518, 2483-2443	20-414'	16"	24"
HS17	2847.45			?						
HS18	2835.12	390	2445.12	390	2445.12	235-390'	2600-2445	20-390'	16"	30"
HS19	2843.22	660	2183.22	540	2303.22	305-325, 347-417, 472-482, 497-537'	2538-2518, 2496-2426, 2371-2361, 2345-2306	20-540'	16"	24"
HS20	2828.57	315	2513.57	300	2528.57	220-300'	2609-2529		16"	26"
HS21	2821.67	502	2319.67	383	2438.67	220-280, 350-380	2601-2542, 2472-2442		16"	
HS22	2893.22			?						
HS23	2789.93	195	2594.93	186	2603.93	166-186	2624-2604	20-186	16	
HS24	2792.27			?						
HS25	2771.18				2771.18					

SITE_ID	SURF ELEV	EOH DEPTH	EOH ELEV	WELL DEPTH	ELEV DEPTH	SCREENED INTERVAL	ELEVATION SCREENED INTERVAL	Gravel Pack	Casing Dia.	BH Dia.
HS26	2818.32			?						
HS27	2837.85	460	2377.85	432	2405.85	420-430	2417-2408	325-460		
HS28										
HS29		490		382		342-362, 362-382		20-382	16"	
HS30	2813									
HS31	2812	350	2462.00	336		216-256, 296-336		20-336	16"	26"

Table A.1.1-3. Database information for wells referred to in the Index Well Study, Haskell Co.

SITE_ID	Wizard Years	Water Use '06	Water Use '07	Water Use '08	WIMAS	WIZARD	WWC5
HS1		113.6	158.76	187.54	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=72530		http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=385288
HS2		66	101	89	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=72546		http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=385642
HS3							http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=28165
HS4							http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=390016

SITE_ID	Wizard Years	Water Use '06	Water Use '07	Water Use '08	WIMAS	WIZARD	WWC5
HS5							http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=389767
HS6							http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=389768
HS7		349	256	287	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list.cfm		http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=320718
HS8							http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=395017
HS9		330	264	184	http://hercules.kgs.ku.edu/geohydro/wimas/water_right_list.cfm?wr_id=19905		http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=363947
HS10							http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=28170
HS11		212.16	228	211			http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=396941
HS12		0	0	0			NA
HS13		0	0	0			NA
HS14		0	0	0			http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=341913
HS15		0	0	0			NA
HS16							http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=28168
HS17		0	0	0			NA
HS18		257	185	174	http://hercules.kgs.ku.edu/geohydro/wimas/water_right_list.cfm?wr_id=19390		http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=304615

SITE_ID	Wizard Years	Water Use '06	Water Use '07	Water Use '08	WIMAS	WIZARD	WWC5
HS19							http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=319354
HS20		253	221	219			http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=28166
HS21	1991-2009	250	166	205	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=6471	http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=374044100395001	http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=28160
HS22	1948-2009					http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=373929100453601	NA
HS23	2005-2009					http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=374319100375801	http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=114859
HS24	1964-2004					http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=374317100375501	NA
HS25	1993-2009					http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=374125100344101	
HS26	1959-2009					http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=373709100374701	NA
HS27					NA	http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=373925100395301	http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=406332
HS28		205	110	0	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=44189		

SITE_ID	Wizard Years	Water Use '06	Water Use '07	Water Use '08	WIMAS	WIZARD	WWC5
HS29		NA	NA	159	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=75355		http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=416154
HS30		0	0	0	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=1668		
HS31		319	261	298	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=63077		http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=302391

A.1.2 Thomas County

Table A.1.2-1. Well identification data for wells referred to in the Index Well Study, Thomas Co.

SITE_ID	LEGAL	Well Type	USGS_ID	OTHER IDENTIFIER	Water Right	WWC5
TH1	NW NW NW 33 09-33	Monitoring	383132100543101		NA	403943
TH2	SE NE NE 35 09-33	Irrigation	391355100574901		4418 - 00	
TH3	SW NW NW 06 10-33	Irrigation (ret)	391303101031701	10-33-06BBC		
TH4	NW NE NW 11 10-33	Irrigation	391217100583201		18679 - 00	
TH5	SE SW NW 12 10-34	Irrigation	391200101041601		9144 - 00	329448
TH6	SW SW SW 11 09-34	Irrigation	391646101052901		32652 - 00	88967
TH7	NE SE NE 12 09-34	Irrigation	391718101032301	09-32-12ADA	31070 - 00	
TH8	NE SW NE 28 09-33	Irrigation (ret)	?	H-West, 09-33-28???	20218	422589
TH9	SE NW NW 27 09-33	Irrigation (ret)	?	H-East, 09-33-27???	22814	422588
TH10	NW NW SW 36 09-33	Domestic (abd)	?	09-3306CBB		

Table A.1.2-2. Well construction data for wells referred to in the Index Well Study, Thomas Co.

SITE_ID	SURF_ELEV	EOH_DEPTH	EOH_ELEV	WELL DEPTH	ELEV_WELL_DEPTH	SCRN INT	ELEV_Screen	Grvl Pck	Casing Dia.	BH Dia.
TH1	3187.44	294	2893.44	286	2901.44	274-284	2903-2913	250-284	2.5"	
TH2	3145.31			244	2901.31					
TH3	3191.91			316	2875.91					
TH4	3139.87			299	2840.87					
TH5	3220.55	306	2914.55	293	2927.55	213-293	2927-3007	20-293	16"	28"
TH6	3179.13			215	2964.13	135-195, 195-215	2964-3044			
TH7	3202.16			?						
TH8	?			?	?	?	?	?	?	?
TH9	?			?	?	?	?	?	?	?
TH10	?			?	?	?	?	?	?	?

Table A.1.2-3 Database information for wells referred to in the Index Well Study, Thomas Co.

SITE_ ID	Wizard _Years	Water Use '06	Water Use '07	Water Use '08	Notes:	WIMAS	WIZARD	WWC5
TH1	2007-2009	0	0	0	Note: well drilled to 294', last 10' shale		http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=383132100543101	http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=403943
TH2	1964-2009	149.15	73	69			http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=391355100574901	
TH3	1971-2009						http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=391303101031701	
TH4	1992-2008	191	90	154		http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=41294	http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=391217100583201	
TH5	1964-2009	140	171.3	125	Note: well drilled to 306', last 22 feet yellow ochre-black shale	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=66955	http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=391200101041601	http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=329448
TH6	1984-2006	137.63	156.36	133	Wizard/WWC5 depths disagree. Same well?	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=35372	http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=391646101052901	http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=88967
TH7	1979-2009	267.16	247	283		http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=45398	http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=391718101032301	
TH8	NA	21.82	0	0		http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=11312		http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=422589
TH9	NA	117	0	0		http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=48404		http://abyss.kgs.ku.edu/pls/abyss/wwc5.wwc5d2.well_details?well_id=422588
TH10	NA	0	0	0				

A.1.3 Scott County

Table A.1.3-1. Well identification and construction data for wells referred to in the Index Well Study, Scott Co.

SITE ID	LEGAL	Well Type	USGS ID	Water Right	SURF ELEV	Wizard Years	WELL DEPTH	ELEV WELL DEPTH
SC1	NE NE NE 01 18-33	Monitoring	391404101010701		2967.15	2007-2009	227	2740.15
SC2	NW SW SW 03 18-33	Irrigation	383053100573701	17206 - 00	3009.10	1951-2009	182	2827.1
SC3	NW NW NW 25 18-33	Irrigation	382803100552301	SC 50 - 00, 8057 - 00	2974.82	1951-2009	180	2794.82
SC4	NW SW NE 14 17-33	Irrigation	383448100555801	29967 - 00	3016.81	1969-2009	202	2814.81
SC5	NW NW NW 16 17-32	Irrigation	383501100520601	17478 - 00	2980.82	1971-2009	231	2749.82
SC6	NW NW NW 27 17-32	Irrigation (ret)	383316100505801	6789 - 00	2989.24	1965-2009	185	2804.24
SC7	NE NW NE 17 18-32	Irrigation	382947100522902	SC 16 - 00	2974.56	1981-2009	135	2839.56
SC7 old	NE NW NE 17 18-32		382947100522901	28129 - 00				

Table A.1.1-2. Database information for wells referred to in the Index Well Study, Scott Co.

SITE_ ID	Water Use '06	Water Use '07	Water Use '08	WIMAS	WIZARD
SC1					http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=391404101010701
SC2	58.92	84.84	67.84	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=4361	http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=383053100573701
SC3	0	0	0	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=47736	http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=382803100552301
SC4	166	155	231	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=54891	http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=383448100555801
SC5	193.31	158.26	205	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=15886	http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=383501100520601
SC6	0	0	0	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=32431	http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=383316100505801

SC7	56.68	3.25	9.13	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=15168	http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=382947100522902
SC7old	0	0	0	http://hercules.kgs.ku.edu/geohydro/wimas/pd_list_direct.cfm?pdiv_id=47593	

A.2 Precipitation, inches, 2000-2009

A.2.1 Thomas county

	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Mar-Oct	Mar-Sep
COLBY 1 SW	2000	0.12	0.78	2.44	1.07	0.18	2.06	3.12	0.88	0.96	3.25	1.12	0	15.98	13.96	10.71
COLBY 1 SW	2001	1.47	0.65	0.38	3.01	3.35	0.41	3.08	1.71	3.03	0.45	0.98	0.09	18.61	15.42	14.97
COLBY 1 SW	2002	0.57	0.22	0.16	0.42	1.39	1.42	1.49	4.17	1.23	2.53	0.06	0	13.66	12.81	10.28
COLBY 1 SW	2003	0	0.4	1.38	2.24	2.33	4.52	0.42	3.03	0.02	0.23	0.18	0.09	14.84	14.17	13.94
COLBY 1 SW	2004	0.07	0.68	0.74	2.7	0.95	3.2	4.12	1.23	2.59	1.25	2.51	0.03	20.07	16.78	15.53
COLBY 1 SW	2005	0.2	0.34	0.74	3.62	3.75	3.12	2.35	2.89	0.08	2.52	0.23	0.08	19.92	19.07	16.55
COLBY 1 SW	2006	0.55	0.03	2.05	0.64	1.03	3.17	1.68	2.44	2.11	3.14	0.02	4.23	21.09	16.26	13.12
COLBY 1 SW	2007	0.63	0.61	0.63	3.45	1.15	1.61	2.73	3.25	1.98	0.24	0.1	0.87	17.25	15.04	14.8
COLBY 1 SW	2008	0	0.2	0.84	0.7	3.33	0.93	3.54	3.05	3.06	3.54	0.74	0.65	20.58	18.99	15.45
COLBY 1 SW	2009	0.15	0.49	0.1	3.44	5.53	3.69	4.1	3.33	1.55	3.11			*25.49*	24.85	21.74
	Normal[1]	0.3	0.35	1.17	1.56	3.67	3.17	3.16	2.04	1.7	1.05	0.61	0.36	19.14		
	New Normal[2]	0.4	0.46	1.2	1.93	3.6	2.96	3.95	2.47	1.39	1.24	0.81	0.36	20.77		

Colby 1 SW, Kansas (14699): http://www.hprcc.unl.edu/cgi-bin/cli_perl_lib/cliMAIN.pl?ks1699

	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Mar-Oct	Mar-Sep
MINGO 5 E	2000	0.08	0.64	2.61	1	0.61	1.6	4.73	0.47	0.58	4.4	1.47	0.05	18.24	16	11.6
MINGO 5 E	2001	1.08	0.97	0.6	2.43	4.19	0.13	4.83	1.78	2.72	0.23	0.93	0.25	20.14	16.91	16.68
MINGO 5 E	2002	0	0.16	0.22	0.44	1.23	0.76	0.49	2.35	0.61	3.39	0.07	M	9.72	9.49	6.1
MINGO 5 E	2003	0.05	0.17	1.31	1.77	2.86	2.96	0.17	2.32	0.14	0.29	0.2	0.3	12.54	11.82	11.53
MINGO 5 E	2004	0.17	0.4	1.23	3.25	0.88	3.37	2.82	1.61	2.36	0.92	1.93	0.06	19	16.44	15.52
MINGO 5 E	2005	0.5	0.75	0.98	3.94	3.93	2.68	2.25	2.66	0.1	2.9	0.53	0.08	21.3	19.44	16.54
MINGO 5 E	2006	0.25	0.02	1.25	0.55	1.17	3.18	0.64	2.39	1.51	2.31	0.03	5.07	18.37	13	10.69
MINGO 5 E	2007	0.9	0.3	0.69	3.74	1.69	1.52	1.59	2.78	0.63	0.09	0.15	0.84	14.92	12.73	12.64
MINGO 5 E	2008	0.35	0.3	0.79	1.87	4.52	1.03	5.01	3.57	1.42		0.92		19.78	18.21	18.21
MINGO 5 E	2009	0.07	0.17	0.02	0	4.16	3.12	3.9	3.75	3.16	3.33			21.68	21.44	18.11
	Normal[1]	0.39	0.37	1.2	1.76	3.32	3.05	2.63	2.07	1.72	1.14	0.77	0.41	18.83		
	New Normal[2]	0.41	0.44	1.22	1.83	3.05	2.57	3.58	2.58	1.39	1.2	0.99	0.35	19.61		

Mingo 5 E, Kansas (145355): http://www.hprcc.unl.edu/cgi-bin/cli_perl_lib/cliMAIN.pl?ks5355

[1] "Normal" is a 30-year average covering 1961-1990.

[2] "New-Normal" is a 30-year average covering 1971-2000.

	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Mar-Oct	Mar-Sep
REXFORD 1 SW	2000	0.04	0.58	2.38	0.95	0.35	1.46	3.04	0.63	1.11	3.15	1.03	0.02	14.74	13.07	9.92
REXFORD 1 SW	2001	1.09	0.59	0.44	2.98	5.55	4.06	3.14	4.11	1.5	0.4	1.05	0.03	24.94	22.18	21.78
REXFORD 1 SW	2002	0.37	0.07	0.24	0.24	1.39	1.4	1.91	3.96	2.04	3.08	0	0	14.7	14.26	11.18
REXFORD 1 SW	2003	0	0.34	1.07	2.82	3.16	4.34	0.92	1.28	0.15	0.25	0.06	0.24	14.63	13.99	13.74
REXFORD 1 SW	2004	0.07	0.23	1.1	2.3	0.76	2.53	7.17	0.68	2.78	0.7	2.21	0.03	20.56	18.02	17.32
REXFORD 1 SW	2005	0.04	0.4	1.4	3.36	3.02	3.41	4.78	3.65	0	2.83	0.37	0.25	23.51	22.45	19.62
REXFORD 1 SW	2006	0.25	0	0.8	0.47	0.69	3.05	2.24	2.56	1.32	3.71	0	3.15	18.24	14.84	11.13
REXFORD 1 SW	2007	0.95	0.15	1.03	3.92	1.59	1.96	3.02	2.82	1.39	0.32	0	1.17	18.32	16.05	15.73
REXFORD 1 SW	2008	0.02	0.21	0.64	1.73	4.55	2.61	4.98	3.54	3.09	3.63	0.74	0.41	26.15	24.77	21.14
REXFORD 1 SW	2009	0.06	0.22	0	0	5.72	4.37	2.86	5.08	3.07	3.54			24.92	24.64	21.1
	Normal[1]	0.42	0.49	1.36	1.81	3.51	3.02	2.76	2.13	1.58	1.15	0.76	0.49	19.48		
	New Normal[2]	0.45	0.54	1.39	2.1	3.64	2.86	3.59	2.65	1.18	1.13	0.94	0.45	20.92		

Rexford 1 SW, Kansas (146787): http://www.hprcc.unl.edu/cgi-bin/cli_perl_lib/cliMAIN.pl?ks6787

County Average

	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Normal[1]	0.42	0.48	1.27	1.95	3.43	2.8	3.71	2.57	1.32	1.19	0.91	0.39	20.43
	New Normal[2]	0.37	0.4	1.24	1.71	3.5	3.08	2.85	2.08	1.67	1.11	0.71	0.42	19.15
	2000	0.08	0.67	2.48	1.01	0.38	1.71	3.63	0.66	0.88	3.6	1.21	0.02	16.32
	2001	1.21	0.74	0.47	2.81	4.36	1.53	3.68	2.53	2.42	0.36	0.99	0.12	21.23
	2002	0.31	0.15	0.21	0.37	1.34	1.19	1.3	3.49	1.29	3	0.04	0	12.69
	2003	0.02	0.3	1.25	2.28	2.78	3.94	0.5	2.21	0.1	0.26	0.15	0.21	14
	2004	0.1	0.44	1.02	2.75	0.86	3.03	4.7	1.17	2.58	0.96	2.22	0.04	19.88
	2005	0.25	0.5	1.04	3.64	3.57	3.07	3.13	3.07	0.06	2.75	0.38	0.14	21.58
	2006	0.35	0.02	1.37	0.55	0.96	3.13	1.52	2.46	1.65	3.05	0.02	4.15	19.23
	2007	0.83	0.35	0.78	3.7	1.48	1.7	2.45	2.95	1.33	0.22	0.08	0.96	16.83
	2008	0.12	0.24	0.76	1.43	4.13	1.52	4.51	3.39	2.52	3.59	0.8	0.53	23.54
	2009	0.09	0.29	0.04	1.15	5.14	3.73	3.62	4.05	2.59	3.33			24.03

[1] "Normal" is a 30-year average covering 1961-1990.
[2] "New-Normal" is a 30-year average covering 1971-2000.

A.2.2 Scott county

	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Mar-Oct	Mar-Sep
SCOTT CITY	2000	0.29	0.32	4.06	1.53	0.82	0.87	3.32	1.46	1.25	2.54	1.55	0.25	18.26	15.85	13.31
SCOTT CITY	2001	0.97	0.53	0.87	2.22	7.22	0.52	3.12	1.26	0.83	0	0.21	0.05	17.8	16.04	16.04
SCOTT CITY	2002	0.35	0.08	0.02	2.59	0.7	2.39	0.84	2.55	0.59	2.92	0.04	0.11	13.18	12.6	9.68
SCOTT CITY	2003	0	0.51	1.18	1.86	3.55	5.05	1.32	2.83	0.24	0.06	0.06	0.29	16.95	16.09	16.03
SCOTT CITY	2004	0.06	0.57	0.8	2.64	0.26	7.38	2.44	3.73	2.56	0.82	1.27	0.08	22.61	20.63	19.81
SCOTT CITY	2005	0.79	1.32	0.74	1.29	3.61	1.64	2.51	2.65	3.98	3.54	0.09	0.21	22.37	19.96	16.42
SCOTT CITY	2006	0.25	0	1.27	0.54	2.78	3.25	1.55	2.39	1.19	2.96	0.01	5.58	21.77	15.93	12.97
SCOTT CITY	2007	0.74	0.14	2.46	2.62	1.13	3.09	2	2.89	2.35	0.02	0.1	1.02	18.56	16.56	16.54
SCOTT CITY	2008	0.16	0.24	0.33	2.02	2.25	1.71	1.66	1.79	1.08	5.6	0.91	0.2	17.95	16.44	10.84
SCOTT CITY	2009	0.16	0.04	0.7	0	1.71	1.36	2.69	2.72	1.64	2.19			13.21	13.01	10.82
	Normal[1]	0.6	0.63	1.39	1.69	3.09	3.04	2.96	2.27	2.01	1.04	0.96	0.62	20.3		
	New Normal[2]	0.7	0.64	1.52	1.7	3.01	2.83	3.19	2.62	1.66	1.09	1.14	0.6	20.7		

Scott City, Kansas (147271): http://www.hprcc.unl.edu/cgi-bin/cli_perl_lib/cliMAIN.pl?ks7271

[1] "Normal" is a 30-year average covering 1961-1990.

[2] "New-Normal" is a 30-year average covering 1971-2000.

A.2.3 Haskell county

	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Mar-Oct	Mar-Sep
SUBLETTE	2000	0.22	0.02	4.4	1.92	2.73	1.58	2.04	0.58	0.05	3.12	0.62	0	17.28	16.42	13.3
SUBLETTE	2001	1.14	0.84	1.07	0.75	3.5	1.3	1.43	1.98	0.34	0	0.17	0.11	12.63	10.37	10.37
SUBLETTE	2002	0.46	0.12	0	1.56	0.62	1.56	0.94	2.61	0.87	2.56	0.05	0.51	11.86	10.72	8.16
SUBLETTE	2003	0	0.43	1.01	0.68	2.59	3.82	0.1	2.09	2.85	0	0	0.41	13.98	13.14	13.14
SUBLETTE	2004	0	0.65	1.85	1.53	0	4.12	4.93	2.37	1.81	1.14	3.15	0	21.55	17.75	16.61
SUBLETTE	2005	1.77	0.8	1	1.89	2.47	3.8	1.19	4.32	1.32	2.53	0.35	0.08	21.52	18.52	15.99
SUBLETTE	2006	0	0	0.83	0.32	3.33	2.15	2.82	3.48	4.38	1.64	0	5.35	24.3	18.95	17.31
SUBLETTE	2007	0.61	0.3	2.26	2.9	1.49	0.89	0.49	0.95	1.16	0.12	0.2	1.04	12.41	10.26	10.14
SUBLETTE	2008	0.11	0.31	0.15	0.52	0.77	2.92	0.24	5.41	0.14	4.2	0.15	0.11	15.03	14.35	10.15
SUBLETTE	2009	0.07	0.12	1.18	0	0.78	4.42	2.59	1.92	0.57	2.86			14.51	14.32	11.46
	Normal[1]	0.35	0.48	1.23	1.44	3.21	3.22	2.59	2.35	2.1	1.11	0.81	0.38	19.27		
	New Normal[2]	0.46	0.44	1.44	1.5	3.19	2.94	2.59	2.32	1.71	1.27	0.94	0.42	19.22		

Sublette, Kansas (147922): http://www.hprcc.unl.edu/cgi-bin/cli_perl_lib/cliMAIN.pl?ks7922

[1] "Normal" is a 30-year average covering 1961-1990.

[2] "New-Normal" is a 30-year average covering 1971-2000.

A.3 Water use, total AF in circles of 1, 2, 3, 4, and 5-mile radius around each of the index wells for the years 2005-2008. Two estimates of growing season precipitation from Appendix A.2 are also tabulated for comparison.

A.3.1 Comparative data on circles used to evaluate water use

Table A.3.1-1:

Radius (mi)	1	2	3	4	5
Area (mi^2)	3.14	12.56	28.26	50.24	78.5
area ratio to r = 1 mi	1	4	9	16	25
area ratio to r = 2 mi	0.25	1	2.25	4	6.25

Haskell	year	Water use, AF/A					Precip	
		1 mi	2 mi	3 mi	4 mi	5 mi	Mar-Oct	Mar-Sep
	2005	1200	8550	17919	31660	43580	18.52	15.99
	2006	1927	9304	20421	37773	51492	18.95	17.31
	2007	1642	**8764**	18304	34228	45983	10.26	10.14
	2008	1825	9932	22703	40185	54612	14.35	10.15
	Avg	1648.5	9137.5	19836.75	35961.5	48916.75	15.52	13.3975
Ratio to 2 mi circle		0.18	1.00	2.17	3.94	5.35		

Scott								
		1 mi	2 mi	3 mi	4 mi	5 mi	Mar-Oct	Mar-Sep
	2005	1027	4765	10019	14390	19355	19.96	16.42
	2006	1034	3739	9571	13452	19188	15.93	12.97
	2007	901	**3175**	8474	11660	16767	16.56	16.54
	2008	933	4059	10231	13896	19551	16.44	10.84
	Avg	973.75	3934.5	9573.75	13349.5	18715.25	17.2225	14.1925
Ratio to 2 mi circle		0.25	1.00	2.43	3.39	4.76		

Thomas with Colby precip								
		1 mi	2 mi	3 mi	4 mi	5 mi	Mar-Oct	Mar-Sep
	2005	974	2662	5927	9567	14330	19.07	16.55
	2006	1220	3455	7693	11999	17149	16.26	13.12
	2007	808	**2710**	6205	9651	13997	15.04	14.8
	2008	879	2686	6152	9458	13541	18.99	15.45
	Avg	970.25	2878.25	6494.25	10168.75	14754.25	17.34	14.98
Ratio to 2 mi circle		0.34	1.00	2.26	3.53	5.13		

Thomas with Mingo precip

	1 mi	2 mi	3 mi	4 mi	5 mi	Mar-Oct	Mar-Sep
2005	974	2662	5927	9567	14330	19.44	16.54
2006	1220	3455	7693	11999	17149	13	10.69
2007	808	**2710**	6205	9651	13997	12.73	12.64
2008	879	2686	6152	9458	13541	18.21	18.21
Avg	970.25	2878.25	6494.25	10168.75	14754.25	18.21	18.21
Ratio to 2 mi circle	0.34	1.00	2.26	3.53	5.13	15.845	14.52

A.4 Haskell site hydrographs and BEF plots

The text box accompanying each group of plots (belopw) provides the following information:

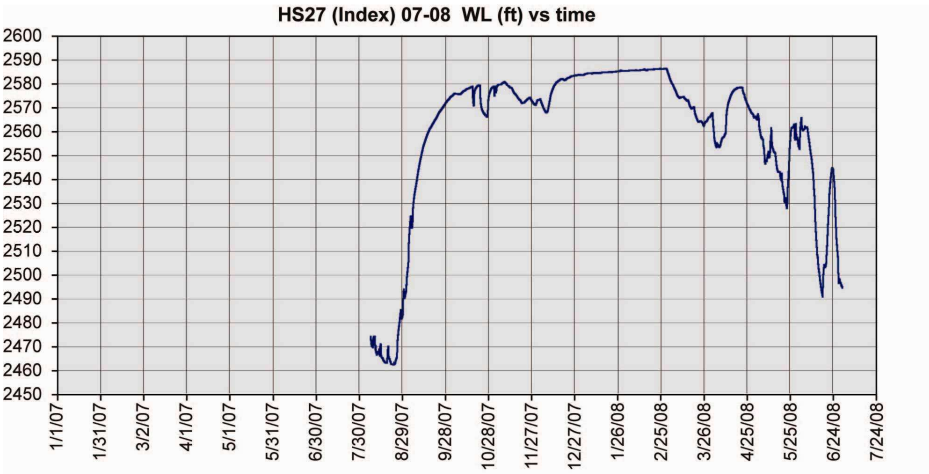
Well number (this study; see Appendix A.1.1 for the corresponding numbers used by DWR in the Haskell study site) – this is the identifier used in project reports.

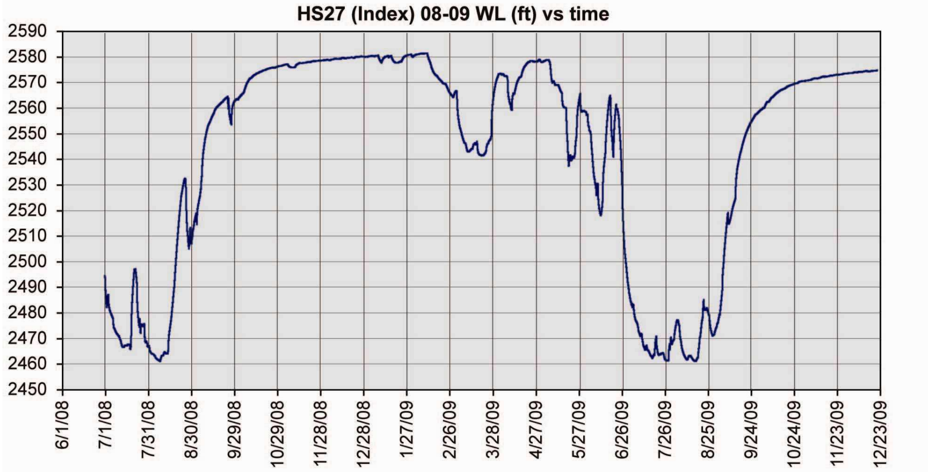
USGS ID: useful for searching for the well in (e.g.) the WIZARD database.
Legal location (PLSS) – see Appendix A.1.1 for latitude and longitude or other location information.
WWC5 identifier, for searching in the well log database.
Well type and/or use
Water levels for the years of the study, in feet above mean sea level. "est-recov" are the best estimates of fully equilibrated recovery; "Wiz-Elev" are the tape WL measurements (also feet asl) at the time of the annual survey.

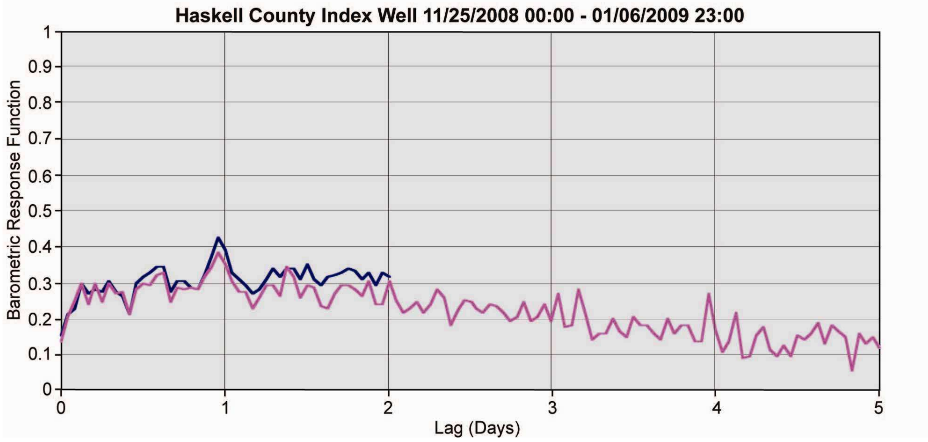
Surface Elev. = feet asl, ground surface at the well location.
Bedrock Elev. = feet asl, approx bedrock surface at well site.
EOH ("Extent of Hole") = total drilled depth, ft below surface.
Well Depth = completed (cased) well depth, feet below surface.
Depth Elev. = Surface Elev – Well depth
Screen Elevation = feet asl of the screened interval(s) in the casing.
Gravel Pack: borehole depth interval packed with gravel.
Casing diameter
Borehole diameter

Water Use:
WU = acre-feet pumped from this well in the indicated year
WU (2mi-totirrac) = total irrigated acres from all points of groundwater diversion located within the 2-mile radius circle around this well.
WU (2mi-AF) = total acre –feet of water pumped from all points of groundwater diversion located within the 2-mile radius circle around this well.
WU (2mi- AF/irrac) = acre-feet pumped per irrigated acre within the 2-mile circle.
'06 WU (2mi- AF /ac) = acre feet per total acres within the 2-mile circle in 2006.

Growing season precipitation = county rainfall in inches during the indicated year (Note: one inch = 0.083 AF/ac, or 670 total AF within the 2-mile circle).







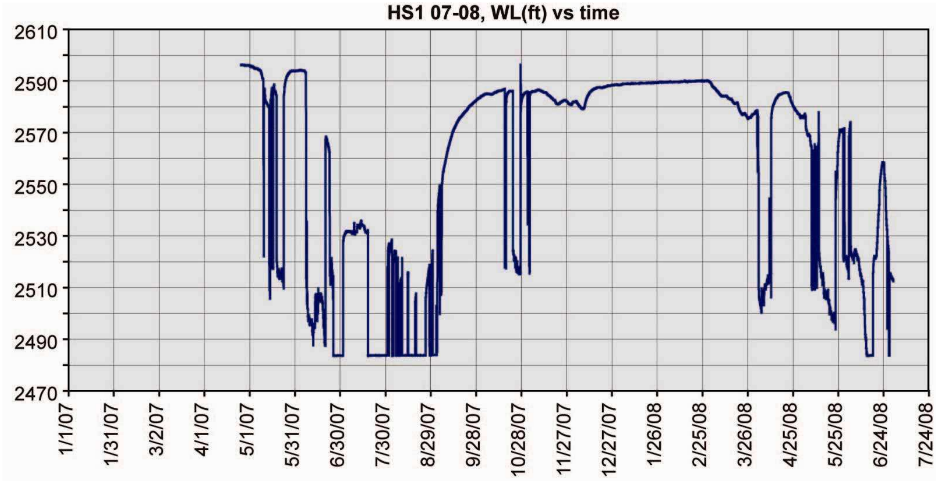
HS-27 (Index Well, Haskell)
USGS ID: 373925100395301
SW SE NW 36 27-31
WWC5: 406332
Well Type: Monitoring

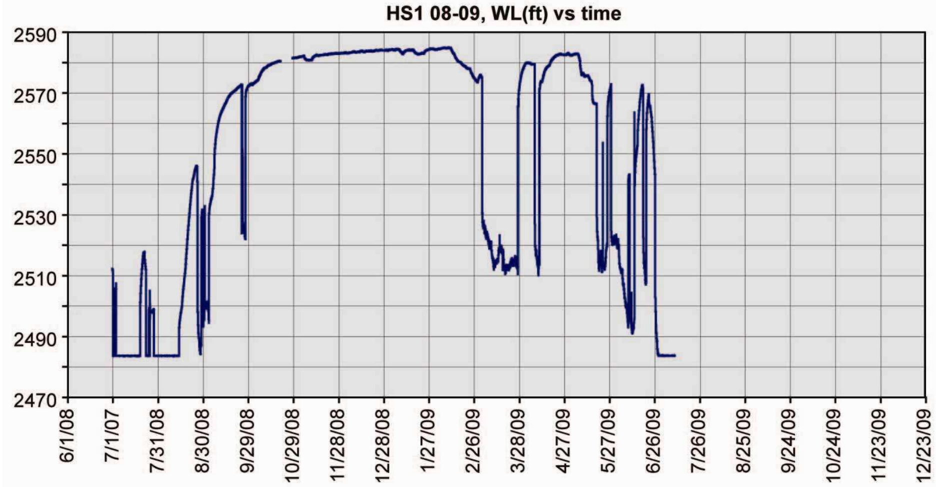
’07 WL(est-recov): NA
’08 WL(est-recov): 2584.5
’09 WL(est-recov): 2580.43
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): 2584.77
’09 WL(Wiz-Elev): 2580.43

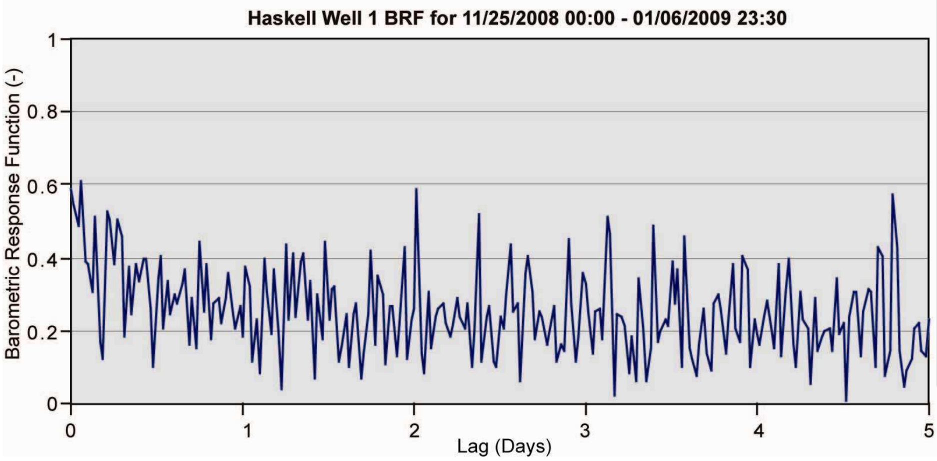
Surface Elev.:2837.85
Bedrock Elev: ?
EOH: 460’
Well Depth: 432’
Depth Elev: 2405.85
Screen: 420-430’
Screen Elev: 2407-2417
Gravel Pack: 325-460
Casing Diameter: 2.5”
Borehole Diameter: 2.5”

’06 WU: 0
’07 WU: 0
’08 WU: 0
’06 WU (2mi-totirrac): 6735
’07 WU (2mi-totirrac): 3475
’08 WU (2mi-totirrac): 7755
’06 WU (2mi-AF): 9304.02
’07 WU (2mi- AF): 8764.01
’08 WU (2mi- AF): 9931.71
’06 WU (2mi- AF/irrac): 1.38
’07 WU (2mi- AF/irrac): 1.35
’08 WU (2mi- AF /irrac): 1.28
’06 WU (2mi- AF /ac): 1.16
’07 WU (2mi- AF /ac): 1.09
’08 WU (2mi- AF /ac): 1.23

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







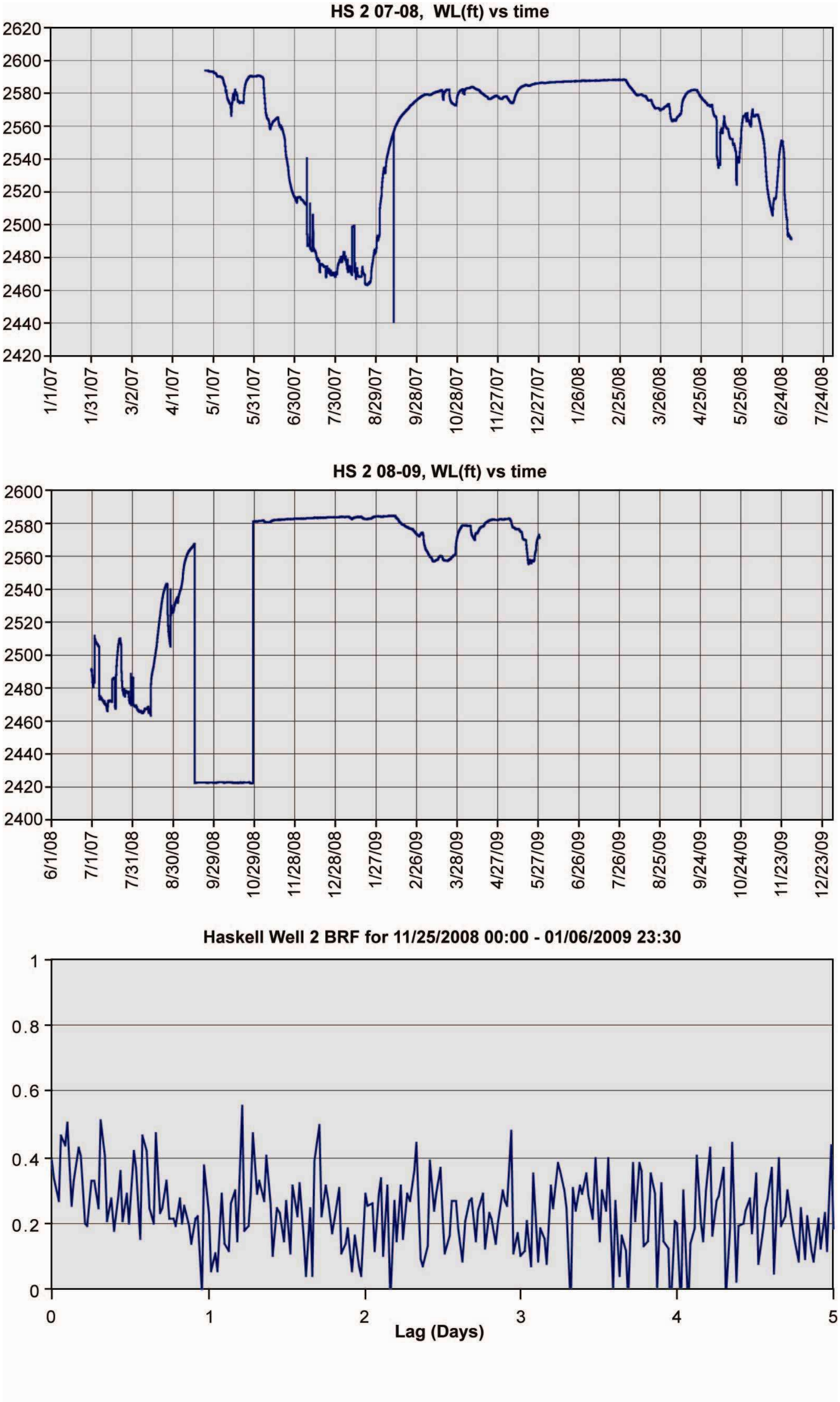
HS-1 (HS3 new, 8157)
USGS ID: ?
NE NE NW 36 27-31
WWC5: 385288
Well Type: Irrigation

’07 WL(est-recov): 2595.95
’08 WL(est-recov): 2589.92
’09 WL(est-recov): 2584.64
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

Surface Elev.:2854.24
Bedrock Elev: ?
EOH: 435’
EOH Elev: 2419.24
Well Depth: 428’
Depth Elev: 2426.24
Screen: 398-418, 418-428
Screen Elev: 2426-2456’
Gravel Pack: 20-428’
Casing Diameter:16”
Borehole Diameter: ?

’06 WU: 113.6
’07 WU: 158.76
’08 WU: 187.54
’06 WU (totac): 6526
’07 WU (totac): 6453
’08 WU (totac): 6714
’06 WU (2m-af): 9374.03
’07 WU (2mi-af): 8756.78
’08 WU (2mi-af): 8406.61
’06 WU (2mi-per irrac): 1.44
’07 WU (2mi-per irrac): 1.36
’08 WU (2mi-per irrac): 1.25
’06 WU (2mi-perac): 1.17
’07 WU (2mi-perac): 1.09
’08 WU (2mi-perac): 1.05

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”



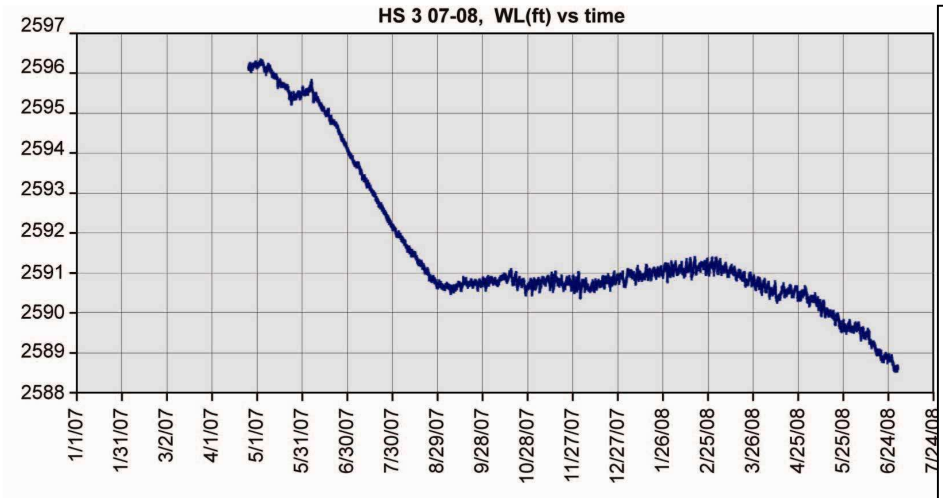
HS-2 (25275new)
USGS ID: ?
SW SW SW 25 27-31
WWC5: 385642
Well Type: Irrigation

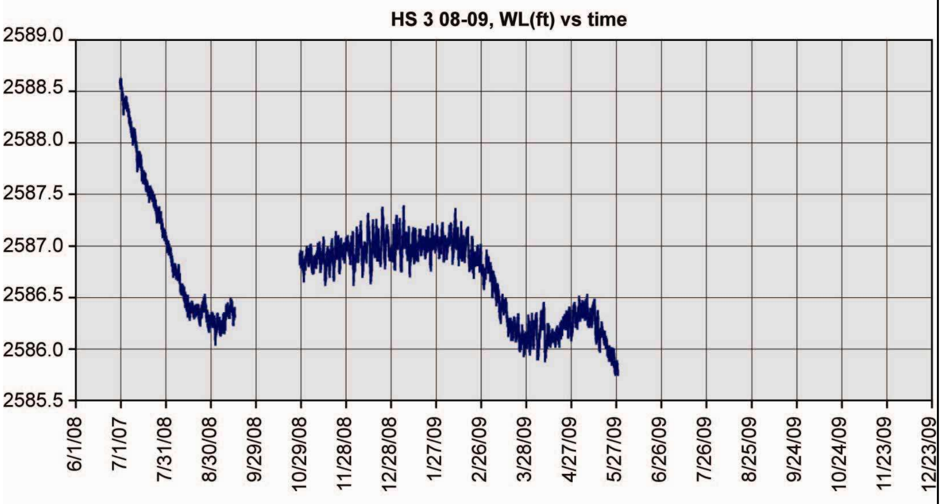
’07 WL(est-recov): 2593.4
’08 WL(est-recov): 2588.27
’09 WL(est-recov): 2583.82
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

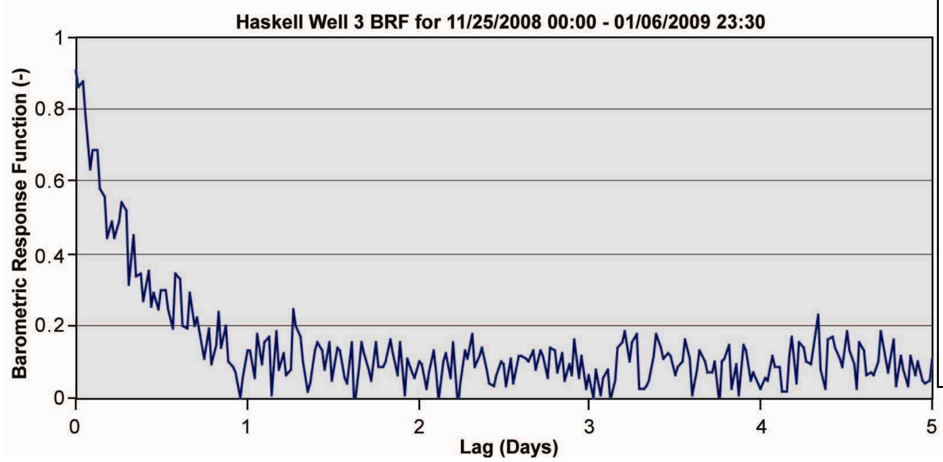
Surface Elev.:2823.98
Bedrock Elev: ?
EOH: 420’
EOH Elev: 2403.98
Well Depth: 410’
Depth Elev: 2413.98
Screen: 370-390, 390-410
Screen Elev: 2413.98-2453.98
Gravel Pack: 20-410
Casing Diameter: ?
Borehole Diameter: ?

’06 WU: 66
’07 WU: 101
’08 WU: 89
’06 WU (totac): 6444
’07 WU (totac): 6389
’08 WU (totac): 6632
’06 WU (2m-af): 9253.03
’07 WU (2mi-af): 8723.78
’08 WU (2mi-af): 8431.61
’06 WU (2mi-per irrac): 1.44
’07 WU (2mi-per irrac): 1.37
’08 WU (2mi-per irrac): 1.27
’06 WU (2mi-perac): 1.15
’07 WU (2mi-perac): 1.08
’08 WU (2mi-perac): 1.05

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







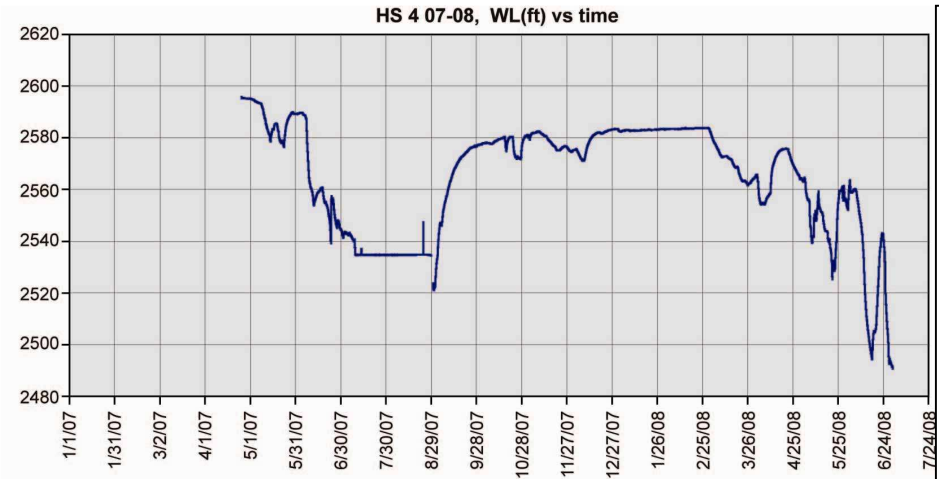
HS-3 (25275 old casing)
USGS ID: ?
SE SW SW 25 27-31
WWC5: 28165
Well Type: Irrigation (ret.)

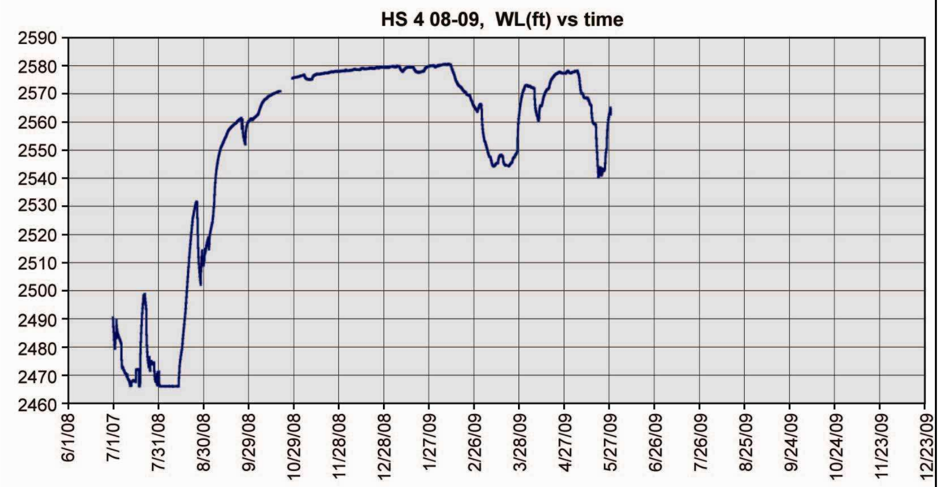
’07 WL(est-recov): 2596.1
’08 WL(est-recov): 2591.2
’09 WL(est-recov): 2587.2
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

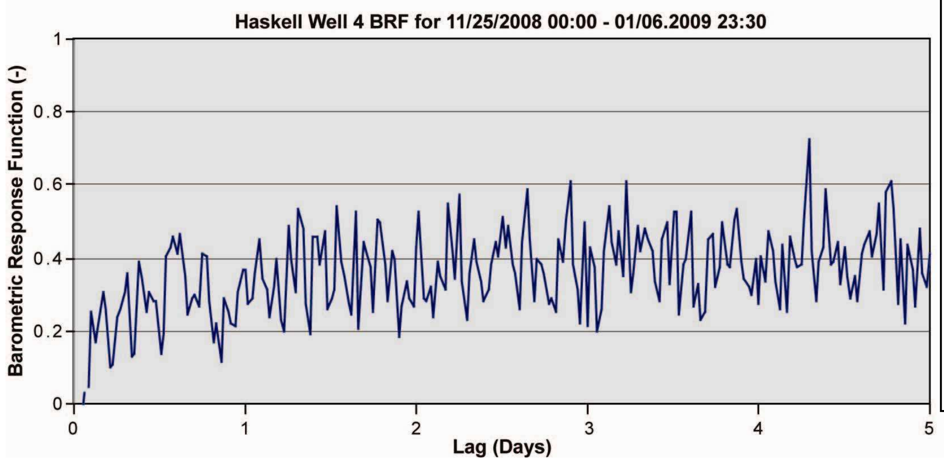
Surface Elev.:2838.76
Bedrock Elev: ?
EOH: 340’
EOH Elev: 2498.76
Well Depth: 284
Depth Elev: 2554.76
Screen: 145-284’
Screen Elev: 2555-2694’
Gravel Pack: 10-2874’
Casing Diameter:16”
Borehole Diameter:28”

’06 WU: 0?
’07 WU: 0?
’08 WU: 0?
’06 WU (totac): 6268
’07 WU (totac): 6207
’08 WU (totac): 6450
’06 WU (2m-af): 8923.03
’07 WU (2mi-af): 8443.78
’08 WU (2mi-af): 8147.61
’06 WU (2mi-per irrac): 1.42
’07 WU (2mi-per irrac): 1.36
’08 WU (2mi-per irrac): 1.26
’06 WU (2mi-perac): 1.11
’07 WU (2mi-perac): 1.05
’08 WU (2mi-perac): 1.01

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







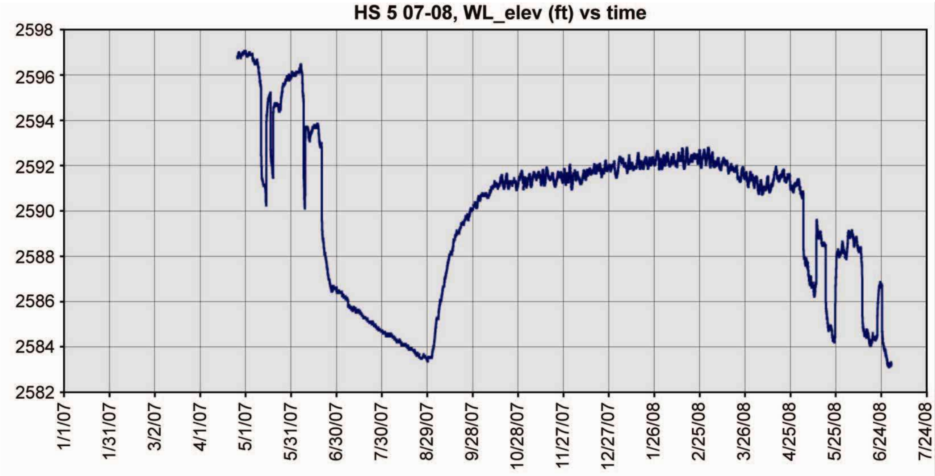
HS-4 (25275obs)
USGS ID: ?
SE SW SW 25 27-31
WWC5: 390016
Well Type: Monitoring

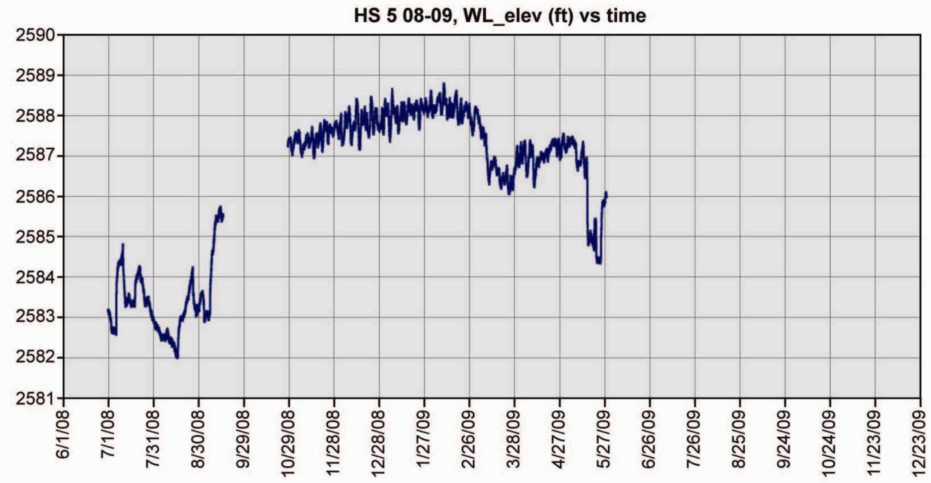
’07 WL(est-recov): NA
’08 WL(est-recov): 2583.59
’09 WL(est-recov): 2579.84
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

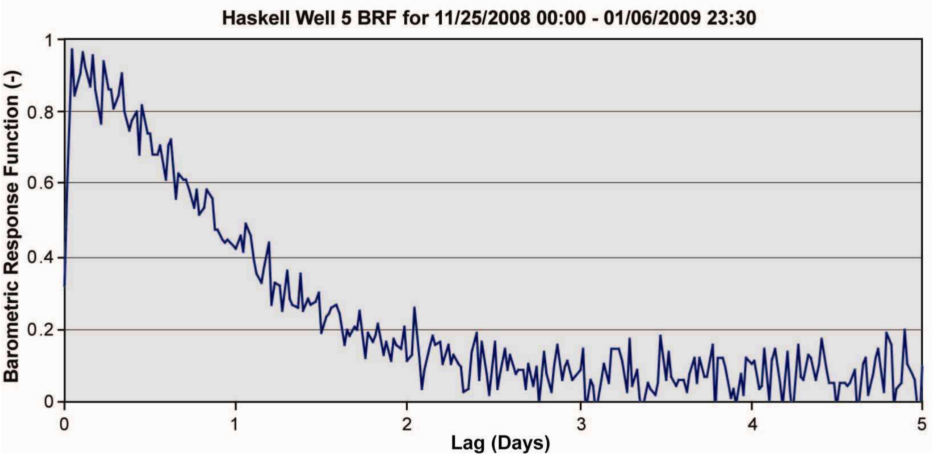
Surface Elev.:2827.57
Bedrock Elev: ?
EOH: 420’
EOH Elev: 2407.57
Well Depth: 420’
Depth Elev: 2407.57
Screen: 380-400, 400-420
Screen Elev: 2407.57-2447.57
Gravel Pack: 20-420
Casing Diameter: ?
Borehole Diameter: ?

’06 WU: 0
’07 WU: 0
’08 WU: 0
’06 WU (totac): 6444
’07 WU (totac): 6389
’08 WU (totac): 6632
’06 WU (2m-af): 9253.03
’07 WU (2mi-af): 8723.78
’08 WU (2mi-af): 8431.61
’06 WU (2mi-per irrac): 1.44
’07 WU (2mi-per irrac): 1.37
’08 WU (2mi-per irrac): 1.27
’06 WU (2mi-perac): 1.15
’07 WU (2mi-perac): 1.08
’08 WU (2mi-perac): 1.05

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







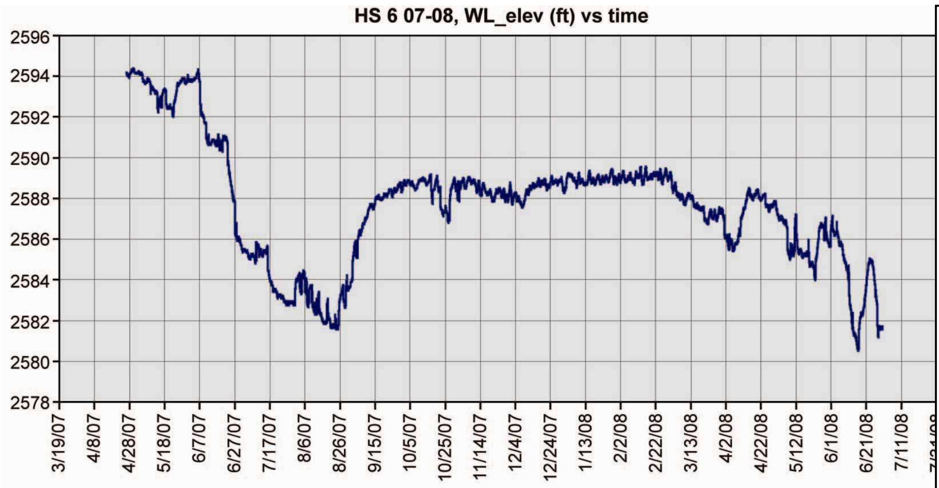
HS-5 (10467obs)
USGS ID: ?
NE NW NE 36 27-31
WWC5: 389767
Well Type: Monitoring

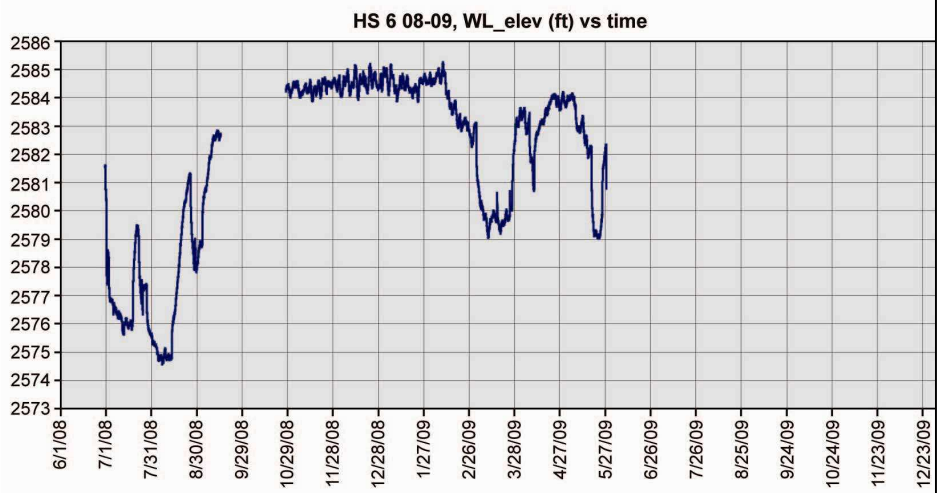
’07 WL(est-recov): 2596.8
’08 WL(est-recov): 2592.32
’09 WL(est-recov): 2588.67
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

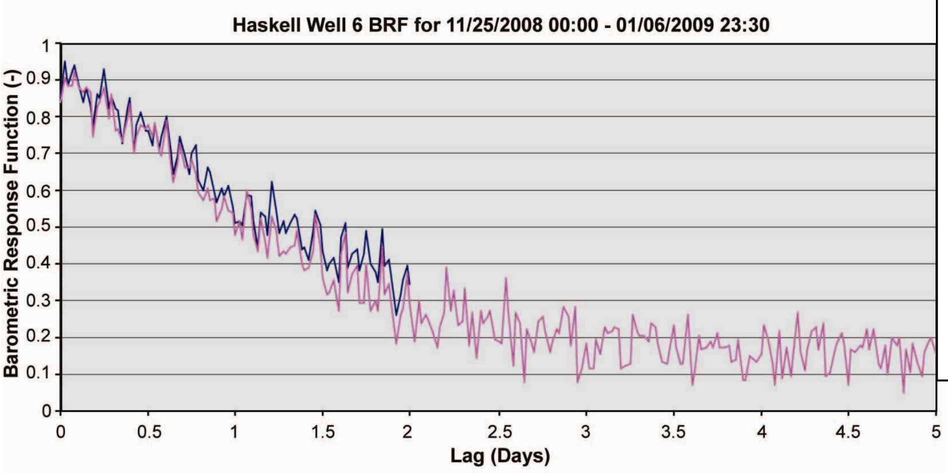
Surface Elev.:2853.43
Bedrock Elev: ?
EOH: 420’
EOH Elev: 2433.43
Well Depth: 420
Depth Elev: 2433.43
Screen: 240-280’
Screen Elev: 2573-2613’
Gravel Pack: 20-420’
Casing Diameter: 2”
Borehole Diameter: ?

’06 WU: 0
’07 WU: 0
’08 WU: 0
’06 WU (totac): 5436
’07 WU (totac): 5386
’08 WU (totac): 5510
’06 WU (2m-af): 8221.21
’07 WU (2mi-af): 7313.85
’08 WU (2mi-af): 7466.19
’06 WU (2mi-per irrac): 1.51
’07 WU (2mi-per irrac): 1.36
’08 WU (2mi-per irrac): 1.36
’06 WU (2mi-perac): 1.02
’07 WU (2mi-perac): 0.91
’08 WU (2mi-perac): 0.93

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







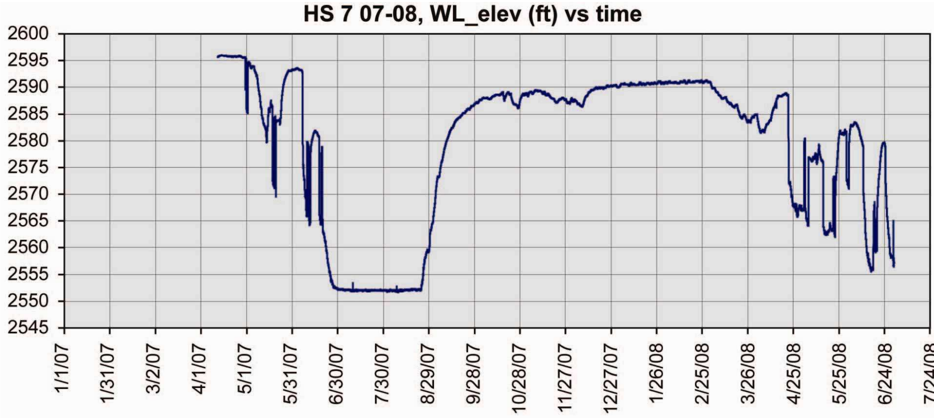
HS-6 (8157s obs)
USGS ID: ?
SE SW SW 36 27-31
WWC5: 389768
Well Type: Monitoring

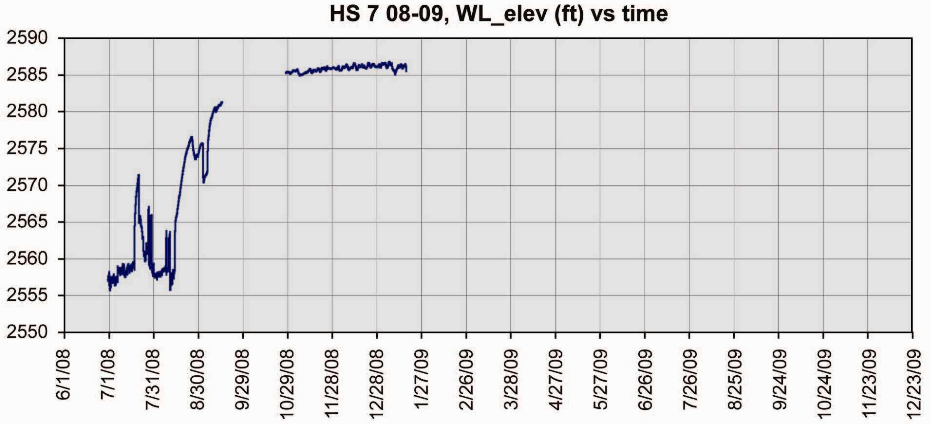
’07 WL(est-recov): 2594.2
’08 WL(est-recov): 2589.13
’09 WL(est-recov): 2584.67
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

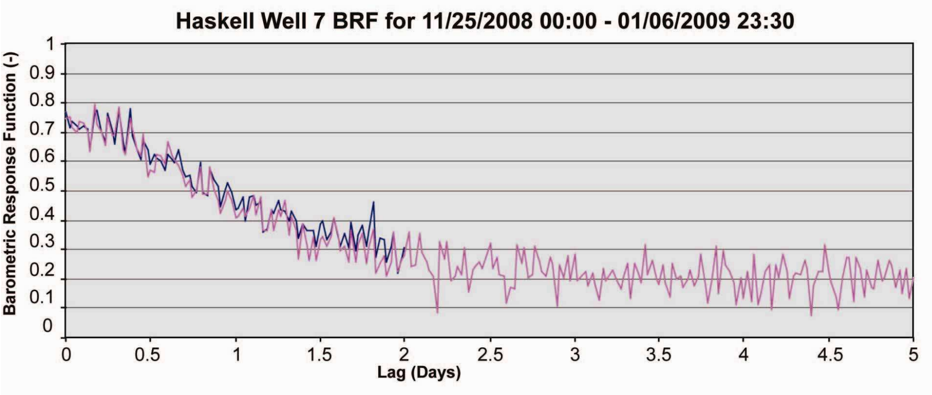
Surface Elev.:2846.74
Bedrock Elev: ?
EOH: 465’
EOH Elev: 2381.74
Well Depth: 465’
Depth Elev: 2381.74
Screen: 425-445, 445-465
Screen Elev: 2382-2422
Gravel Pack: 20-465’
Casing Diameter: ?
Borehole Diameter:?

’06 WU: 0
’07 WU: 0
’08 WU: 0
’06 WU (totac): 6237
’07 WU (totac): 6197
’08 WU (totac):6392
’06 WU (2m-af): 8588.91
’07 WU (2mi-af): 8397.86
’08 WU (2mi-af): 8179.64
’06 WU (2mi-per irrac): 1.38
’07 WU (2mi-per irrac): 1.36
’08 WU (2mi-per irrac): 1.28
’06 WU (2mi-perac): 1.07
’07 WU (2mi-perac): 1.04
’08 WU (2mi-perac): 1.02

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







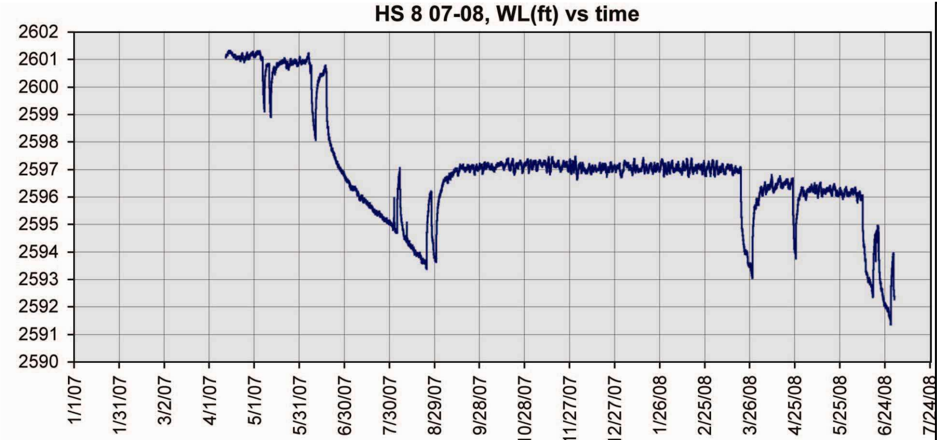
HS-7 (11750)
USGS ID: ?
SE SE NE 36 27-31
WWC5: 320718
Well Type: Irrigation

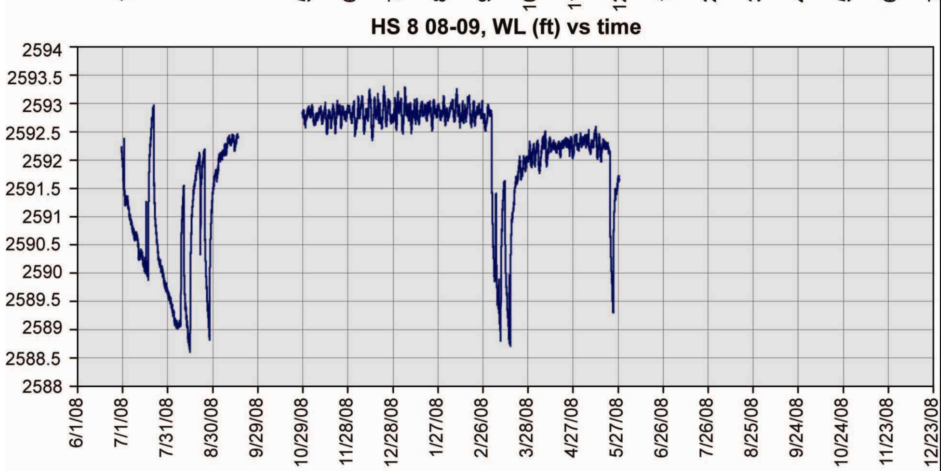
’07 WL(est-recov): 2595.5
’08 WL(est-recov): 2590.91
’09 WL(est-recov): 2586.51
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

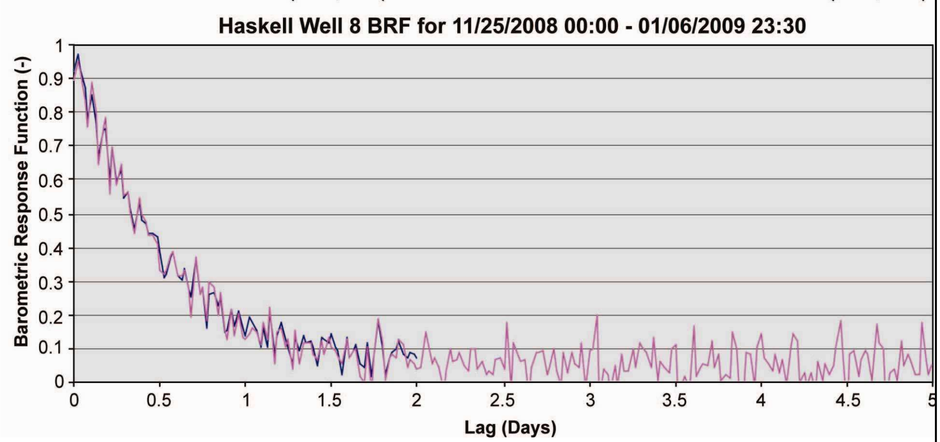
Surface Elev.: 2845.99
Bedrock Elev: ?
EOH: 435’
EOH Elev: 2410.99
Well Depth: 430
Depth Elev: 2415.99
Screen: 411-531
Screen Elev: 2315-2435
Gravel Pack: 20-411’
Casing Diameter: 16”
Borehole Diameter: ?

’06 WU: 349
’07 WU: 256
’08 WU: 287
’06 WU (totac): 5490
’07 WU (totac): 5289
’08 WU (totac):5352
’06 WU (2m-af): 8601.09
’07 WU (2mi-af): 7378.93
’08 WU (2mi-af): 7313.22
’06 WU (2mi-per irrac): 1.57
’07 WU (2mi-per irrac): 1.40
’08 WU (2mi-per irrac): 1.37
’06 WU (2mi-perac): 1.07
’07 WU (2mi-perac): 0.92
’08 WU (2mi-perac): 0.91

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







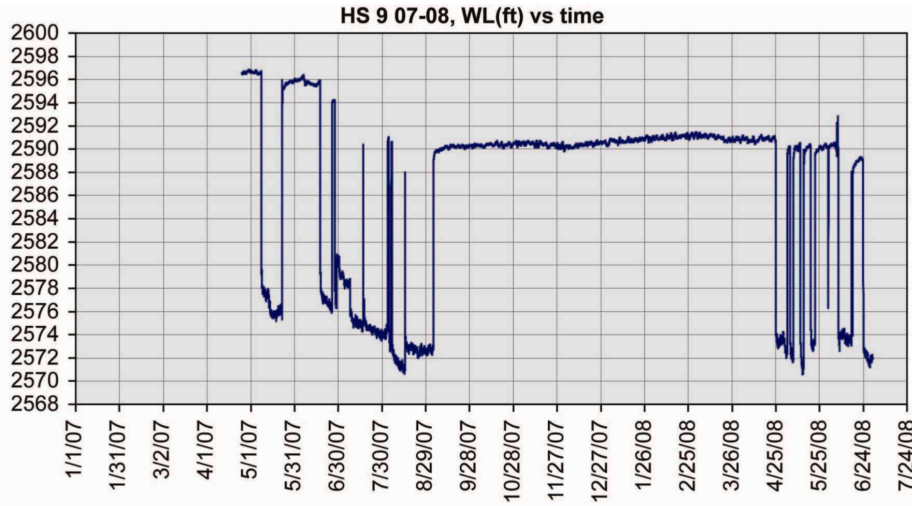
HS-8 (18715 obs)
USGS ID: ?
SE SE NW 25 27-31
WWC5: 395017
Well Type: Monitoring

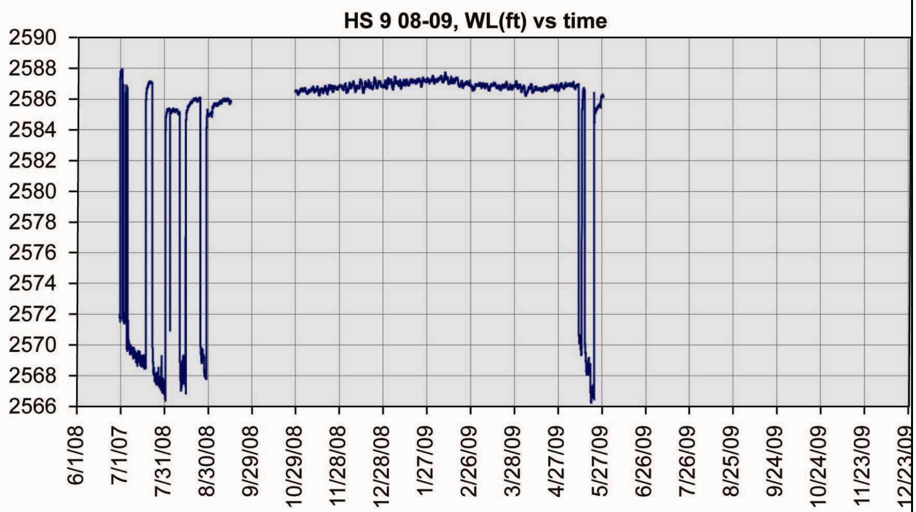
’07 WL(est-recov): 2601.2
’08 WL(est-recov): 2597
’09 WL(est-recov): 2592.9
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

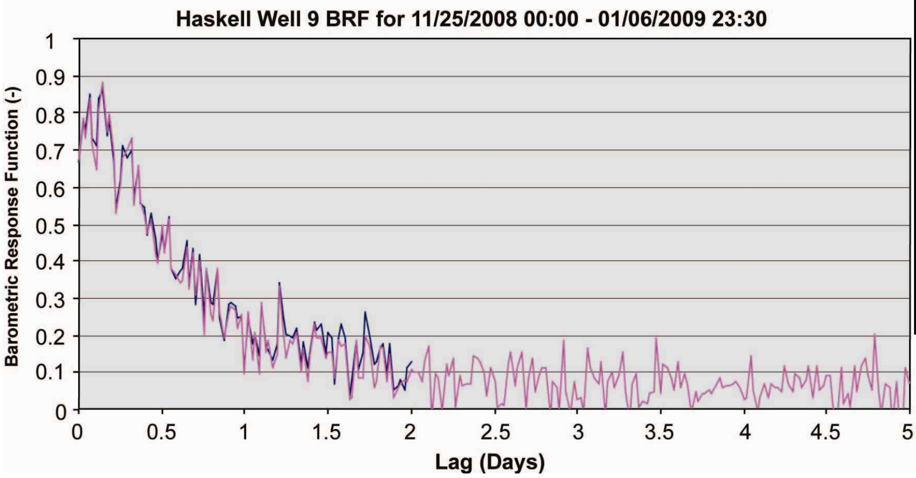
Surface Elev.: 2828.66
Bedrock Elev: ?
EOH: 320’
EOH Elev: 2508.66
Well Depth: 305’
Depth Elev: 2523.66
Screen: 240-300’
Screen Elev: 2529-2589’
Gravel Pack: 20-305’
Casing Diameter: 2”
Borehole Diameter: ?

’06 WU: 0
’07 WU: 0
’08 WU: 0
’06 WU (totac): 6170
’07 WU (totac): 6189
’08 WU (totac):6305
’06 WU (2m-af): 7984.87
’07 WU (2mi-af): 6816.2
’08 WU (2mi-af): 7163.61
’06 WU (2mi-per irrac): 1.29
’07 WU (2mi-per irrac): 1.10
’08 WU (2mi-per irrac): 1.14
’06 WU (2mi-perac): 0.99
’07 WU (2mi-perac): 0.85
’08 WU (2mi-perac): 0.89

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







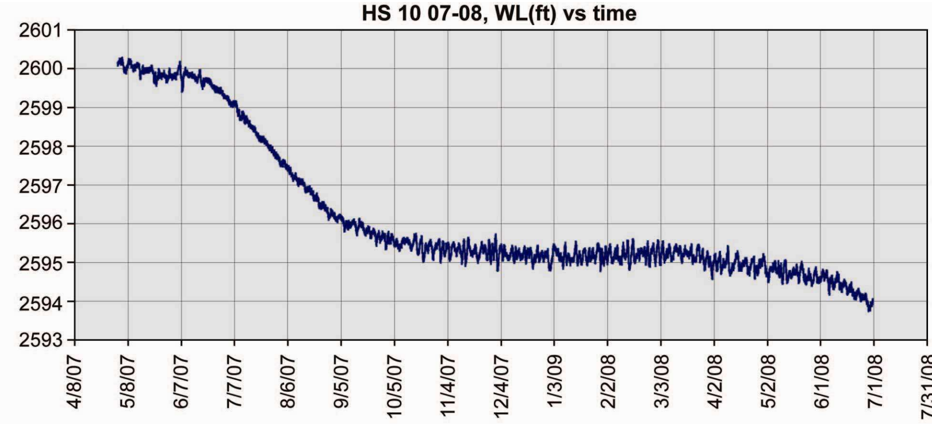
HS-9 (19542)
USGS ID: ?
SW SE NW 35 27-31
WWC5: 363947
Well Type: Irrigation

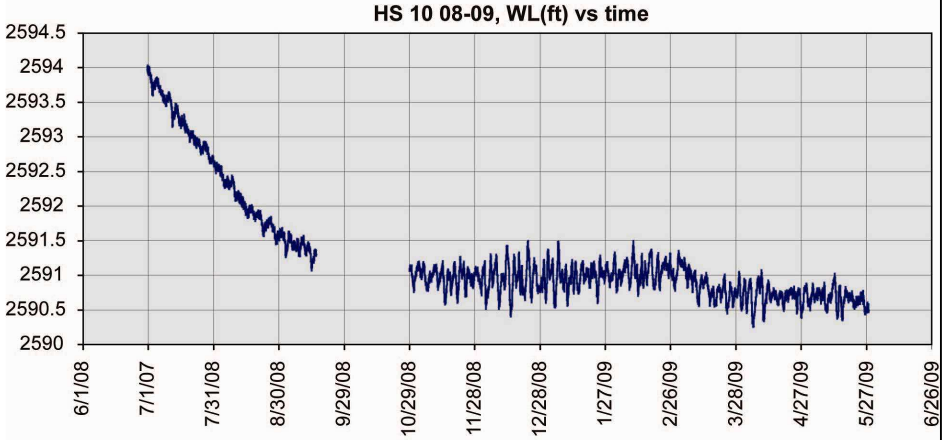
’07 WL(est-recov): 2596.57
’08 WL(est-recov): 2591
’09 WL(est-recov): 2587.15
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

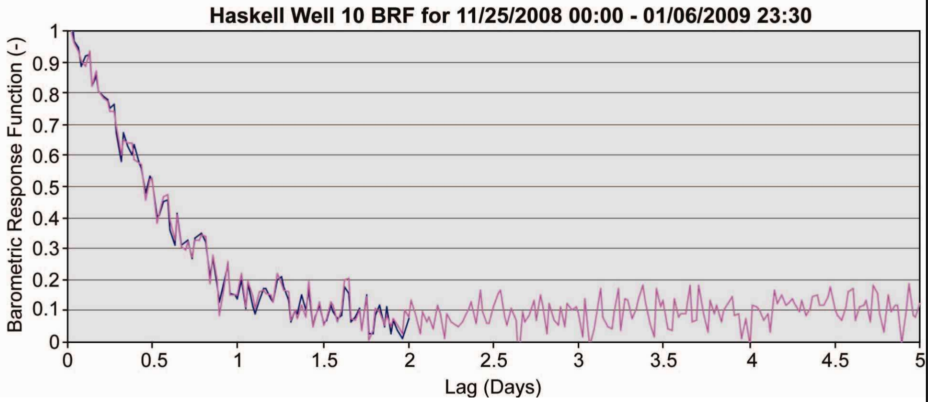
Surface Elev.:2847.17
Bedrock Elev: ?
EOH: 405’
EOH Elev: 2442.17
Well Depth: 398’
Depth Elev: 2449.17
Screen: 318-338, 358-378, 378-398
Scrn Elv: 2449-2489, 2509-2529
Gravel Pack: 20-398’
Casing Diameter: 16”
Borehole Diameter: ?

’06 WU: 330
’07 WU: 264
’08 WU: 184
’06 WU (totac): 7643
’07 WU (totac): 7657
’08 WU (totac):8133
’06 WU (2m-af): 12012.39
’07 WU (2mi-af): 10468.46
’08 WU (2mi-af): 10793.43
’06 WU (2mi-per irrac): 1.57
’07 WU (2mi-per irrac): 1.37
’08 WU (2mi-per irrac): 1.33
’06 WU (2mi-perac): 1.49
’07 WU (2mi-perac): 1.30
’08 WU (2mi-perac): 1.34

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







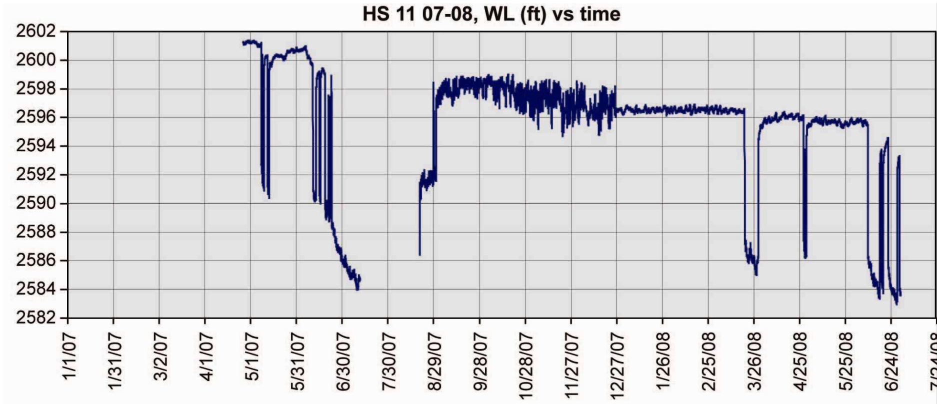
HS-10 (1207 old casing)
USGS ID: ?
SE SW NE 26 27-31
WWC5: 28170
Well Type: Irrigation (ret?)

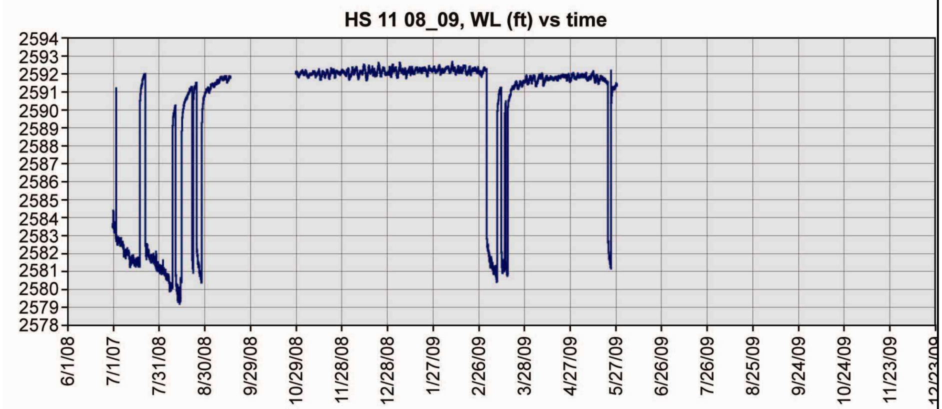
’07 WL(est-recov): 2600.1
’08 WL(est-recov): 2595.3
’09 WL(est-recov): 2591
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

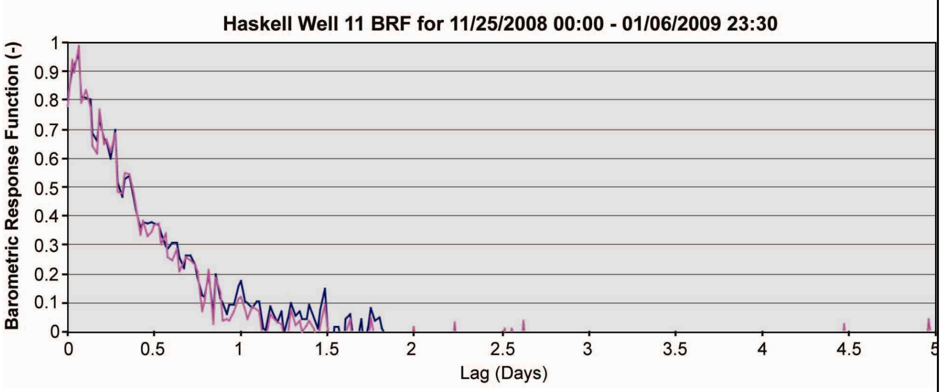
Surface Elev.: 2822.94
Bedrock Elev: ?
EOH: 300’
EOH Elev: 2522.94
Well Depth: 255
Depth Elev: 2567.94
Screen: 195-255’
Screen Elev: 2568-2628’
Gravel Pack: ?
Casing Diameter: 16”
Borehole Diameter: 26”

’06 WU: 0?
’07 WU: 0?
’08 WU: 0?
’06 WU (totac):
’07 WU (totac):
’08 WU (totac):
’06 WU (2m-af):
’07 WU (2mi-af):
’08 WU (2mi-af):
’06 WU (2mi-per irrac):
’07 WU (2mi-per irrac):
’08 WU (2mi-per irrac):
’06 WU (2mi-perac):
’07 WU (2mi-perac):
’08 WU (2mi-perac):

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







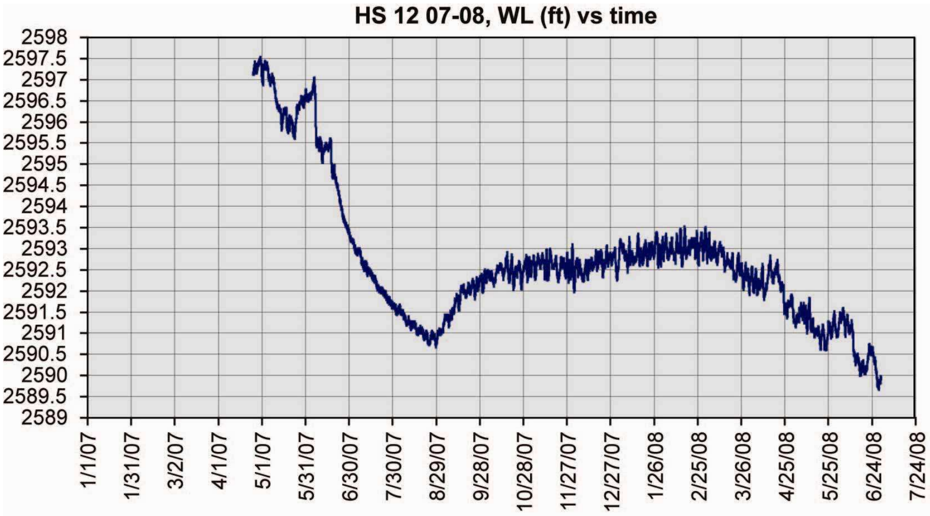
HS-11 (1207 new)
USGS ID: ?
NE SW NE 26 27-31
WWC5: 396941
Well Type: Irrigation

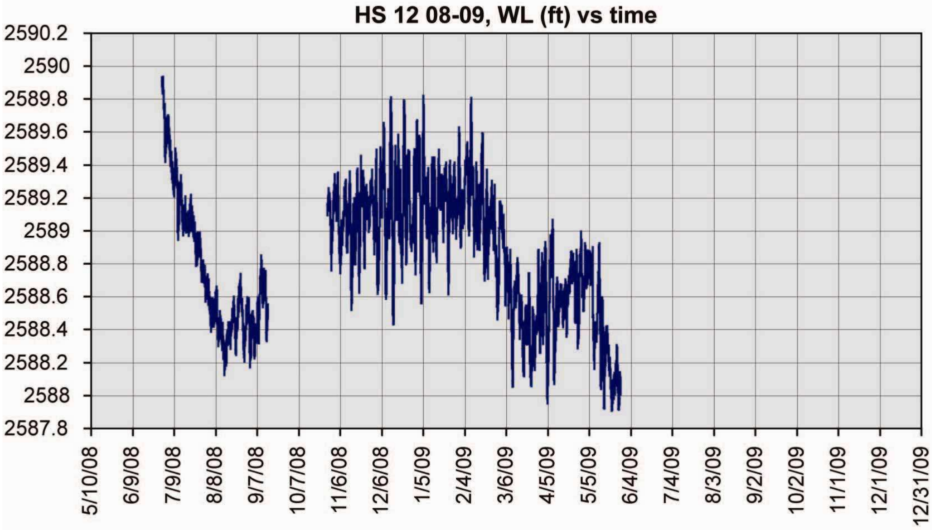
’07 WL(est-recov): 2601
’08 WL(est-recov): 2596.5
’09 WL(est-recov): 2592.3
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

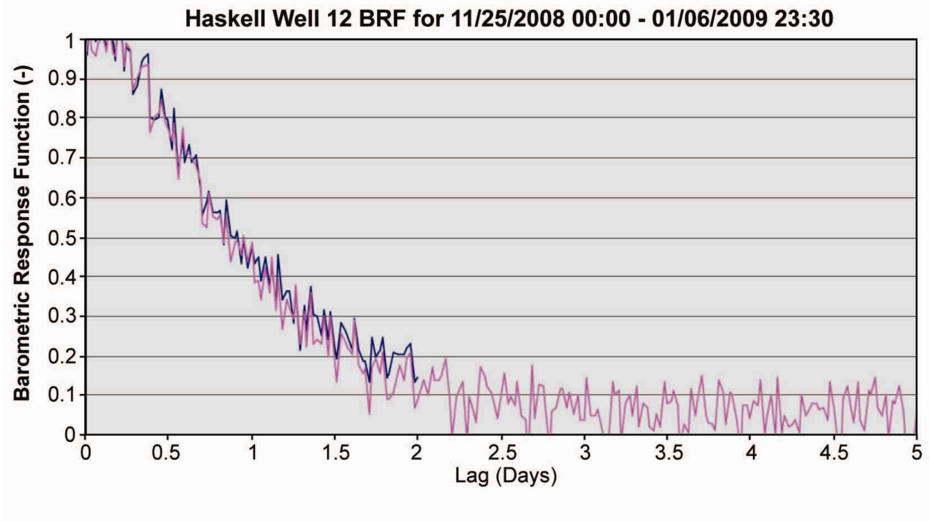
Surface Elev.: 2817.54
Bedrock Elev: ?
EOH: 425’
EOH Elev: 2392.54
Well Depth: 420’
Depth Elev: 2397.54
Screen: 250-420’
Screen Elev: 2398-2568’
Gravel Pack: 20-420’
Casing Diameter: 16”
Borehole Diameter: ?

’06 WU: 212.16
’07 WU: 228
’08 WU: 211
’06 WU (totac): 6545
’07 WU (totac): 6179
’08 WU (totac):6597
’06 WU (2m-af): 9364.87
’07 WU (2mi-af): 8104.91
’08 WU (2mi-af): 7946.61
’06 WU (2mi-per irrac): 1.43
’07 WU (2mi-per irrac): 1.31
’08 WU (2mi-per irrac): 1.20
’06 WU (2mi-perac): 1.16
’07 WU (2mi-perac): 1.01
’08 WU (2mi-perac): 0.99

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







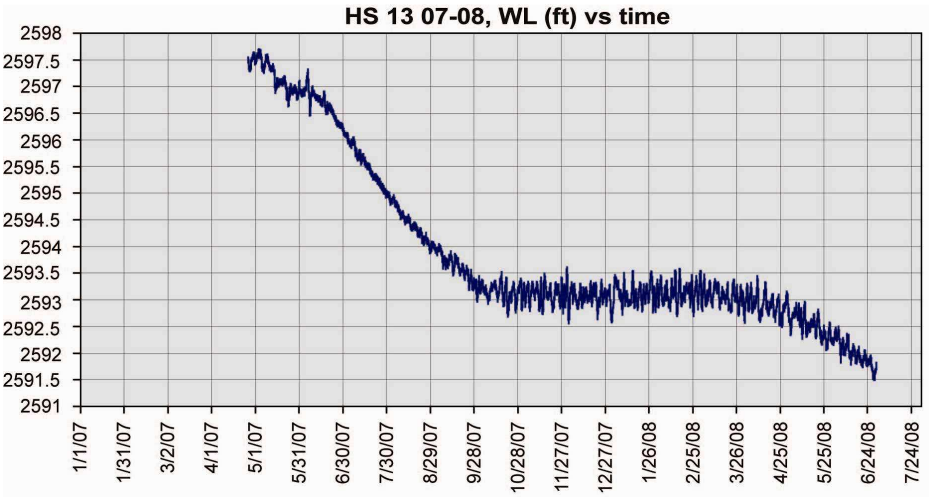
HS-12 (11750 old casing)
USGS ID:?
SE SW NW 31 27-30
WWC5: ?
Well Type: Irrigation (ret?)

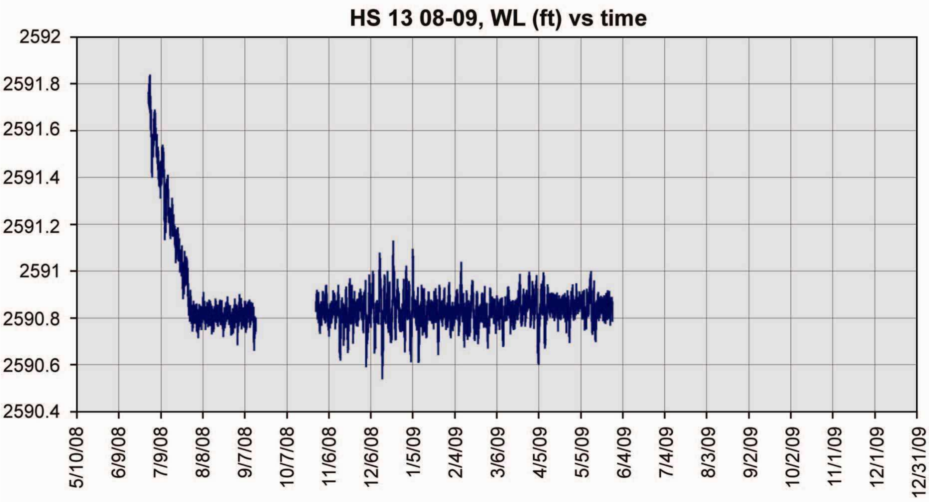
’07 WL(est-recov): 2597.3
’08 WL(est-recov): 2593
’09 WL(est-recov):
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

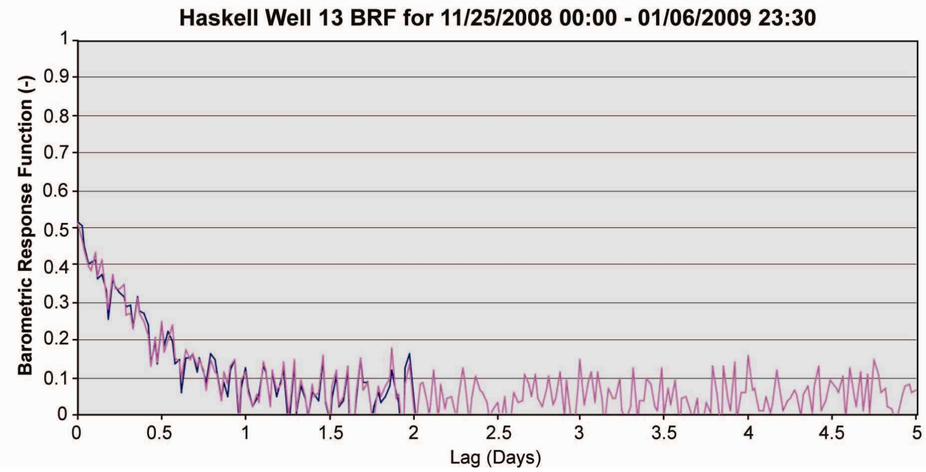
Surface Elev.: 2848.75
Bedrock Elev: ?
EOH: ?
Well Depth: ?
Depth Elev: ?
Screen: ?
Screen Elev: ?
Gravel Pack: ?
Casing Diameter: ?
Borehole Diameter: ?

’06 WU: 0
’07 WU: 0
’08 WU: 0
’06 WU (totac): 5365
’07 WU (totac): 5284
’08 WU (totac):5347
’06 WU (2m-af): 8376.09
’07 WU (2mi-af): 7380.58
’08 WU (2mi-af): 7319.37
’06 WU (2mi-per irrac): 1.56
’07 WU (2mi-per irrac): 1.40
’08 WU (2mi-per irrac): 1.37
’06 WU (2mi-perac): 1.04
’07 WU (2mi-perac): 0.92
’08 WU (2mi-perac): 0.91

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







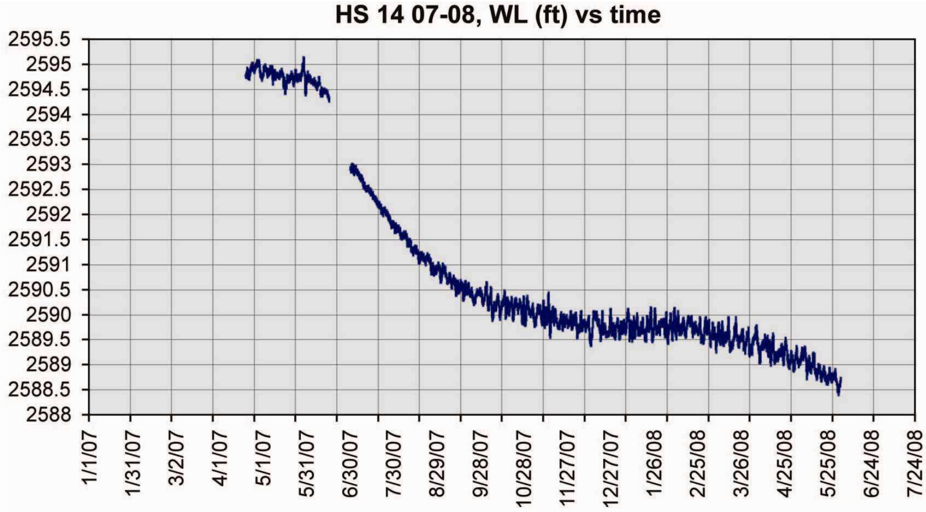
HS-13 (10035 old casing)
USGS ID: ?
SE SE SE 25 27-31
WWC5: ?
Well Type: Irrigation (ret?)

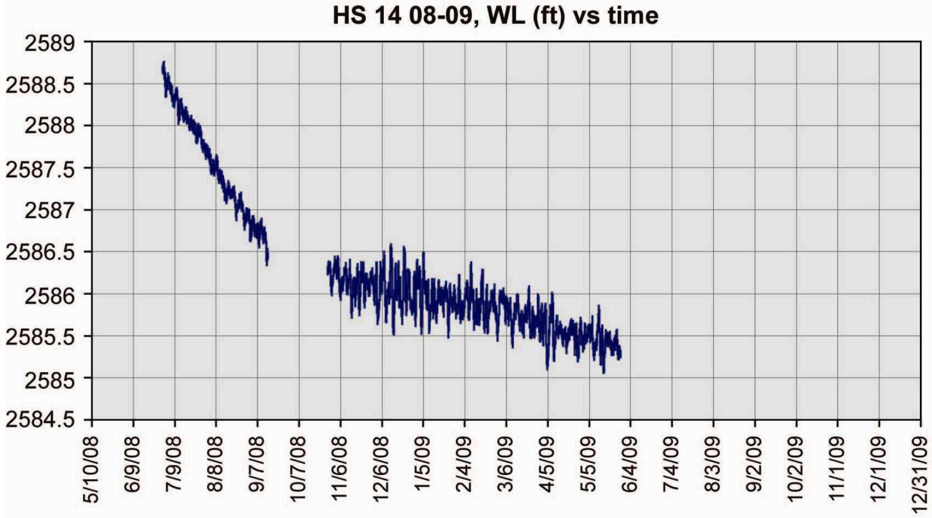
’07 WL(est-recov): 2597.4
’08 WL(est-recov): 2593.1
’09 WL(est-recov): 2590.8
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

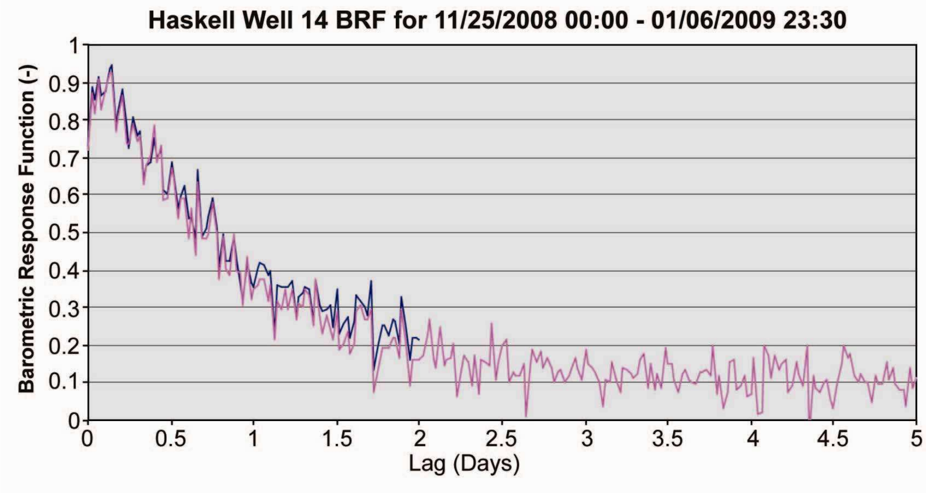
Surface Elev.: 2848.74
Bedrock Elev: ?
EOH: ?
Well Depth: ?
Depth Elev: ?
Screen: ?
Screen Elev: ?
Gravel Pack: ?
Casing Diameter: ?
Borehole Diameter: ?
WWC5: ?

’06 WU: 0
’07 WU: 0
’08 WU: 0
’06 WU (totac): 4660
’07 WU (totac): 4648
’08 WU (totac):4732
’06 WU (2m-af): 7247.95
’07 WU (2mi-af): 6374.29
’08 WU (2mi-af): 6431.4
’06 WU (2mi-per irrac): 1.56
’07 WU (2mi-per irrac): 1.37
’08 WU (2mi-per irrac): 1.36
’06 WU (2mi-perac): 0.90
’07 WU (2mi-perac): 0.79
’08 WU (2mi-perac): 0.80

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







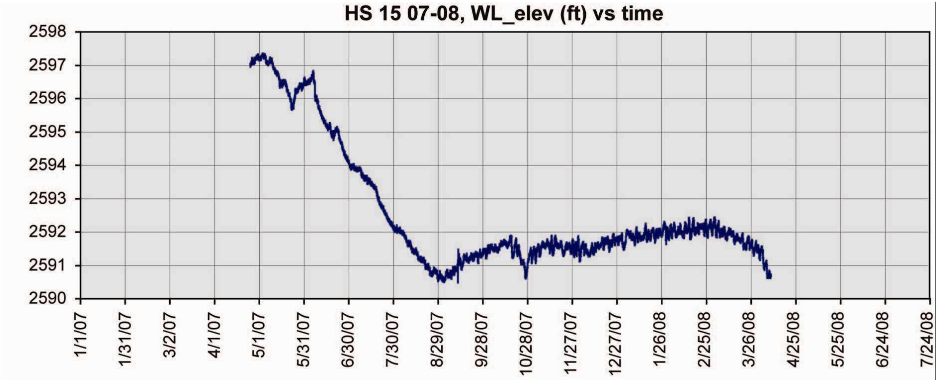
HS-14 (8157s old casing)
USGS ID: ?
SE SW SE 36 27-31
WWC5: 341913
Well Type: Irrigation (ret?)

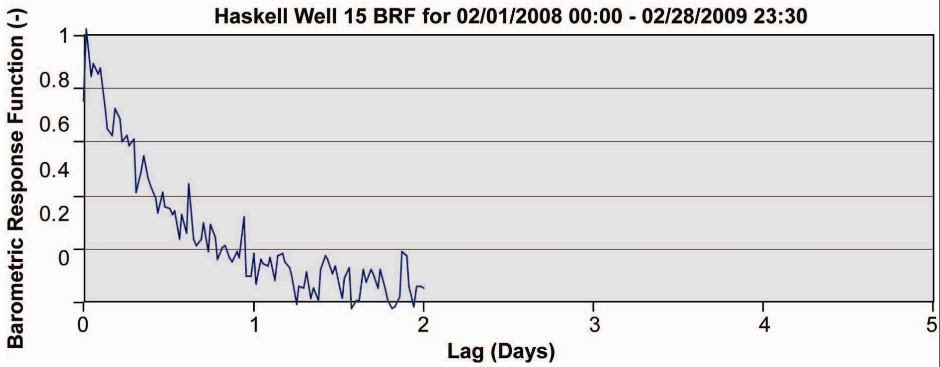
’07 WL(est-recov): 2594.9
’08 WL(est-recov): 2589.7
’09 WL(est-recov): 2586.51
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

Surface Elev.: 2845.63
Bedrock Elev: ?
EOH: 461’
EOH Elev: 2384.63
Well Depth: 455
Depth Elev: 2390.63
Screen: 415-435, 435-455’
Screen Elev: 2391-2431’
Gravel Pack: 20-455’
Casing Diameter: 16”
Borehole Diameter: ?

’06 WU: 0
’07 WU: 0
’08 WU: 0
’06 WU (totac): 5751
’07 WU (totac): 5873
’08 WU (totac):5939
’06 WU (2m-af): 8495.75
’07 WU (2mi-af): 8287.79
’08 WU (2mi-af): 7822.5
’06 WU (2mi-per irrac): 1.48
’07 WU (2mi-per irrac): 1.41
’08 WU (2mi-per irrac): 1.32
’06 WU (2mi-perac): 1.06
’07 WU (2mi-perac): 1.03
’08 WU (2mi-perac): 0.97

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”





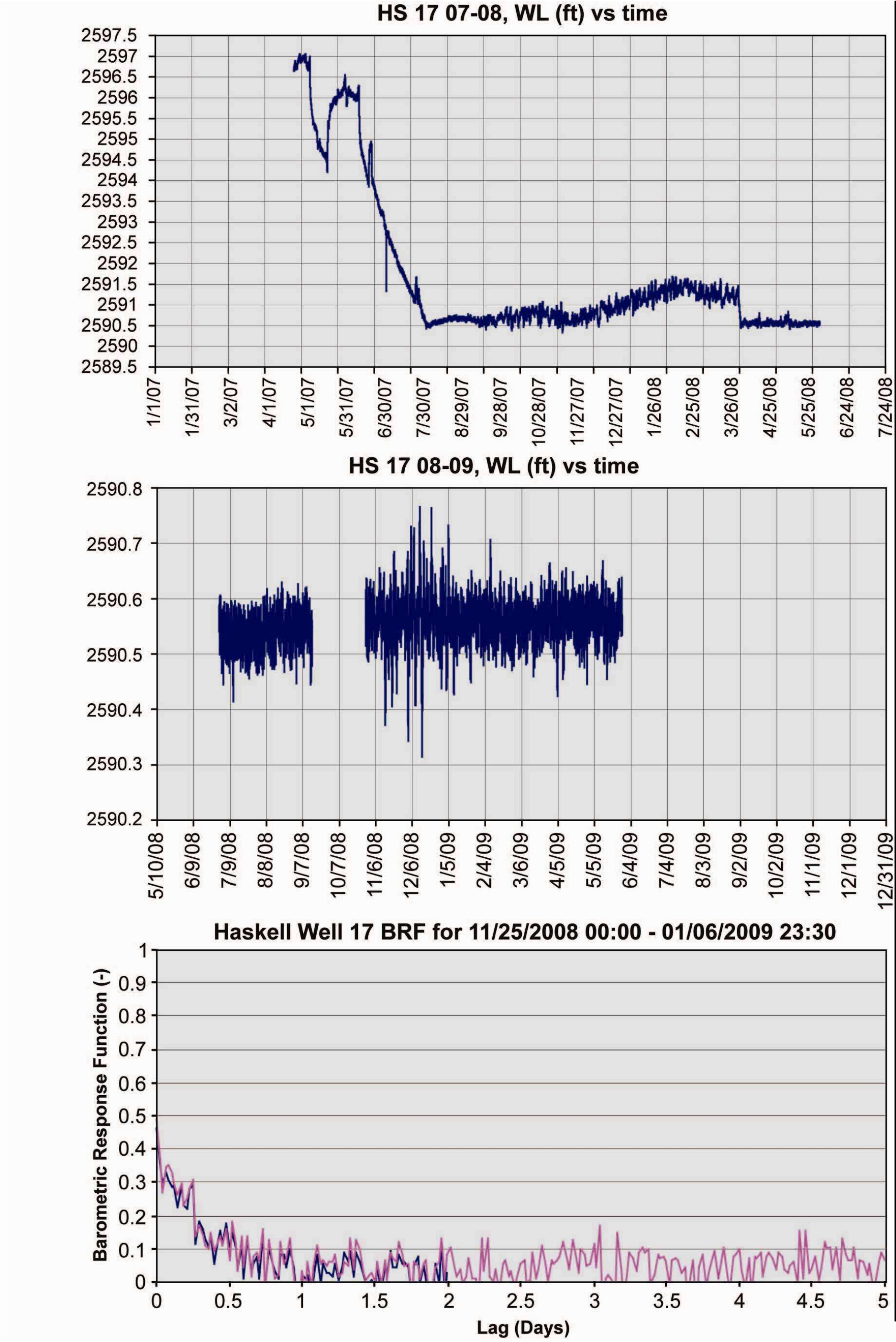
HS-15 (HS3 old casing, 8157)
USGS ID: ?
NE NE NW 36 27-31
WWC5: ?
Well Type: Irrigation (ret?)

’07 WL(est-recov): 2597.2
’08 WL(est-recov): 2592.17
’09 WL(est-recov):
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

Surface Elev.:2855.85
Bedrock Elev: ?
EOH: ?
Well Depth: ?
Depth Elev: ?
Screen: ?
Screen Elev: ?
Gravel Pack: ?
Casing Diameter: ?
Borehole Diameter: ?

’06 WU: 0
’07 WU: 0
’08 WU: 0
USED HS1 VALUES BLW:
’06 WU: 113.6
’07 WU: 158.76
’08 WU: 187.54
’06 WU (totac): 6526
’07 WU (totac): 6453
’08 WU (totac): 6714
’06 WU (2m-af): 9374.03
’07 WU (2mi-af): 8756.78
’08 WU (2mi-af): 8406.61
’06 WU (2mi-per irrac): 1.44
’07 WU (2mi-per irrac): 1.36
’08 WU (2mi-per irrac): 1.25
’06 WU (2mi-perac): 1.17
’07 WU (2mi-perac): 1.09
’08 WU (2mi-perac): 1.05

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”



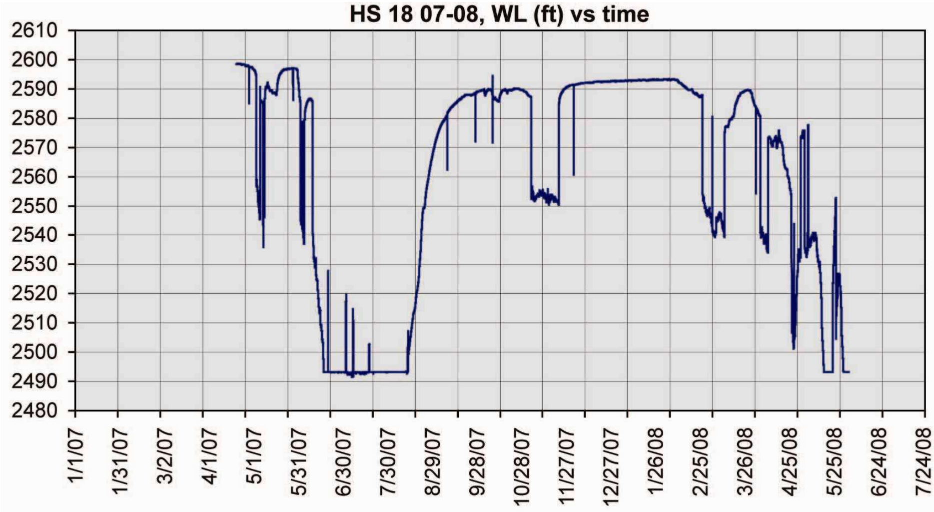
HS-17 (19542 old casing)
USGS ID: ?
SE SW NW 35 27-31 WWC5:
WWC5: ?
Well Type: Irrigation (ret?)

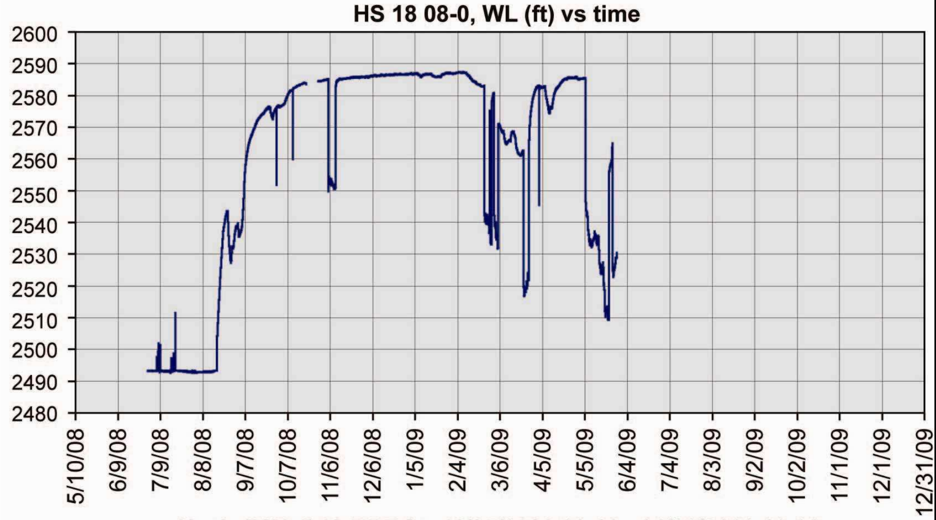
’07 WL(est-recov): 2596.9
’08 WL(est-recov): 2591.4
’09 WL(est-recov): 2590.56
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

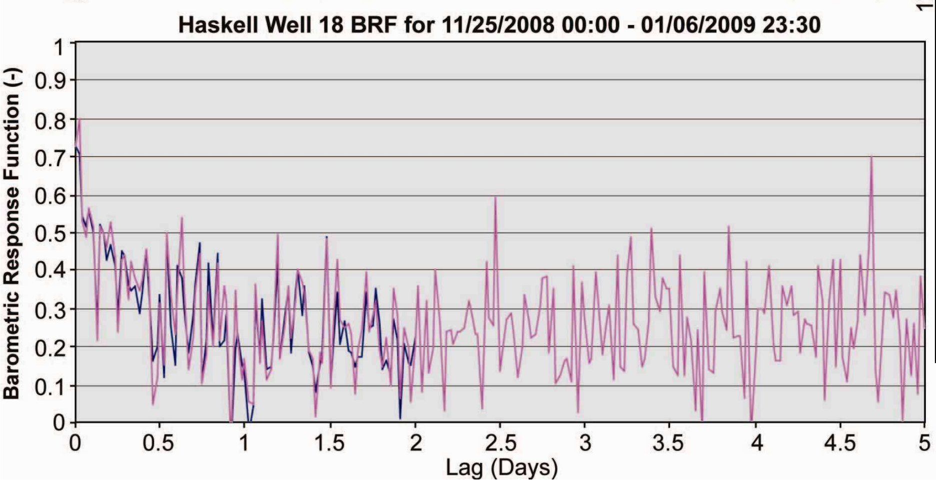
Surface Elev.: 2847.45
Bedrock Elev: ?
EOH: ?
Well Depth: ?
Depth Elev: ?
Screen: ?
Screen Elev: ?
Gravel Pack: ?
Casing Diameter: ?
Borehole Diameter: ?

’06 WU: 0
’07 WU: 0
’08 WU: 0
’06 WU (totac): 7873
’07 WU (totac): 7869
’08 WU (totac):8363
’06 WU (2m-af): 12075.39
’07 WU (2mi-af): 10462.46
’08 WU (2mi-af): 10462.72
’06 WU (2mi-per irrac): 1.53
’07 WU (2mi-per irrac): 1.33
’08 WU (2mi-per irrac): 1.25
’06 WU (2mi-perac): 1.5
’07 WU (2mi-perac): 1.3
’08 WU (2mi-perac): 1.3

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







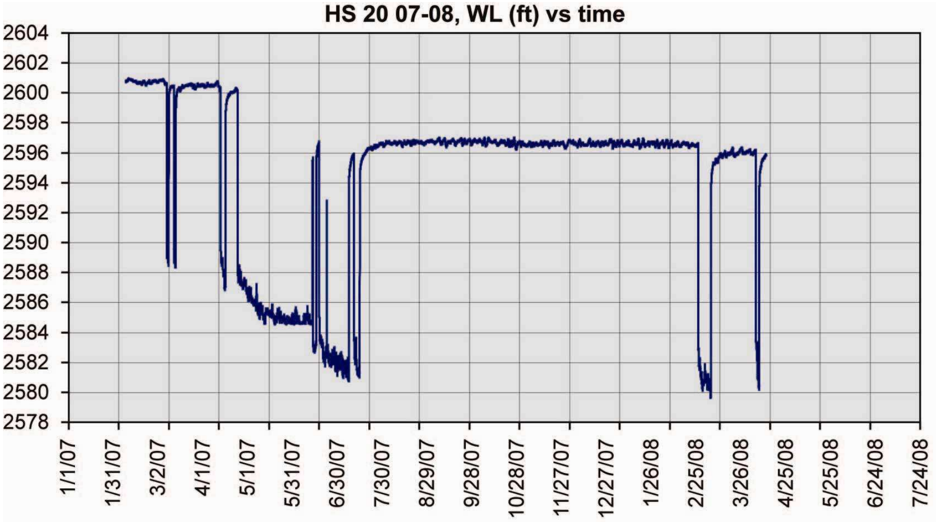
HS-18 (19032)
USGS ID: ?
SW SE NE 25 27-31
WWC5: 304615
Well Type: Irrigation

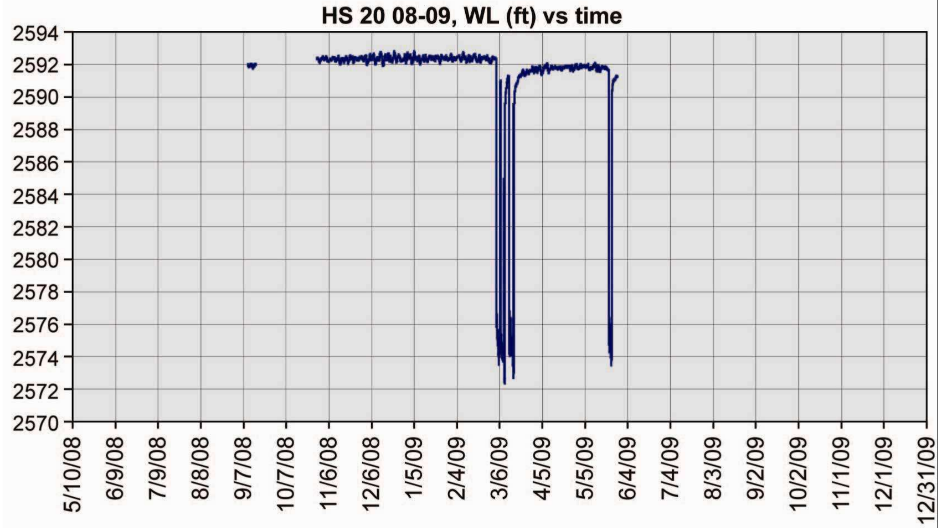
’07 WL(est-recov): 2597.1
’08 WL(est-recov): 2592.8
’09 WL(est-recov): 2582.67
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

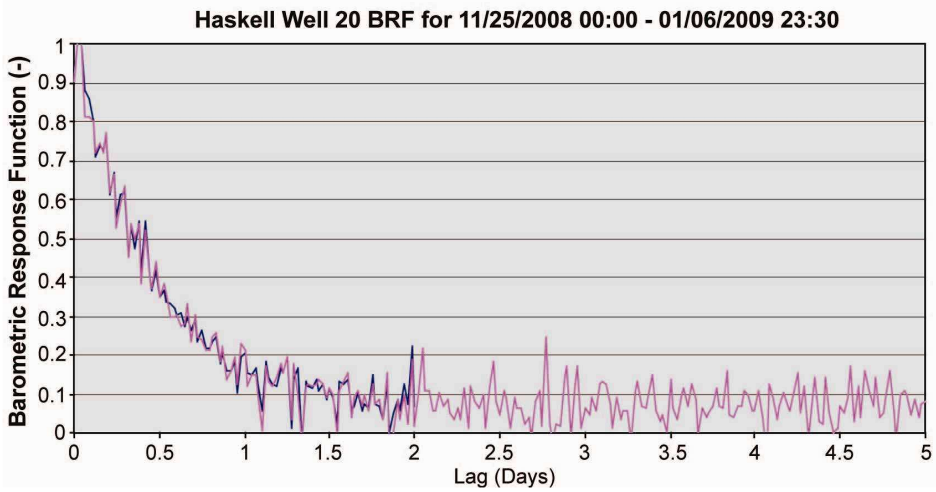
Surface Elev.: 2835.12
Bedrock Elev: ?
EOH: 390’
EOH Elev: 2445.12’
Well Depth: 390
Depth Elev: 2445.12
Screen: 235-390’
Screen Elev: 2445-2600’
Gravel Pack: 20-390’
Casing Diameter: 16”
Borehole Diameter: 30”

’06 WU: 257
’07 WU: 185
’08 WU: 174
’06 WU (totac): 6120
’07 WU (totac): 6070
’08 WU (totac):6194
’06 WU (2m-af): 8362.42
’07 WU (2mi-af): 6998.14
’08 WU (2mi-af): 7264.19
’06 WU (2mi-per irrac): 1.37
’07 WU (2mi-per irrac): 1.15
’08 WU (2mi-per irrac): 1.17
’06 WU (2mi-perac): 1.04
’07 WU (2mi-perac): 0.87
’08 WU (2mi-perac): 0.90

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







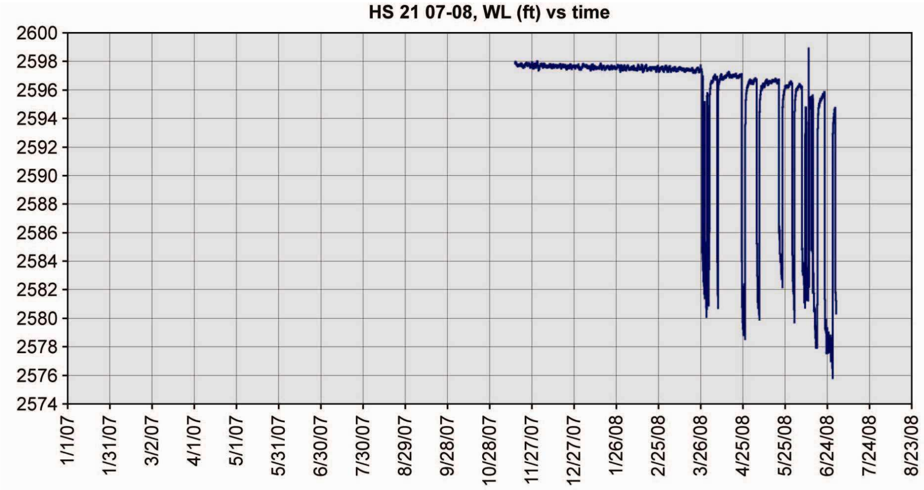
HS-20 (18715)
USGS ID: ?
SE SE NW 25 27-31
WWC5: 28166
Well Type: Irrigation

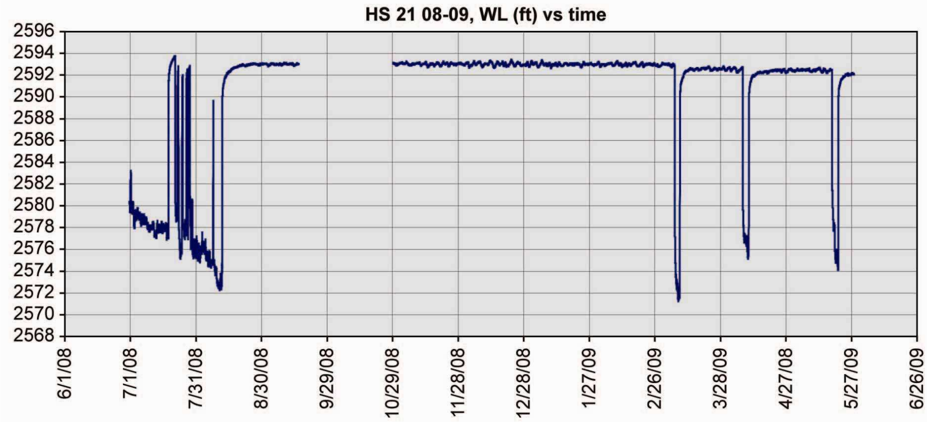
’07 WL(est-recov): 2600.8
’08 WL(est-recov): 2596.5
’09 WL(est-recov): 2592.3
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

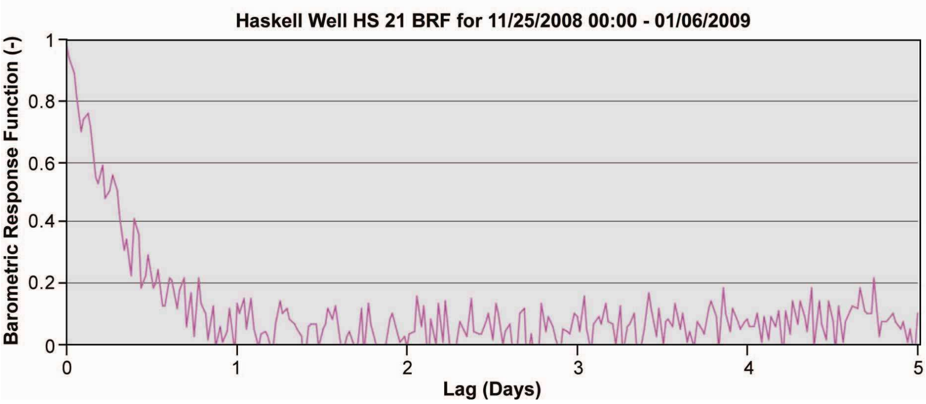
Surface Elev.: 2828.57
Bedrock Elev: ?
EOH: 315’
EOH Elev: 2513.57’
Well Depth: 300
Depth Elev: 2528.57
Screen: 220-300’
Screen Elev: 2529-2609’
Gravel Pack: ?
Casing Diameter: 16”
Borehole Diameter: 26”

’06 WU: 253
’07 WU: 221
’08 WU: 219
USED HS8 VALUES BLW:
’06 WU (totac): 6170
’07 WU (totac): 6189
’08 WU (totac):6305
’06 WU (2m-af): 7984.87
’07 WU (2mi-af): 6816.2
’08 WU (2mi-af): 7163.61
’06 WU (2mi-per irrac): 1.29
’07 WU (2mi-per irrac): 1.10
’08 WU (2mi-per irrac): 1.14
’06 WU (2mi-perac): 0.99
’07 WU (2mi-perac): 0.85
’08 WU (2mi-perac): 0.89

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







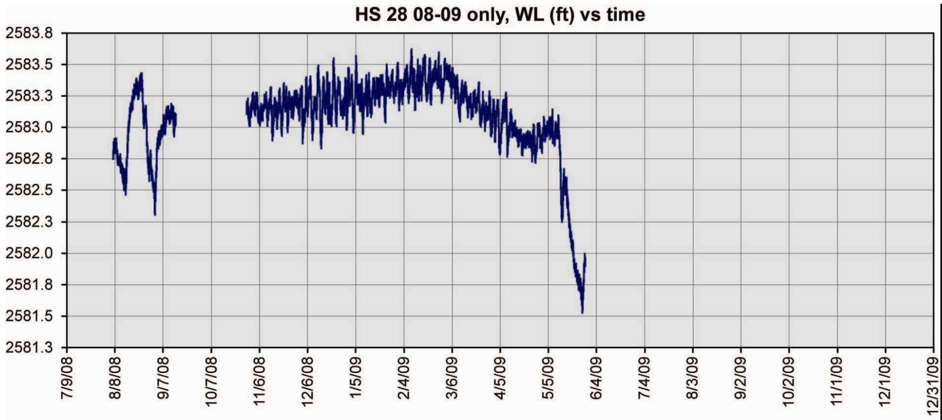
HS-21 (Annual, 6281)
USGS ID: 374044100395001
SW SE SW 24 27-31
WWC5: 28160
Well Type: Irrigation

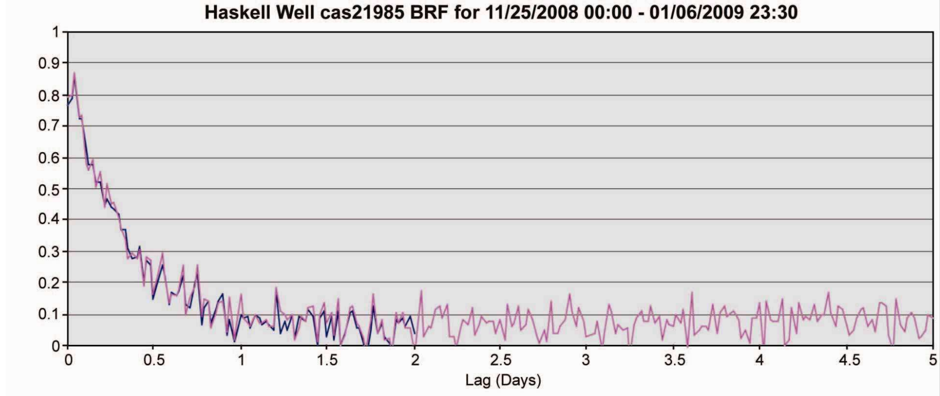
’07 WL(est-recov): NA
’08 WL(est-recov): 2597.8
’09 WL(est-recov): 2592.9
’07 WL(Wiz-Elev): 2604.95
’08 WL(Wiz-Elev): 2600.35
’09 WL(Wiz-Elev): 2595.78

Surface Elev.: 2821.67
Bedrock Elev: ?
EOH: 502
EOH Elev: 2319.67’
Well Depth: 383
Depth Elev: 2438.67
Screen: 220-280, 350-380
Scr Elv: 2442-2472, 2542-2601
Gravel Pack: ?
Casing Diameter: 16”
Borehole Diameter: ?

’06 WU: 250
’07 WU: 166
’08 WU: 205
’06 WU (totac): 6128
’07 WU (totac): 6107
’08 WU (totac):6244
’06 WU (2m-af): 7557.87
’07 WU (2mi-af): 6423.2
’08 WU (2mi-af): 6772.61
’06 WU (2mi-per irrac): 1.23
’07 WU (2mi-per irrac): 1.05
’08 WU (2mi-per irrac): 1.08
’06 WU (2mi-perac): 0.94
’07 WU (2mi-perac): 0.80
’08 WU (2mi-perac): 0.84

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”





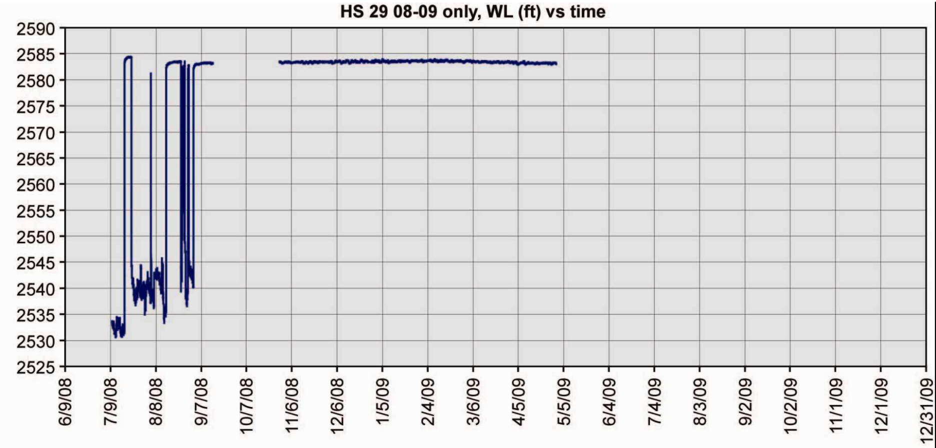
HS-28 (21985)
USGS ID: ?
NW SW NE 35 27-31
WWC5: ?
Well Type: Irrigation (ret.)

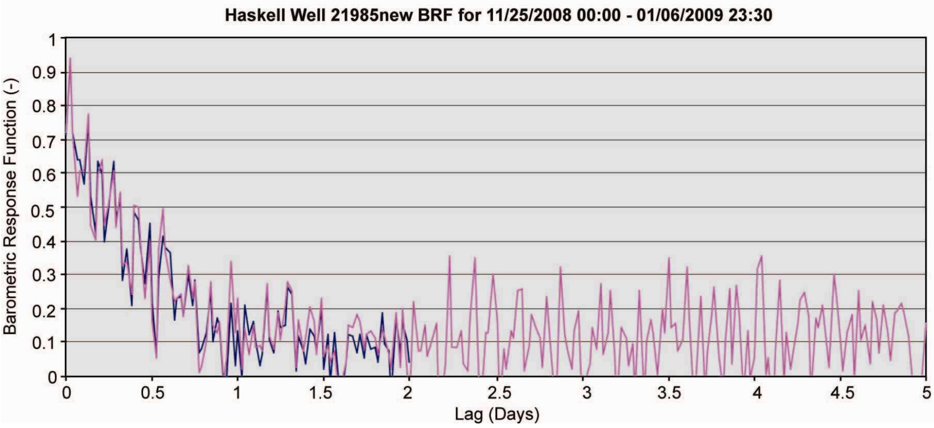
’07 WL(est-recov):
’08 WL(est-recov):
’09 WL(est-recov):
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

Surface Elev.: ?
Bedrock Elev: ?
EOH: ?
Well Depth: ?
Depth Elev: ?
Screen: ?
Screen Elev: ?
Gravel Pack: ?
Casing Diameter: ?
Borehole Diameter: ?

’06 WU: 205
’07 WU: 110
’08 WU: 0
’06 WU (totac):
’07 WU (totac):
’08 WU (totac):
’06 WU (2m-af):
’07 WU (2mi-af):
’08 WU (2mi-af):
’06 WU (2mi-per irrac):
’07 WU (2mi-per irrac):
’08 WU (2mi-per irrac):
’06 WU (2mi-perac):
’07 WU (2mi-perac):
’08 WU (2mi-perac):

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”





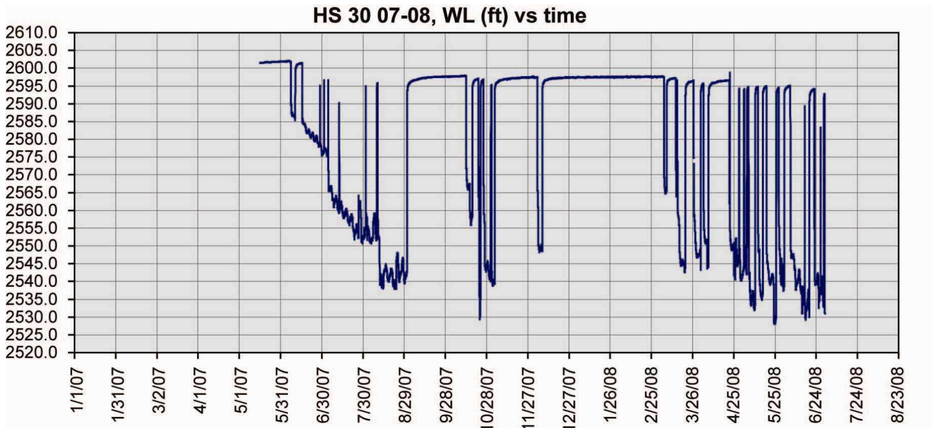
HS-29 (21985 new)
USGS ID: ?
NW SW NE 35 27-31
WWC5: ?
Well Type: Irrigation

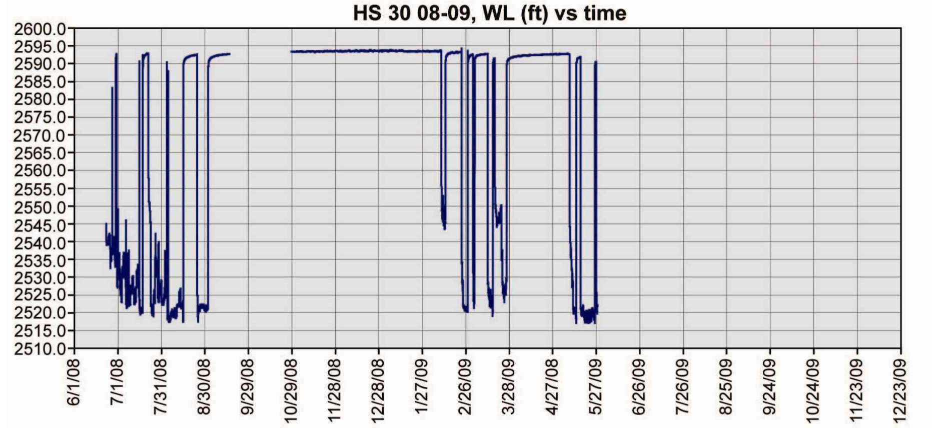
’07 WL(est-recov): NA
’08 WL(est-recov): NA
’09 WL(est-recov): 2583.5
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

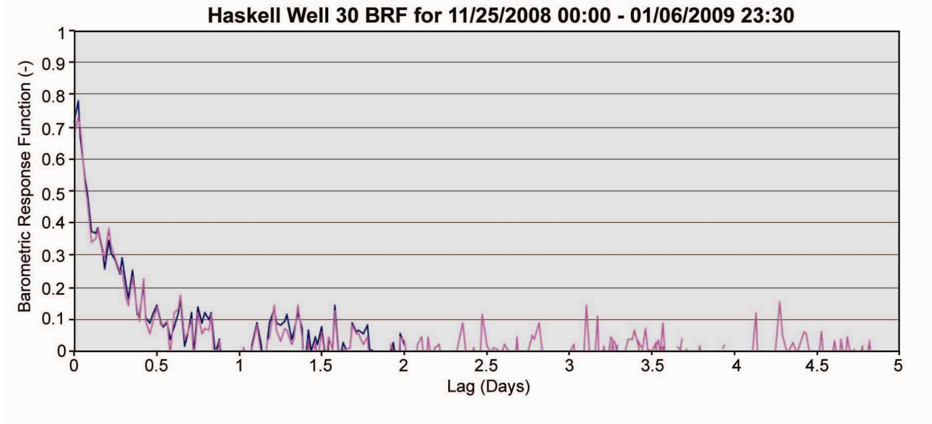
Surface Elev.: 2843 (est)
Bedrock Elev: ?
EOH: 490’
Well Depth: 382’
Depth Elev: 2461’
Screen: 342-362, 362-382
Screen Elev: 2461-2501’
Gravel Pack: 20-382
Casing Diameter: 16”
Borehole Diameter: ?

’06 WU: NA
’07 WU: NA
’08 WU: 159
’06 WU (totac):
’07 WU (totac):
’08 WU (totac):
’06 WU (2m-af):
’07 WU (2mi-af):
’08 WU (2mi-af):
’06 WU (2mi-per irrac):
’07 WU (2mi-per irrac):
’08 WU (2mi-per irrac):
’06 WU (2mi-perac):
’07 WU (2mi-perac):
’08 WU (2mi-perac):

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”







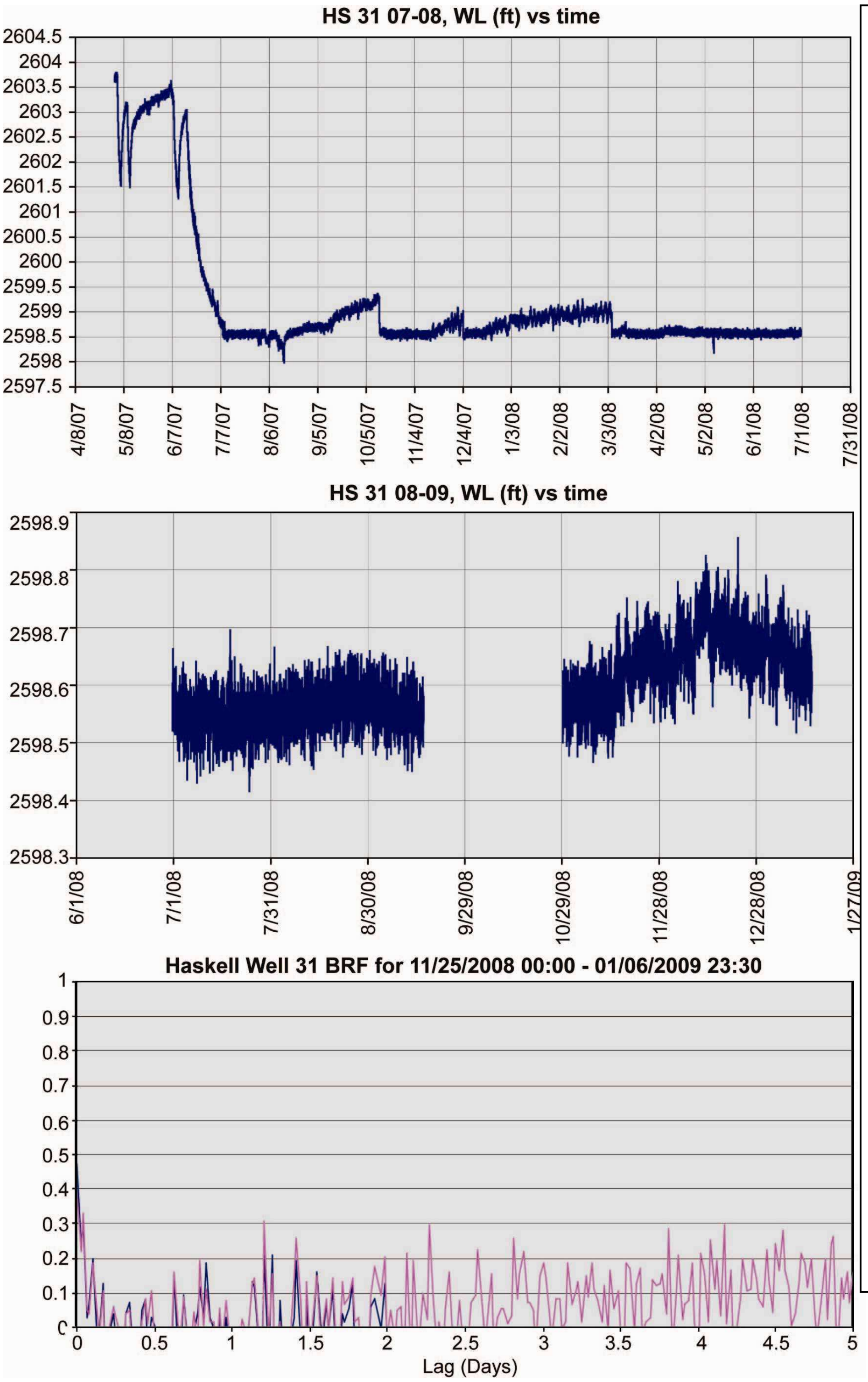
HS-30 (cas 16212)
USGS ID: ?
NW NW SE 23 27-31
WWC5: ?
Well Type: Irrigation (ret)

’07 WL(est-recov): 2601.5
’08 WL(est-recov): 2597.3
’09 WL(est-recov): 2593.3
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

Surface Elev.: 2813 (est)
Bedrock Elev: ?
EOH: ?
Well Depth: ?
Depth Elev: ?
Screen: ?
Screen Elev: ?
Gravel Pack: ?
Casing Diameter: ?
Borehole Diameter: ?

’06 WU: 0
’07 WU: 0
’08 WU: 0
Below From HS-31:
’06 WU (totac): 6400
’07 WU (totac): 6374
’08 WU (totac):6394
’06 WU (2m-af): 9008.42
’07 WU (2mi-af): 8130.44
’08 WU (2mi-af): 7821.54
’06 WU (2mi-per irrac): 1.41
’07 WU (2mi-per irrac): 1.28
’08 WU (2mi-per irrac): 1.22
’06 WU (2mi-perac): 1.12
’07 WU (2mi-perac): 1.01
’08 WU (2mi-perac): 0.97

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”



HS-31 (16212)
USGS ID: ?
NW NW SE 23 27-31
WWC5: 302391
Well Type: Irrigation

’07 WL(est-recov): 2603.7
’08 WL(est-recov): 2598.6
’09 WL(est-recov): 2598.6
’07 WL(Wiz-Elev): NA
’08 WL(Wiz-Elev): NA
’09 WL(Wiz-Elev): NA

Surface Elev.: 2812 (est)
Bedrock Elev: ?
EOH: 350’
Well Depth: 336’
Depth Elev: 2476’
Screen: 216-256’, 296-336’
Screen Elev: 2476-2516’, 2556-2596’
Gravel Pack: 20-336’
Casing Diameter: 16”
Borehole Diameter: 26”

’06 WU: 319
’07 WU: 261
’08 WU: 298
’06 WU (totac): 6400
’07 WU (totac): 6374
’08 WU (totac):6394
’06 WU (2m-af): 9008.42
’07 WU (2mi-af): 8130.44
’08 WU (2mi-af): 7821.54
’06 WU (2mi-per irrac): 1.41
’07 WU (2mi-per irrac): 1.28
’08 WU (2mi-per irrac): 1.22
’06 WU (2mi-perac): 1.12
’07 WU (2mi-perac): 1.01
’08 WU (2mi-perac): 0.97

Mar-Sep Precip
’06: 17.31”
’07: 10.14”
’08: 10.15”
’09: 11.46”

Appendix B: Well Recovery Studies

B.1 Estimation of water-level elevation at full recovery and the date of recovery

It is clear by inspection of the detailed well hydrographs produced by the transducers at each of the index wells that water levels are often still rising when the next season's pumping starts (Figure 3.1). 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 in many cases, so, as part of this project, we are developing methods for estimating the elevation to which the water level in a well would recover if full recovery could be attained.

Our major focus for this period has been on two methods: an extension of a method that was originally developed for estimating full-recovery formation pressures in oil reservoirs from pressure data collected following a period of pumping, and an empirical approach that involves fitting a quadratic expression to the recovery data. The first method (the Horner method; Streltsova, 1988) is itself an extension of the Theis recovery method (Batu, 1998), an approach commonly used by groundwater hydrologists to estimate transmissivity from water-level data collected during the recovery period following a pumping test. We will briefly describe both approaches in this appendix and then demonstrate the approaches in Appendix B.2 using three years of data from the long-term KGS field site in Pawnee County along the Arkansas River just northeast of Larned (Larned Research Site). This site is utilized for the demonstration because water levels fully recover each winter prior to the next pumping season. Thus, we can check the estimates produced by the methods against the actual recovery levels.

In this section, we will present the basic foundations of the first approach using the water-level recovery from a single pumping well. We will then extend the approach to the more general case, but we will not present a derivation here. The full derivation is presented in Appendix B.4.

We will begin by considering a single well pumping at a constant rate (Q) for a finite period in a homogeneous, unbounded confined or thick unconfined aquifer. The water-level elevation [h(r,t)] in the recovery period following the cessation of pumping can be written as:

$$h(r,t) = h_0 - s(r,t_p) \tag{B.1.1}$$

where

h_0 = water-level elevation at full recovery;

$s(r,t_p)$ = residual drawdown (drawdown still remaining after pump is cut off) at location r and time t_p;

r = radial distance from pumping well to well at which water level is measured;

t and t_p = time since some reference time and time since pumping began, respectively.

A short time after pumping has ceased, the residual drawdown from that time on can be approximated using image well theory and the Cooper-Jacob semilog truncation of the Theis equation (Batu, 1998):

$$s(r,t_p) \approx \frac{Q}{4\pi T} log\left(\frac{2.25Tt_p}{r^2 S}\right) - \frac{Q}{4\pi T} log\left(\frac{2.25Tt_r}{r^2 S}\right)$$

(B.1.2)

where

T = transmissivity of the aquifer;

S = storage coefficient of the aquifer;

t_r = time since pumping stopped.

Equation (B.1,2) can be simplified by using a log identity:

$$s(r,t_p) \approx \frac{Q}{4\pi T} log\left(\frac{t_p}{t_r}\right)$$

(B.1.3)

Equation (B.1.2) is the Theis recovery equation that is commonly used for estimating aquifer transmissivity from recovery period data. Substitution of (B.1.3) into (B.1.1) produces the equation for estimating the water-level elevation at full recovery with the Horner plot method:

$$h(r,t) \approx h_0 - \frac{Q}{4\pi T} log\left(\frac{t_p}{t_r}\right)$$

(B.1.4)

As the time since the cessation of pumping (t_r) increases, the ratio in the log term approaches one and the log of that ratio approaches zero. The Horner plot approach is similar to the Theis recovery method except that the water-level elevation (h) is plotted versus the log ratio instead of residual drawdown(s). In either case, the relationship should be linear in the semilog plotting format. Given that one often is not able to continue to measure water levels until full recovery, the head at full recovery can be estimated by projecting the best-fit straight line to a t_p/t_r ratio of 1 (log ratio is zero). The corresponding water-level elevation value is the water level at full recovery (h_0 in equations (B.1.1) and (B.1.4)).

We have extended the Horner plot approach to the more general case of an arbitrary number of wells pumping periodically over an irrigation season. The resulting extension of equation (B.1.4) can be written as:

$$h(r,t) \approx h_0 - A log\left(\frac{t_{pf}}{t_{rf}}\right)$$

(B.1.5)

where

A = constant coefficient depending on pumping rate and schedule, number of wells, transmissivity, etc.

t_{pf} = time since the start of the final (f) period of pumping;

t_{rf} = time since the end of the final (f) period of pumping.

Although the value for A will typically not be known, the key point is that the plotting relationship is still linear in the water-level elevation versus log ratio format. Thus, the projection of the best-fit straight line to a t_{pf}/t_{rf} ratio of 1 (log ratio is zero) can still be done to estimate the water-level elevation at full recovery. The full development of equation (B.1.5) is given in Appendix B.4. A major assumption of this approach is that inflow from more distant regions of the aquifer is the source of all of the pumped water. We are currently exploring modifying the approach for application to conditions where virtually all of the pumped water comes from local aquifer storage, i.e. aquifer dewatering in the vicinity of the well, so that the approach is more consistent with the common conditions in the High Plains aquifer in the three western GMDs.

The second approach that we are pursuing is the simple fitting of a curve to the smoothest part of the recovery plot, covering as long a time as possible, but clearly between any noticeable effects of pumping. We have tested various standard mathematical functions, and find that the simple quadratic (second order polynomial) curve consistently provides a good fit to the water-level data. The best-fit curve is extrapolated to its maximum value, which is taken as the elevation at full recovery, and the corresponding time is taken as the date at which full recovery would be attained. Given that the recovery data generally plot as a smooth curve with a monotonically decreasing slope and no inflection points on a water-level elevation versus time plot, a quadratic expression should provide a reasonable fit to the data in most cases. The key question that we are currently exploring is how much reliability can we place in the elevation and recovery date estimates we obtain using this approach.

B.2 Methods comparison at the Larned Research Site

To demonstrate these methods and assess the reliability of the estimates obtained with them, we used water-level data from four wells at the Larned Research Site over the three consecutive winters between 2004 and 2006 (Butler et al. 2008). An example winter season for a well in this data set is shown in Figure B.2-1. Both the extended Horner method and the curve-fitting method were used to calculate the water-level elevation at full recovery for each of the three years. These calculations were performed both before and after correcting the water-level data for fluctuations in barometric pressure. We also estimated the water level at full recovery and the approximate date at which it was attained from a visual inspection of the data plots.

For the extended Horner method, the end of the final pumping period was set at the time where the water-level elevation during that period reached a minimum. The start of the final pumping period was set four days before this time, a reasonable duration of pumping for irrigating a complete circle by the central-pivot systems used in the Larned area. Values for t_{pf} and t_{rf}, as well as the ratio of the total time since pumping began to the recovery time (t_{pf}/t_{rf}), were calculated for 15-minute intervals throughout the recovery period. Water-level elevation was plotted against this ratio on a log scale (Figure B.2-2). A straight line was fit to the final part of this curve (the portion of the curve where $t_{pf}/t_{rf} \leq 1.1$) and extrapolated to $t_{pf}/t_{rf} = 1$ (value can also be obtained by adding the slope and intercept). The water-level elevation at $t_{pf}/t_{rf} = 1$ is the water level that would be reached if the well had unlimited time to recover.

For the curve-fitting method, a quadratic curve was fit to the final portion of the recovery data (where $t_{pf}/t_{rf} \leq 1.1$), producing a very shallow, downward-facing parabola (Figure B.2-3). The maximum of this curve is assumed to be the water elevation at full recovery and the time of the maximum is assumed to be the date on which full recovery would be reached.

The results of these calculations are shown in Table B.1-1. The calculations were performed using the original water-level data, as well as data that had been corrected for fluctuations in barometric pressure. There was good agreement between the recovered water levels calculated using the extended-Horner and curve-fitting methods. In all cases, the results from the two methods agreed to within about 0.1 ft. On average, the extended-Horner method produced slightly higher static water elevation results than did the curve-fitting method. The estimates of the water level at full recovery agreed well with a visual estimation from the data plot. When compared to the recovered water levels determined by visual inspection, the extended-Horner method results differed by an average of 0.08 ft, and the curve-fitting method results differed by an average of 0.05 ft. However, the recovery dates obtained using the curve-fitting method varied widely and did not necessarily correspond to the section of the recovery curve where water level appeared to stabilize. This suggests that quadratic curve-fitting is not an effective way to determine recovery dates, although it did appear to provide a reasonable approximation of the water elevation at full recovery for this field demonstration.

A further check on these methods was performed by removing the data for the last half of the interval used in the analysis and repeating the analysis for all three years for well LWC 2. This exercise, the results of which are presented in Table B.1-2, was done to assess performance when wells are further away from complete recovery. These results indicate that the methods are still useful. The extended Horner method is less sensitive to the removal of the late recovery data, producing results within a few hundredths of a foot of those obtained using the full data set. The curve-fitting method was more sensitive to this change but still produced water-level results within 0.15 ft of those previously calculated.

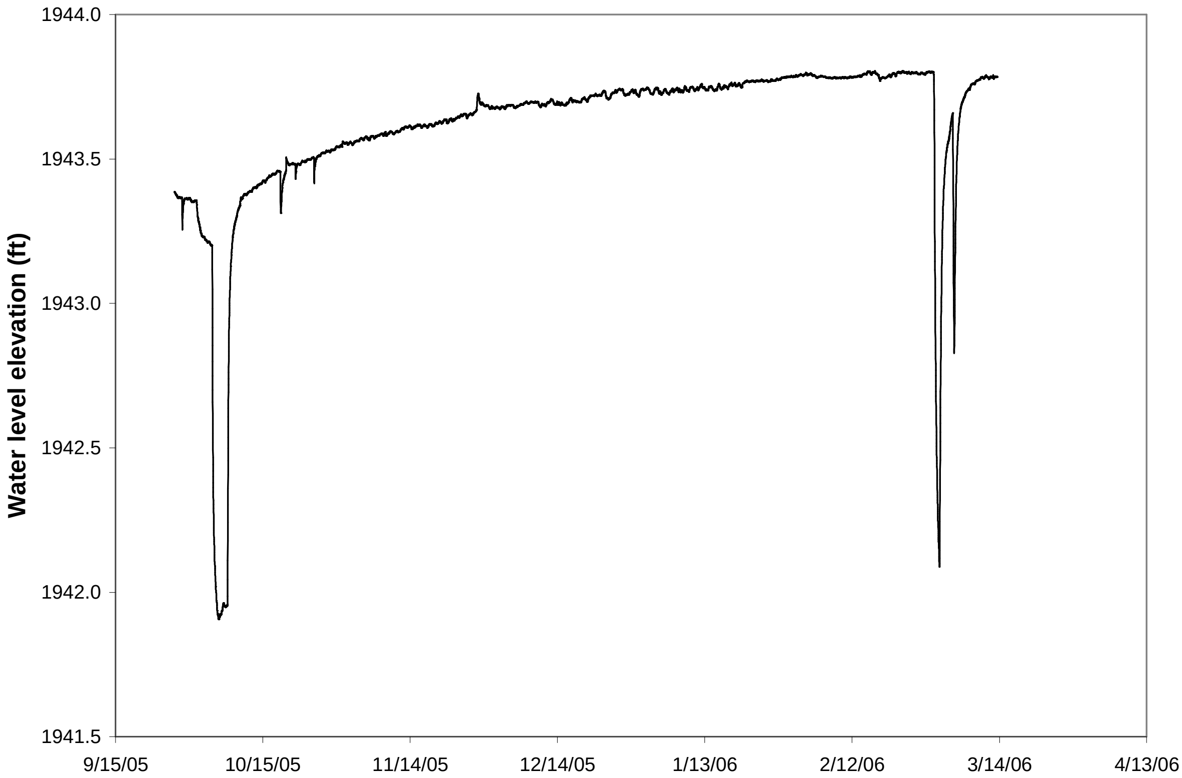


Figure B.2-1 Corrected water-level elevation at well LWC 2, winter season 2005-2006. Pumping ceased in October, and the water level recovered until pumping began again at the end of February.

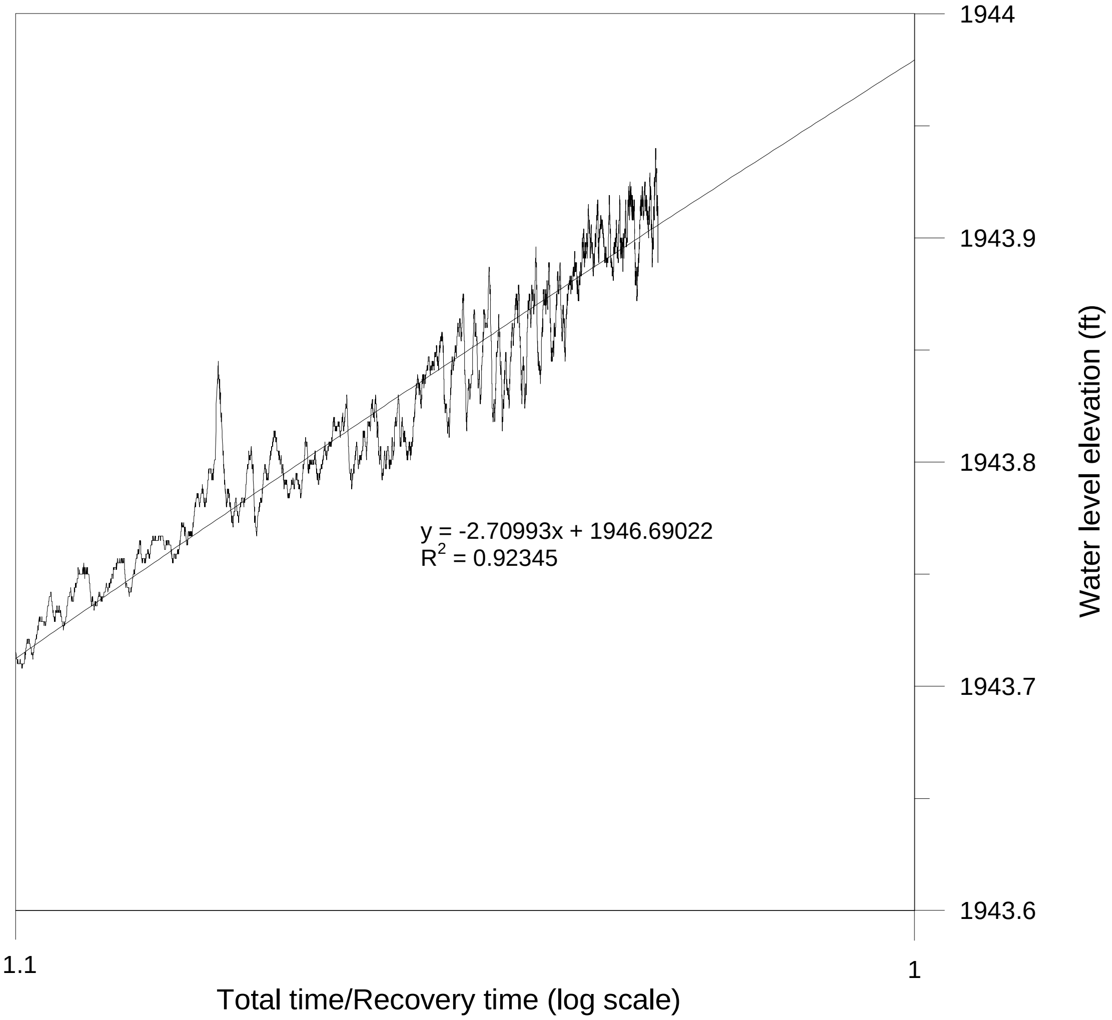


Figure B.2-2 Horner method for well LWC 2, winter season 2005-2006. A straight line is fit to the data and projected to the right. Adding the slope and the intercept gives the water-level elevation when $t_{pf}/t_{rf} = 1$, which is an estimate of the water level at full recovery.

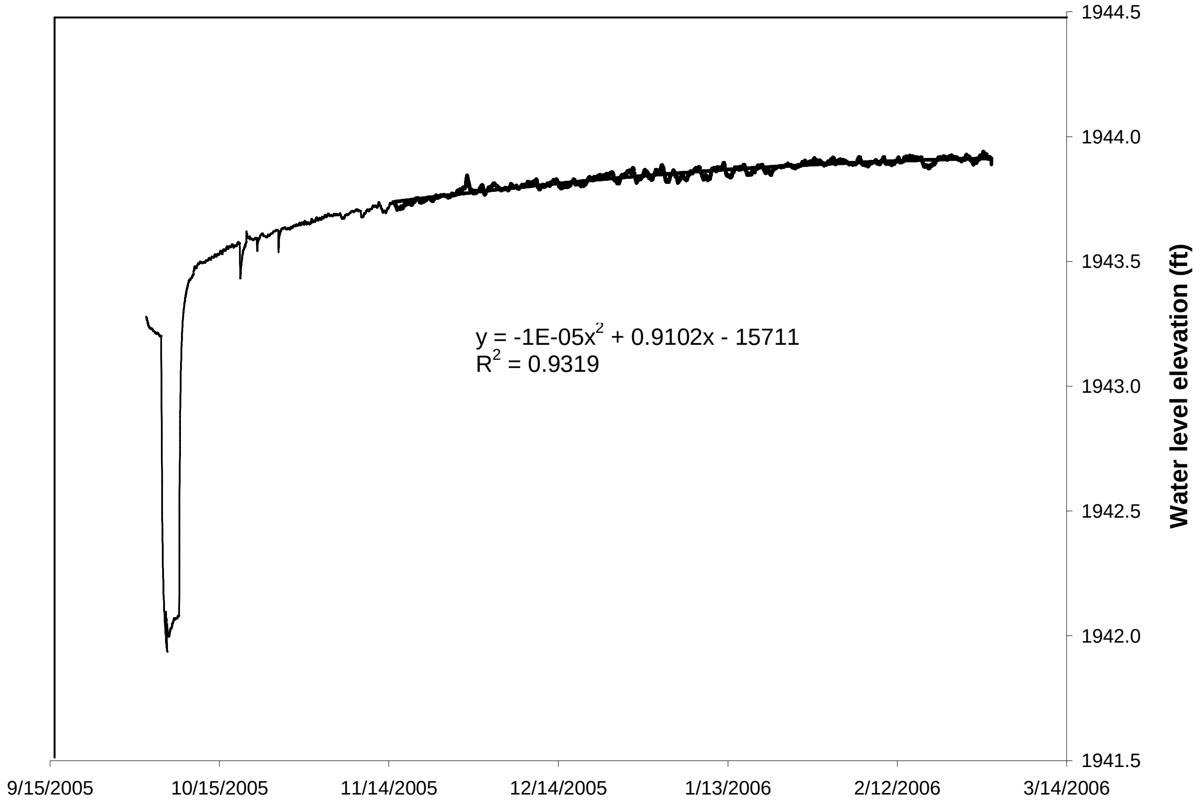


Figure B.2-3. Quadratic curve fit to corrected water-level elevation data from well LWC 2, winter season 2005-2006. The heavier line shows the portion of the data to which the curve is fit, and the quadratic curve-fit line is superimposed on that. The maximum of the quadratic curve is the fully recovered water level.

Table B.1.1. Estimated water levels at full recovery and recovery dates at the Larned Research Site.

2003-2004

	Water level at full recovery (ft)			Recovery date	
	Horner method	Curve-fitting method	Visual inspection	Curve-fitting method	Visual inspection
LWC 2	1945.03	1944.93	1944.95	12/18/2003	1/23/2004
LWPH 4C	1944.47	1944.49	1944.44	2/19/2004	1/2/2004
LEA 5	1944.26	1944.27	1944.24	2/12/2004	1/24/2004
LEC 2	1941.49	1941.55	1941.48	2/19/2004	12/24/2003
LWC 2 corrected	1944.88	1944.80	1944.82	2/19/2004	12/25/2003
LEA 5 corrected	1944.22	1944.14	1944.18	2/13/2004	1/9/2004
LEC 2 corrected	1941.47	1941.43	1941.44	2/3/2004	12/24/2003

2004-2005

	Water level at full recovery (ft)			Recovery date	
	Horner method	Curve-fitting method	Visual inspection	Curve-fitting method	Visual inspection
LWC 2	1944.84	1944.81	1944.75	2/7/2005	12/5/2004
LWPH 4C	1944.32	1944.25	1944.25	3/8/2005	12/27/2004
LEA 5	1944.04	1944.04	1943.98	12/18/2004	12/2/2004
LEC 2	1941.25	1941.25	1941.17	1/29/2005	12/15/2004
LWC 2 corrected	1944.75	1944.81	1944.65	3/29/2005	12/16/2004
LEA 5 corrected	1943.92	1943.82	1943.88	12/18/2004	12/15/2004
LEC 2 corrected	1941.18	1941.06	1941.10	1/27/2005	12/13/2004

2005-2006

	Water level at full recovery (ft)			Recovery date	
	Horner method	Curve-fitting method	Visual inspection	Curve-fitting method	Visual inspection
LWC 2	1943.98	1943.86	1943.90	3/19/2006	2/11/2006
LWPH 4C	1943.49	1943.41	1943.40	2/26/2006	1/21/2006
LEA 5	1943.24	1943.18	1943.15	2/28/2006	1/11/2006
LEC 2	1940.57	1940.49	1940.50	2/14/2006	1/7/2006
LWC 2 corrected	1943.98	1943.96	1943.90	3/18/2006	1/30/2006
LEA 5 corrected	1943.15	1943.12	1943.04	3/3/2006	1/5/2006
LEC 2 corrected	1940.43	1940.39	1940.35	2/11/2006	1/6/2006

Table B.1.2. Estimated water levels at full recovery at well LWC 2 (corrected for barometric pressure).

		Water level at full recovery (ft)	
		Horner method	Curve-fitting method
2003-2004	Full recovery curve, $t_{pf}/t_{rf} \leq 1.1$	1944.88	1944.80
	Removed last half of data	1944.88	1944.80
2004-2005	Full recovery curve, $t_{pf}/t_{rf} \leq 1.1$	1944.75	1944.81
	Removed last half of data	1944.73	1944.66
2005-2006	Full recovery curve, $t_{pf}/t_{rf} \leq 1.1$	1943.98	1943.96
	Removed last half of data	1943.95	1943.84

B.3 Estimates of water level at full recovery for the index wells

Calculations of water level at full recovery were also performed for the three index wells, using uncorrected water-level data from the winters of 2007-2008 and 2008-2009 (Table B.3-1). For the Scott County well, results from the Horner method and the curve-fitting method agreed to within 0.1 ft. There was poorer agreement for the other two index wells, with discrepancies of up to 3 ft in the results from the two different calculation methods. For the Haskell County well, part of this discrepancy was due to a brief interval of pumping that occurred during the middle of the recovery period. When only the portion of the recovery curve after this mid-recovery pumping was considered, the discrepancy between the two methods was reduced from 3 ft to 2 ft. Overall water-level changes from year to year are clear using either method. Between the winters of 2007-2008 and 2008-2009, the water level dropped about 5 ft at the Haskell County index well. The water level dropped about 1.2 ft at the Scott County well, and it remained about the same at the Thomas County well. We are currently investigating the factors that could be responsible for the larger differences between the estimates from the two methods for the Haskell County and Thomas County wells.

Table B.3-1. Estimated water levels at full recovery at the index wells (no barometric pressure correction).

	Water level at full recovery (ft)	
	Horner method	Curve-fitting method
Haskell County		
2007-2008	2587.49	2586.58
2008-2009	2582.91	2579.98
Change	-4.58	-6.60
Thomas County		
2007-2008	2975.62	2975.35
2008-2009	2974.69	2975.82
Change	-0.93	0.47
Scott County		
2007-2008	2836.42	2836.24
2008-2009	2835.15	2835.08
Change	-1.27	-1.16

B.4 Derivation of Horner plot (Theis recovery) approach to estimate head at full recovery

We will start with a single well pumping at a constant rate for a finite period (Section I). We will then extend the approach to n wells pumping at the same rate for the same period (Section II). We will then extend the approach to the entire pumping season by representing the season as a series of pumping periods and allowing differences in the number of pumping wells and the pumping rate between periods (Section III).

I. Single well pumping at a constant rate (Q) for a finite period in a homogeneous, unbounded confined or thick unconfined aquifer

The head [h(r,t)] in the recovery period following the cessation of pumping can be written as:

$$h(r,t) = h_0 - s(r,t_p)$$

(B.4.1)

where

h_0 = the head at full recovery;
$s(r,t_p)$ = the residual drawdown at location r and time t_p;
r = radial distance from pumping well;
t and t_p = time since some reference time and time since pumping began, respectively.

A short time after pumping has ceased, the residual drawdown from that time on can be approximated using image well theory and the Cooper-Jacob semilog truncation of the Theis equation:

$$s(r,t_p) \approx \frac{Q}{4\pi T} log\left(\frac{2.25Tt_p}{r^2S}\right) - \frac{Q}{4\pi T} log\left(\frac{2.25Tt_r}{r^2S}\right)$$

(B.4.2)

where

T = the transmissivity of the aquifer;
S = the storage coefficient of the aquifer;
t_r = time since pumping stopped.

Equation (B.4.2) can be simplified by using a log identity:

$$s(r,t_p) \approx \frac{Q}{4\pi T} log\left(\frac{t_p}{t_r}\right)$$

(B.4.3)

Equation (B.4.3) is the Theis recovery equation. Substitution of (B.4.3) into (B.4.1) produces the equation for the Horner plot method for estimating head at full recovery:

$$h(r,t) \approx h_0 - \frac{Q}{4\pi T} log\left(\frac{t_p}{t_r}\right)$$

(B.4.4)

As the time since the cessation of pumping increases, the ratio in the log term approaches one and the log of that ratio approaches zero. The Horner plot approach is similar to the Theis recovery method except that aquifer head (h) is plotted versus the log ratio instead of residual drawdown (s). In either case, the relationship should be linear in the semilog plotting format. Given that one often is not able to continue to measure water levels until full recovery, the head at full recovery can be estimated by projecting the best-fit straight line to a t_p/t_r ratio of 1 (log ratio is zero). The corresponding head value is the head at full recovery (h_0 in equation (B.4.1)).

II. An arbitrary number (n) of wells pumping at a constant rate for a finite period in a homogeneous, unbounded confined or thick unconfined aquifer

If there are multiple pumping wells but all wells are starting to pump at the same time and are pumping for the same duration, then equation (B.4.2) can be extended to the n-well case:

$$s(R,t_p) \approx \frac{Q}{4\pi T} log\left(\frac{2.25Tt_p}{r_1^2 S}\right) - \frac{Q}{4\pi T} log\left(\frac{2.25Tt_r}{r_1^2 S}\right) + \frac{Q}{4\pi T} log\left(\frac{2.25Tt_p}{r_2^2 S}\right) - \frac{Q}{4\pi T} log\left(\frac{2.25Tt_r}{r_2^2 S}\right) + ...$$

$$\approx \frac{Q}{4\pi T} \sum_{i=1}^{n} \left[log\left(\frac{2.25Tt_p}{r_i^2 S}\right) - \frac{Q}{4\pi T} log\left(\frac{2.25Tt_r}{r_i^2 S}\right)\right]$$

(B.4.5)

where

R = a one-dimensional array with the distances from each pumping well to the well at which the water level is being measured (r_1, r_2, ….).

Using log identities, equation (B.4.5) can be rewritten as:

$$s(R,t_p) \approx \frac{Q}{4\pi T}\left[log\left(\frac{(2.25Tt_p)^n}{\left(\prod_{i=1}^{n} r_i^2\right) S^n}\right) - log\left(\frac{(2.25Tt_r)^n}{\left(\prod_{i=1}^{n} r_i^2\right) S^n}\right)\right] = \frac{Q}{4\pi T} log\left(\frac{t_p^n}{t_r^n}\right) = \frac{Q}{4\pi T} log\left(\left(\frac{t_p}{t_r}\right)^n\right)$$

$$s(R,t_p) \approx \frac{Qn}{4\pi T} log\left(\frac{t_p}{t_r}\right)$$

(B.4.6)

Equation (B.4.4) can therefore be rewritten for the n-well case as:

$$h(R,t) \approx h_0 - \frac{Qn}{4\pi T} log\left(\frac{t_p}{t_r}\right)$$

(B.4.7)

Thus, the extended Horner plotting approach for estimation of the fully recovered head is also equally valid for the n-well case when each well is pumping at the same rate for the same period of time.

III. Representation of entire pumping season as a series of m individual pumping periods of the same length during which an arbitrary number of wells are pumping at the same constant rate in a homogeneous, unbounded confined or thick unconfined aquifer

For this case, equation (B.4.6) can be generalized to:

$$s(R_{all}, t_p) \approx \frac{Q}{4\pi T}\left[n_1 \log\left(\frac{t_p}{t_r}\right) + n_2 \log\left(\frac{t_p + \Delta_1}{t_r + \Delta_1}\right) + n_3 \log\left(\frac{t_p + \Delta_2}{t_r + \Delta_2}\right) + \ldots + n_m \log\left(\frac{t_p + \Delta_{m-1}}{t_r + \Delta_{m-1}}\right)\right]$$

(B.4.8)

where

n_i = number of pumping wells in period i (by convention, period 1 is the last period of the pumping season);

R_{all} = the radial distance from a pumping well in any period to the point at which head is measured, i.e. the R of equation (B.4.5) expanded to include all pumping periods;

Δ_{i-1} = the time difference between the start of the final pumping period and the start of the ith pumping period.

a) Assume the number of pumping wells is not changing between periods ($n = n_1 = n_2 = \ldots = n_m$):

$$s(R_{all}, t_p) \approx \frac{Qn}{4\pi T}\left[\log\left(\frac{t_p}{t_r}\right) + \log\left(\frac{t_p + \Delta_1}{t_r + \Delta_1}\right) + \log\left(\frac{t_p + \Delta_2}{t_r + \Delta_2}\right) + \ldots\right] = \frac{Qn}{4\pi T}\sum_{i=0}^{m} \log\left(\frac{t_p + \Delta_i}{t_r + \Delta_i}\right)$$

(B.4.9)

For the pumping periods expected in western Kansas (three to six days in duration) and for late in the recovery period ($t_p/t_r < 1.1$), equation (B.4.9) can be approximated by:

$$s(R_{all}, t_p) \approx \frac{Qnx}{4\pi T}\log\left(\frac{t_p}{t_r}\right)$$

(B.4.10)

where

x = a multiplication factor that depends on length of pumping period and number of periods in the season.

Although the value for x will typically not be known, the key point is that the plotting relationship is still linear in the head versus log ratio format.

b) Assume the number of pumping wells does change between periods but that the average over the pumping season of the number of pumping wells in an individual period (n_{av}) is a reasonable value for any particular period:

$$s(R_{all}, t_p) \approx \frac{Qn_{av}x}{4\pi T}\log\left(\frac{t_p}{t_r}\right)$$

(B.4.11)

c) Assume the number of pumping wells does change between periods and that the number of wells pumping in individual periods cannot be represented well by the average over the pumping season (n_{av}):

In this case, we can simplify the development by assuming that the number of wells in a particular pumping period can be reasonably represented by one of a small number of average values (n_{av1}, n_{av2}, n_{av3},..) that represent the number of pumping wells for a particular set of pumping periods. Then equation (B.4.11) can be generalized to:

$$s(R_{all},t_p) \approx \frac{Qn_{av1}x_1}{4\pi T} log\left(\frac{t_{p1}}{t_{r1}}\right) + \frac{Qn_{av2}x_2}{4\pi T} log\left(\frac{t_{p2}}{t_{r2}}\right) + ... + \frac{Qn_{avj}x_j}{4\pi T} log\left(\frac{t_{pj}}{t_{rj}}\right)$$

(B.4.12)

where

t_{pi} = the time since pumping began for final pumping period in which n_{avi} wells were pumped;

t_{ri} = the time since pumping stopped for final pumping period in which n_{avi} wells were pumped;

j = total number of averages used to represent number of pumping wells in various periods during pumping season;

x_i = multiplication factor for n_{avi} pumping wells.

Late in the recovery period ($t_{pi}/t_{ri} < 1.1$), the log ratio terms should be approximately equal as long as the final pumping periods for each set of pumping wells are reasonably close in time. Equation (B.4.12) can then be rewritten as:

$$s(R_{all},t_p) \approx \frac{Q(n_{av1}x_1 + n_{av2}x_2 + ... n_{avj}x_j)}{4\pi T} log\left(\frac{t_{p1}}{t_{r1}}\right)$$

(B.4.13)

Although the values for n_{avi} and x_i will typically not be known, the key point is that the plotting relationship is still linear in the head versus log ratio format. Note that the time ratio used in equation (B.4.13) does not necessarily have to be the ratio for the final pumping period but use of the final pumping period is convenient when working with field data. Also note that the approach used in these last two sections can also be used for the case of the pumping rate varying between periods while the number of pumping wells does not. In that case, Q and n, along with the notation, are switched in equations (B.4.11)-(B.4.13).

d) Assume that both the number of pumping wells and the pumping rate change between periods and that neither the number of wells for an individual period nor the pumping rate can be reasonably represented by the pumping season averages (n_{av} and Q_{av}, respectively):

Assume the same set of assumptions as in section c) but relax the assumption of the same constant pumping rate. Instead, assume that each group of pumping wells (n_{avi}) has its own pumping rate (Q_{avi}). Then, equation (B.4.12) can be generalized to:

$$s(R_{all},t_p) \approx \frac{Q_{av1}n_{av1}x_1}{4\pi T} log\left(\frac{t_{p1}}{t_{r1}}\right) + \frac{Q_{av2}n_{av2}x_2}{4\pi T} log\left(\frac{t_{p2}}{t_{r2}}\right) + ... + \frac{Q_{avj}n_{avj}x_j}{4\pi T} log\left(\frac{t_{pj}}{t_{rj}}\right)$$

(B.4.14)

Late in the recovery period ($t_{pi}/t_{ri} < 1.1$), the log ratio terms should be approximately equal as long as the final pumping periods for each set of pumping wells are reasonably close in time. Equation (B.4.14) can then be rewritten as:

$$s(R_{all},t_p) \approx \frac{(Q_{av1}n_{av1}x_1 + Q_{av2}n_{av2}x_2 + \ldots Q_{avj}n_{avj}x_j)}{4\pi T} log\left(\frac{t_{p1}}{t_{r1}}\right)$$

(B.4.15)

Although the values for Q_{avi}, n_{avi} and x_i will typically not be known, the key point, as with equations (B.4.10) and (B.4.13), is that the plotting relationship is still linear in the head versus log ratio format. Note that equations (B.4.14)-(B.4.15) should also be applicable for pumping periods of different durations given the small differences in duration expected in western Kansas. This extension, which is not presented here, requires additional notation but, other than that, is straight-forward.

All of the extensions of the Horner plot approach discussed in this section can be written as:

$$h(r,t) \approx h_0 - A log\left(\frac{t_{pf}}{t_{rf}}\right)$$

(B.4.16)

where

A = constant coefficient depending on pumping rate and schedule, number of wells, transmissivity, etc.

t_{pf} = time since the start of the final (f) period of pumping;

t_{rf} = time since the end of the final (f) period of pumping.

Although the value for A will typically not be known, the key point is that all of these approximate extensions result in a plotting relationship that is linear in the water-level elevation versus log ratio format. Thus, the projection of the best-fit straight line to a t_{pf}/t_{rf} ratio of 1 (log ratio is zero) can still be done to estimate the water-level elevation at full recovery.

The developments in this section are based on a series of assumptions that enable us to simplify the expressions to the relationship given in equation (B.4.16). We are currently assessing the appropriateness of these assumptions for conditions commonly met in western Kansas. As stated in Appendix B.1, a major assumption of this approach is that inflow from more distant regions of the aquifer is the source of all of the pumped water. We are currently exploring modifying the approach fro application to conditions where virtually all of the pumped water comes from local aquifer storage, i.e. aquifer dewatering in the vicinity of the well, so that the approach is more consistent with the common conditions in the High Plains aquifer in the three western GMDs.

B.5 An Excel-based approach to analyzing recovery curves by the Theis curve

As described above, a Theis recovery curve can be represented as:

$$h(t) = h_0 - s_0 \log\left(\frac{t_p}{t_r}\right) = h_0 - s_0 \log\left(\frac{t - t_0}{t - t_1}\right)$$

where h_0 is the head at full recovery, s_0 is ratio incorporating pumping rate and aquifer transmissivity, t_p is an effective time since beginning of pumping and t_r is an effective time since beginning of recovery. On the right, t_p and t_r are represented as differences between the observation time t, and the effective beginning times of pumping and recovery, t_0 and t_1, respectively.

The term "effective" here means that the quantities represent integrated measures of the influence of the variations of the pumping record on the particular recovery record being analyzed. Thus, although s_0, t_0, and t_1 have unambiguous physical interpretations when applied to the ideal case of recovery from constant-rate pumping at a single well, they should not be interpreted too literally when applied in the present context of recovery from an unknown record of variable pumping at an unspecified number of wells. Nevertheless, the hope is that after a certain point in the recovery curve, the effects of the variable pumping record can be reasonably accurately represented using these effective parameters, allowing for prediction of the remaining recovery.

If t_0 and t_1 are known, then $\log(t_p/t_r)$ can be computed with certainty and the recovery can be represented as a linear model versus $\log(t_p/t_r)$, with slope $-s_0$ and intercept h_0, as described in the previous section. When t_0 and t_1 are not known with certainty, one could attempt to estimate them by adjusting them to improve the match between the observed and modeled recovery records versus t, with the modeled head given by the equation above. This estimation problem is nonlinear, due to the nonlinear dependence of $h(t)$on t_0 and t_1. Nevertheless, is it reasonably straightforward to set up a set of equations in an Excel spreadsheet allowing for fitting of a recovery record through either manual adjustment of h_0, s_0, t_0, and t_1 or automated adjustment of those parameters (or a subset of them) using Excel's Solver add-in.

Once a satisfactory fit is obtained, then h_0 provides an estimate of the head at full recovery. However, the form of the model dictates that this head value is only approached asymptotically; it is never actually attained. In this case, it is reasonable to estimate a time to recovery as the time at which the residual drawdown

$$s(t) = s_0 \log\left(\frac{t - t_0}{t - t_1}\right)$$

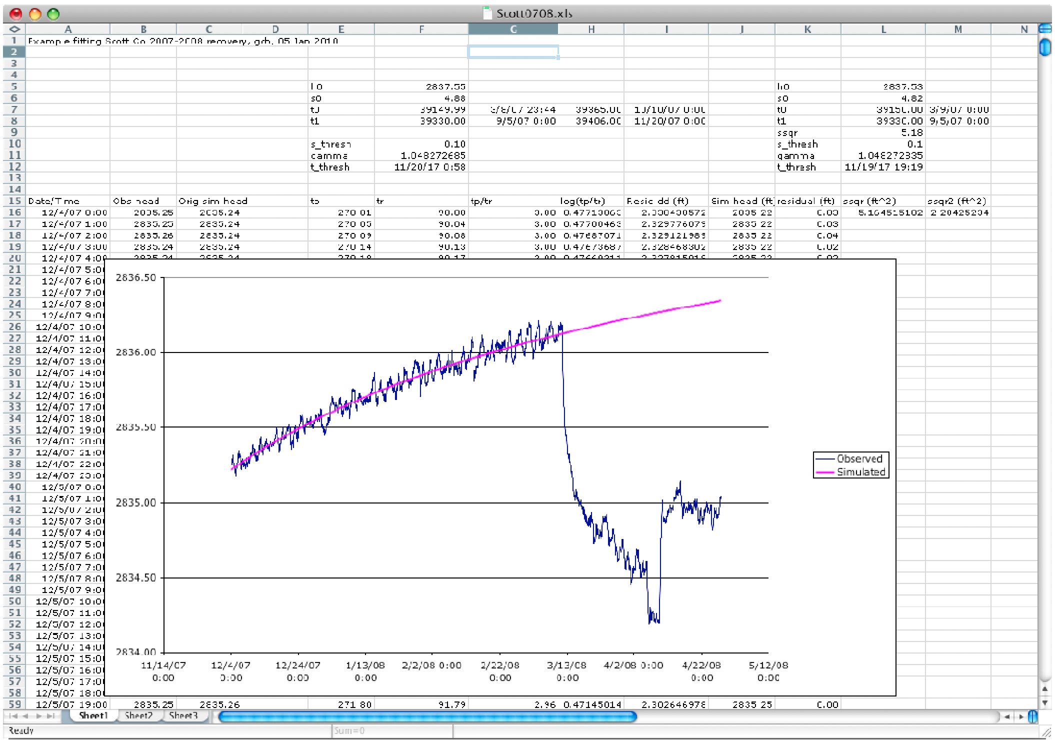
reaches some specified small value, s_c. Using the estimated values of s_0, t_0, and t_1, this time can be computed as

$$t_c = \frac{\gamma t_1 - t_0}{\gamma - 1}$$

where $\gamma = 10^{(s_c/s_0)}$.

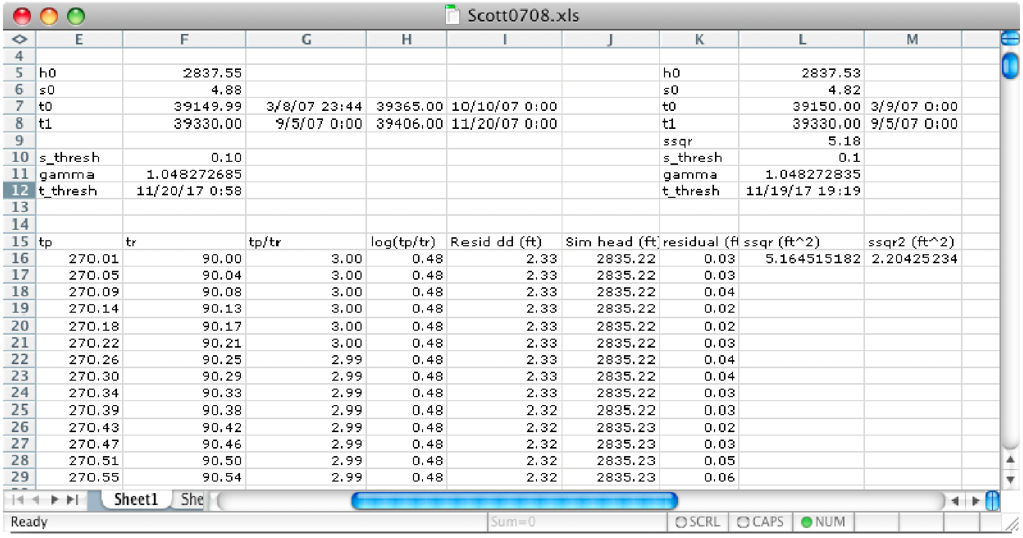
Here we present an example of a spreadsheet set up for the analysis of the 2007-2008 recovery data from the Scott County index well. It should be noted at the outset that this example demonstrates some problematic aspects of the fitting and prediction process, at least in this particular case. Nevertheless, we will use this example to illustrate the setup of the spreadsheet, in the hopes that this approach will prove to be of greater use in other cases.

The workbook, Scott0708.xls, contains the Scott County index well data between Dec. 4, 2007 and April 27, 2008, including the winter recovery record and the beginning of the pumping season. The screen shot below is an overview of the spreadsheet including a fit (heavier smooth line) to the recovery portion of the observed heads (thinner jagged line).



Although the fit to the recovery record looks very good, it has unfortunately been obtained with fairly unrealistic values of t_0 and t_1, the effective beginning times of pumping and recovery, respectively, and the resulting prediction for the recovery time (in 2017, using $s_c = 0.1$ ft) is of no practical utility.

The screen shot below focuses in on the cells containing the adjustable parameters and the data columns containing the model computations:



Scott0708.xls

	E	F	G	H	I	J	K	L	M
4									
5	h0	2837.55					h0	2837.53	
6	s0	4.88					s0	4.82	
7	t0	39149.99	3/8/07 23:44	39365.00	10/10/07 0:00		t0	39150.00	3/9/07 0:00
8	t1	39330.00	9/5/07 0:00	39406.00	11/20/07 0:00		t1	39330.00	9/5/07 0:00
9							ssqr	5.18	
10	s_thresh	0.10					s_thresh	0.1	
11	gamma	1.048272685					gamma	1.048272835	
12	t_thresh	11/20/17 0:58					t_thresh	11/19/17 19:19	
13									
14									
15	tp	tr	tp/tr	log(tp/tr)	Resid dd (ft)	Sim head (ft	residual (ft	ssqr (ft^2)	ssqr2 (ft^2)
16	270.01	90.00	3.00	0.48	2.33	2835.22	0.03	5.164515182	2.20425234
17	270.05	90.04	3.00	0.48	2.33	2835.22	0.03		
18	270.09	90.08	3.00	0.48	2.33	2835.22	0.04		
19	270.14	90.13	3.00	0.48	2.33	2835.22	0.02		
20	270.18	90.17	3.00	0.48	2.33	2835.22	0.02		
21	270.22	90.21	3.00	0.48	2.33	2835.22	0.03		
22	270.26	90.25	2.99	0.48	2.33	2835.22	0.04		
23	270.30	90.29	2.99	0.48	2.33	2835.22	0.04		
24	270.34	90.33	2.99	0.48	2.33	2835.22	0.03		
25	270.39	90.38	2.99	0.48	2.32	2835.22	0.03		
26	270.43	90.42	2.99	0.48	2.32	2835.23	0.02		
27	270.47	90.46	2.99	0.48	2.32	2835.23	0.03		
28	270.51	90.50	2.99	0.48	2.32	2835.23	0.05		
29	270.55	90.54	2.99	0.48	2.32	2835.23	0.06		

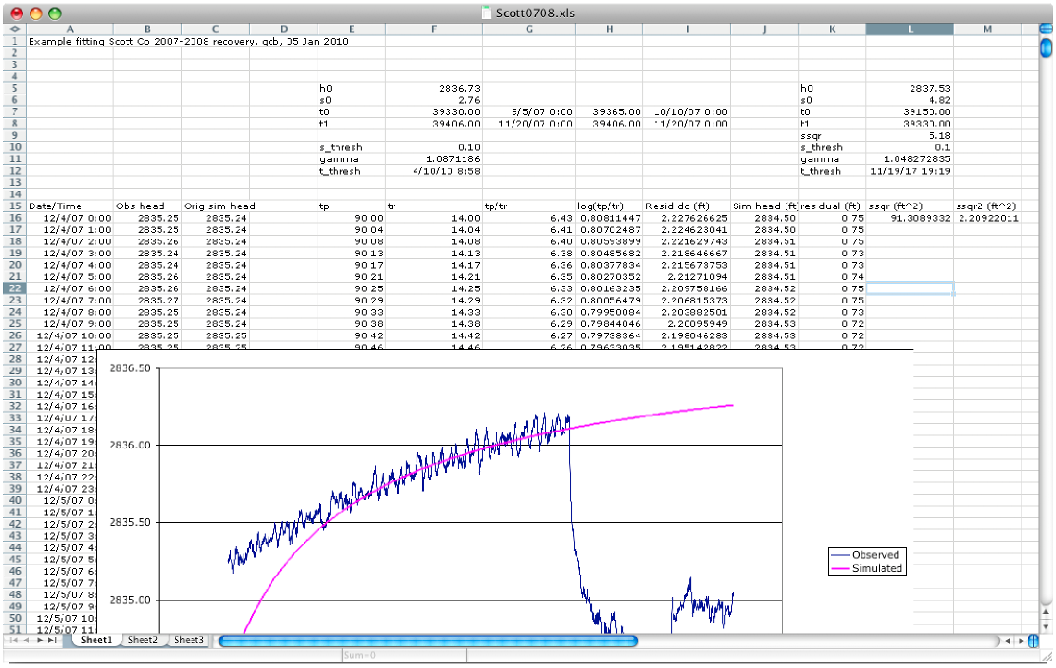
Sheet1 She

Ready Sum=0 SCRL CAPS NUM

The four adjustable parameters are in cells F5-F8, with their labels (h0, s0, t0, and t1) immediately to the left in column E. Date/time values in Excel are actually just numbers, representing days since Jan 1, 1900 (unless the 1904 date convention has been checked in Excel's options). The values for t0 and t1 in cells F6 and F7 are formatted as numbers, since they are easier to adjust in this format. The date-formatted versions of these numbers are shown immediately to the right, in cells G7 and G8 (set up by formula link, so they adjust automatically with changes in cells F7 and F8). Cells I7 and I8 represent dates that have been copied to the spreadsheet for guidance; they are dates (Oct. 10 and Nov. 20, 2007) that seem to correspond to the beginning and end of the final period of pumping in 2007, based on visual inspection of the data record. Cells H7 and H8 contain the number-formatted versions of theses dates, providing guidance for determining plausible values for t0 and t1 in F7 and F8. Note that the values of t0 and t1 had to be adjusted to much earlier dates (here, March 8 and Sept. 5, 2007) in order to obtain the fit to the recovery record shown above. In fact, a wide variety of combinations of t0 and t1 can yield nice fits to the observed recovery record, but the values had to be adjusted to significantly earlier dates than October 10 and November 20 to obtain a match to the entire record. Note that, based on the "fitted" values of t0 and t1, the resulting values for tp/tr (column G, rows 16 on) are significantly larger than 1.1, calling into question a key assumption made in the development of this approach, namely, that the observation times are late enough in the recovery period to allow the representation of the pumping history using a single effective s0 value (see development of equations 10, 13, and15 of this appendix).

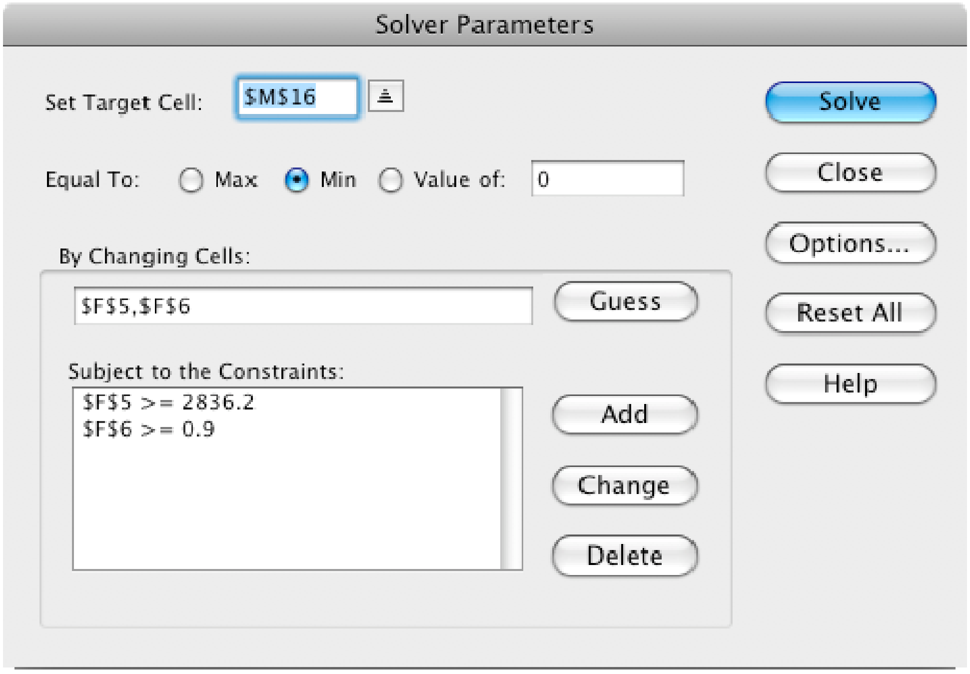
To continue with the explanation of the spreadsheet, columns E through K, rows 16 on, contain the sequence of computations, all linked ultimately to the parameter values in cells F5-F7, so that adjusting the parameters changes the fitted curve. The labels (row 15) for columns E-H should be fairly self-explanatory. Column I contains the computed residual (in the sense of remaining) drawdowns, $s(t)$, column J contains the simulated heads, $h(t) = h_0 - s(t)$, and column K contains the residuals from the fitted (observed minus simulated heads). Cell J16 contains the sum of squared residuals computed over most of the recovery record, from Dec. 4, 2007, through Feb. 29, 2008. The formula for this cell is "=SUMSQ(K16:K2127)". This represents an "objective function" for the fitting process. The aim is to find parameter values that minimize this function. Due to the formula links in the spreadsheet, the value in this cell will automatically update to reflect changes in the parameters. The parameters can be changed manually or adjusted automatically using Solver, illustrated briefly below.

The value in cell M16 is the sum of squared residuals just for the month of February, 2008, the latter part of the recovery record. The screen shot below shows a fit aimed to minimize this "late time" objective function – that is, just fitting the February data – keeping the beginning time of recovery fixed at Nov. 20, 2007. In this case, the estimated value of h0 is 2836.75 feet, s0 is 2.86 feet, t1 is estimated as Sept. 5, 2007, and the projected recovery date, using s_c = 0.1, is in April 2010.



In the attempts to fit this data record using the Solver, it was found that Solver's automated fitting algorithm never adjusted t0 and t1 significantly from the user-specified initial values. Instead, it just adjusted h0 and s0 to give the best match given t0 and t1. So, the estimated values of t0 and t1 have been determined primarily through manual adjustment in both cases shown, somewhat defeating the purpose of employing the Solver's nonlinear estimation procedure. Nevertheless, it is possible that the objective function would be more sensitive to t0 and t1, increasing Solver's ability to find reasonable values for these parameters, in other cases.

To use Solver, select **Solver…** from the **Tools** menu. (You may first need to install Solver; see the Excel help.) You will then be presented with a dialog box like the following, here set up for the fit to the February 2008 data illustrated above:



The **Target Cell** is the cell containing the value that we want to maximize, minimize, or adjust to some specified value. Here it is M16, the cell containing the sum of squared residuals for the February data, which we want to minimize (**Min**). We are trying to achieve this minimum by changing the values in cells F5 and F6, containing h0 and s0. Here we have also added constraints that h0 should equal or exceed 2836.2 feet, essentially the maximum observed head in the recovery record, and s0 should equal or exceed 0.9. The constraints were added to maintain sensible results when we were also trying to adjust t0 and t1 using Solver. They are probably unnecessary when t0 and t1 are not included as parameters in the automated fitting process, as shown here.

Clearly, the proposed fitting process has not yielded results of practical utility in this particular case. We will investigate other data records and possible modifications to the process to determine whether the procedure could be of use in some situations.

Appendix C: Water-level correction

C.1 Atmospheric pressure effects

Barometric pressure fluctuations can introduce “noise” into the water-level signal. As shown in the Year Two Report, that noise can be largely removed by correcting the water level observations using the estimated barometric response functions. Figure 3.5 illustrates the reduction of barometric noise in water level signals that can be achieved through this correction. There are two changes in the correction procedure between that used here and that used in the Year Two Report.

First, a different formula was used for the water-level correction. In the previous report, the correction was done using the following expression:

$$W_{\text{corrected}}(t) = W(t) + \sum_{i=0}^{m} \alpha(i) \Delta B(t-i) \tag{1}$$

where $W_{\text{corrected}}(t)$ and $W(t)$ are the corrected and uncorrected water level for time t, respectively, $\alpha(i)$ is the impulse response function of water level at lag i, m is the maximum lag, and $\Delta B(t\text{–}i)$ is the change in barometric pressure (B_p) at time $t\text{–}i$,

$$\Delta B(t-i) = B_p(t-i) - B_p(t-i-1) \tag{2}$$

This formula is essentially identical to what Toll and Rasmussen (2007) used. We have found, however, that it formula leads to corrected water levels that are dependent on the period over which the correction is used. This dependence arises because there is not a reference barometric pressure, so the corrected water levels are dependent on the starting point of the period for which the correction is applied. As a result of the recognition of this dependence, a new formula was developed and is now used for the water-level correction:

$$W_{\text{corrected}}(t) = W(t) + \sum_{i=0}^{m} \alpha(i) B(t-i) \tag{3}$$

where $B(t\text{–}i)$ is the difference between the barometric pressure, B_{p}, at time $t\text{–}i$ and a reference barometric pressure, B_{p0}, which is a long-term average for the site:

$$B(t-i) = B_{\text{p}}(t-i) - B_{\text{p0}} \tag{4}$$

The corrected water level obtained using the new formula is not dependent on the period for which the correction is performed.

Second, the correction for the Thomas County well was done using a barometric response function that has a maximum lag of five days instead of the two days used in the previous analyses. The justification for using a longer lag is clear from Figure 3.4c, as the function continues to decrease beyond two days. Using the larger maximum lag enables the correction to take into consideration the effects of atmospheric pressure for a longer period of time, resulting in a slightly different corrected water level signal.

C.2 Earth tide effects

Earth-tide effects on the water level records were also examined for the 2008-2009 water level observations. The earth tide (gravity) potentials were generated for the three index wells using TSOFT, which is a public domain code for generating synthetic earth tide records for a given location (Van Camp and Vauterin, 2005). Water level observations were corrected for changes in earth tide potentials using the synthetic earth tide records. However, the correction for earth-tide effects was minimal at all three wells; the maximum water-level correction was 0.018 ft for the Thomas County well, 0.010 ft for the Scott County well, and 0.038 ft for the Haskell County well. Based on these results, we conclude that earth-tide effects on water levels can be ignored at these three wells.