Kansas Geological Survey

Statistical and Geostatistical Analysis of the Kansas High Plains Water-Table Elevations, 2011 Measurement Campaign

By

Geoffrey Bohling and Brownie Wilson

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

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Geoffrey C. Bohling
Blake B. Wilson

Kansas Geological Survey
Geohydrology Section
The University of Kansas Geological Survey
1930 Constant Avenue
Lawrence, KS 66047

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 Some water is also withdrawn from underlying bedrock units, primarily Cretaceous strata, in this region.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 region on an annual basis in a network of over 1380 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 2011 water-level measurements and water-level changes for the one-year and five-year periods preceding the 2011 measurements. The majority of the 2011 measurements were obtained between January 3 and January 7, 2011, although measurement dates range from Dec. 20, 2010, to March 24, 2011.

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 2010 and January 2011 measurements represents the water level decline for 2010.

Recent work carried out as part of the Kansas Geological Survey's High Plains Aquifer Calibration Monitoring Well Program ("index well program") has demonstrated that the January water level measurements may be far from static, fully recovered values (Stotler et al., 2011). Water level recovery from the previous pumping season can continue throughout the winter and often is still incomplete when the next season's pumping begins in the spring. Water levels can also show significant responses to atmospheric pressure variations that must be accounted for in order to obtain accurate estimates of annual differences. Furthermore, the index well program has made it clear that in some areas the High Plains aquifer can not be accurately represented as a single unconfined aquifer, a conceptualization that implicitly underlies the two-dimensional interpolation approach that has played a central role in the geostatistical analysis of the annual water level measurements for a number of years now. In fact, the accuracy of this conceptualization has been called into question in previous versions of this report (Bohling and Wilson, 2007; 2006), where we noted that some wells have exhibited large and consistent differences in water level from their neighboring wells for a number of years, most likely as a result of persistent vertical gradients between different units tapped by the wells in these areas.

2. Data Extraction

The SQL query shown in Listing 1 was used to extract water-level measurements for the 2011 campaign from the Kansas Geological Survey's Water Information Storage and Retrieval Database (WIZARD). Natively, WIZARD is an Oracle relational database schema storing 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 2011 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,
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-2010' and
    bwilson.wizard_network_wells_wl.measurement_date_and_time <=
          '30-Mar-2011'
order by
    bwilson.wizard_network_wells_wl.usgs_id,
```

The query yields 1513 measurements from 1374 distinct wells, with measurement dates ranging from Dec 20, 2010, to March 24, 2011. Of these wells, 1333 are located within the geographic boundaries demarking the saturated extent of the High Plains aquifer, 845 of them measured by DWR staff and 488 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.

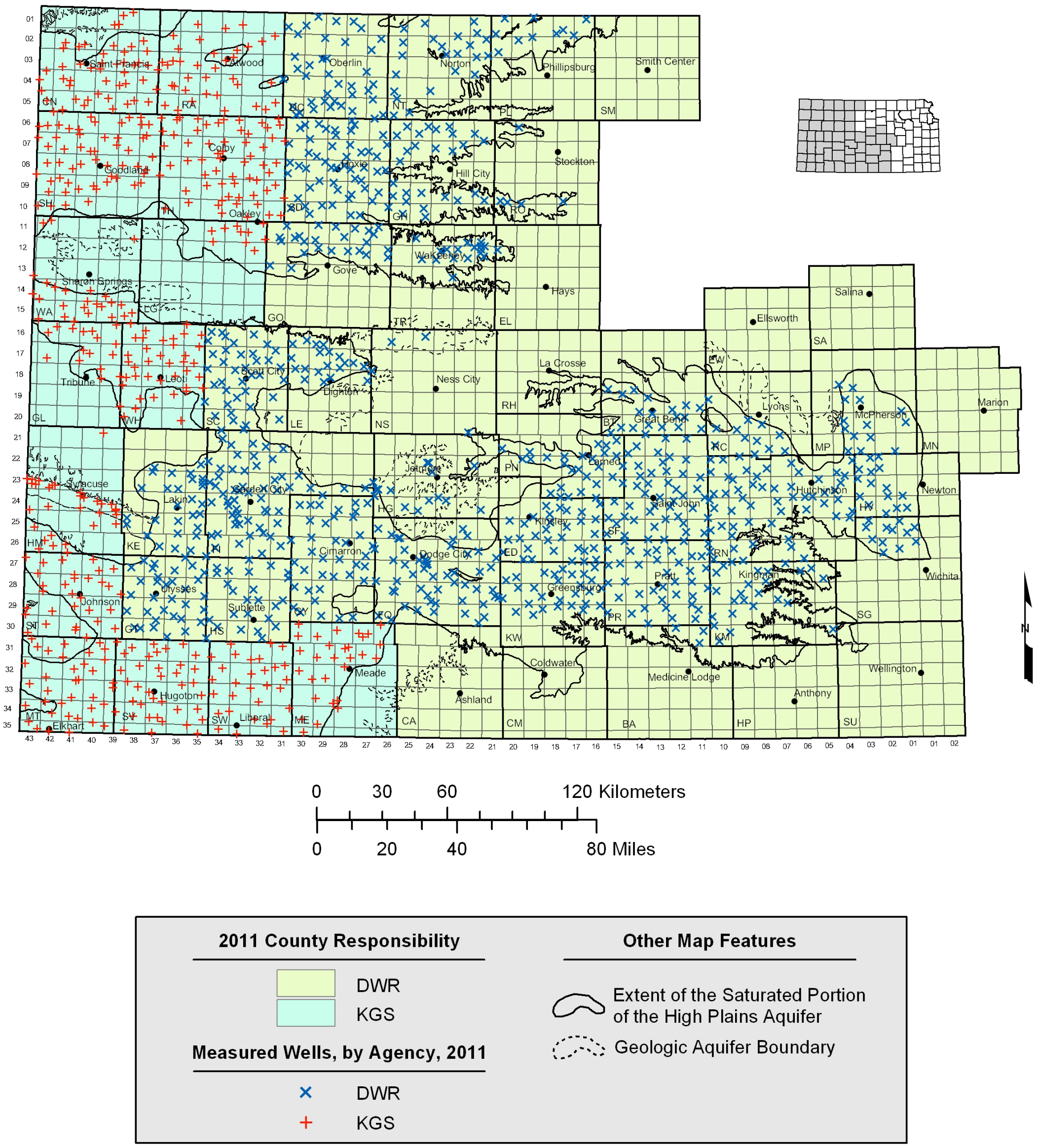

Figure 1. Wells measured and responsible agency in 2011

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 following is a list of the distinct combinations of geologic unit codes, with the number of wells for that code in parentheses. For wells tapping multiple units, the ordering of the two-letter codes reflects an estimate of the order of predominance of the contributing units. The top-level five-part grouping is used in the quality control analysis discussed in Section 8.

Quaternary only (410)
QA (131): Quaternary alluvium
QU (263): Undifferentiated Quaternary aquifers
QAQU (15): Quaternary alluvium + undifferentiated
QUQA (1): Quaternary undifferentiated + alluvium

Quaternary + Tertiary Ogallala (254)
QUTO (238): Quaternary undifferentiated + Ogallala
QATO (13): Quaternary alluvium + Ogallala
TOQU (2): Ogallala + Quaternary undifferentiated
QAQUTO (1): Quaternary alluvium + Quaternary undifferentiated + Ogallala

Tertiary Ogallala (590)
TO (590): Tertiary Ogallala

Quaternary and/or Tertiary Ogallala + Cretaceous/Jurassic (49)
QUKD (1): Quaternary undifferentiated + Cretaceous Dakota
QUTOKD (15): Quat. undifferentiated + Ogallala + Cretaceous Dakota
QUTOKJ (17): Quat. undiff. + Ogallala + undifferentiated Cretaceous/Jurassic
QUTOJM (1): Quaternary undifferentiated + Ogallala + Jurassic Morrison
TOKD (7): Ogallala + Cretaceous Dakota
TOKJ (8): Ogallala + undifferentiated Cretaceous/Jurassic

Cretaceous (30)
KD (23): Cretaceous Dakota
KJ (6): Undifferentiated Cretaceous/Jurassic
KN (1): Cretaceous Niobrara

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 2010 and 2006 measurement campaigns for the sake of computing 1-year and 5-year water-level changes.

Figure 2 shows the sequence of measurement times for the wells within the HPA extent. There are 1460 total measurements, including repeat measurements at about 125 wells. Traditionally, the vast majority of measurements each year are taken in the first week of January. The measurements in February and March primarily represent follow-up visits to wells that have either shown anomalous depth to water measurements (in comparison to a well's historic trends or in relation to neighboring wells), were not initially measured for a variety of reasons (e.g., closed roads, locked gates, etc.), or were re-measured independently as part of regional networks maintained through other State programs or Groundwater Management Districts.

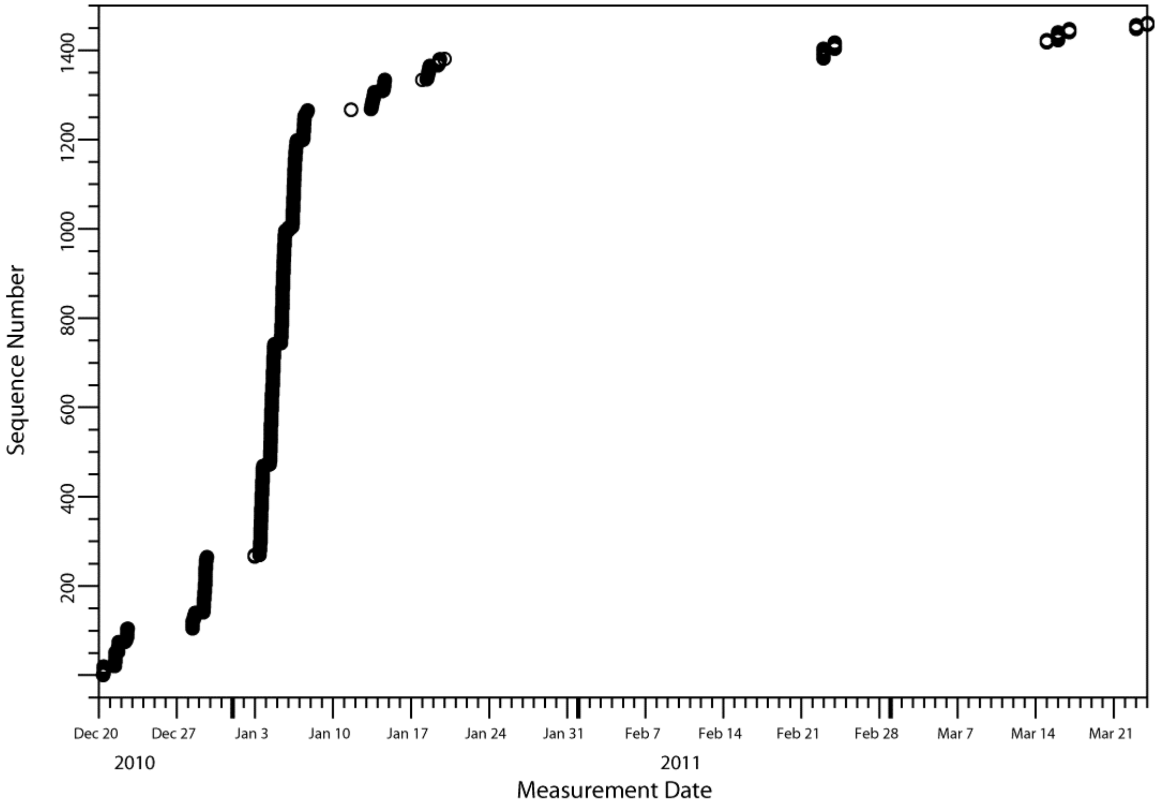

Figure 2. Sequence of measurement dates for water-level measurements at wells within the High Plains aquifer extent, 2011 measurement campaign.

3. Repeat Measurements

The 2011 water-level data include repeat measurements at 125 wells within the High Plains aquifer extent. For those wells, Figure 3 shows the difference between the measured depths to water versus the time span, in days, between the measurements. The difference is the second measurement minus the first measurement, so a positive value indicates an (apparent) increase in depth to water between measurements.

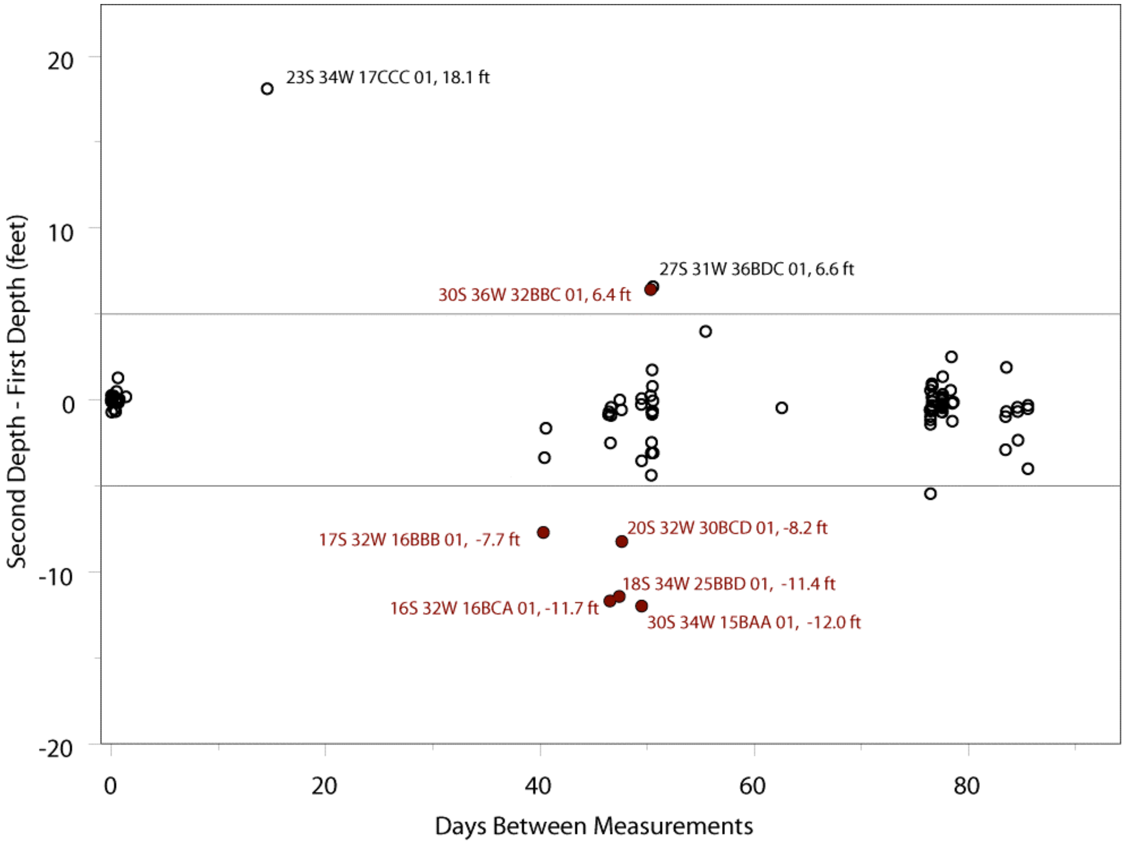

Figure 3. Difference between second and first measured depths to water versus time span between measurements for 125 wells with repeat measurements. Horizontal lines represent differences of -5 and 5 feet and red points and labels indicate wells whose first measurements are considered anomalous.

Forty-seven of the wells have repeat measurements taken on the same day as the first measurement, and one has a repeat measurement on the next day. For these 48 wells, the differences between repeat measurements range from -0.7 to 1.3 feet. The cluster of points with time spans between roughly 40 and 65 days represent the wells with follow-up measurements in February while those with time spans greater than 70 days are associated with March follow-up measurements. Of the 76 repeats with time spans exceeding 40 days, 68 have depth differences between -5 and 5 feet (indicated by the horizontal lines) and 56 have differences between -2 and 2 feet. The wells with more extreme differences are labeled. The differences between repeat measurements show no systematic trend versus time between measurements, regardless of whether the more extreme measurements are included in or excluded from the trend computations.

The red symbols and labels indicate those wells whose first measurements have been determined to be anomalous (and excluded from subsequent analyses). Both the 18.1-foot difference observed at well 23S 34W 17CCC 01 and the 6.6-foot difference at well 27S 31W 36BDC 01 appear to accurately represent changes in the water level. For well 23S 34W 17CCC 01 (USGS ID 380253101045501), the first measured depth was 144.7 feet on January 5 and the second was 162.8 feet on January 20. This well, in western Finney County, has additional measurements taken in the spring and fall over the last several years and has exhibited notable water-level variations over that time. Well 27S 31W 36BDC 01 (USGS ID 373925100395301) is one of the three continuous recording sites associated with the index well program and has shown to be very responsive to pumping, both in terms of drawdown and recovery. The difference between the initial and follow-up measurements in 2011 (270.2 feet on Jan. 4 and 276.8 feet on Feb. 24) is likely caused by nearby irrigation of wheat fields (early irrigation was common in southwest Kansas in 2011 given the extreme drought conditions experienced over the previous year).

Subsequent analyses employ the first measurement from each well with repeat measurements in 2011, except for the six wells with anomalous first measurements. For these six wells, the second measurement is used instead.

4. Summary Statistics of Primary Variables

Summary statistics for the 2011 depth to water (from ground surface) and water-table elevation, along with the declines since 2010 and 2006, are shown in Table 1. The average water-level decline between 2010 and 2011 was 1.18 feet, but this value should not be viewed as a representative decline value, due to the significant spatial variation in one-year water-level changes throughout the region, with large declines predominating in the southwest and notable increases in water level in the east and north.

Table 1. Summary statistics for 2011 water-level measurements and prior one- and five-year water-level declines.

	2011 Depth (feet)	2011 Elevation (feet a.s.l.)	2010 to 2011 Decline (feet)	2006 to 2011 Decline (feet)
Minimum:	1.10	1324.55	-12.50	-84.1
1st Quartile:	32.32	2180.96	-0.04	-0.91
Mean:	115.26	2591.33	1.18	3.51
Median:	107.80	2640.10	0.59	0.98
3rd Quartile:	172.64	3009.60	1.71	5.28
Maximum:	408.29	3833.44	39.40	60.90
Std. Dev.:	87.00	575.18	2.80	9.00
Count:	1333	1333	1298	1262

Figures 4 and 5 show two different displays of the distribution of water-level declines between 2010 and 2011, first as a histogram and then as a normal quantile-quantile (QQ) plot. A normal QQ plot shows the sorted data values plotted versus corresponding quantiles of a standard normal distribution. The straight line on the plot represents a theoretical normal (Gaussian) distribution with the same mean and standard deviation as the observed data, so that deviations between the data points and the line show the extent to which the actual data distribution deviates from a normal distribution. In this report we use normal QQ plots as a conventional means for displaying data distributions, even though we are not particularly concerned about whether the data are normally distributed. A shortcoming of histograms is that different choices of bin width and bin origin can lead to significantly different impressions of the same data distribution. A normal QQ plot provides a less subjective display and also allows extreme values or outliers to be identified more readily.

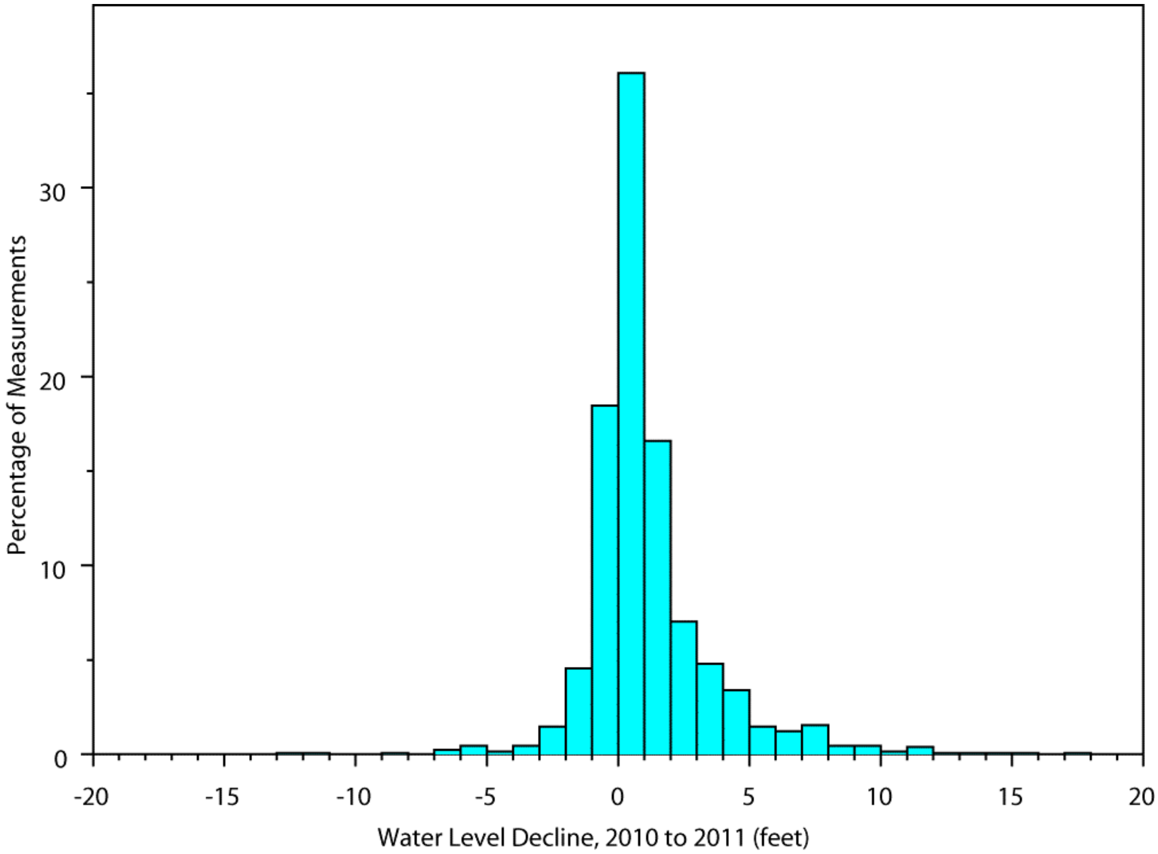

Figure 4. Histogram of water-level declines between 2010 and 2011 campaigns.

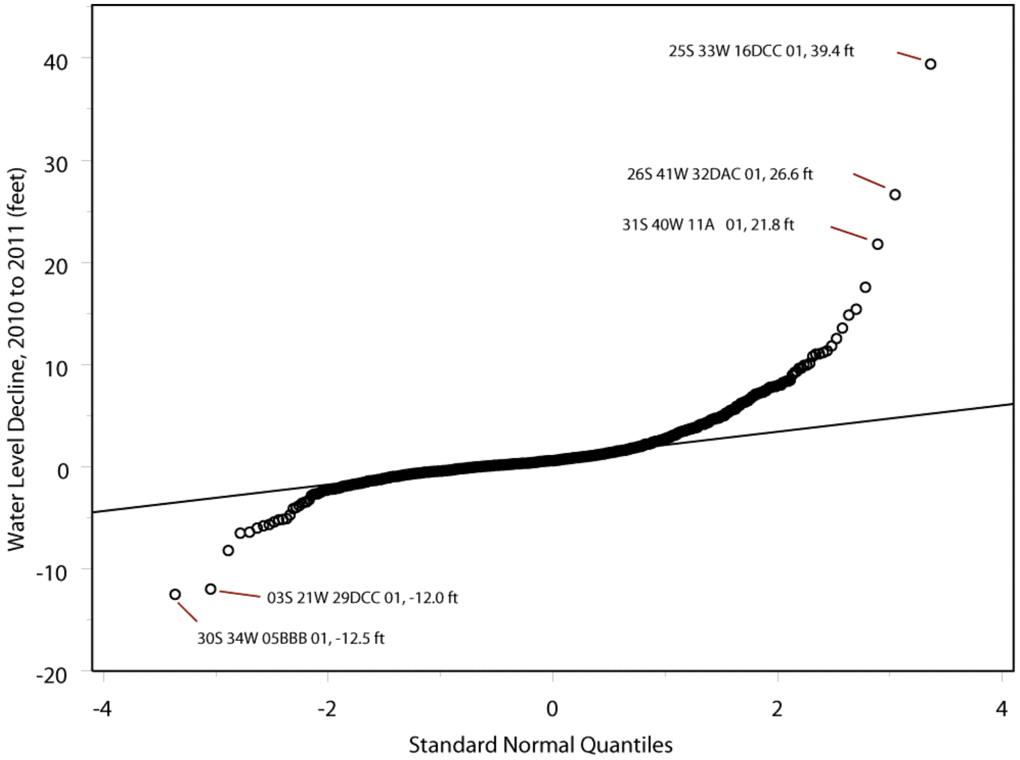

Figure 5. Normal QQ plot of water-level declines between 2010 and 2011 campaigns.

The five wells with the most extreme one-year water-level changes are labeled on Figure 5 and listed in Table 2.

Table 2. Wells with most extreme one-year water-level changes.

KGS ID	USGS ID	2010 to 2011 Decline (ft)	Geol Units
25S 33W 16DCC 01	375226100564601	39.4	QUTO
26S 41W 32DAC 01	374421101490902	26.6	KJ
31S 40W 11A 01	372211101375701	21.8	KD
03S 21W 29DCC 01	394523099423801	-12.0	TO
30S 34W 05BBB 01	372825101041201	-12.5	QUTO

Except for well 03S 21W 29DCC 01, these wells also turn out to be the wells with the most anomalous one-year declines relative to the declines observed in neighboring wells (Section 7). Well 25S 33W 16DCC 01 is an observation well in southwestern Finney County that has shown significant declines since 2000, but none as large as the 39.4-foot decline observed in 2010. The 2011 measurement was reported to be very spotty with a steel tape and an electric tape was used. The well is in an area of relatively large declines, but shows by far the largest decline of any network well in its vicinity. The seven nearest network wells, with distances ranging between 1 and 5 miles from 25S 33W 16DCC 01, also have geologic unit designations of "QUTO", meaning they tap both undifferentiated Quaternary and Ogallala deposits. These wells show one-year declines ranging from 2.5 to 11.8 feet.

Well 26S 41W 32DAC 01, in southern Hamilton County, is a KJ (undifferentiated Cretaceous/Jurassic) well surrounded by wells listed as tapping Quaternary and Ogallala deposits, primarily, showing declines up to a few feet. Well 26S 41W 32DAC 01 was constructed in 2007 and has only been measured since 2009, so this is only the second annual decline period observed for the well. Similarly, well 31S 40W 11A 01, in northeastern Morton County, is a Cretaceous Dakota well surrounded by wells predominantly tapping Quaternary and Ogallala deposits and showing declines around 2 to 5 feet. This well has been measured since 2001 and the 2010 to 2011 decline of 21.8 feet is significantly larger than any previously observed one-year decline.

Well 03S 21W 29DCC 01, in eastern Norton County near the edge of the High Plains aquifer extent, showed a 12-foot increase in water level between 2010 and 2011, while nearby wells (also primarily Ogallala wells) showed increases up to a few feet. The 12-foot increase is also unprecedented relative to the previously recorded values in well 03S 21W 29DCC 01. The observed depth to water in this well varied between 104.7 and 104 feet between 2004, when it was first measured, and 2010. The measured depth to water in 2011 was 92 feet.

The 12.5-foot water level increase in well 30S 34W 05BBB 01, in southwestern Haskell County, is quite anomalous, since this well is surrounded by wells showing water-level declines. In fact, the nearest well, 2.5 miles from 30S 34W 05BBB 01, which is also a

QUTO well, showed a decrease of 11.2 feet between 2010 and 2011. However, this well is in an area of fairly variable decline rates, specifically a SE-NW-trending trough of reduced decline rates cutting through a broader region of high decline rates. Also, well 30S 34W 05BBB 01 has exhibited fairly oscillatory behavior since the beginning of measurement in 1957, with some significant one-year increases superimposed on a generally decreasing trend.

Figures 6 and 7 show the histogram and normal QQ plot of the five-year declines, between 2006 and 2011. The three wells with the most extreme five-year changes are labeled in Figure 7 and listed in Table 3.

Table 3. Wells with most extreme five-year water-level changes.

KGS ID	USGS ID	2006 to 2011 Decline (ft)	Geol Units
25S 33W 05ABD 01	375449100574301	60.9	QUTO
28S 36W 24AAD 01	373607101121001	50.7	QUTO
24S 23W 06AAB 01	375958099530101	-84.1	KD

All three of the wells are also among the wells identified in Section 6 as exhibiting the most anomalous five-year declines relative to surrounding wells. The most extreme five-year “decline” value, actually representing a water-level rise of 84.1 feet between the 2006 and 2011, is quite anomalous. (The next largest five-year water-level rise is 18.0 feet.) This well, 24S 23W 06AAB 01 in south-central Hodgeman County and screened in the Cretaceous Dakota formation, showed a water-level rise of 88 feet between December 2008, and April 2009. This well exhibited artesian conditions when it was first inventoried in 1973 and exhibited dramatic water-level increases after the pump was pulled in 2000. Geographically, this well falls within (that is, it is screened below) a fairly isolated “peninsula” of the High Plains aquifer and nearby wells are primarily Ogallala wells showing slight declines to moderate increases in water level.

Well 28S 36W 24AAD 01, in Grant County, with a five-year decline of 50.7 feet, is in a region of highly variable decline rates, near the edge of the SE-NW-trending trough of lower decline rates mentioned earlier. This well exhibited a 41.6-foot drop in water level between January 2008 and January 2009.

The largest five-year decline, 60.9 feet, was observed in well 25S 33W 05ABD 01 just southwest of Garden City in Finney County. This well is centrally located in a region of large declines. Nearby wells show declines ranging between about 20 and 40 feet. Well 25S 33W 05ABD 01 showed steadily declining water levels from the beginning of its measurement record, in 1973, until 2006. Between January 2006 and January 2007 the water level in this well dropped by 41.7 feet, with an additional 19.2 feet of decline occurring since 2007.

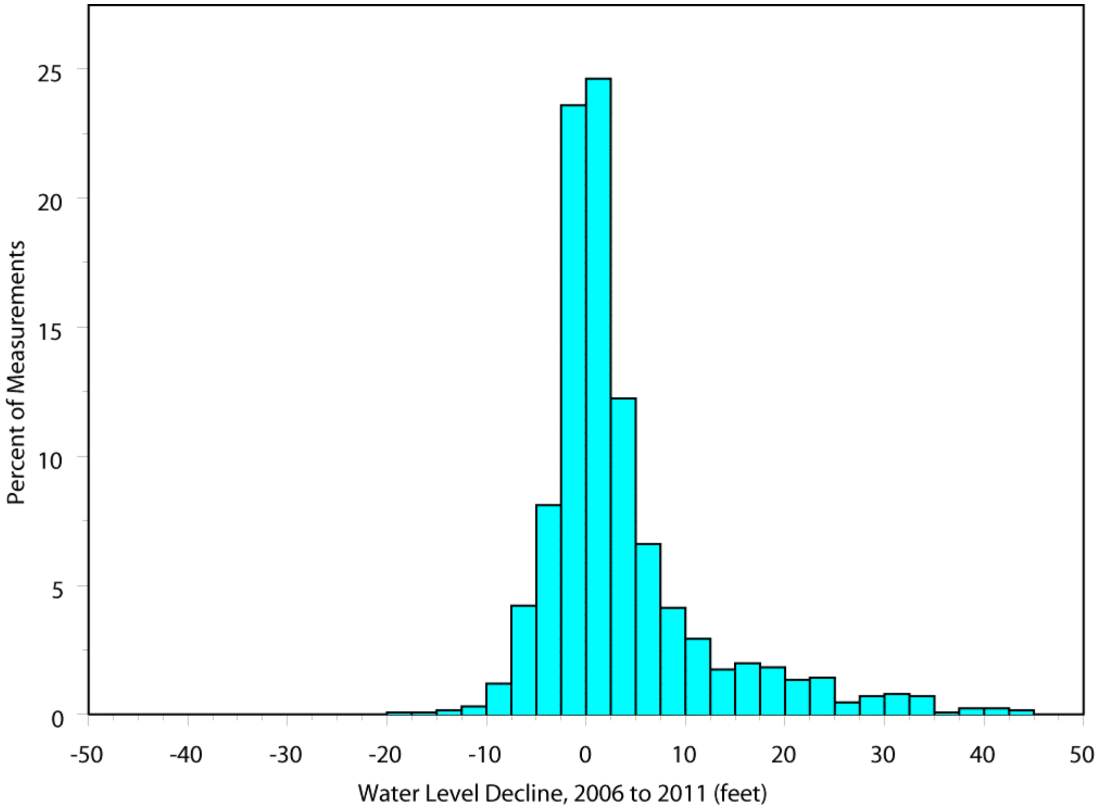

Figure 6. Histogram of water-level declines between 2006 and 2011 campaigns.

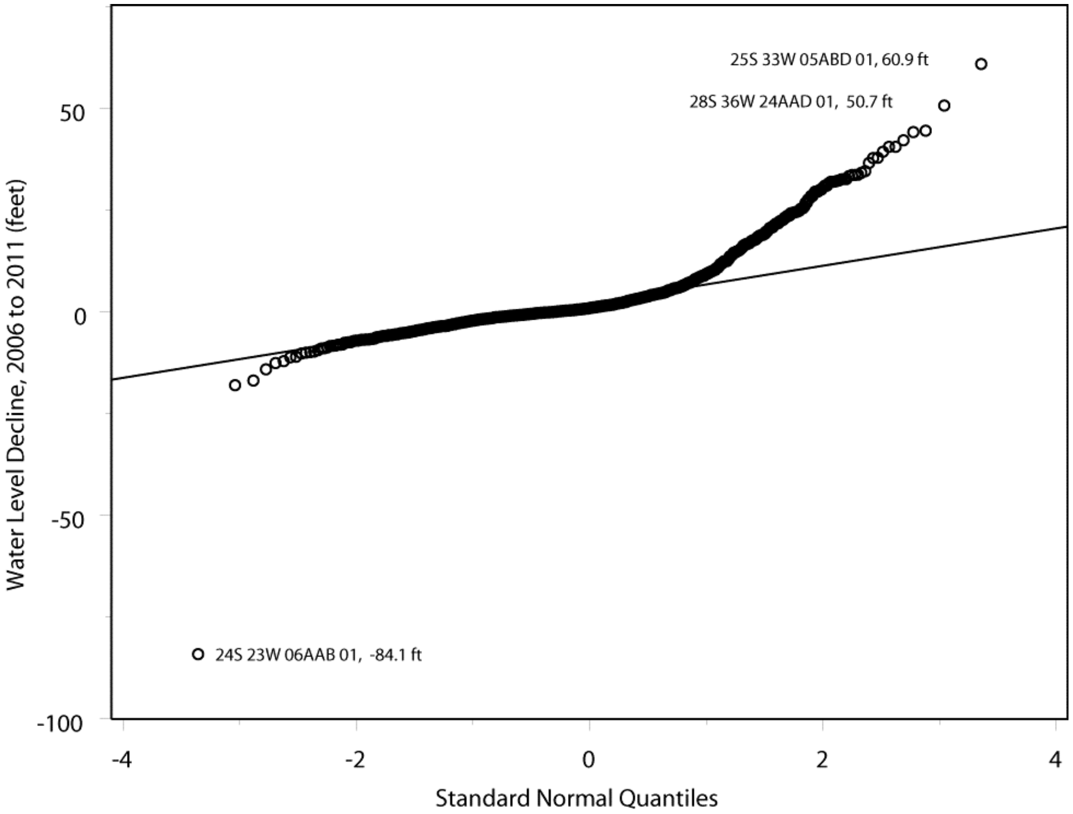

Figure 7. Normal QQ plot of water-level declines between 2006 and 2011 campaigns.

5. Geostatistical Analysis of 2011 Water-Table Elevations

For the geostatistical analysis of 2011 water-table elevations, we employed the measurements from both the DWR and KGS at 1333 wells located within the High Plains aquifer extent, using the first measured value for those wells with repeat measurements (except for the six wells with anomalous first measurements, discussed on page 7).

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.

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. This also seems to be a reasonably trend-free direction for the 2011 measurements. Figure 8 shows the empirical semivariogram for the 2011 water-table elevation measurements in the direction N 12° E, along with a 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. This model is Gaussian in shape with a nugget of 44 square feet, an overall sill of 12871 square feet, and a range of 65.1 km.

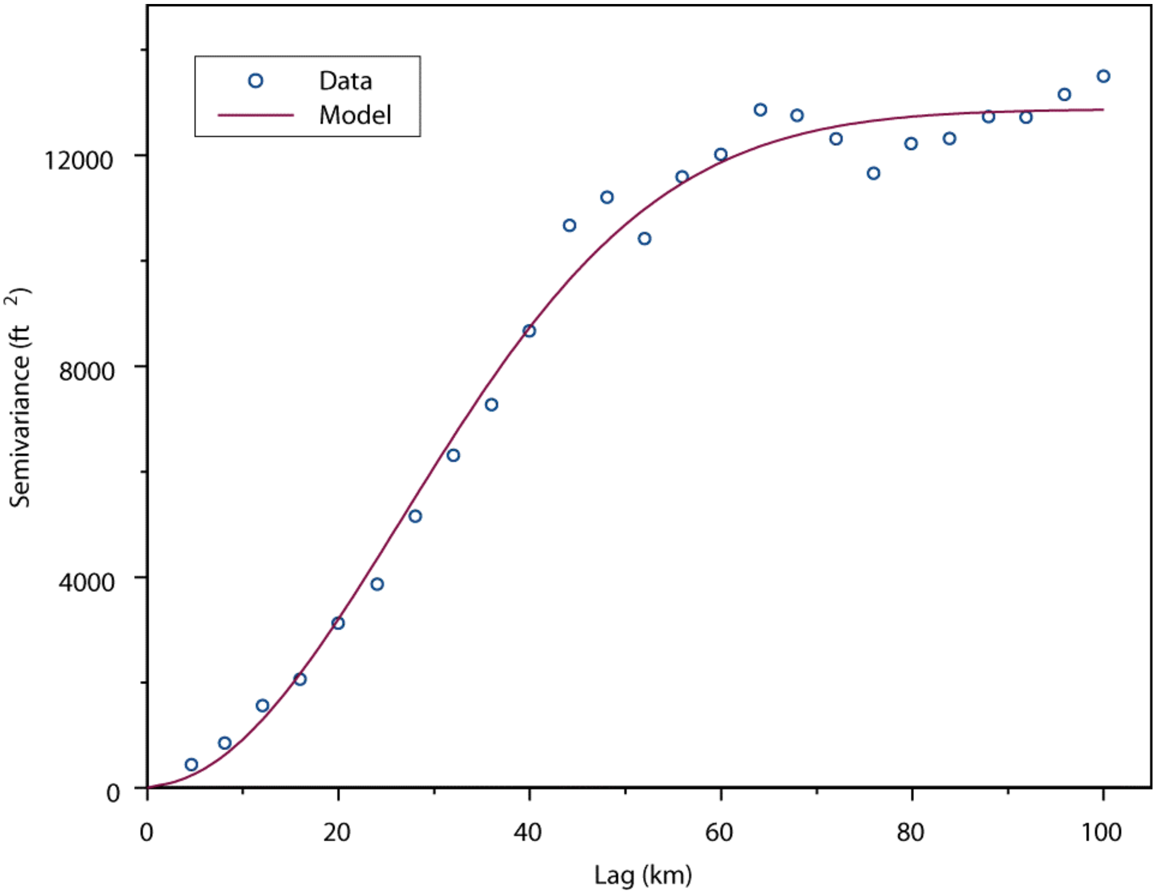

Figure 8. Semivariogram of 2011 water-table elevation measurements in direction N 12° E along with fitted Gaussian model (line).

As in years past, the observed water-table elevations have been kriged (interpolated) to a regular grid, using weights computed on the basis of the estimated semivariogram model. Figures 9 shows the resulting map of kriged water-table elevations. By and large, water levels mirror the land-surface elevations with highs along the Kansas-Colorado border running to lower elevations in the eastern portions of the aquifer.

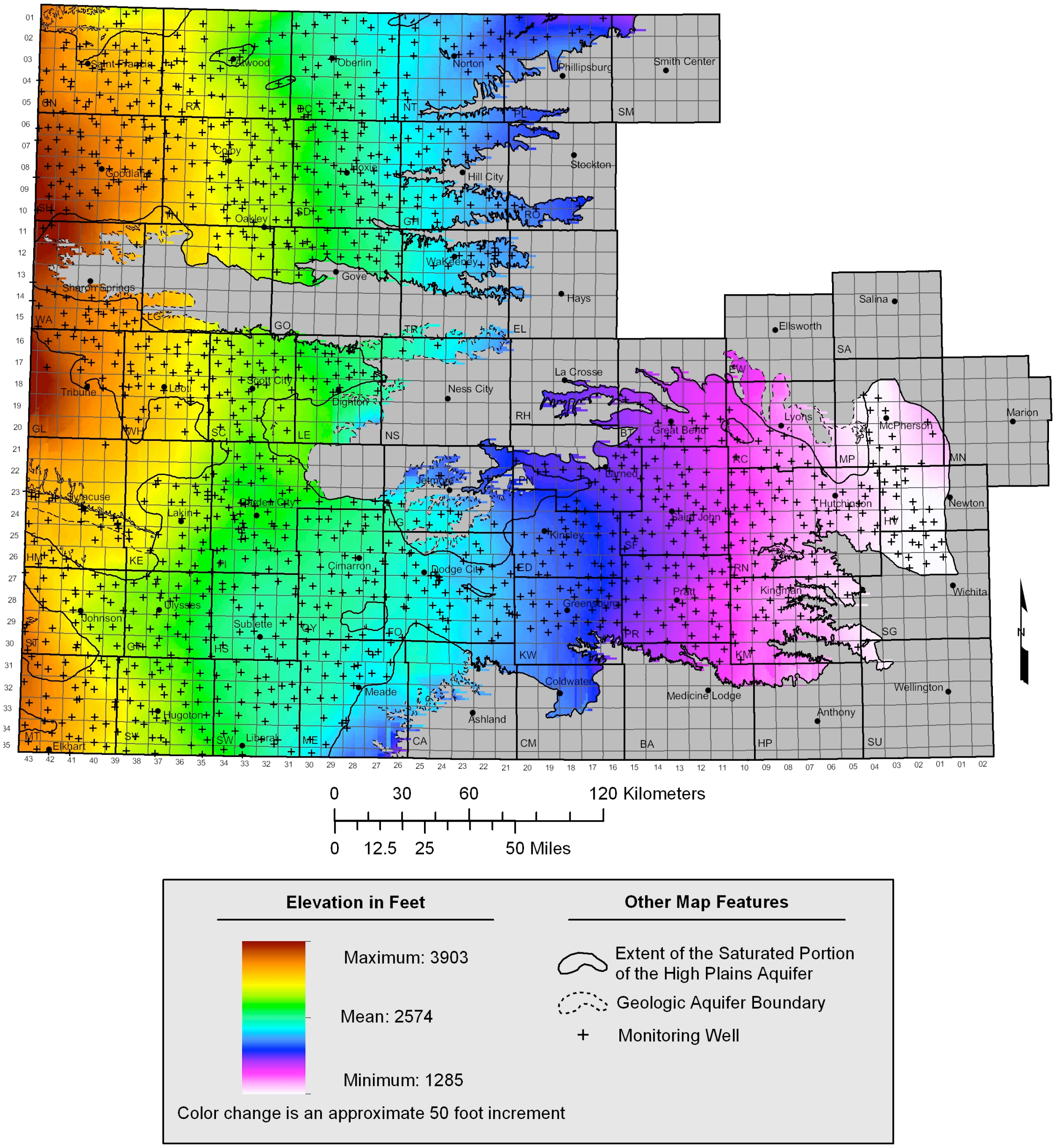

Figure 9. Kriged 2011 water-table elevation.

Kriging also provides a mechanism for estimating the uncertainty in each interpolated value, expressed in terms of a standard deviation. The kriging standard deviation map for the 2011 water levels is shown in Figure 10. This map is used in the identification of holes or gaps in the measurement network, as described in Section 9. For 2011, almost the entire HPA extent is characterized by a kriging standard deviation below 10 feet, the threshold uncertainty level used to identify network holes in earlier years. The minimum attainable kriging standard deviation is roughly determined by the square root of the nugget of the semivariogram model, which for 2011 is 6.6 ft (square root of 44 ft^2). The nugget of the 2011 semivariogram model is significantly lower than that estimated in more recent years of analysis; for example, in 2007 the nugget was estimated as 237 ft^2 (Bohling and Wilson, 2007). This reduction is due in part to a change in protocol in this year's analysis: the semivariogram has been computed using a two-step procedure that filters out the influence of very close wells (wells in clusters) screened at different depths. Such measurements result in anomalous estimates of short-scale variability in the measurements, resulting in an inflated estimate of the semivariogram nugget. Prior to this filtering step, the estimated nugget for the 2011 semivariogram model was 102 ft^2, and the resulting kriging standard deviations were above 10 feet throughout most of the HPA extent. Note that the filtering step resulted in the exclusion of only 10 of the 1333 wells from the semivariogram computation, a seemingly minor change that results in a significant change in the kriging standard deviation map. (These 10 wells were excluded from the computation of the semivariogram in the filtered case but were included in the interpolation step in both cases, so the difference between the standard deviation maps was purely a result of the difference between the estimated semivariogram models.) This should serve as a caution against reading the kriging standard deviation map too literally.

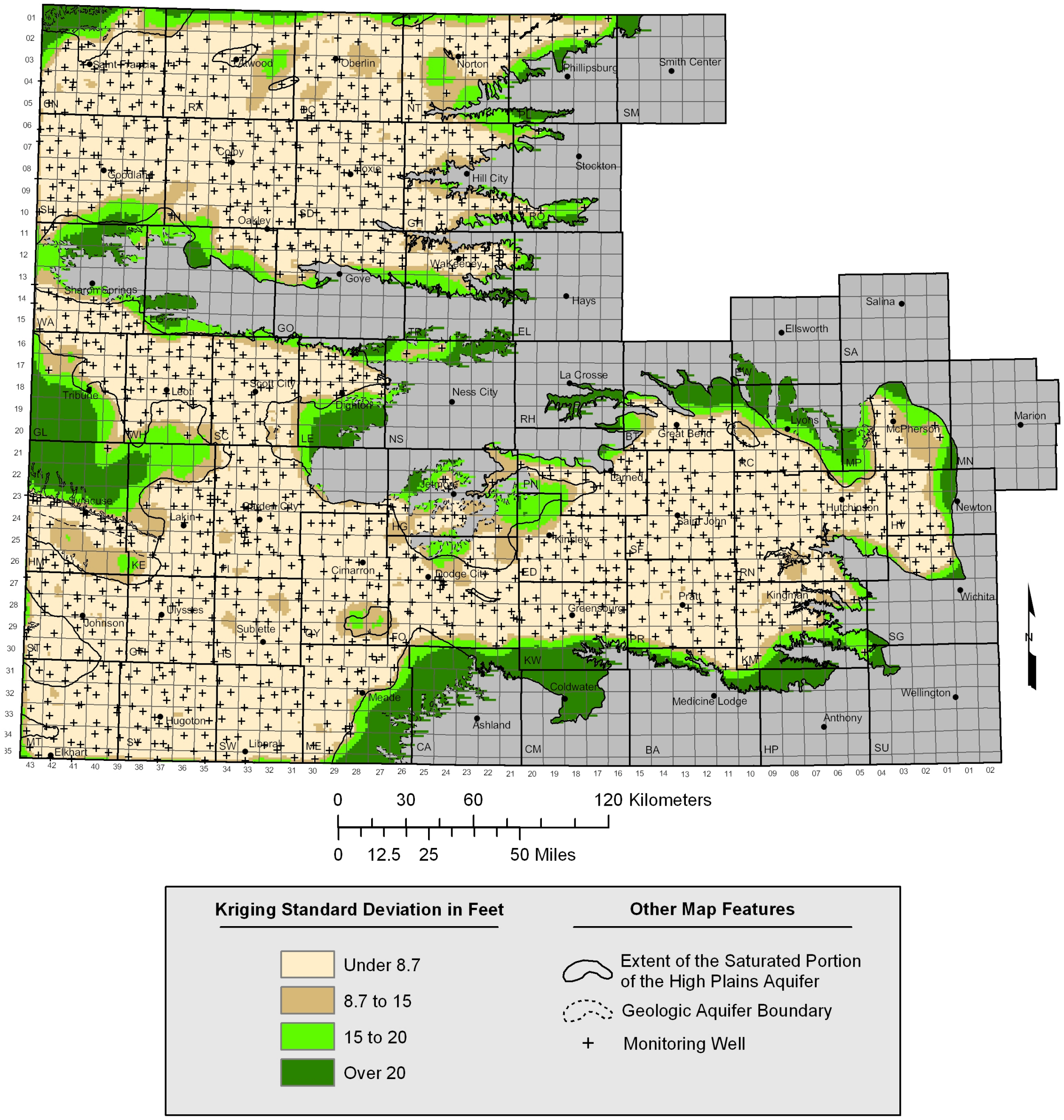

Figure 10. Kriging standard deviation for 2011 water-table elevation.

Figure 11 shows the results of a kriging crossvalidation analysis for the 2011 water levels. In this analysis, each well is removed in turn from the dataset, the water level at that location is interpolated based on measurements at surrounding wells, and the interpolated and true water levels are compared. Figure 11 is a crossplot of the interpolated versus true water levels. As shown on the plot, the correlation between interpolated and actual values is very close to 1 and the root mean squared difference between the two is 23.2 feet. However, the strong correlation over the broad range of water-level values masks the fact that some of the errors are in fact quite large.

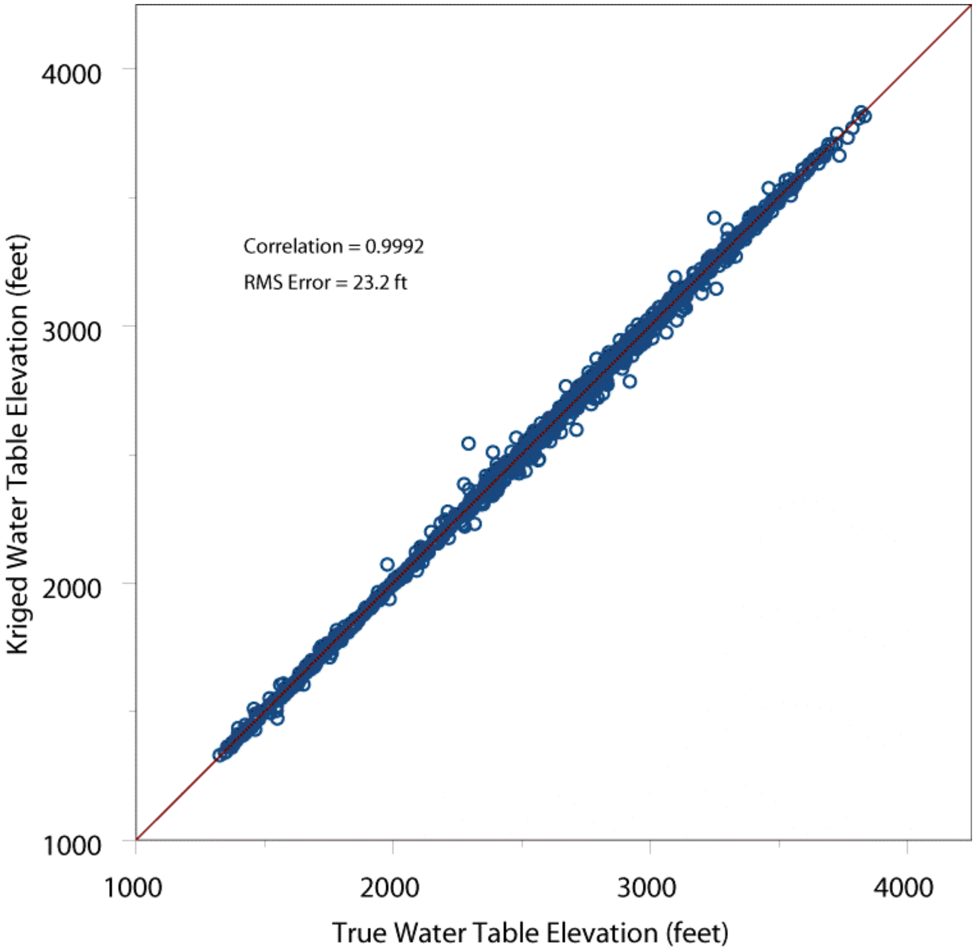

Figure 11. Kriging crossvalidation results for 2011 water-table elevations.

Figure 11 is essentially identical to the crossvalidation plots from previous years (e.g., Bohling and Wilson, 2007). This is because the most significant discrepancies between interpolated and actual water levels are due to systematic, rather than random, factors, most notably the mixing of measurements from wells screened in different units. The interpolation approach makes the implicit assumption that the measurements represent a single, continuous surface that is purely a function of the two-dimensional geographic coordinates of the wells, ignoring the fact that the true flow system is three-dimensional, probably with significant and persistent vertical gradients in some locations. Thus, the largest crossvalidation errors tend to occur where geographically close wells are screened in different units, improving the odds of observing the influence of vertical gradients.

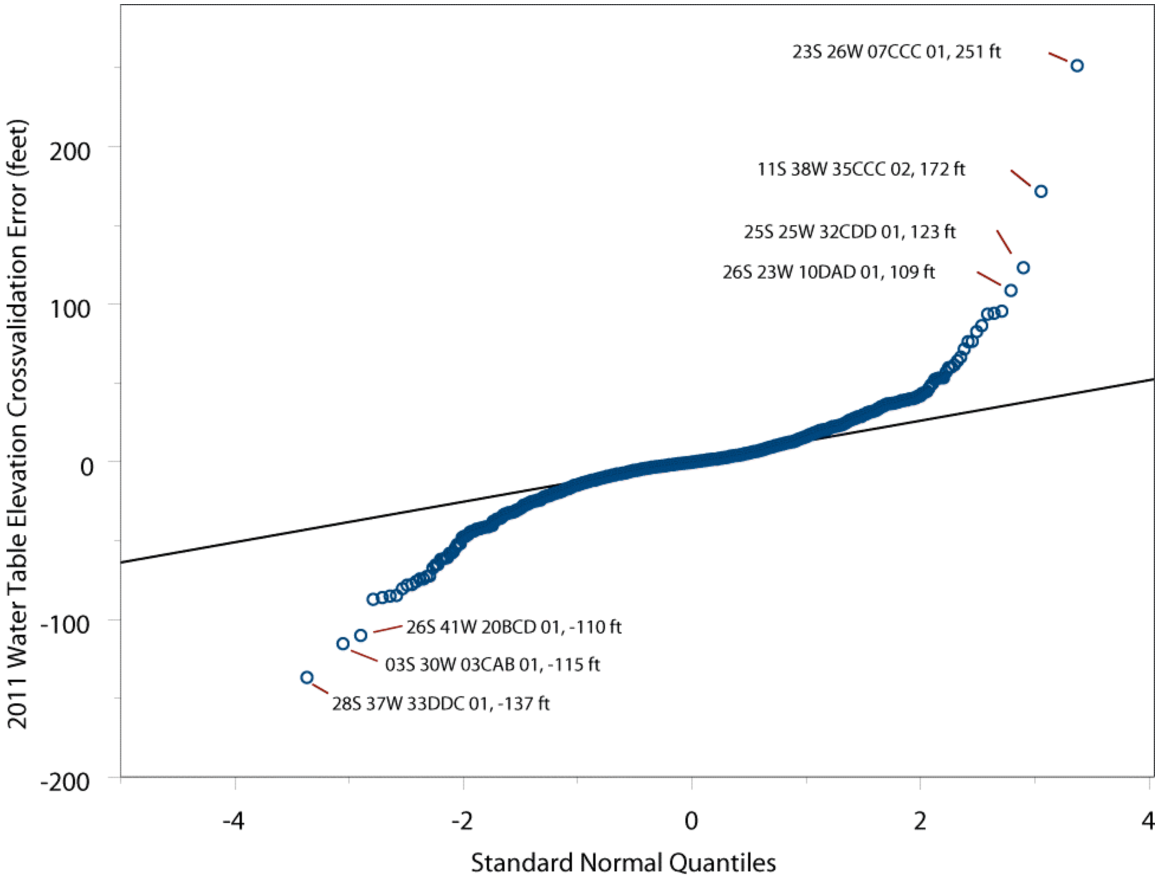

Figure 12: Normal QQ plot of kriging crossvalidation errors for 2011 water-table elevations.

Figure 12 is a normal QQ plot of the kriging errors (residuals) identified in the crossvalidation analysis. The values plotted on the vertical axis represent the interpolated water-level value at a well location minus the actual water level measured in the well. The interpolated value is essentially the expected water level at that location based on water levels measured in nearby wells, so a positive error indicates that the measured water level in a well is lower than what would be expected based on nearby measurements. The wells with crossvalidation errors larger than 100 feet in magnitude are flagged in Figure 12 and Table 4 contains additional information for these wells.

Table 4. Wells with kriging crossvalidation errors larger than 100 feet in magnitude.

KGS ID	USGS ID	2011, 2007 kriging residual (feet)	GeolUnits
23S 26W 07CCC 01	380335100132701	251, 246	KD
11S 38W 35CCC 02	390254101305402	171, NA	TO
25S 25W 32CDD 01	374936100052801	123, 110	KD
26S 23W 10DAD 01	374725099485601	109, 110	KD
26S 41W 20BCD 01	374638101495001	-110, -65	QUTO
03S 30W 03CAB 01	394913100404001	-115, -113	TO
28S 37W 33DDC 01	373346101215801	-137, -124	QUTO

For comparison, the errors from the kriging crossvalidation analysis performed in 2007 are also included in Table 4. Note that these errors are quite similar to the 2011 errors. Furthermore, the results for 2005 and 2006 are also similar, indicating that these differences have persisted over a number of years. As noted in earlier reports, large positive errors, where the interpolated water level is significantly higher than the actual water level in the withheld well, tend to be associated with Cretaceous wells surrounded by wells tapping shallower units, primarily the Ogallala. Well 23S 26W 07CCC 01, in western Hodgeman County and at the edge of the High Plains aquifer extent, has consistently been associated with the largest positive kriging error. This well is screened in the Dakota and the measured 2011 water-table elevation was 2292 feet. The nearest network wells (all to the south, since the HPA is absent to the north) are Ogallala and QUTO wells with water levels above 2500 feet, resulting in an interpolated water level of 2543 feet at well 23S 26W 07CCC 01. The two other Dakota (KD) wells listed in Table 4 are also in the neighborhood of primarily Ogallala wells with significantly higher water levels. In these cases, the "errors" are almost certainly indications that the water levels in the Ogallala are in fact significantly higher than the water levels in the Cretaceous in the vicinity of these wells.

Well 11S 38W 35CCC 02, in northeastern Wallace County, is an Ogallala well that is at the very edge of the aquifer extent and is also quite distant from the nearest neighboring wells, all further to the north in Thomas and Sherman counties. The closest well is about 12 miles away, whereas most wells have nearest neighbors within a few miles.

Well 28S 37W 33DDC 01, in central Grant County, is associated with the largest negative kriging residual, -137 feet. The measured water-table elevation in this QUTO well is 2921 feet above sea level, whereas the water levels in nearby wells (a mix of QUTO and TOKJ wells) range roughly between 2750 and 2850 feet, leading to an interpolated water level of 2784 feet at well 28S 37W 33DDC 01, 137 feet below the measured water level. Well 28S 37W 33DDC 01 was constructed in the summer of 1994 and does not appear to be screened within the lower Cretaceous material.

Well 03S 30W 03CAB 01, in west-central Decatur County, is an Ogallala well located on the uplands of the middle fork to Sappa Creek that is surrounded primarily by wells tapping Quaternary alluvium in the adjacent stream valleys. This is probably part of the reason its measured water-table elevation is roughly 115 feet higher than those at nearby wells. Well 26S 41W 20BCD 01, in south-central Hamilton County, is a QUTO well with a measured water-table elevation of 3256 feet. Its nearest neighboring well is 26S 41W 32DAC 01, a KJ well with a measured 2011 water level of 3096 feet. This well was already identified above as having the second largest decline between 2010 and 2011. The next two nearest wells are a TO well and a QUTO well with measured levels of 3168 and 3148 feet, respectively. The next five nearest wells have measurements much more similar to that in 26S 41W 20BCD 01, but the interpolated value at 26S 41W 20BCD 01 ends up being 3146 feet, due to the strong influence of the three nearest wells.

6. Geostatistical Analysis of Five-Year Water-Level Declines

Figure 13 shows the omnidirectional semivariogram for the water-level changes over the five-year period from 2006 to 2011, along with the fitted semivariogram model. The model is exponential in form, with a range of 115 km, nugget of 8.9 ft^2, and overall sill of 65.5 ft^2. Like the water-level semivariogram presented earlier, this semivariogram has been computed using a two-step process that filters out the undue influence of clustered wells. Because this procedure is new this year, this semivariogram is not strictly comparable to those computed in earlier years. It is presented here as a baseline for comparison in future reports.

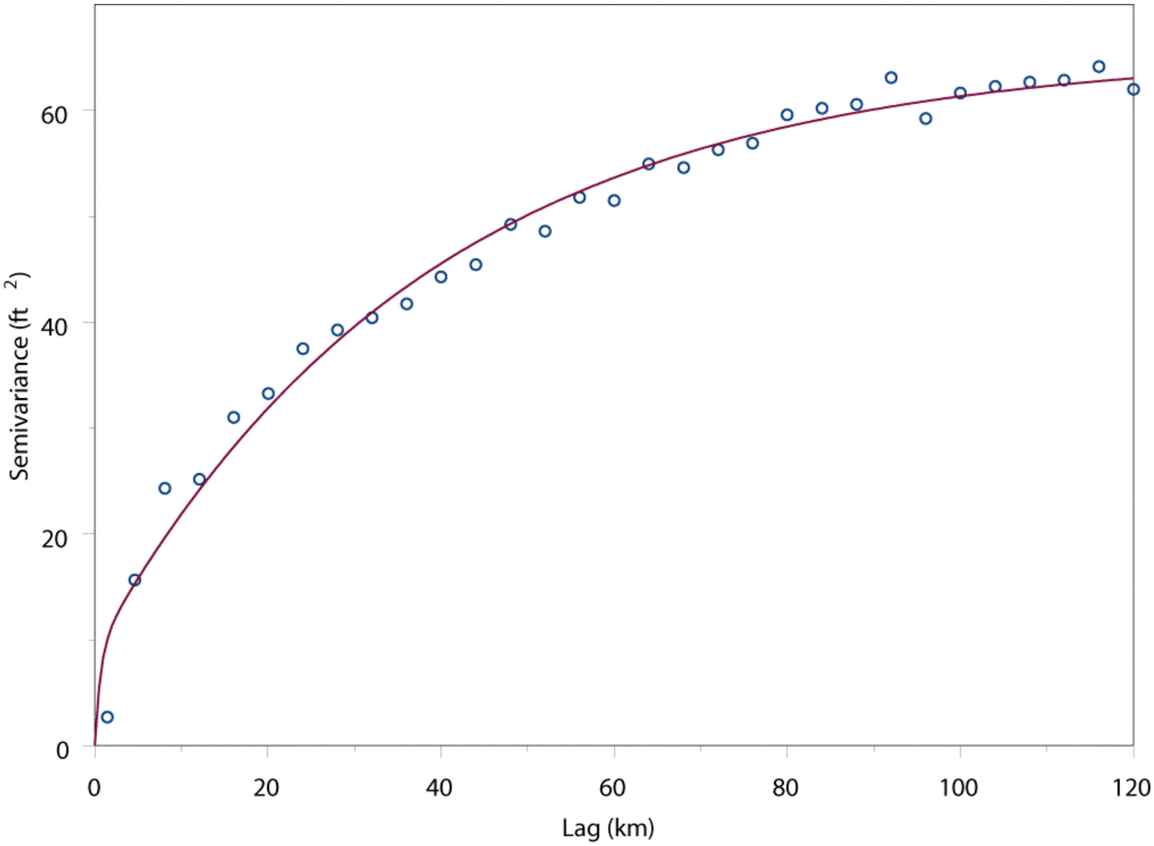

Figure 13. Omnidirectional semivariogram for changes in water level over the five-year period from 2006 to 2011.

Figure 14 is a map of the kriged water-level declines between 2006 and 2011. The average interpolated decline within the extent of High Plains aquifer region is almost 3 feet although this is made up of extremes. The core areas of the Ogallala portion of the High Plains aquifer (generally the western third of the state) showed notable groundwater declines in comparison to water-level increases seen in most of south-central Kansas and also the Ogallala fringe areas (eastern edges of the High Plains aquifer in northwest Kansas). The largest declines over this 5-year period are generally found in Finney County south of the Arkansas River and along a line running roughly between Liberal and Hugoton. Declines in these two areas are over 30 feet. Much of this area was (and still is at the time of this report) in extreme drought conditions.

In comparison, the Great Bend Prairie and Equus Beds aquifers of south-central Kansas show significant water-level rises over the same time period. Much of this increase can be attributed to above normal (at times, flooding) levels and timely precipitation patterns that occurred over the growing seasons in 2008, 2009, and 2010. Increased precipitation amounts combined with the fact the aquifer here is generally within 50 feet of the land surface allows for greater aquifer recharge rates than occur in the Ogallala portion of the aquifer. Similarly, much of the increase in the water table seen in northwest Kansas can likely be attributed to the large number of alluvial aquifer wells in this area.

Well 18S 31W 24BCB 01 in eastern Scott County is an abandoned irrigation well tapping the Ogallala just inside the southern edge of aquifer. Water levels in the well have shown a gradually rising trend since the mid-1980’s and its 2011 depth-to-water measurement of 65.35 feet is the shallowest on record. This trend is not shown by other monitoring wells in the immediate area.

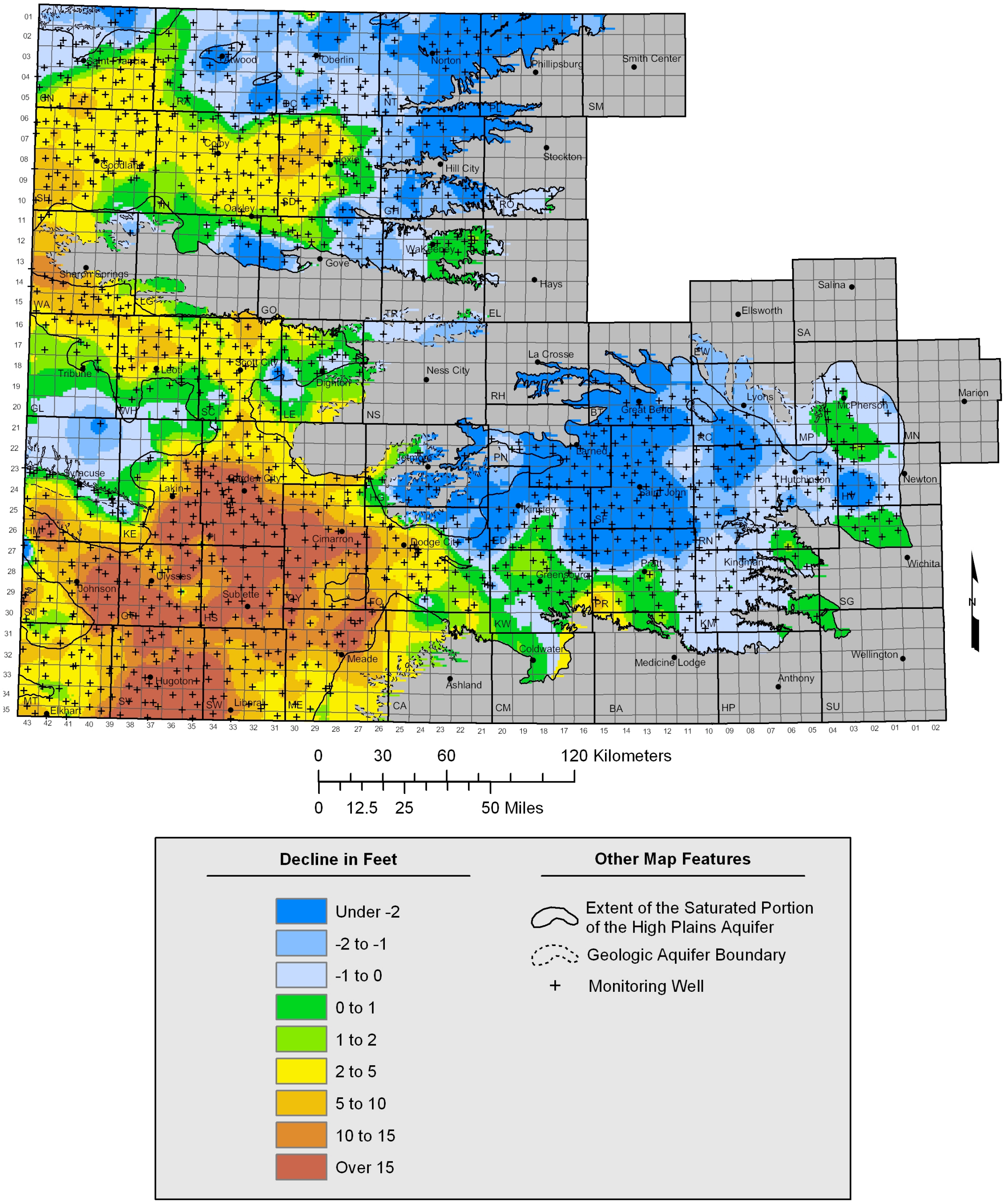

Figure 14. Kriged water-level declines for the five-year period from 2006 to 2011.

Figure 15 shows the results of the kriging crossvalidation analysis for the water-level declines between 2006 and 2011. The correlation between the true and estimated declines is 0.79 and the root mean squared (rms) error is 5.5 feet. These two statistics have been computed including the well with a water-level increase of 84 feet between 2006 and 2011, although that point is excluded from Figure 15. If that well is excluded from the computation of the statistics, then the correlation increases to 0.82 and the rms error decreases to 5.0 feet.

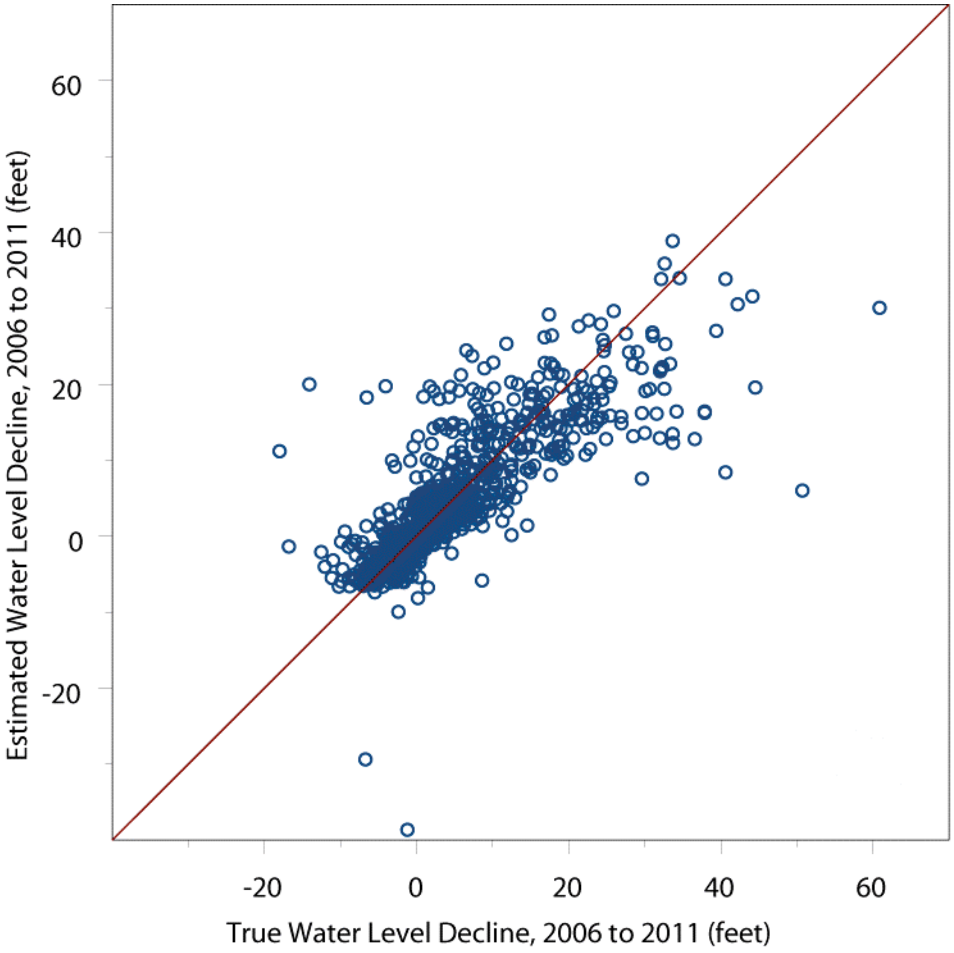

Figure 15. Kriging crossvalidation results for 5-year water-level changes.

Figure 16 is a normal QQ plot of the kriging crossvalidation errors (residuals) for the water-level declines between 2006 and 2011. The values plotted represent the estimated (kriged) decline minus the actual decline, so a positive error indicates that the observed decline at the well in question is smaller than would be expected based on the declines at neighboring wells (which determine the kriging estimate).

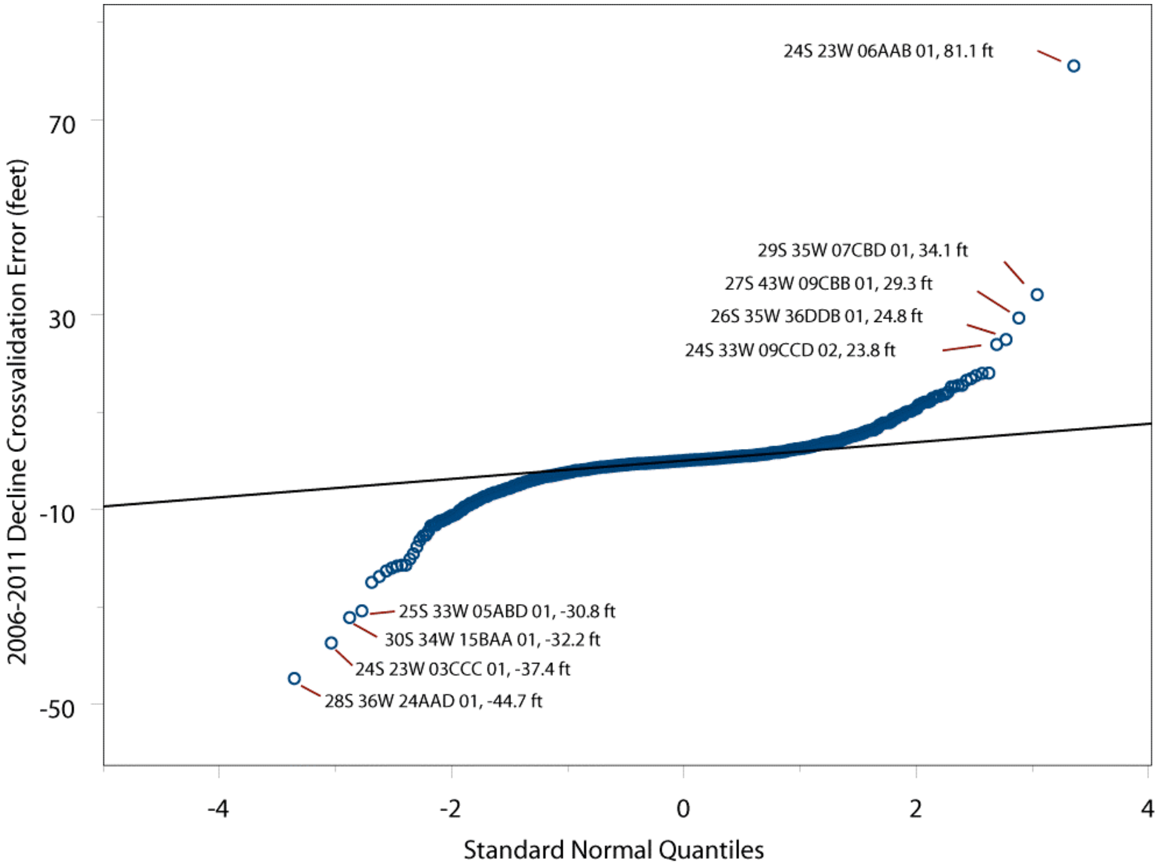

Figure 16. Normal QQ plot of kriging crossvalidation residuals for water-level declines between 2006 and 2011.

The largest error, 81.1 feet, is associated with well 24S 23W 06AAB 01, the Dakota well discussed in Section 4 of this report.

7. Geostatistical Analysis of 2010 to 2011 Water-Level Declines

Figure 17 shows the omnidirectional semivariogram for the water-level changes from 2010 to 2011, along with the best-fit semivariogram model. The fitted model is exponential with a range of 63 km, a nugget of 2.8 ft^2, and an overall sill of 6.4 ft^2.

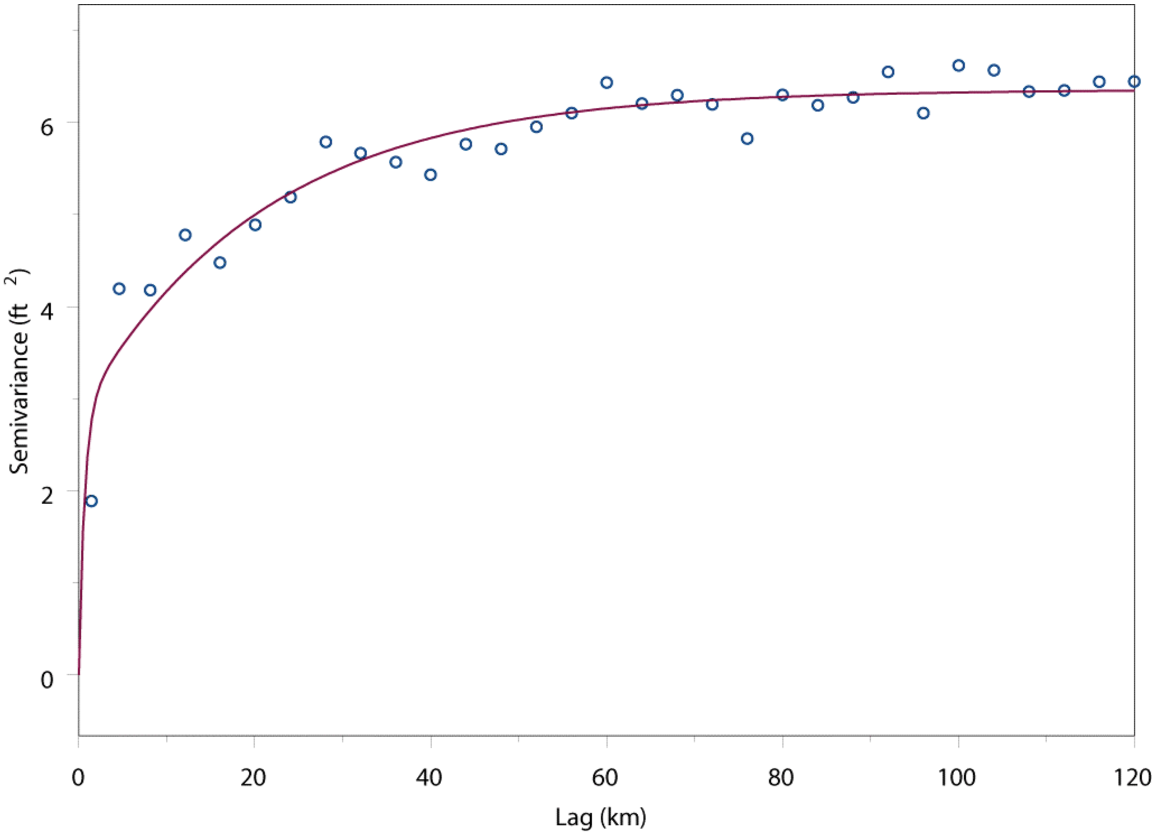

Figure 17. Omnidirectional semivariogram for changes in water level between 2010 and 2011 measurement campaigns.

Figure 18 is a map of the kriged water-level declines between 2010 and 2011. Most of the High Plains aquifer region saw groundwater declines over this period, averaging a little over a foot. The greatest declines were in drought-stricken southwest Kansas, particularly in the sand hills south of the Arkansas River and along the Stanton/Grant county line, where declines of over 5 feet were common. Overall declines in southwest Kansas averaged almost 3 feet, which represents the third largest overall decline since the State began administrating the water-level network in 1996. The periods 2002-2003 and 2008-2009 had slightly larger overall declines, 3.35 and 3.03 feet, respectively. Declines in south-central Kansas were mostly under half a foot with areas along the Stafford/Reno county line showing slightly higher decline rates. The thin line of rising water levels in northern Pratt County was generally less than half a foot with a small area of southwest Reno, northwest Kingman, and northeast Pratt County showing rises over a foot. Much of the increase in the water table seen in northwest Kansas can be attributed in part to the predominance of alluvial aquifer wells in this area.

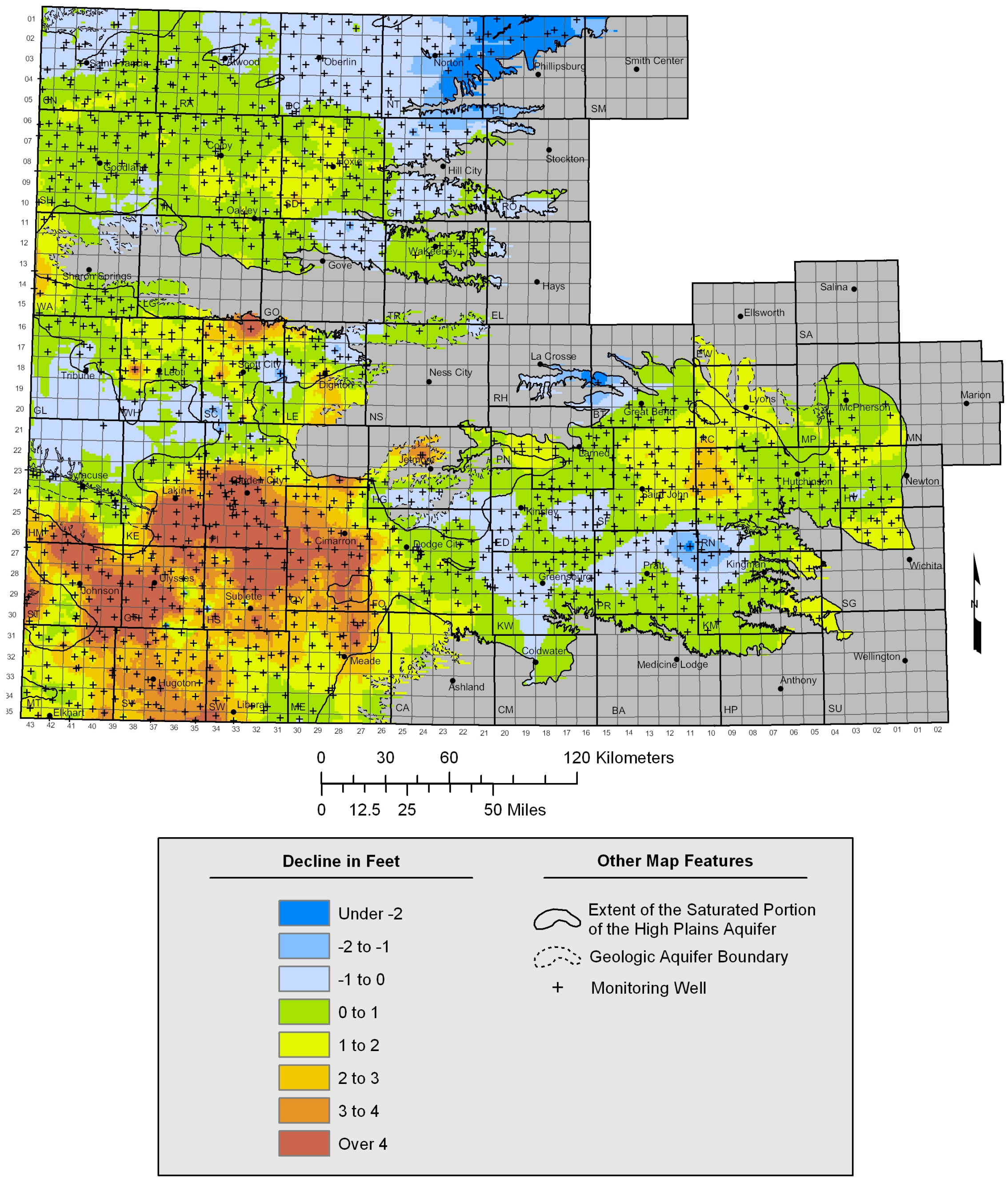

Figure 18. Kriged water-level declines for one-year period from 2010 to 2011

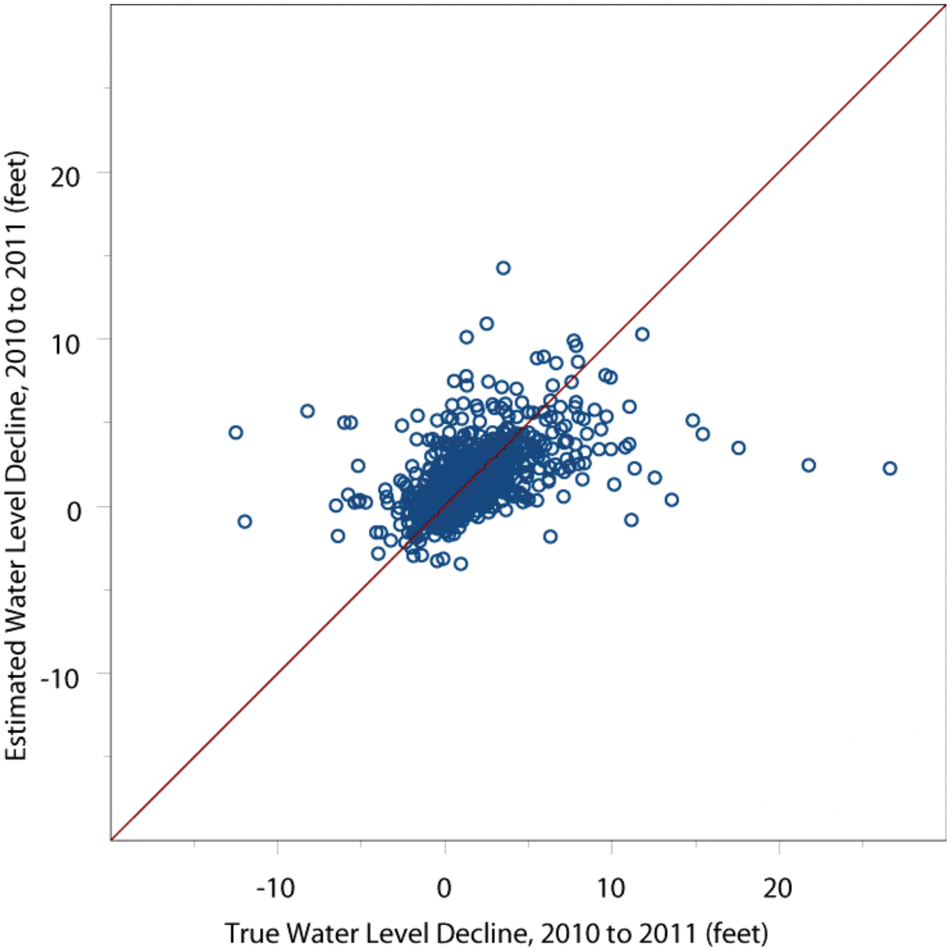

Figure 19. Kriging crossvalidation results for changes in water level between 2010 and 2011.

The kriging crossvalidation results for the one-year declines, shown in Figure 19, demonstrate that the interpolation process smooths out a considerable amount of the actual variability in the measured declines. The correlation between actual and estimated declines is 0.50 and the rms error is 2.4 feet.

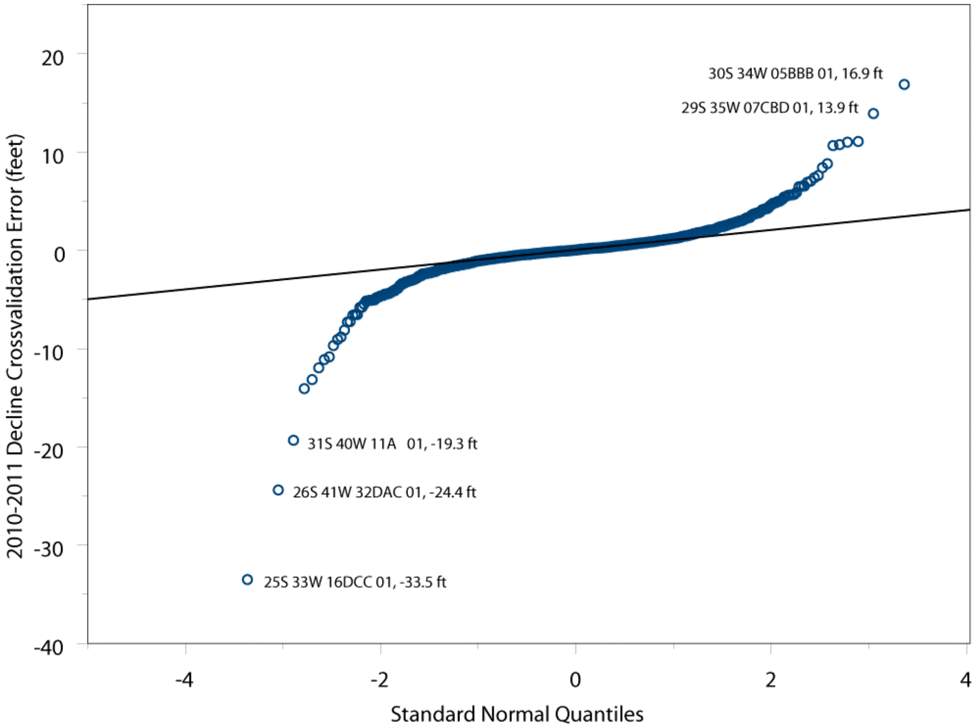

Figure 20. Normal QQ plot of kriging crossvalidation errors for 2010-2011 water-level declines.

Figure 20 is a normal QQ plot of the kriging crossvalidation errors for the one-year declines, with the most extreme errors flagged. Except for well 29S 35W 07CBD 01, which swaps places with well 03S 21W 29DCC 01 when the wells are ordered by crossvalidation error, as they are here, rather than by decline value itself, as in Figure 5, these are also the wells with the most extreme one-year declines, identified in Table 2 and discussed on page 10.

8. Analysis of Variance

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 5 contains the results of an analysis of variance of the kriging crossvalidation errors for the 2010 to 2011 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. Except perhaps for chalk cut quality, none of the factors appears to contribute to significant, systematic aberrations in the decline values. Closer examination indicates that there could be a slight tendency for declines to be overestimated when the chalk cut quality for the 2011 measurement is lower, but it is difficult to draw definitive conclusions due to the limited number of lower-quality chalk cut values (23 "fair") compared to the higher-quality values (296 "good" and 996 "excellent").

Table 5. Analysis of variance of kriging crossvalidation errors for 2010 to 2011 declines.

Source	Df	Sum of Sq	Mean Sq	F Value	Pr > F
Measurer	21	111.38	5.30	0.97	0.50
Downhole.Access	1	0.44	0.44	0.08	0.78
Weighted.Tape	1	14.24	14.24	2.61	0.11
Well.Use	3	11.98	3.99	0.73	0.53
Oil.On.Water	1	2.83	2.83	0.52	0.47
Chalk.Cut.Quality	2	55.61	27.80	5.10	0.0063
Aq.Group5	4	23.24	5.81	1.06	0.37
Residuals	1025	5592.67	5.46		

Residual standard error: 2.34 feet

9. Identification of Network Holes

The kriging error (standard deviation) map for the 2011 water-table elevations (Figure 10) 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 hexagonal 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 21 shows the 17 network hole centers that were identified based on the 2011 measurement campaign.

For each hole center, a list of well candidates is selected from the three major inventories of groundwater 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.

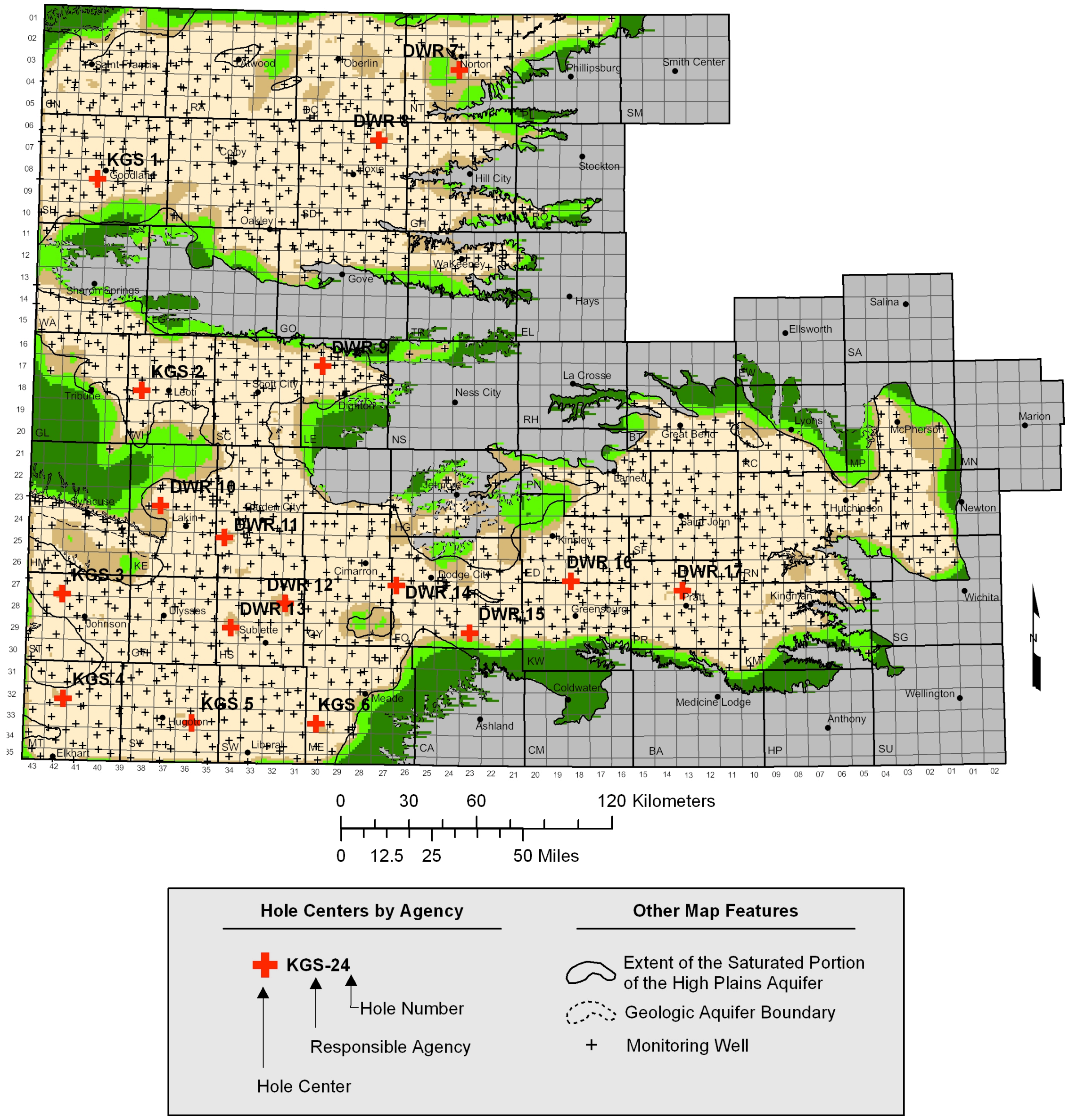

Figure 21. Network holes from the 2011 measurement campaign.

10. Concluding Remarks

The purpose of this report is to present statistical and geostatistical analyses of water-level measurements taken over the winter months of 2011. We also present an overview of water-level changes occurring primarily in the High Plains aquifer, the region's primary water source.

Overall from 2010 to 2011, groundwater elevations declined across most of the core aquifer areas of the High Plains region of Kansas. The declines were the greatest in traditional high pumping areas, especially in southwest Kansas. Similar decline areas were also present over the 2006 to 2011 time period. The added stress of continued drought conditions likely served to accentuate the pumping stress on the aquifer as the southwest region of Kansas showed the third highest rate of decline in that area since the State assumed administration of the water-level program in 1996.

Groundwater declines were also present in south-central Kansas from 2010 to 2011. However, aquifer recharge in this part of the state is more responsive to above-normal precipitation events. This is evident by the widespread water-level rises shown over the five-year period of 2006 to 2011, where precipitation was above normal for three of the five years.

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Appendix A: Network Hole Centers

COUNTY	AGENCY	HOLE NUMBER	UTM X	UTM Y
Sherman	KGS	1	262749.41040	4355433.11660
Wichita	KGS	2	282474.13740	4261710.89790
Stanton	KGS	3	247248.63340	4171593.68180
Morton	KGS	4	247582.22850	4125390.75730
Stevens	KGS	5	304460.19700	4114382.11830
Meade	KGS	6	359503.39220	4114048.52320
Norton	DWR	7	422928.48080	4403693.21310
Sheridan	DWR	8	387368.40970	4372578.15090
Lane	DWR	9	362466.54820	4272401.98070
Kearny	DWR	10	290782.79690	4210624.31120
Finney	DWR	11	318971.58480	4196446.51850
Haskell	DWR	12	345992.78980	4167256.94520
Haskell	DWR	13	321807.14340	4156581.90130
Ford	DWR	14	395082.71050	4175254.91690
Ford	DWR	15	427523.51700	4154212.23160
Edwards	DWR	16	472395.07970	4177156.51000
Pratt	DWR	17	521671.17830	4173029.00180