Kansas Geological Survey

Statistical and Geostatistical Analysis of the Kansas High Plains Water Table Elevations, 2007 Measurement Campaign

By

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1. Introduction

The High Plains aquifer is the primary source of water for the High Plains region of western and south-central Kansas. Some water is also withdrawn from bedrock units, primarily Cretaceous strata, in this region. The Kansas Geological Survey (KGS) and the Kansas Department of Agriculture's Division of Water Resources (DWR) measure water levels in aquifers of the High Plains on an annual basis in a network of over 1300 wells, in order to assist in the management of this vital resource. This report presents statistical and geostatistical analyses for the High Plains region in Kansas based on data from the 2007 water-level measurements and water-level changes for the one-year and five-year periods preceding the 2007 measurements. In contrast to previous years, when the majority of water level measurements were obtained in a short time frame (a few weeks) in January, the 2007 measurement campaign extended into April 2007, due to heavy snowfall throughout much of western Kansas. However, it should be noted that wide-scale pumping had <u>not</u> yet started.

Section 3 of this report examines temporal variations in the water level measurements over the time frame of the 2007 measurements (Dec. 2006 – April 2007), showing that it is difficult to discern systematic temporal trends over this time period. Therefore, these measurements are treated as a single snapshot of the water table, *nominally* referred to as the "January 2007" measurements, following the practice of earlier water level reports.

Throughout this report we refer to water-level declines, with a *positive decline* meaning an *increase in depth to water from the land surface* (or decrease in water-table elevation) and a *negative decline* meaning a *decrease in depth to water from the land surface* (increase in water-table elevation). Water levels are measured in the winter so that the water table (or potentiometric surface) will have had a chance to recover from the more transient and localized effects of pumping for irrigation. The measurements are presumed to represent a new "static" water level, with the difference from the previous year's measurements representing the net loss or gain of saturated thickness over the preceding year. The difference in depth to water between the January 2007 and January 2006 measurements represents the water level decline for 2006.

The overall average water-level decline in the High Plains region over the 2006 calendar year was 1.28 feet. This represents a return to declines like those for the early 2000's (ranging from 0.92 feet for 2001 to 1.98 feet for 2002) after two years of relatively small average declines (0.14 feet for 2004 and 0.57 feet for 2005). Below-average precipitation during the 2006 growing season (April to September) is a likely cause. Precipitation levels, particularly in the western portions of the High Plains region, influence the amount of ground-water pumping, which in turn, affects water levels.

2. Data Extraction

The SQL query shown in Listing 1 was used to extract water-level measurements for the 2007 campaign from the Kansas Geological Survey's Water Information Storage and Retrieval Database (WIZARD). Natively, WIZARD is stored in an Oracle relational database schema containing depth to water information across the state. To facilitate SQL queries for analysis, the official network wells targeted each year for the water level measurement campaigns have been identified into Oracle "Views". The view BWILSON.WIZARD_NETWORK_WELLS represents the individual well locations where measurements are attempted each year and the view BWILSON.WIZARD_NETWORK_WELLS_WL accesses the corresponding water level measurements for those sites.

Listing 1. SQL query for extracting 2007 water-level measurements from WIZARD.

```
select
   bwilson.wizard_network_wells_wl.*,
   bwilson.wizard_network_wells.land_surface_altitude as surf_elev,
   bwilson.wizard_network_wells.latitude as latitude,
   bwilson.wizard_network_wells.longitude as longitude,
   bwilson.wizard_network_wells.well_access,
   bwilson.wizard_network_wells.downhole_access,
   bwilson.wizard_network_wells.use_of_water_primary,
   bwilson.wizard_network_wells.geological_unit1 ||
   bwilson.wizard_network_wells.geological_unit2 ||
   bwilson.wizard_network_wells.geological_unit3 as geol_units,
   bwilson.wizard_network_wells.local_well_number as kgs_id,
   bwilson.wizard_network_wells.other_identifier as AnnProv
from
   bwilson.wizard_network_wells_wl, bwilson.wizard_network_wells
where
   bwilson.wizard_network_wells_wl.usgs_id
   bwilson.wizard_network_wells.usgs_id and
   bwilson.wizard_network_wells_wl.depth_to_water is not null and
   (bwilson.wizard_network_wells_wl.agency = 'KGS' or
          bwilson.wizard_network_wells_wl.agency = 'DWR' ) and
    bwilson.wizard_network_wells_wl.measurement_date_and_time >=
          '01-Dec-2006' and
    bwilson.wizard_network_wells_wl.measurement_date_and_time <=
          '30-Apr-2007'
order by
    bwilson.wizard_network_wells_wl.usgs_id,
    bwilson.wizard_network_wells_wl.measurement_date_and_time
```

The query yields 1596 measurements from 1361 distinct wells, with measurement dates ranging from December 6, 2006, to April 12, 2007. Of these wells, 1322 are located within the geographic boundaries demarking the saturated extent of the High Plains aquifer, 857 of them measured by DWR staff and 465 by KGS staff. Figure 1 shows the distribution of responsibility between the two agencies. The KGS is primarily responsible for measuring wells in the western and southwestern portions of the network, whereas the DWR is responsible for the central and eastern portions.

The wells within the extent of the High Plains aquifer are screened primarily in that aquifer but also include some wells screened in alluvial aquifers or in underlying bedrock. WIZARD contains fields identifying up to three different geologic units tapped by each well and the SQL query extracts this unit information, concatenated into the single variable "geol_units". The query also extracts location data (latitude, longitude, and surface elevation) along with the additional variables used in the statistical quality control analysis. Similar queries were used to extract data from the 2006 and 2002 measurement campaigns for the sake of computing 1-year and 5-year water-level changes.

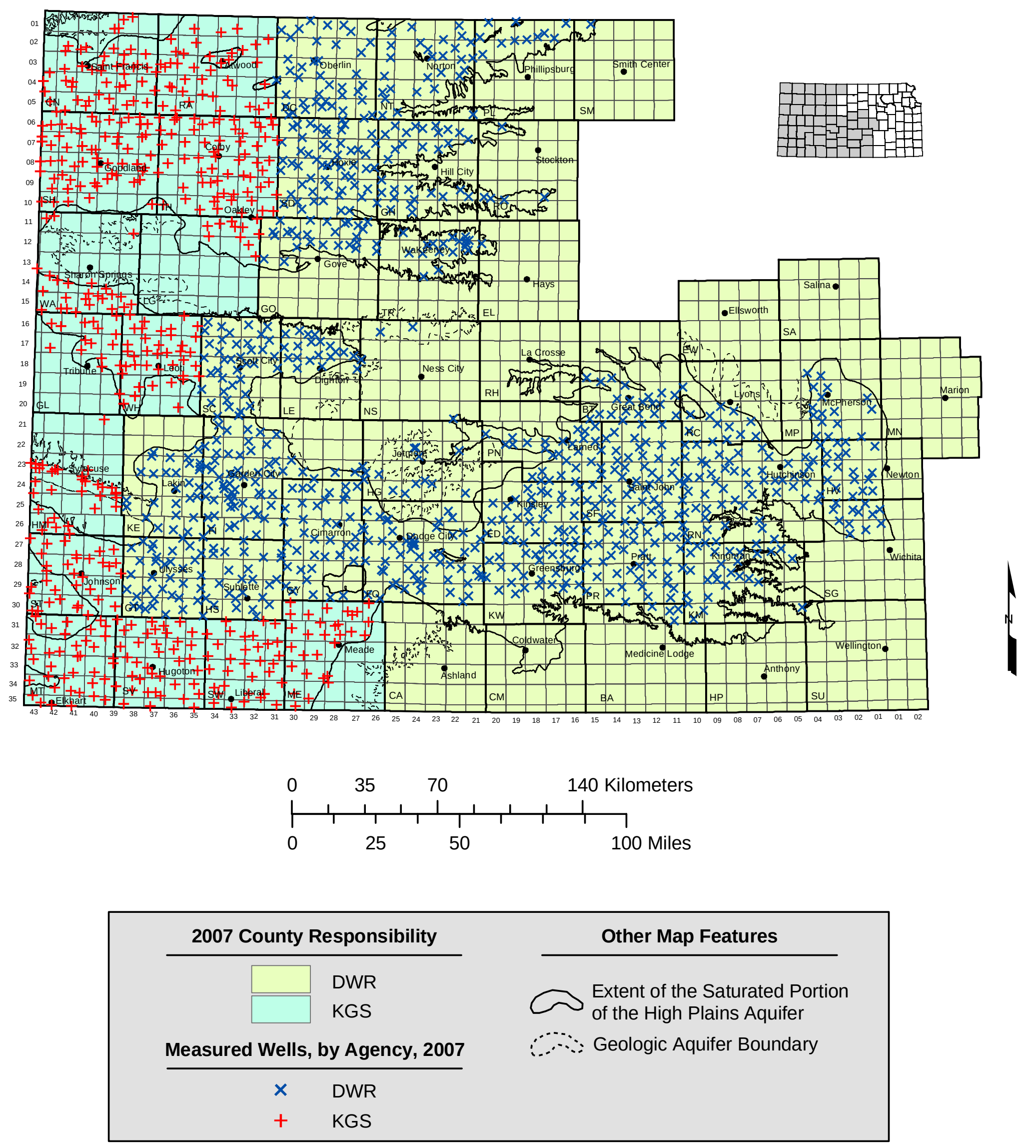

Figure 1. Wells measured and responsible agency in 2007.

3. Assessment of Temporal Variability Over Course of Measurement Campaign

In this section we investigate whether it is possible to discern systematic temporal trends in the High Plains aquifer water table elevations over the course of the 2007 water level measurement campaign, extending in its entirety from Dec. 6, 2006, to April 12, 2007. The purpose of this investigation is two-fold: 1) to determine whether it is reasonable to treat the entire set of measurements as a snapshot of the water table configuration at more or less a single time, and 2) to use the unplanned extension of the sampling period forced by the heavy snowfall as an opportunity to evaluate the impact of temporal variations on the order of weeks and months on the sampling process. In the past, some have questioned whether it is legitimate to consider the set of annual water level measurements as a single snapshot, due especially to variations in the degree of recovery from irrigation pumping from one place to another. The analysis described in this section does not show clear evidence of significant, systematic temporal variation over the time frame of the 2007 measurement campaign. However, as discussed later, the data do not allow a clear separation of temporal and spatial variability.

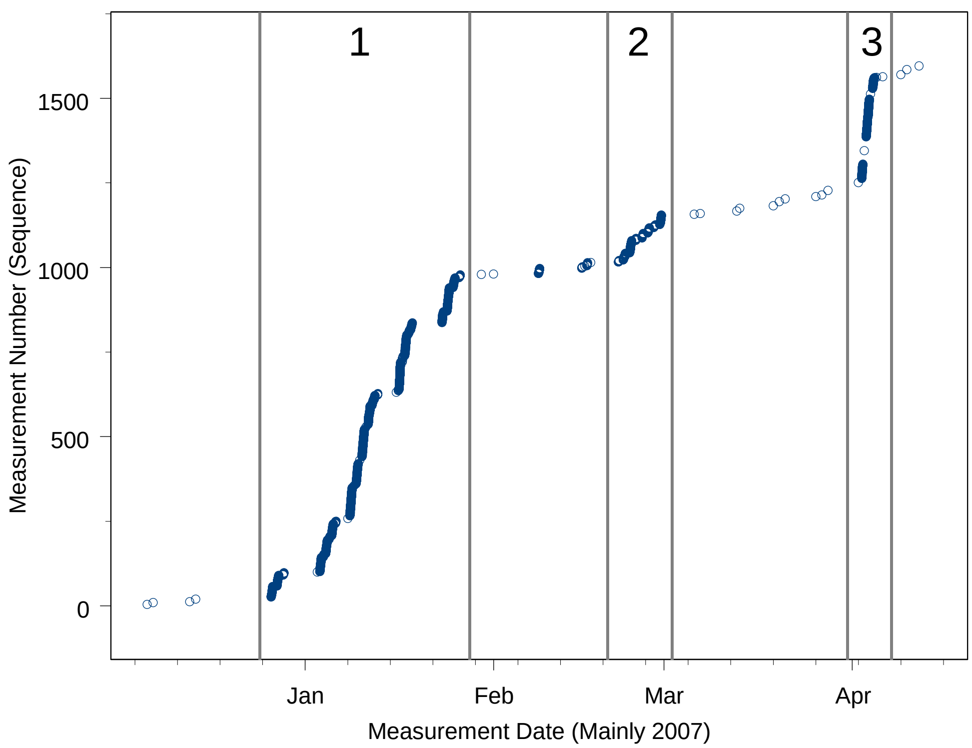

Figure 2. Time sequence of "2007" High Plains water level measurements (including some measurements in December 2006).

Figure 2 shows the sequence of measurement times for the 2007 water level measurements, for those wells within the saturated extent of the High Plains aquifer. It is clear that most of the measurements fall into one of three clusters, as indicated on the plot. Group 1 extends from Dec. 26, 2006, through Jan., 26 2007 (953 measurements).

Group 2 runs from Feb. 21-28, 2007 (140 measurements). Group 3 runs from Apr. 2-6 2007 (326 measurements). There are 177 measurements not included in these three groups. A plot of the geographic distribution associated with the different sampling groups is shown in Figure 3.

It is apparent that a number of the Group 2 and Group 3 measurements represent repeats of Group 1 measurements, although the measurements in these groups are primarily "new" measurements further west. We will concentrate on the Group 3 measurements in the upcoming discussion. Of these, 83 represent repeat measurements of Group 1 wells, primarily in central Kansas. Most of these repeat measurements are part of other State and local programs namely through the DWR and the Big Bend Groundwater Management District (GMD) #5. The other 243 represent new measurements, primarily in areas of western Kansas where exceptionally high snow fall depths were recorded in the months of January to March, 2007.

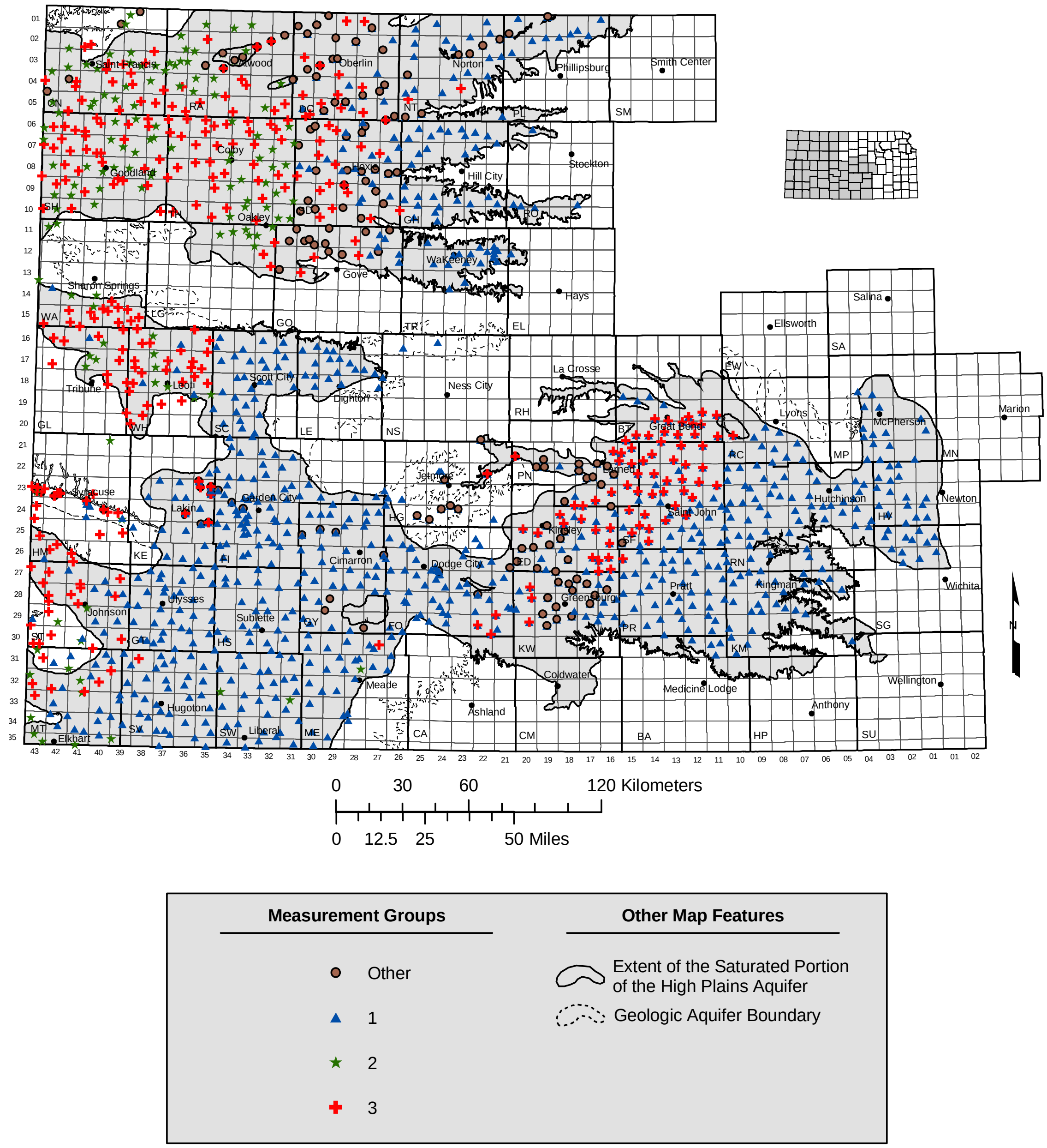

Figure 3. Geographic distribution of wells in three measurement groups.

We will consider the whole dataset together, looking at the absolute value of the differences in measured water table depth for the 200 wells with repeat measurements within the saturated extent of the High Plains aquifer. In normal years (for example, those years without three feet plus of snow lying across much of the High Plains region) a number of repeat measurements are made on selected wells for enhanced quality control and analysis. Given the field conditions in 2007, very few of these planned repeat measurements where taken. Instead, the repeats used in this report were obtained by taking advantage of measurements in the DWR and GMD-based water-level networks used in support of other State and local programs. Figure 4 shows the differences in repeat depth measurements sorted in order of decreasing magnitude.

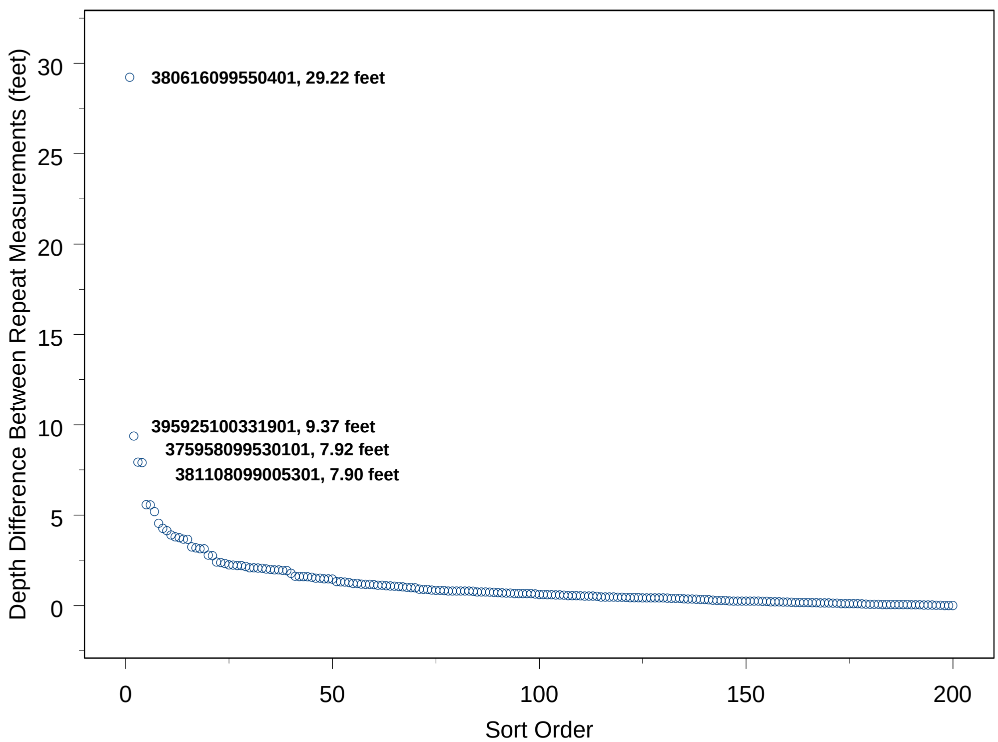

Figure 4. Absolute differences in measured depth to water for 200 wells with repeat measurements.

Sixty-seven of these differences are greater than 1 foot in magnitude. The USGS ID's and measured depth values for the wells with the four largest differences are as follows:

USGS_ID	Measurement 1	Measurement 2
380616099550401	164.6 ft on 18 Jan 2007	135.4 ft on 09 Apr 2007
395925100331901	18.5 ft on 15 Feb 2007	27.9 ft on 28 March 2007
375958099530101	135.5 ft on 17 Jan 2007	143.5 ft on 09 Apr 2007
381108099005301	27.6 ft on 03 Jan 2007	19.7 ft on 03 Apr 2007

For well 380616099550401, showing the largest magnitude difference (29.2 feet), the April 9 measurement is almost certainly incorrect, as a subsequent measurement (in September 2007) shows a depth of 163.9 feet, much closer to the January measurement.

Well 375958099530101 is an older artesian well drilled into the Dakota Aquifer system in Hodgeman County. This well has an interesting water-level history with rises and declines with a notable rising trend in the water-table since the pumping stopped in the late 1990s. A September 2007 measurement from this same well showed the depth-to-water at 129.88 feet.

Wells with relatively shallow (close to the land surface) depths-to-water generally have a greater response to both changes in pumping and precipitation. Well 395925100331901 is located in the alluvium of Beaver Creek in northwest Kansas and has a relatively shallow depth to water; wide variations in its water-table can be expected. The difference between measurements of over 9 feet over a period of months has been recorded on several occasions. In a similar fashion, well 381108099005301 has also shown abrupt changes in the water table. An October 4, 2007, measurement from this well shows the water table to be relatively stable over the summer at 19.25 feet below the land surface.

Ignoring the third measurements for those wells with three measurements (19 of the 200 wells with repeats), Figure 5 shows a plot of second measured depth minus first measured depth (signed, not absolute), versus the time span between those two measurements, with the vertical axis restricted to the range -5 to 5 feet, excluding the seven differences outside this range.

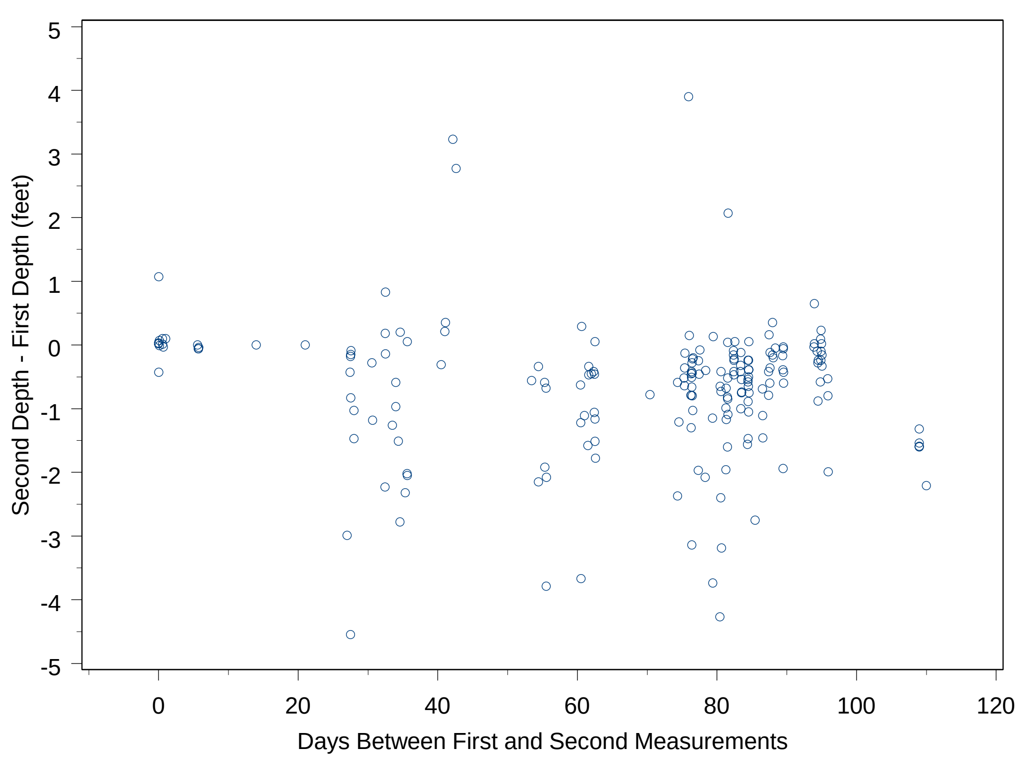

Figure 5. Differences between second and first measurements at wells with repeat measurements.

A regression analysis of these differences versus time span between measurements does not reveal a significant trend. However, it is clear from Figure 5 that there appears to be a preponderance of negative differences, a least for time spans greater than 20 days.

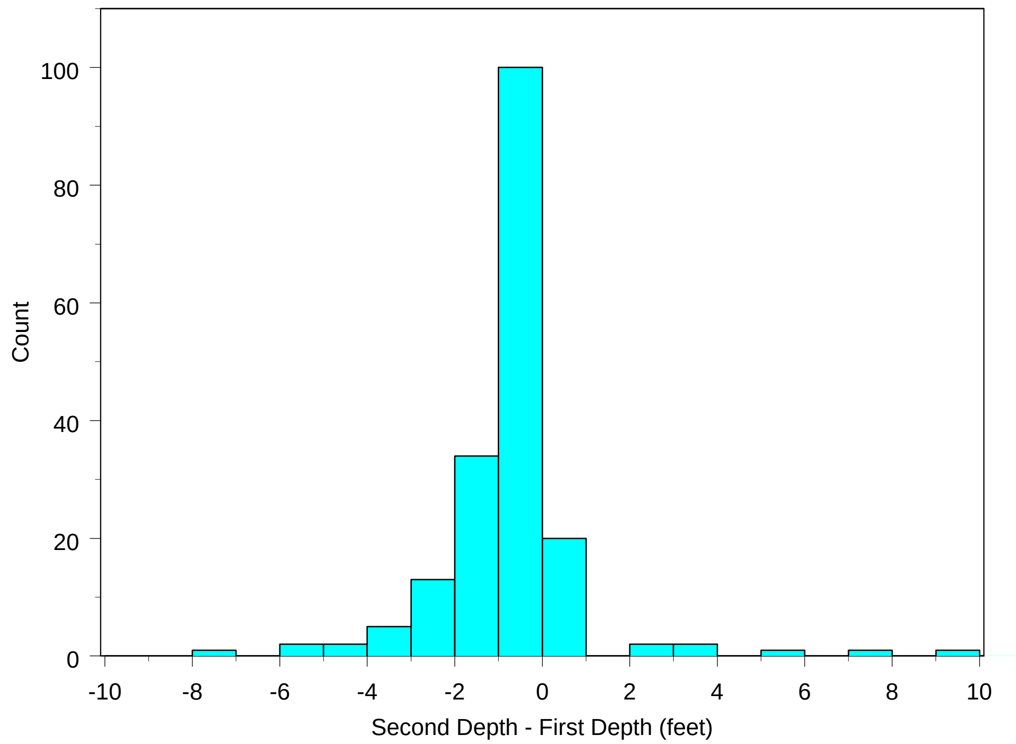

Figure 6. Histogram of depth differences for time spans exceeding 20 days.

Figure 6 is a histogram of depth differences for time spans exceeding 20 days, excluding the extreme difference of -29.22 feet for well 380616099550401. The mean of these data is -0.69 feet, and a t-test indicates that this mean is significantly different from zero. That is, there does seem to be some indication that the second measured depths tend to be less than the first measured depths, possibly indicating a general increase in water level (decrease in depth to water) between the first and second measurements.

To further explore the significance of temporal variations over the course of the measurement campaign, we have fit a smoothing spline model to the entire set of water table elevation data (within the saturated extent of the High Plains aquifer). This approach produces a localized spatial regression model, representing the water table elevations as a smooth function of the spatial coordinates of the wells. Unlike kriging, the smoothing spline does not try to do exact interpolation. Instead, it yields a smooth, compromise fit, using an optimal degree of smoothing estimated from a crossvalidation process. In particular, the smoothing spline model estimates a single, compromise value at those wells with multiple measurements. The point of fitting the spline model is to filter out the predominant influence of spatial variation in the water table elevations, in the hopes that any significant temporal trends will be more clearly revealed in the residuals from this model.

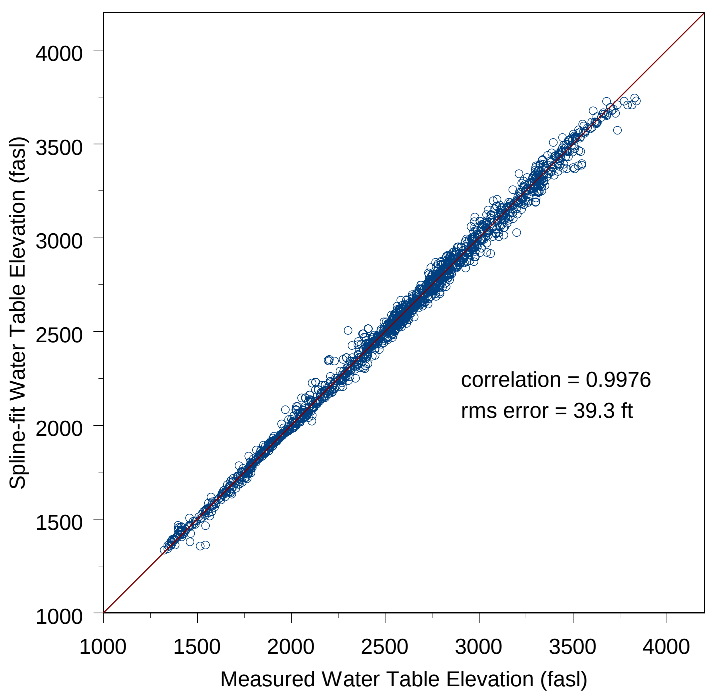

Figure 7. Crossvalidation plot for smoothing spline model of water table elevations.

Figure 7 shows the cross-plot of spline-predicted versus measured water table elevations, indicating that the spline model does in fact account for the majority of variation in the measured data. Note that this plot is not a “leave-one-out” crossvalidation plot as in the kriging crossvalidation analysis discussed later. Instead, it shows the actual spline-predicted water table elevation at a well location versus the measured water table elevation at that well. Since the smoothing spline does not yield an exact interpolation, these two values will always be different.

Figure 8 shows the residuals from the smoothing spline model – actual minus predicted water table elevations – versus measurement time. There does not seem to be any temporal trend apparent in these data, and a regression analysis of residual versus time supports the conclusion that these data show no significant trend in time.

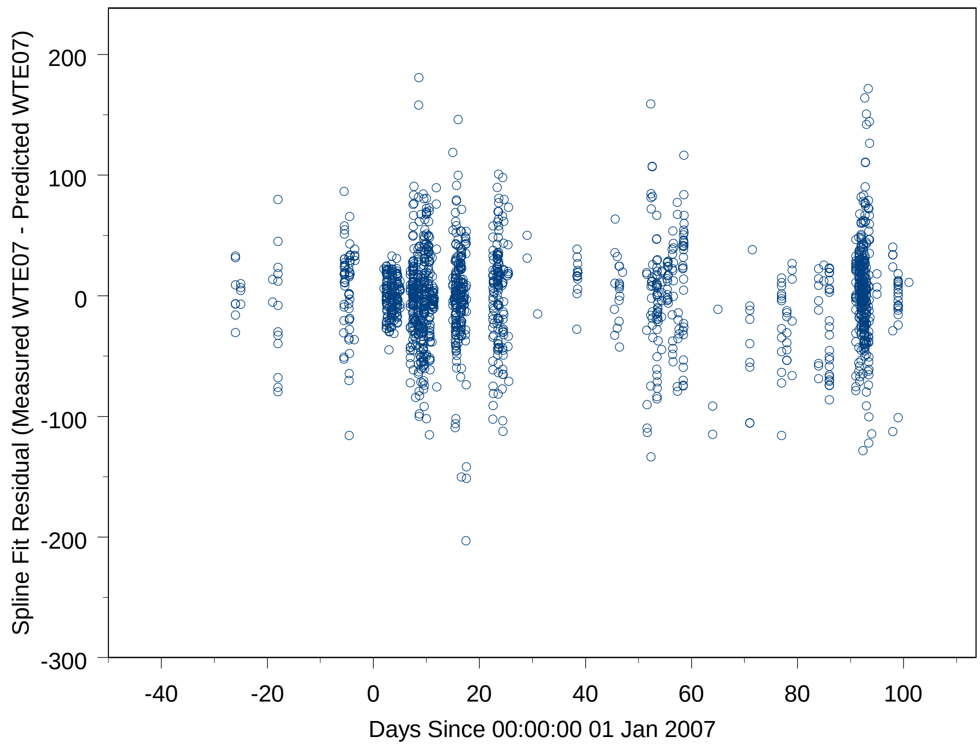

Figure 8. Residuals from smoothing spline model of water table elevations versus measurement time.

Another way to test for significant temporal trends is to plot histograms of the residuals for the three different measurement groups described above. Figure 9 shows such a plot.

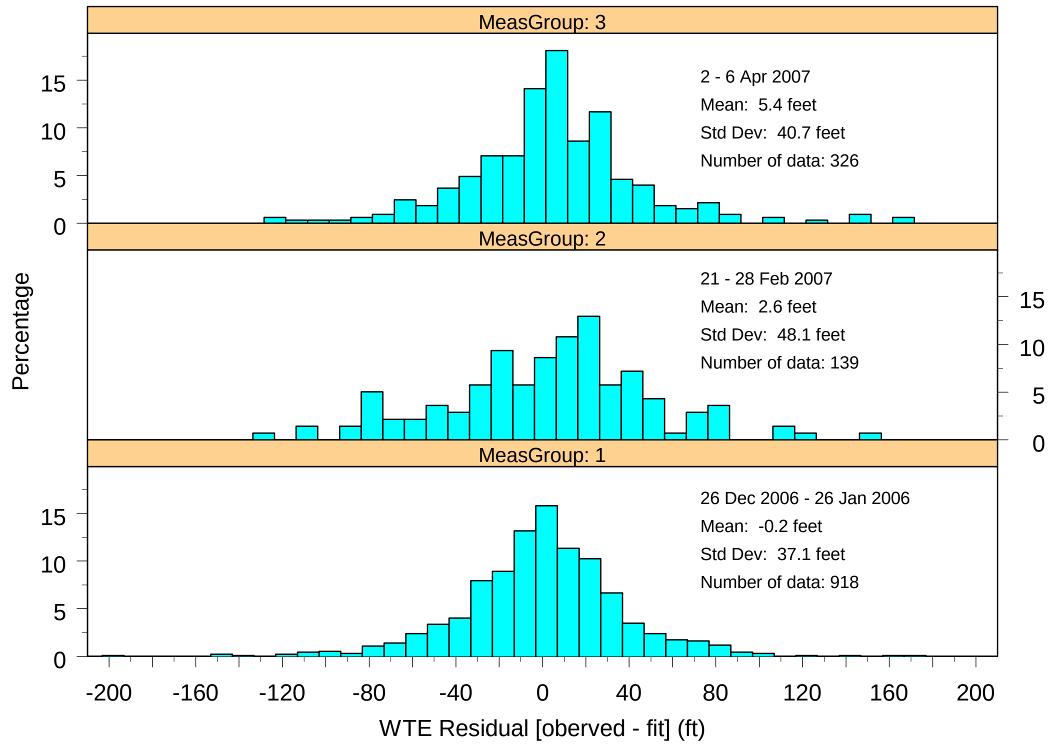

Figure 9. Residuals from smoothing spline model by measurement group.

A two-sample t-test deems the difference in means between the Group 3 (April) residuals and the Group 1 (January) residuals to be statistically significant and a one-sample t-test deems the mean of the Group 3 residuals to be significantly larger than zero. A tendency towards positive residuals in the Group 3 data – meaning measured elevations above the smoothed surface – could be caused in part by a general increase in water table elevation between January and April as the aquifer slowly recovers from the pumping season (with the smoothed surface reflecting the predominance of the earlier measurements). However, it is clear from the plots above that the evidence is not overwhelming.

One problem in evaluating these results is that it is essentially impossible to separate temporal variability from spatial variability particularly for the "Group 3 only" regions in western Kansas. Since there are no earlier measurements in these areas, there is nothing to stop the model from attributing possible temporal variation in these to spatial variability. The data simply do not contain the information required for evaluating these factors (time and space) independently.

We can examine this issue further by fitting the smoothing spline model solely to the Group 1 data and then examining the residuals for the Group 2 and Group 3 measurements from the resulting model, focusing in particular on the differences between residuals for Group 3 measurements that represent repeats of Group 1 wells (primarily central Kansas) and those representing wells that were measured for the first time in April (primarily western Kansas). Figure 10 shows the histograms of the residuals by measurement group in this case.

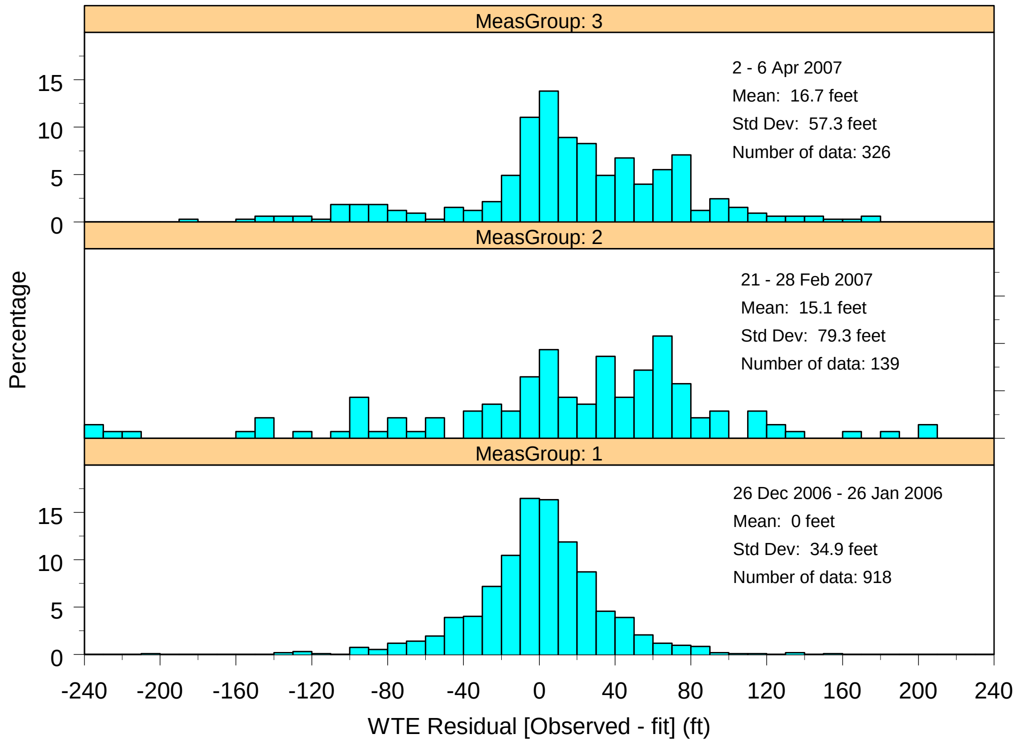

Figure 10. Residuals by measurement group from smoothing spline model fit to Group 1 data only.

By construction, the Group 1 data now show a normal distribution with a zero mean, since they were the data fit by the model. The residuals for the Group 2 and Group 3 data, which were not included in the development of the model, are now much more variable and are also decidedly more positive than before. T-tests show that the Group 3 mean is decidedly greater than zero, but results are a little more ambiguous for Group 2. That is not surprising given the spread of the data. The distributions are fairly non-normal in both cases, so the applicability of the t-test is a little questionable.

Of the 326 Group 3 wells, 83 represent repeat measurements of wells that were also measured during Dec-Jan, that is, that are also Group 1 wells. The remaining 243 are "new" wells, not measured during the Group 1 phase. It is interesting to compare the Group 3 residuals for these two sets of wells, as shown in Figure 11. In the panel labels in Figure 11, "G1Well: Yes" means the well is a repeat measurement of a Group 1 well and "G1Well: No" means it is a "new" well.

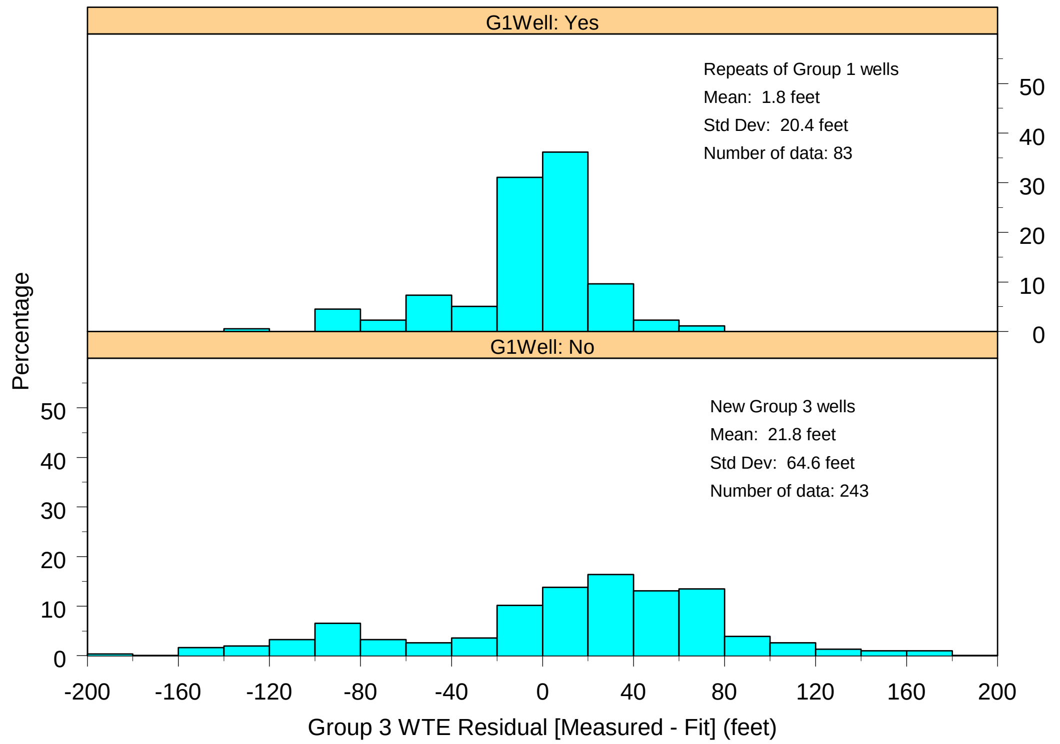

Figure 11. Group 3 residuals for repeat ("G1Well: Yes") and new ("G1Well: No") measurements.

The mean of the residuals for the 83 repeat measurements (1.8 feet) is not significantly different from zero, and these data are reasonably normally distributed, so the t-test is fairly reliable. Thus, the Group 3 (April) measurements that represent repeat measurements of Group 1 (Dec-Jan) wells do not show a significant, systematic deviation from the original (Group 1) measurements. That is, these data do not show significant evidence of a systematic temporal trend between the two sets of measurements. A t-test does deem the mean of the "new" Group 3 measurements (21.8 feet) to be significantly different from zero, but these data are fairly non-normally distributed.

Figure 12 is a map of the Group 3 residuals in feet (filled circles, with residual represented by the color scale), together with the locations of the Group 1 measurements (triangles):

So, again, the “repeat” Group 3 wells show relatively little deviation from the predictions based on the Group 1 spline model, while the “new” Group 3 wells show quite a lot of deviation from those predictions. However, the new measurements, to the west, are generally far from the Group 1 measurements in both space and time, so these data provide no means of separating out the spatial and temporal contributions to the deviations.

Overall the analysis in this section has shown that although there are some hints of a tendency for water levels to increase over the time frame in which the 2007 measurements were obtained, it is difficult to find conclusive evidence for significant temporal trends using this data set. Therefore, in the remainder of this report, the entire set of data will be treated as a single snapshot in time, as in previous reports.

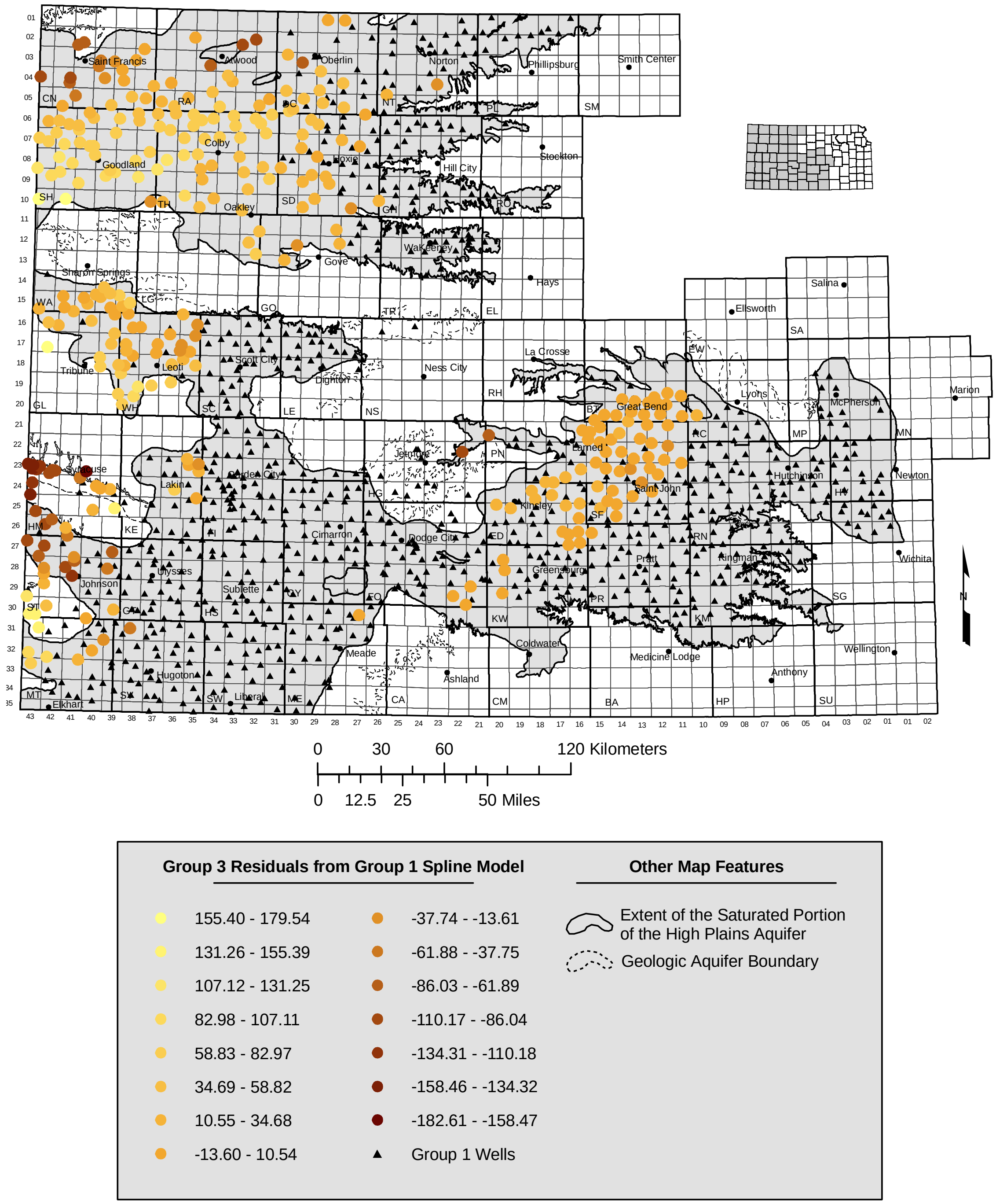

Figure 12. Map of Group 3 residuals from Group 1-based spline model together with locations of Group 1 wells.

4. Summary Statistics of Primary Variables

Summary statistics for the 2007 depth to water (from ground surface) and water-table elevation, along with the declines since 2006 and 2002, are shown in Table 1. Unlike previous years, when we used average depths for wells with repeat measurements, for this analysis we have selected the first measured depths for wells with repeat measurements in 2007. Overall, the declines for the one- and five-year periods preceding 2007 are larger than the corresponding periods preceding the 2006 measurements. The average decline over the 2006 calendar year, 1.28 feet, is more in keeping with the declines seen in the first few years of this decade (1.18 feet in 2000, 0.92 feet in 2001, 1.98 in 2002, and 1.18 feet in 2003), following two years of relatively small declines (0.14 feet in 2004 and 0.57 feet in 2005). Figures 13 and 14 show histograms of the one- and five-year water-level declines and Figures 15 and 16 are the corresponding normal quantile-quantile (QQ) plots. A normal QQ plot shows sorted data values plotted against the corresponding quantiles of a standard normal distribution, highlighting deviations from normality. Normally distributed data with the same mean and standard deviation as the sample data would fall along the straight line shown in the plot. In this report we use normal QQ plots as a consistent convention for displaying data distributions, even when we are not particularly concerned about whether the data are normally distributed.

Table 1. Summary statistics for 2007 water-level measurements and one- and five-year water-level declines.

	2007 Depth (feet)	2007 Elevation (feet a.s.l.)	2006 to 2007 Decline (feet)	2002 to 2007 Decline (feet)
Minimum:	0.33	1322.82	-16.69	-24.41
1st Quartile:	35.13	2144.74	0.08	1.48
Mean:	111.49	2580.48	1.28	5.29
Median:	104.19	2622.88	0.87	3.64
3rd Quartile:	165.42	2988.24	2.07	7.02
Maximum:	393.60	3836.84	41.70	43.42
Std. Dev.:	81.74	579.73	2.79	6.73
Count:	1322	1322	1297	1124

Table 2. Summary statistics for 2006 water-level measurements and previous one- and five-year water-level declines.

	2006 Depth (feet)	2006 Elevation (feet a.s.l.)	2005 to 2006 Decline (feet)	2001 to 2006 Decline (feet)
Minimum:	0.97	1325.09	-26.82	-31.12
1st Quartile:	35.14	2156.02	-0.12	1.09
Mean:	113.95	2606.96	0.57	4.88
Median:	110.14	2687.91	0.38	3.28
3rd Quartile:	167.52	3040.14	1.12	6.68
Maximum:	390.58	3836.80	23.26	39.18
Std. Dev.:	82.12	590.51	2.34	6.16
Count:	1266	1266	1233	1152

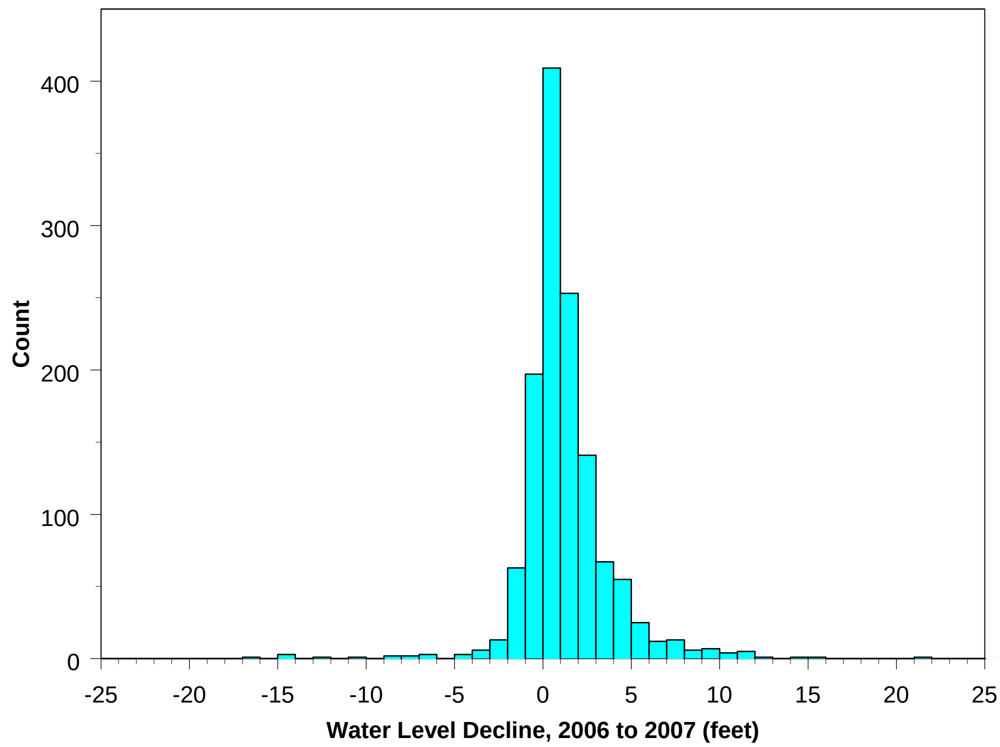

Figure 13. Histogram of water-level declines between 2006 and 2007 campaigns.

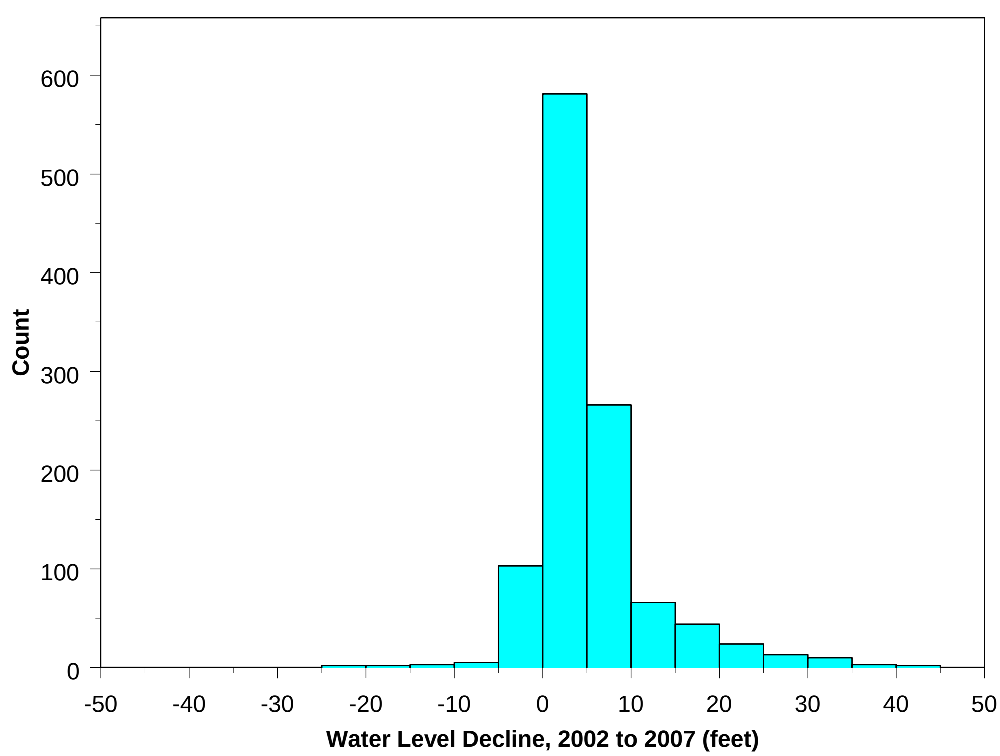

Figure 14. Histogram of water-level declines between 2002 and 2007 campaigns.

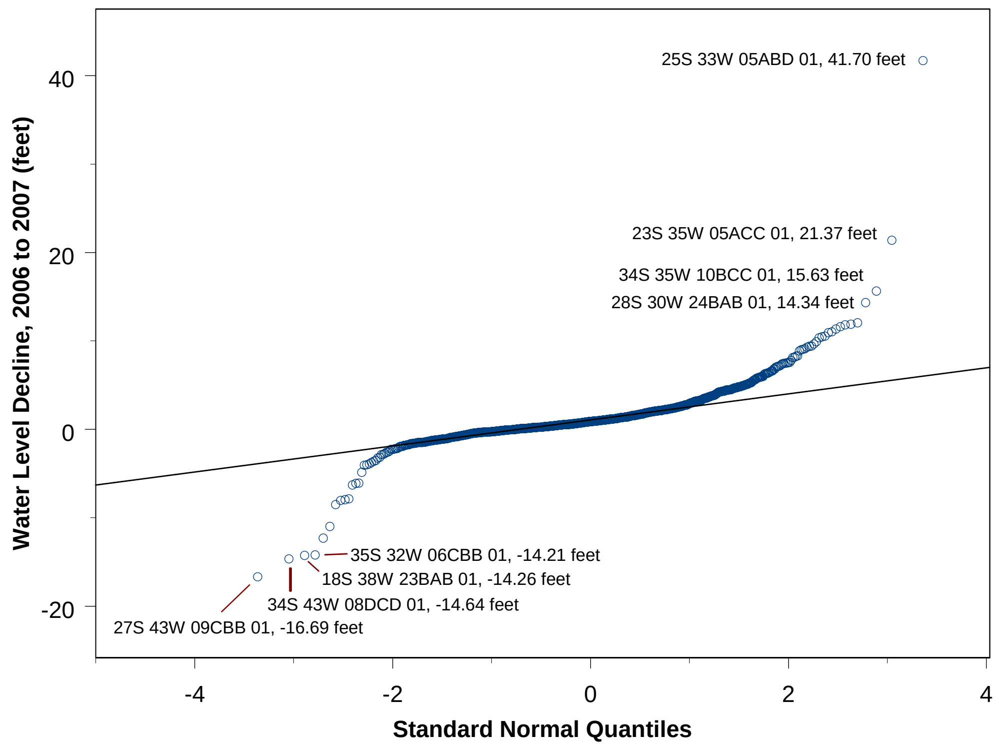

Figure 15. Normal QQ plot for one-year water-level declines.

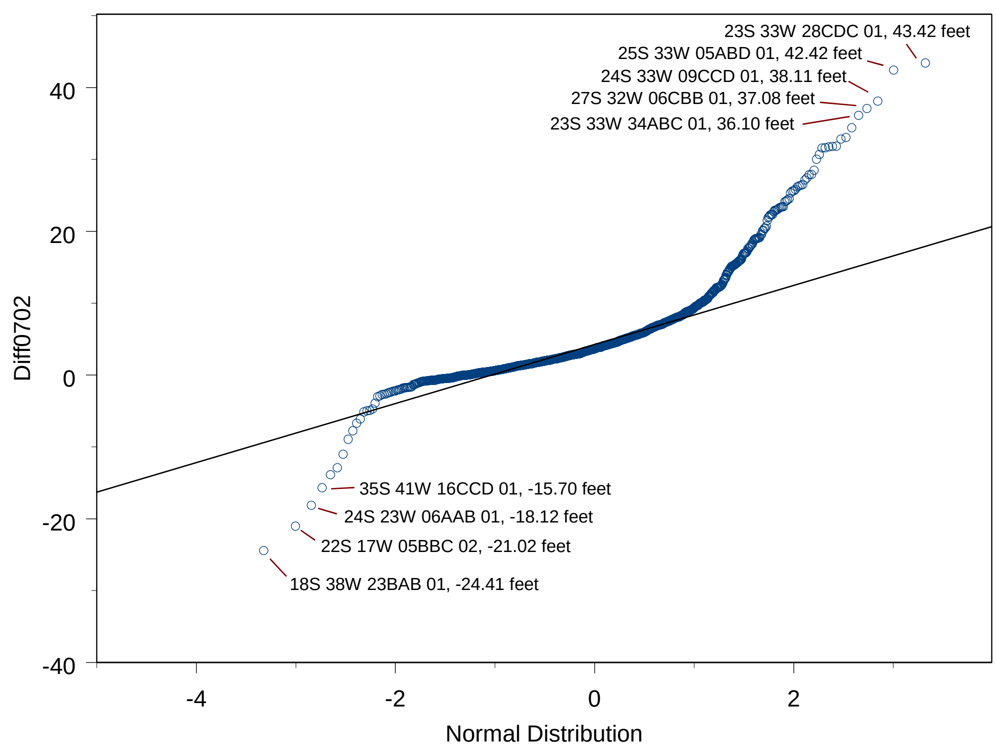

Figure 16. Normal QQ plot for five-year water-level declines.

The eight wells with the most extreme one-year declines, flagged on Figure 15, are

KGS ID	USGS ID	2006 to 2007 decline (feet)
25S 33W 05ABD 01	375449100574301	41.70
23S 35W 05ACC 01	380500101110501	21.37
34S 35W 10BCC 01	370620101071301	15.63
28S 30W 24BAB 01	373614100331601	14.34
35S 32W 06CBB 01	370157100505901	-14.21
18S 38W 23BAB 01	382851101291601	-14.26
34S 43W 08DCD 01	370555102004701	-14.64
27S 43W 09CBB 01	374259102020401	-16.69

The well showing the largest decline, 25S 33W 05ABD 01, is in the sand hills south of Garden City and is surrounded by wells showing fairly large declines, ranging from 5 to almost 12 feet, but none nearly as large as the 41.7 foot decline exhibited by this well. The well was measured three times on Jan. 16, 2007, with all three measurements yielding a depth to water of 186.9 feet, so the measurement is almost certainly accurate for that time and place. It is possible that this well was still recovering from recent pumping at the time of measurement.

The well with the second largest decline, 23S 35W 05ACC 01, has its 2006 measurement flagged as "anomalous" by the 2006 version of this report and explains why it appears again in 2007. Since quarterly measurements started on this well in 2004, the winter 2006 measurement is still considered anomalous with the winter 2007 measurement falling within expected trends of the well.

This area between Liberal and Hugoton, Kansas, has historically shown notable declines in the water table (as well as notable increases). The well, 34S 35W 10BCC 01, is located in the middle of this area. Declines of just over 10 feet have also being recorded in two adjacent monitoring wells indicating the trend of 34S 35W 10BCC 01 is supportable.

Well 28S 30W 24BAB 01 is located west of Montezuma, Kansas, and is bordered by wells showing slight increases in the water table, ranging from 0.3 to 0.5 feet, to the west and wells showing notable declines, ranging from 5.49 to 7.14 feet, to the north. This well has a history of showing "bounces" where the water-table increased or decreased dramatically in a short period of time. The 2007 measurement for this well will need to be reviewed at a later date once future measurements have been taken.

The well with the largest increase in the water-table, 35S 32W 06CBB 01, is located close to the state line southwest of Liberal, Kansas. This well is surrounded by wells with small to moderate declines. The 2007 measurements will need to be reviewed at a later date once future measurements have been taken.

Well 18S 38W 23BAB 01 is located roughly 40 yards from Whitewoman Creek, east of Tribune, Kansas, and is relatively shallow with depths-to-water being under 40 feet since 2005. The well was measured twice in 2007 with depth-to-water measurements at 24.9 and 24.96 feet. Given its shallow depth to water and proximity to the stream, the water table has varied greatly over the years. This latest 2006 to 2007 bounce in the water table is not considered anomalous.

Both wells 34S 43W 08DCD 01 and 27S 43W 09CBB 01 are relatively new the monitoring network with each only being measured twice – 2006 and 2007. Both wells are in areas of relatively little to no ground-water development and will require additional measurements to determine proper trends and behaviors in the water table.

The five wells with the most extreme five-year changes, indicated on Figure 16, are

KSG ID	USGS ID	2002 to 2007 decline (feet)
23S 33W 28CDC 01	380109100570201	43.42
25S 33W 05ABD 01	375449100574301	42.42
24S 33W 09CCD 01	375832100571001	38.11
27S 32W 06CBB 01	374343100520801	37.08
23S 33W 34ABC 01	380056100554001	36.10
35S 41W 16CCD 01	370001101472201	-15.70
24S 23W 06AAB 01	375958099530101	-18.12
22S 17W 05BBC 02	381015099132702	-21.02
18S 38W 23BAB 01	382851101291601	-24.41

Well 23S 33W 28CDC 01 has the largest five-year decline and is located on the north side of the Arkansas River, northwest of Garden City, Kansas. The well was measured twice on the same day in 2007, both measurements indicating a depth-to-water of 120.3 feet. This well is surrounded by other wells indicating five-year declines of 30 to just under 40 feet, two of which are 24S 33W 09CCD 01 and 23S 33W 34ABC 01, the third and fifth wells on the five-year decline list. Well 24S 33W 09CCD 01 was measured twice in 2007 with both readings indicating 83.2 feet depth-to-water, while 23S 33W 34ABC 01 was measured three times in 2007 with 119.9, 119.9, and 119.95 depth-to-water readings. None of the 2002 or 2007 measurements are considered out of trend.

Other wells on the five-year table also have entries in the one-year decline table. The well with the second largest five-year decline is 25S 33W 05ABD 01, the same well showing the largest one-year decline. Well 18S 38W 23BAB 01 shows the largest five-year water level increase (24.41 feet) and the third largest one-year increase (14.26 feet).

Well 27S 32W 06CBB 01 has shown a constant and steady decline since it was first measured in 1973.

The well 35S 41W 16CCD 01 is along the state line east of Elkhart, Kansas, and has shown increases in the water table since 2002. Likewise the Dakota screened well 24S

23W 06AAB 01 south of Jetmore, Kansas, has shown increasing trends in the water-table since the late 1990s.

The winter 2002 measurement for 22S 17W 05BBC 02 at 47.63 feet is noticeably lower than any other measurement in the well's history. Given the other wells that were also measured 2002 in the area do not reflect this same change in depth, the 2002 measurement for 22S 17W 05BBC 02 is considered "anomalous".

5. Geostatistical Analysis of 2007 Water Table Elevations

For the geostatistical analysis of 2007 water-table elevations, we employed the measurements from both the DWR and KGS at 1322 wells located within the High Plains aquifer extent, using the first measured values for those wells with repeat measurements, as described above.

Geostatistical estimation procedures are based on conceptualizing the property under consideration – the water table elevation in this case – as a spatial random function, essentially a set of spatially correlated random values (Goovaerts, 1997; Isaaks and Srivastava, 1989). The most common tool for describing the spatial correlation structure of the property is the semivariogram, which is computed as half of the average squared difference between data values as a function of separation distance, or "lag", between measurement locations. Measurements that are closer in geographic space tend to be more similar than those that are more widely separated, so that the semivariogram value tends to be smaller for shorter lags and larger for longer lags. The geostatistical interpolation procedure, kriging, estimates the property value at selected locations (usually, the nodes of a regular grid) as weighted averages of the surrounding data values, with weights selected in accordance with the correlation structure described by the semivariogram. For technical reasons, the empirical semivariogram computed from the actual data values is replaced with a model semivariogram fitted to the data and this model is used in the computation of the kriging weights.

In addition, the semivariogram should be computed in a way that factors out the effects of large-scale trends in the data. As in previous years, we have accounted for the strong west to east trend in water-table elevation by identifying a trend-free direction, roughly parallel to contours of constant elevation (Olea and Davis, 2003; Bohling and Wilson, 2004; Bohling and Wilson, 2005). The semivariogram computed in the trend-free direction is assumed to represent the random, spatially autocorrelated component of the overall variation and the kriging analysis combines this random field model with a first-order local trend model to estimate the water-table elevation at all points on a regular grid. For the past several years, examination of semivariograms computed in a range of directions from pure north to N 27° E has identified N 12° E as the trend-free direction. For the 2007 measurements, N 9° E appears to be the most trend-free direction, although differences between the variograms are very slight from about N 6° E to N 14° E. Figure 17 shows the semivariogram for the 2007 water table elevation measurements in the direction N 9° E, along with the fitted model. The semivariogram for a trend-free variable levels off at a value called the sill, representing the overall level of variability of the "random" component of the measured quantity. The increase in variogram values from the nugget, at small lags, to the sill, at a lag value referred to as the range, corresponds to a decrease in correlation between pairs of measurements with increasing separation distance. Measurements separated by distances greater than the range are essentially uncorrelated. The fitted model for the 2007 water table elevations is Gaussian in shape with a nugget of 237 square feet, a sill of 11972 square feet, and a range of 69.6 kilometers. Overall, this model is similar to that for pervious years.

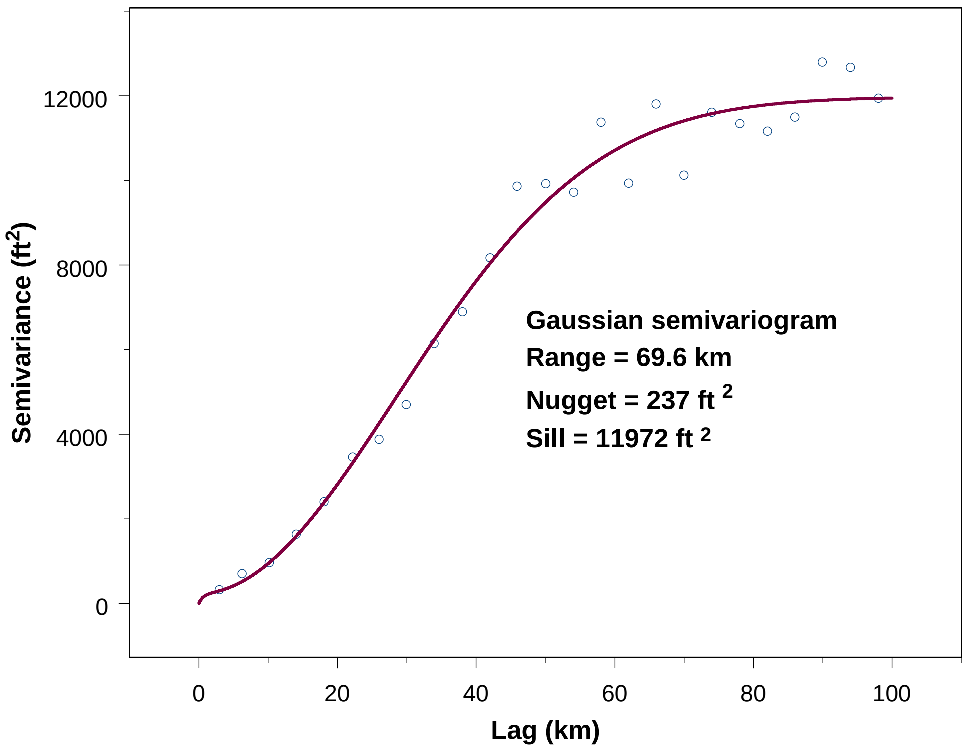

Figure 17. Semivariogram of 2007 water table elevation measurements in direction N 9° E (points) along with fitted Gaussian model (line).

The nugget for the 2007 water table elevation semivariogram, 237 ft^2, is significantly higher than that for previous years (113 ft^2 in 2006, 169 ft^2 in 2005), meaning that the 2007 model indicates a notably higher level of short-scale variability than the models for earlier years. The square root of the nugget, 15.4 feet for the 2007 model, sets the lower limit of the kriging error (standard deviation) for the map used to determine the location of "holes" in the well network, precluding the use of the 10-foot standard deviation threshold used in earlier years. Thus, we will once again use a revised threshold standard deviation value to identify network holes, as we have for the past few years.

Figure 18 shows the results of the kriging crossvalidation analysis for the 2007 water levels. For this analysis, each well is removed in turn from the dataset, the water level at that location is estimated from surrounding measurements, and the estimated and measured values are compared. Because the water table is a very smooth surface and the measurement wells are laid out in a dense, regular network, the crossvalidation results are quite good, with an extremely high correlation (0.9992) between estimated and measured elevations and a very low root-mean squared error (23.4 feet) relative to the range of variation of the water table elevation (about 2500 feet). However, the scale of the axes masks the fact that some of the errors are in fact quite large when considered in terms of local estimation of water table elevation. The crossvalidation errors, which range from −124 feet to 245 feet, are examined in more detail in the following pages.

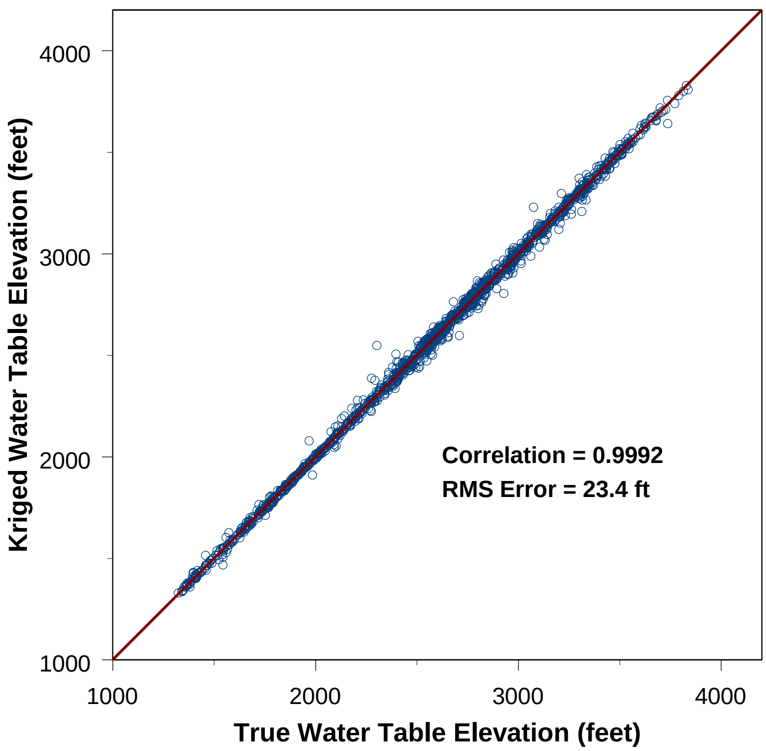

Figure 18. Kriging crossvalidation results for 2007 water-table elevations.

Figure 18 is indistinguishable from the corresponding plot for the 2005 and 2006 water table elevations (Figure 11, Bohling and Wilson, 2005; Figure 8, Bohling and Wilson, 2006), with largely the same set of wells showing the most extreme crossvalidation errors.

Figure 19 is a normal QQ plot for the kriging crossvalidation errors. The error is the difference between the water table elevation estimated (kriged) from the surrounding wells and the actual measured elevation at the well. A large positive error means that the measured water-table elevation in a well is significantly lower than would be expected based on the elevations observed in nearby wells and a large negative error means that the measured elevation is significantly higher than would be expected.

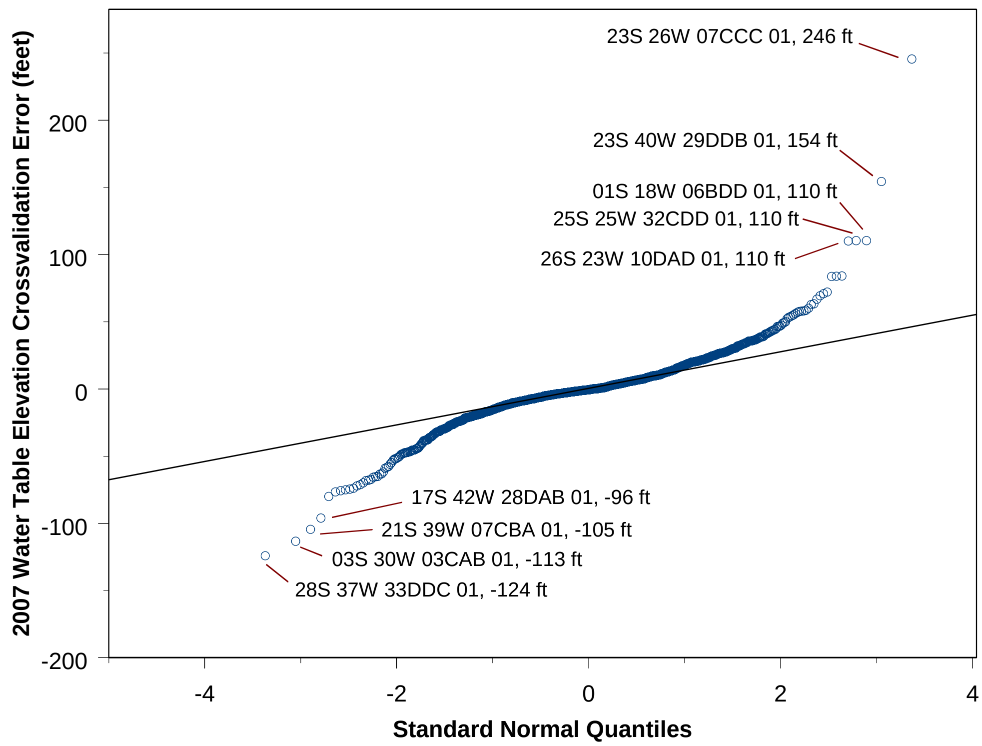

Figure 19. Normal QQ plot of kriging crossvalidation errors for 2006 water-table elevations.

The wells with kriging errors greater than 100 feet (roughly) in magnitude, flagged in Figure 19, together with the 2006 kriging errors at these wells, are:

KGS ID	USGS ID	2007, 2006 kriging residual (feet)	Geol.Units
23S 26W 07CCC 01	380335100132701	246, 242	KD
23S 40W 29DDB 01	380105101433601	154, 153	KD
01S 18W 06BDD 01	395944099234201	110, NA	QA
25S 25W 32CDD 01	374936100052801	110, 118	KD
26S 23W 10DAD 01	374725099485601	110, 102	KD
17S 42W 28DAB 01	383247101573601	-96, -101	TO
21S 39W 07CBA 01	381422101385501	-105, -121	TO
03S 31W 07CBD 01	394814100505201	-113, -100	TO
28S 37W 33DDC 01	373346101215801	-124, -131	QUTO

With the exception of well 01S 18W 06BDD 01, which was not measured in 2006, all of these wells also appeared in the list of wells with errors greater than 100 feet in magnitude for 2006, with only slightly different error values. Furthermore, this list is also similar to the list of large kriging errors for 2005. That is, the elevations measured in these wells are almost certainly due to systematic differences between the piezometric surface in these wells and those in surrounding wells. As pointed out in previous years, the largest positive errors are associated with wells tapping the Cretaceous Dakota aquifer, surrounded primarily by wells tapping the Ogallala aquifer. Thus, these persistent differences could indicate the presence of significant vertical gradients between the Dakota and Ogallala aquifers in the vicinity of these wells, a factor not accounted for in the two-dimensional kriging analysis. Vertical gradients between wells screened at different elevations could also contribute to the large negative errors. Unfortunately we have limited information on screen depths for these wells and even less on the distribution of possible low-permeability units that would allow the maintenance of large vertical gradients, so it is difficult to examine this possibility in more detail.

The map of kriged 2007 water-table elevations is shown in Figure 20 and the kriging error map, represented in terms of standard deviation of the kriging estimate at each location, is shown in Figure 21.

The contour levels used on the kriging error map, 17.5 feet, 18.9 feet, and 25.6 feet, represent the 60^{th}, 75^{th}, and 90^{th} percentiles of the overall distribution of the kriging standard deviation values. The 60^{th} percentile value of 17.5 feet has been chosen to roughly correspond with the 10-foot threshold contour on the kriging standard deviation map for 2003 (Olea and Davis, 2003). Accordingly, we will use a standard deviation of 17.5 feet in the identification of network holes (Section 8) instead. As is apparent from Figure 21, the kriging error map primarily reflects the distance to the nearest measurement point. This distance is scaled according to the semivariogram model to produce the estimated standard deviation value and changes in the nugget value will have a large impact on the prevailing value of standard deviation throughout most of the network, where separation distances are small. The configuration of the standard deviation contours, reflecting the spatial distribution of the measurement points, is more important than the contour levels themselves, which are overly sensitive to fairly small changes in the semivariogram model.

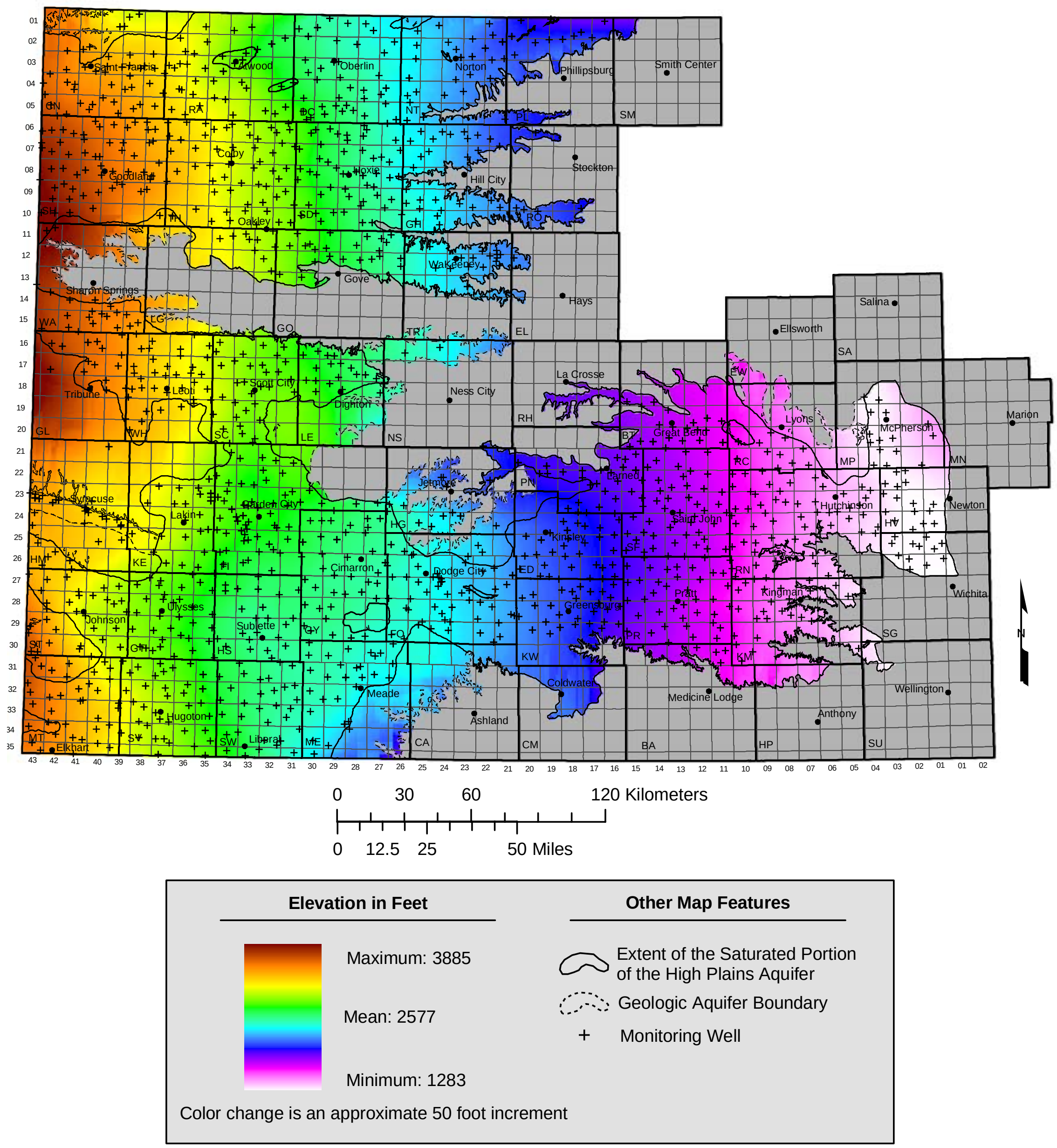

Figure 20. Kriged 2007 water table elevation.

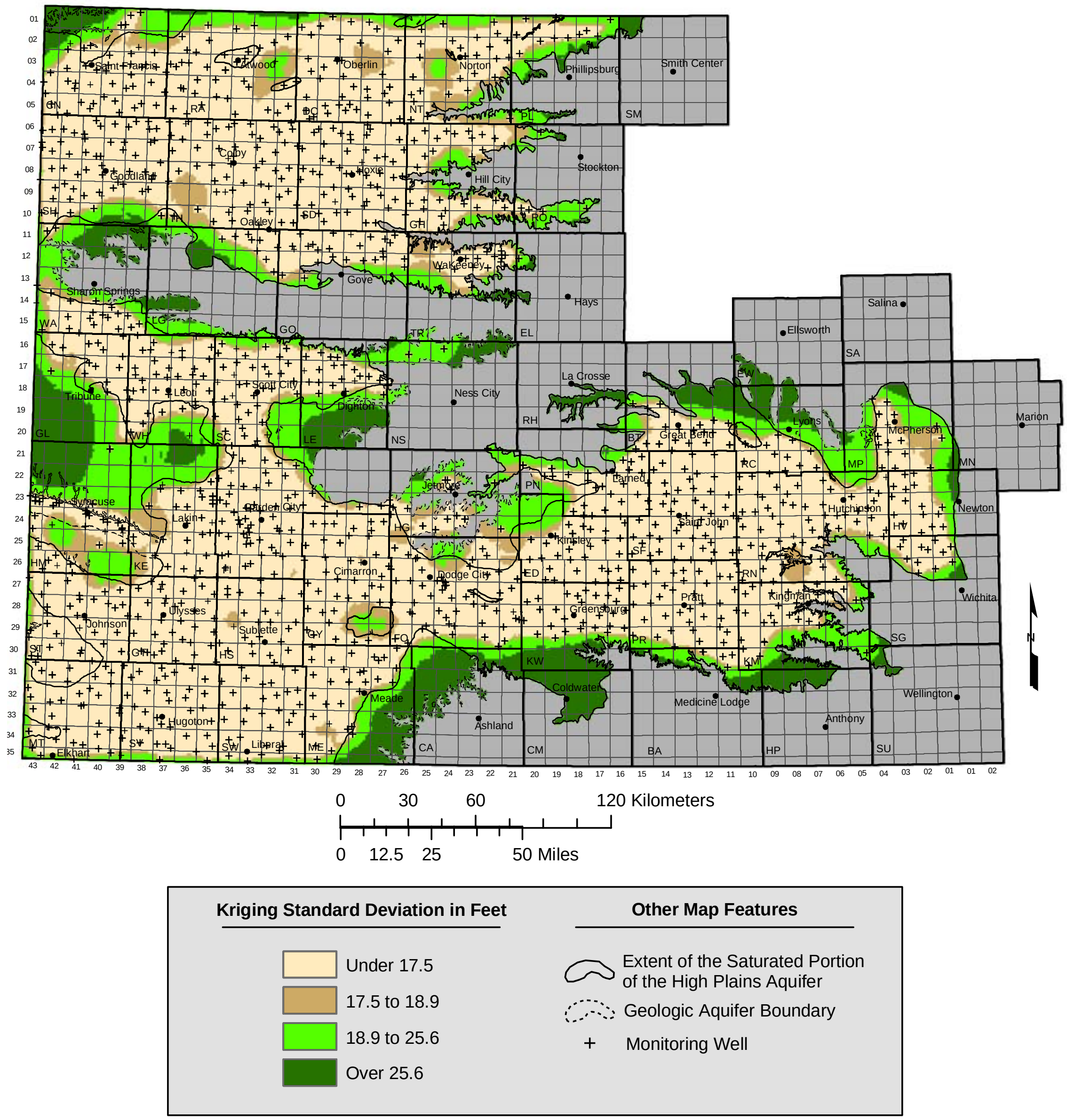

Figure 21. Kriging standard deviation for 2007 water table elevations.

6. Geostatistical Analysis of 2002 to 2007 Water-Level Declines

Figure 22 shows the omnidirectional semivariogram for the water-level changes over the five-year period from 2002 to 2007. An exponential semivariogram model, with a range of 89.7 km, nugget of 7.1 ft^2, and overall sill of 52.5 ft^2, was fitted to the empirical semivariogram using weighted nonlinear least squares (Olea, 1996). This semivariogram exhibits a longer range and a higher level of both short-range (nugget) and overall (sill) variability than those for previous years.

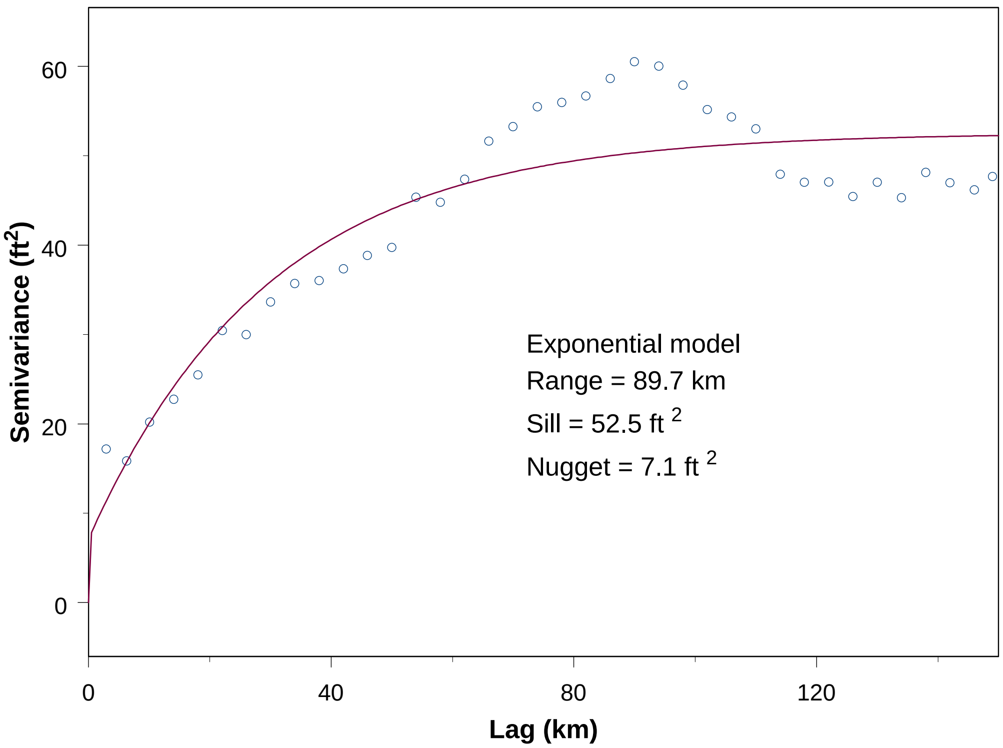

Figure 22. Omnidirectional semivariogram for changes in water level over the five-year period from 2002 to 2007.

Figure 23 shows the results of the kriging crossvalidation analysis for the water-level declines between 2002 and 2007. This analysis shows a slightly higher correlation (0.79) between kriged and predicted declines than that for the 2001 to 2006 declines (0.77), but also shows a higher root-mean-squared residual (4.1 ft as opposed to 3.9 feet), probably reflecting the higher level of overall variability indicated by the variogram shown in Figure 22.

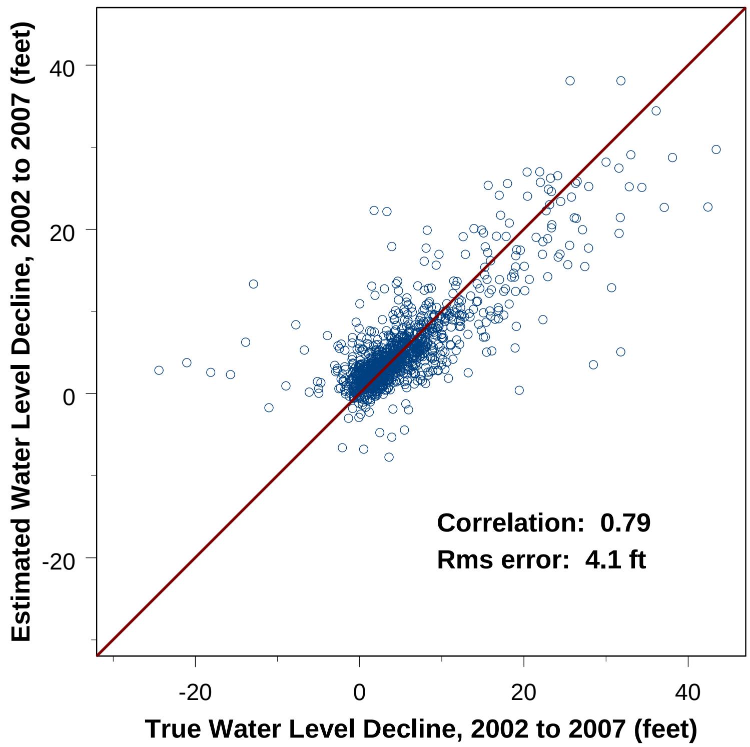

Figure 23. Kriging crossvalidation results for 5-year water-level changes.

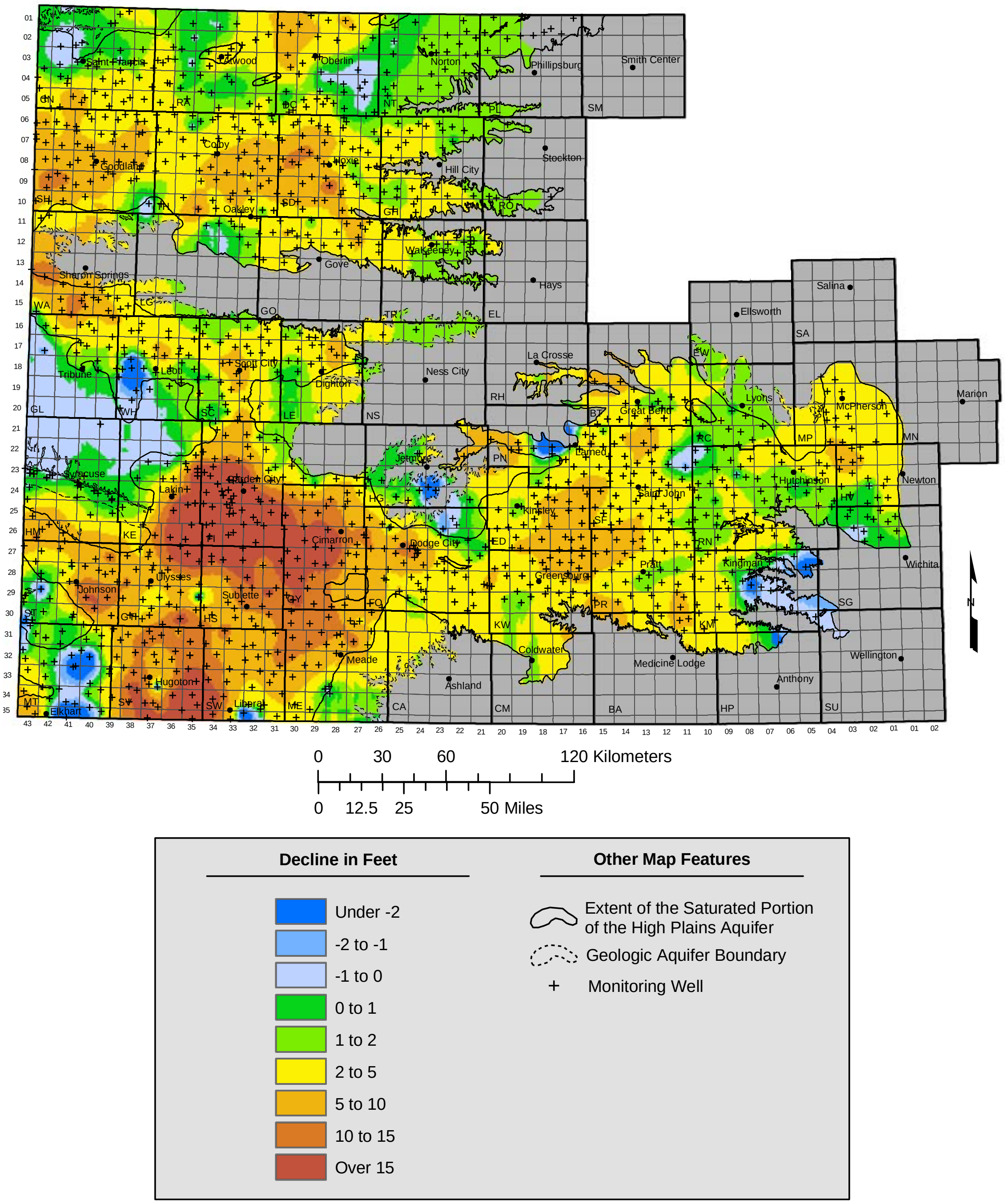

Figure 24. Kriged water level declines for the five-year period from 2002 to 2007.

A map of the kriged water level declines between 2001 and 2006 is shown in Figure 24. The pattern and level of water level declines is again similar to past 5-year intervals and roughly mirrors areas with relatively higher reported ground-water use (Wilson et al., 2002). The most notable decline areas (those with multiple wells displaying the same behavior) can be seen running from Lakin and Garden City to Meade, between Hugoton to Liberal, southern Wallace County, and through the interior of Sherman, Thomas, and Sheridan counties. Declines also occur throughout south-central Kansas, specifically in areas of Kiowa, Edwards, and portions of Stafford counties.

In contrast to past 5-year patterns, notable rises in the water table can be seen in a few wells in south-west Wichita County. Other rises in the water-table observed from 2001 to 2006 in eastern Morton County appear again and are more prominent in the 2002 to 2007 time period.

7. Geostatistical Analysis of 2005 to 2006 Water Level Declines

Figure 25 shows the omnidirectional semivariogram for the water-level changes from 2006 to 2007, along with the best-fit semivariogram model. The fitted model is spherical with a range of 87.3 km, a nugget of 5.00 ft^2, and an overall sill of 8.6 ft^2. This model shows a longer range and a notably higher level of both short- and long-range variability than that for the 2005 to 2006 declines, which was exponential with a nugget of 1.43 ft^2 and sill of 6.47 ft^2 (Bohling and Wilson, 2006). The 2006-2007 variogram is somewhat more similar in character to that for the 2004-2005 declines, which was spherical with a range of 67 km, a nugget of 4.5 ft^2, and a sill of 5.8 ft^2 (Bohling and Wilson, 2005), but still shows a higher level of variability. This higher level of overall variability is almost certainly due at least in part to the higher level of temporal variability resulting from the longer time frame of the 2007 sampling process. Although the analysis in Section 3 failed to find strong evidence of systematic temporal trends in the data, that does not rule out a significant temporal contribution to overall variation.

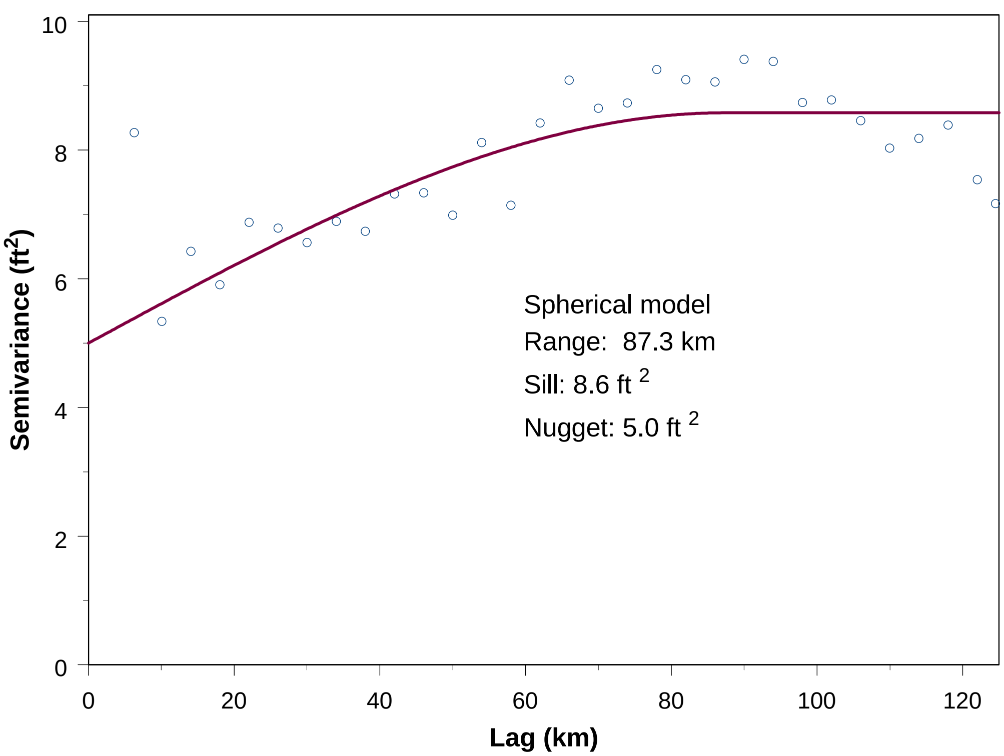

Figure 25. Omnidirectional semivariogram for changes in water level between 2006 and 2007 measurement campaigns.

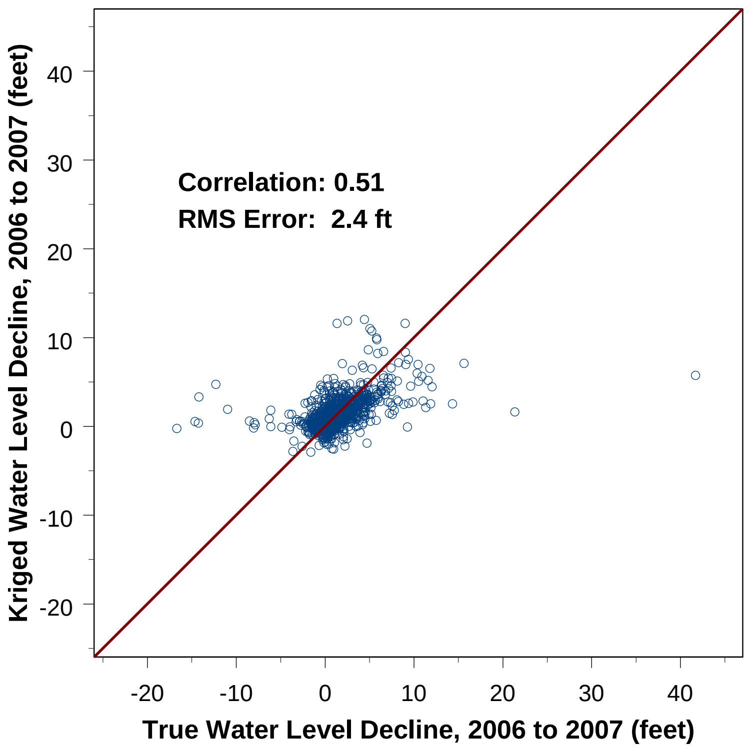

Figure 26. Kriging crossvalidation results for changes in water level between 2006 and 2007.

The kriging crossvalidation results for the one-year declines, shown in Figure 26, demonstrate that the interpolation process smooths out a considerable amount of the actual variability in the measured declines. Like the five-year declines, these results show a higher correlation but also higher root-mean-squared than the corresponding results for the 2005-2006 declines, again reflecting the higher level of variability in the measured 2006-2007 declines.

Past reports have presented an analysis of variance to determine whether any of a set of "exogenous" variables describing the well measurement process and well characteristics seemed to contribute significant variability to the measured one-year declines. However, the declines themselves exhibit some spatial correlation which could contribute variation that might be incorrectly attributed to one or more exogenous variables. Therefore, for this year's report we have chosen to base the analysis of variance on the kriging residuals for the one-year declines; that is, the analysis of variance tries to determine whether any exogenous variable contributes to systematic deviation of measured declines from expectations based on surrounding wells.

Table 3 contains the results of an analysis of variance of the kriging crossvalidation errors for the 2005 to 2006 declines against the exogenous variables describing the measurement process and well characteristics. These variables include the identity of the person responsible for the measurement (Measurer), the ease or difficulty of downhole access (Downhole.Access), whether or not the tape used for the measurement was weighted (Weighted.Tape), the primary use of the well (Well.Use, representing irrigation, domestic, etc.), whether or not oil is present on top of the water column (Oil.On.Water), the quality of the chalk cut on the measurement tape (Chalk.Cut.Quality), and a five-group variable representing the category of formation or formations (aquifers) tapped by the well (Aq.Group5, with categories representing Quaternary sediments [alluvium], Quaternary sediments plus Tertiary Ogallala, Tertiary Ogallala alone, any combination of Quaternary sediments through Cretaceous bedrock, and Cretaceous bedrock alone). These variables are explained in more detail in Bohling and Wilson (2006). The crossvalidation errors describe the extent to which the decline at a well is out of keeping with those at nearby wells, with a positive error indicating that the actual decline is lower than expected based on declines at nearby wells, and vice versa. None of the exogenous variables is deemed to have a significant effect; that is, none of these factors seems to lead to systematic aberrations in the decline measurements.

Table 3. Analysis of variance of kriging crossvalidation errors for 2006 to 2007 declines.

Source	Df	Sum of Sq	Mean Sq	F Value	Pr > F
Measurer	22	70.86	3.221	0.632	0.904
Downhole.Access	1	2.88	2.876	0.564	0.453
Weighted.Tape	1	10.96	10.957	2.149	0.143
Well.Use	4	9.39	2.348	0.461	0.765
Oil.On.Water	1	1.71	1.710	0.335	0.563
Chalk.Cut.Quality	2	10.17	5.085	0.998	0.3691
Aq.Group5	4	28.60	7.150	1.403	0.2310
Residuals	1019	5194.37	5.098		

Residual standard error: 2.26 feet

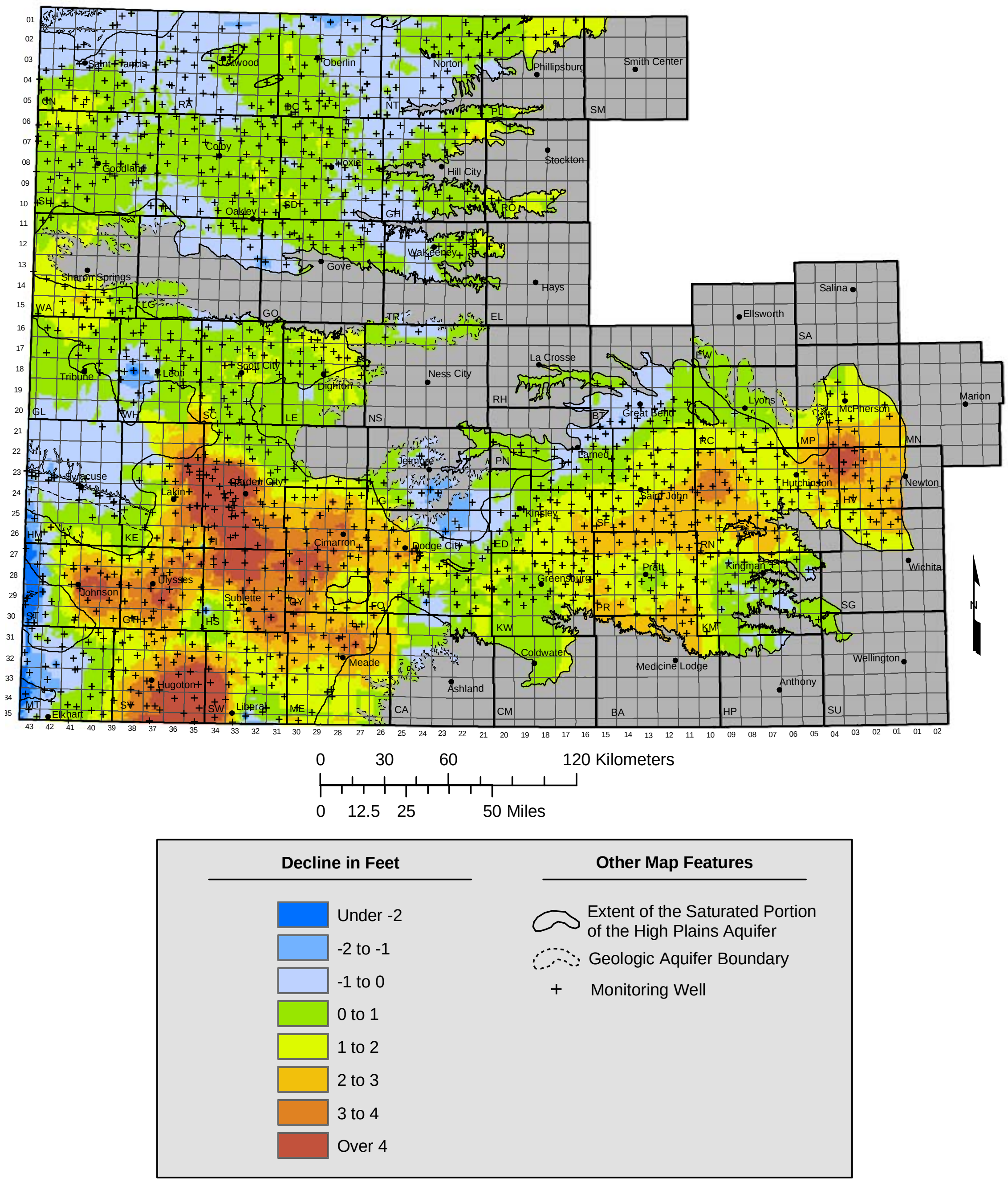

Figure 27. Kriged Water Level Declines for One-Year Period from 2006 to 2007.

Water level declines from 2006 to 2007, shown in Figure 27, show some interesting patterns in relation to past years. The most notable are the size and extent of declines that occurred in south-central Kansas. The Equus Beds and eastern edge of the Great Bend Prairie aquifer portions of the High Plains aquifer had some the highest and most expansive declines for those particular regions seen in recent times. Given the relatively higher precipitation rates and shallower depth to water in these areas, it is likely these areas will recover at some point in the future but the declines measured over this period was of interest none-the-less.

For the Ogallala portion of the High Plains aquifer, areas that have predominately seen water table declines in the past did so again in 2006 to 2007. Excluding some areas, the 2006 to 2007 declines generally mirror many of the same decline areas occurring from 2002 to 2007, only less in intensity.

Of particular interest is the number and extent of wells in north-west Kansas that show relatively no change in the water table. Some of this can be explained by the melting of the heavy snows that occurred over the winter periods, providing some local recharge to the shallow, alluvial-based wells in the Upper Republican River Basin. However, that melt would not have recharged the deeper wells in Sherman, Thomas, and Sheridan counties where declines are generally less than a foot and in most cases, less than a half foot.

8. Identification of Network Holes

The kriging error (standard deviation) map for the 2007 water-table elevations (Figure 21) indicates areas of the High Plains aquifer where suitable well control, in terms of spatial distribution, is lacking. These areas are referred to as network "holes" and are caused by a lack of depth-to-water measurements in those locations. One reason holes occur is that a monitoring well becomes unmeasurable or has been permanently removed or capped. In these cases, a new replacement well is needed. In other cases, a network hole will occur because an existing monitoring well could not be measured for that year because, for example, it was physically inaccessible or was being pumped at measurement time. In these cases, where the lack of a measurement is thought to be temporary in nature, a search is not made for a replacement well. If a measurement cannot be obtained for three years, a replacement well is identified.

Replacement wells are found by placing a hexagonal grid over the kriging error maps (Olea, 1984). Each hexagon cell is roughly 16 square miles in size and the goal is to identify a replacement well at the center of the grid. The grid center is also referred to as the hole center. Figure 28 shows the 16 network hole centers that were identified based on the 2007 measurement campaign.

For each hole center, a list of well candidates is selected from the three major inventories of ground-water wells in Kansas. Those databases are the Water Well Completion Records (WWC5), the Water Information Storage and Retrieval Database (WIZARD), and the Water Information Management and Analysis System (WIMAS). Wells within 1 to 2 miles, and if needed, 3 miles from the hole centers are reviewed for potential inclusion in the monitoring network. The preferred type of replacement well is a well constructed for observation purposes or a newly constructed irrigation well. Once the list of well candidates has been selected, the associated landowners are contacted for permission to measure the well and include it in this voluntary program. The list of network hole centers is shown in Appendix A.

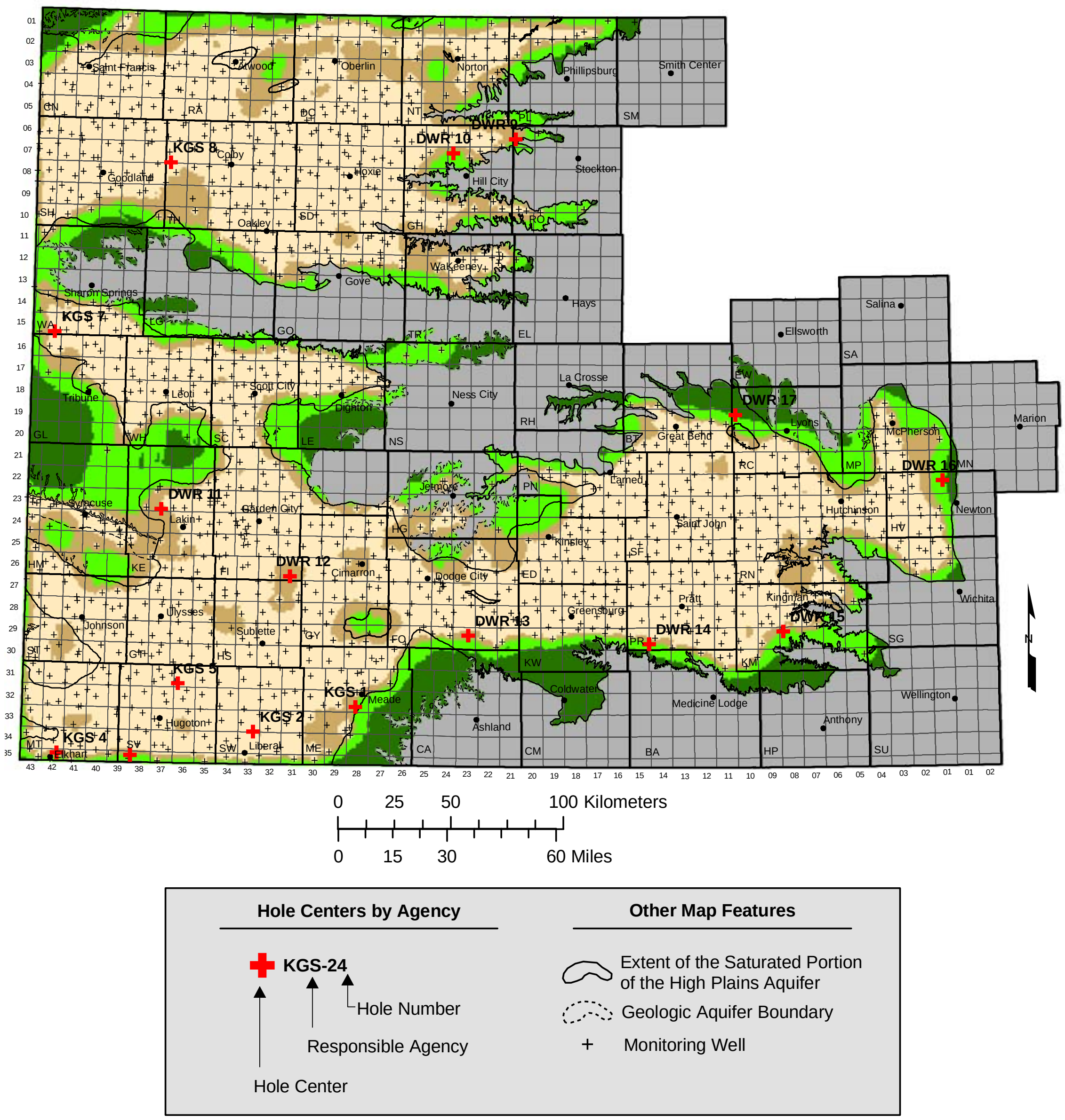

Figure 28. Network holes from the 2007 measurement campaign.

9. Concluding Remarks

The 2007 (December 2006 to April 2007) water-level measurement campaign for the High Plains aquifer was one that will be remembered for a while. Much of the region experienced three-plus feet of snowfall from the end of December to the first days of January and that snow cover stayed in place most of the winter. This made navigation to and access of the wells a real challenge. As such, many of the depth-to-water measurements for the 2007 campaign are spread across a much broader time period than in previous years, going into the month of April.

This report attempted to identify and quantify any temporal changes in the measurements caused by this extended measuring period. Although the data provide some hints that that temporal variations existed, it was very difficult to generate conclusive evidence of systematic trends in time.

Overall the High Plains aquifer region experienced a 1.28 decline in the water table from 2006 to 2007, which is a slightly larger decline than seen in the previous year and more in line with decline over the drought period of 2000 to 2004. The trends in the water-table elevations for both the one year change from 2006 and 2007 and five year change from 2002 to 2007 generally mirror past conditions, both in terms of spatial patterns and relative changes. A notable exception to this was seen from 2006 to 2007 in the areas of south-central Kansas and throughout northwest Kansas.

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Appendix A: Network Hole Centers

COUNTY	AGENCY	HOLE NUMBER	UTM X	UTM Y
Finney	DWR	12	349141.4923	4179726.1778
Ford	DWR	13	428275.0159	4153348.3366
Graham	DWR	10	421575.7064	4367748.3128
Harvey	DWR	16	638745.9078	4222548.7819
Kearny	DWR	11	292081.4760	4209746.1477
Kingman	DWR	15	568110.6845	4155334.9523
Meade	KGS	1	378094.7639	4121638.0571
Morton	KGS	4	245395.5900	4101646.4667
Pratt	DWR	14	508622.5824	4149595.8404
Rice	DWR	17	546772.1153	4251420.6093
Rooks	DWR	9	449436.8873	4373881.3748
Seward	KGS	2	332772.0837	4110790.8850
Stevens	KGS	3	277979.1496	4100385.1676
Stevens	KGS	5	299421.2339	4132232.9693
Thomas	KGS	8	296321.5228	4363685.1847
Wallace	KGS	7	244707.7592	4288640.5467