Kansas Geological Survey

Statistical and Geostatistical Analysis of the Kansas High Plains Water-Table Elevations, 2012 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 Some water is also withdrawn from underlying bedrock units, primarily Cretaceous strata, in this region.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 2012 water-level measurements and water-level changes for the 1-year and 5-year periods preceding the 2012 measurements. The majority of the 2012 measurements were obtained between January 3 and January 7, 2012, although measurement dates range from Dec. 28, 2011, to Feb. 23, 2012.

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 2012 and January 2011 measurements represents the water level decline for 2011.

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 (Butler et al., 2012). 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. Investigation into the impacts of all these factors on annual water-level measurements is ongoing.

2. Data Extraction

The SQL query shown in Listing 1 was used to extract water-level measurements for the 2012 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. Similar queries were used to extract data from the 2011 and 2007 measurement campaigns for the sake of computing 1-year and 5-year water-level changes.

Listing 1. SQL query for extracting 2012 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 >=
          '28-Dec-2011' and
    bwilson.wizard_network_wells_wl.measurement_date_and_time <=
          '28-Feb-2012'
order by
    bwilson.wizard_network_wells_wl.usgs_id,
    bwilson.wizard_network_wells_wl.measurement_date_and_time
```

The query yields 1496 measurements from 1371 distinct wells, with measurement dates ranging from Dec. 28, 2011, to Feb. 23, 2012. Of these wells, 1327 are located within the geographic boundaries demarking the extent of the High Plains aquifer, 836 of them measured by DWR staff and 491 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.

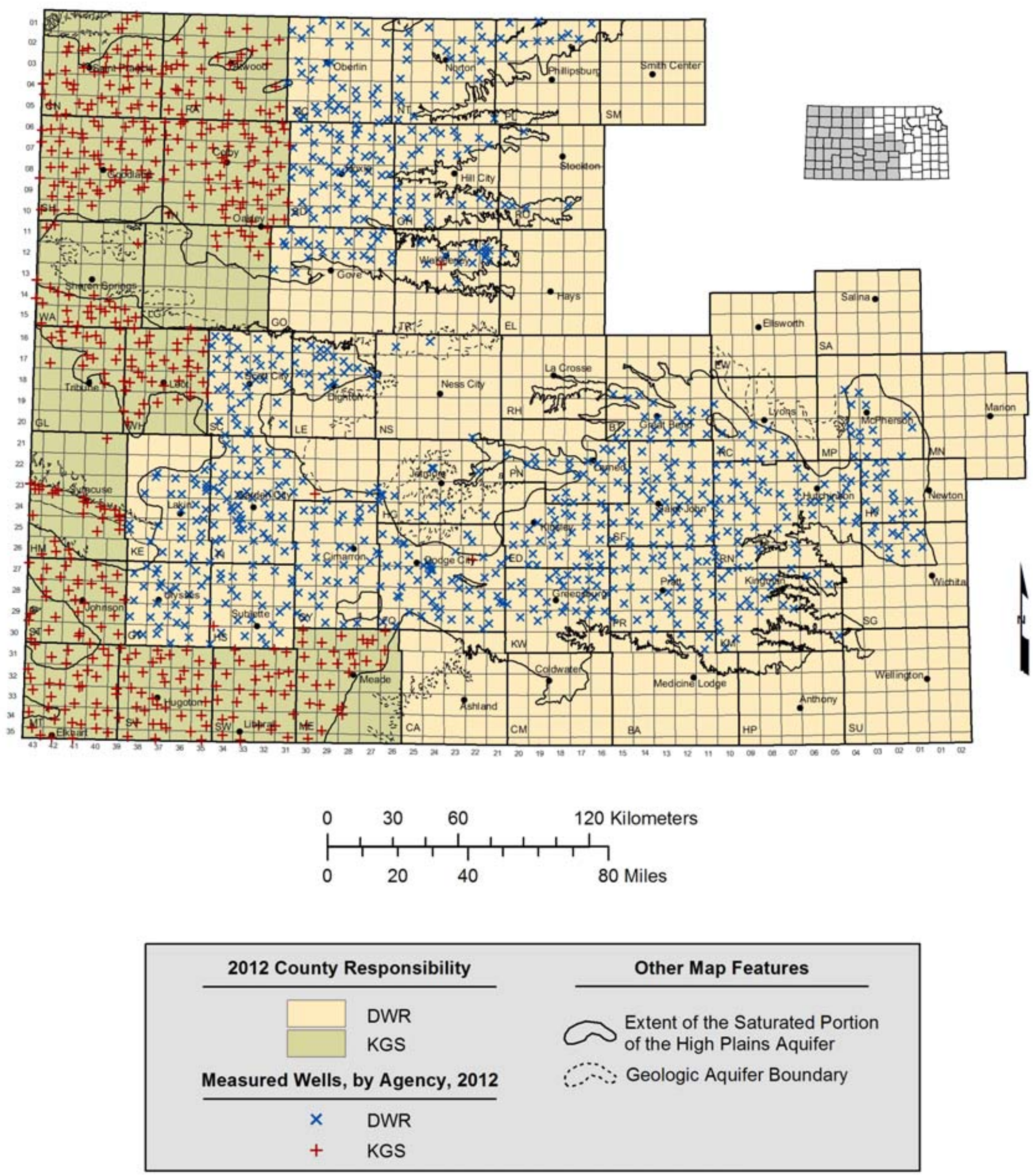

Figure 1. Wells measured and responsible agency in 2012.

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 and/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. The parentheses after the group heading contain the label for that group and the number of wells in the group.

Quaternary only (QA, 405)
- QA (129): Quaternary alluvium
- QU (261): Undifferentiated Quaternary aquifers
- QAQU (14): Quaternary alluvium + undifferentiated
- QUQA (1): Quaternary undifferentiated + alluvium

Quaternary + Tertiary Ogallala (QT, 243)
- QUTO (228): Quaternary undifferentiated + Ogallala
- QATO (12): Quaternary alluvium + Ogallala
- QAQUTO (1): Quaternary alluvium + Quaternary undifferentiated + Ogallala
- TOQU (2): Ogallala + Quaternary undifferentiated

Tertiary Ogallala (TO, 600)
- TO (600): Tertiary Ogallala

Quaternary and/or Tertiary Ogallala + Cretaceous/Jurassic (QK, 52)
- QUTOKJ (18): Quat. undifferentiated + Ogallala + undifferentiated Cretaceous/Jurassic
- QUTOKD (16): Quat. undifferentiated + Ogallala + Cretaceous Dakota
- TOKJ (8): Ogallala + undifferentiated Cretaceous/Jurassic
- TOKD (8): Ogallala + Cretaceous Dakota
- QUTOJM (1): Quaternary undifferentiated + Ogallala + Jurassic Morrison
- QUKD (1): Quaternary undifferentiated + Cretaceous Dakota

Cretaceous (KK, 27)
- KD (21): Cretaceous Dakota
- KJ (5): Undifferentiated Cretaceous/Jurassic
- KN (1): Cretaceous Niobrara

The analyses presented in this report will employ measurements from all 1327 of these wells. The wells solely or partially tapping bedrock units tend to be located near the fringes of the region, effectively substituting for the High Plains aquifer where it is thin or absent. Additionally, there are areas of southwest Kansas where the High Plains aquifer and deeper bedrock formations are in direct contact with each other and some measured wells are screened across both units. Because the primary objective of this report is to provide an assessment of the ground-water resources of the region, rather than to characterize the High Plains aquifer *per se*, these bedrock wells are included in this report. Figure 2 shows the wells coded according to the five-part aquifer grouping used in the list above. This map demonstrates that each Groundwater Management District (GMD) is dominated by a particular type of well: Quaternary wells in GMD 2 and GMD 5, Ogallala wells in GMD 4 and GMD 1, and Quaternary plus Ogallala wells in GMD3. The wells in GMD 3, in southwest Kansas, tap a greater diversity of units than wells in other districts. Of the 79 wells throughout the region that tap bedrock units (possibly in combination with overlying units), 68 are in GMD 3, accounting for almost 17% of the wells in GMD 3.

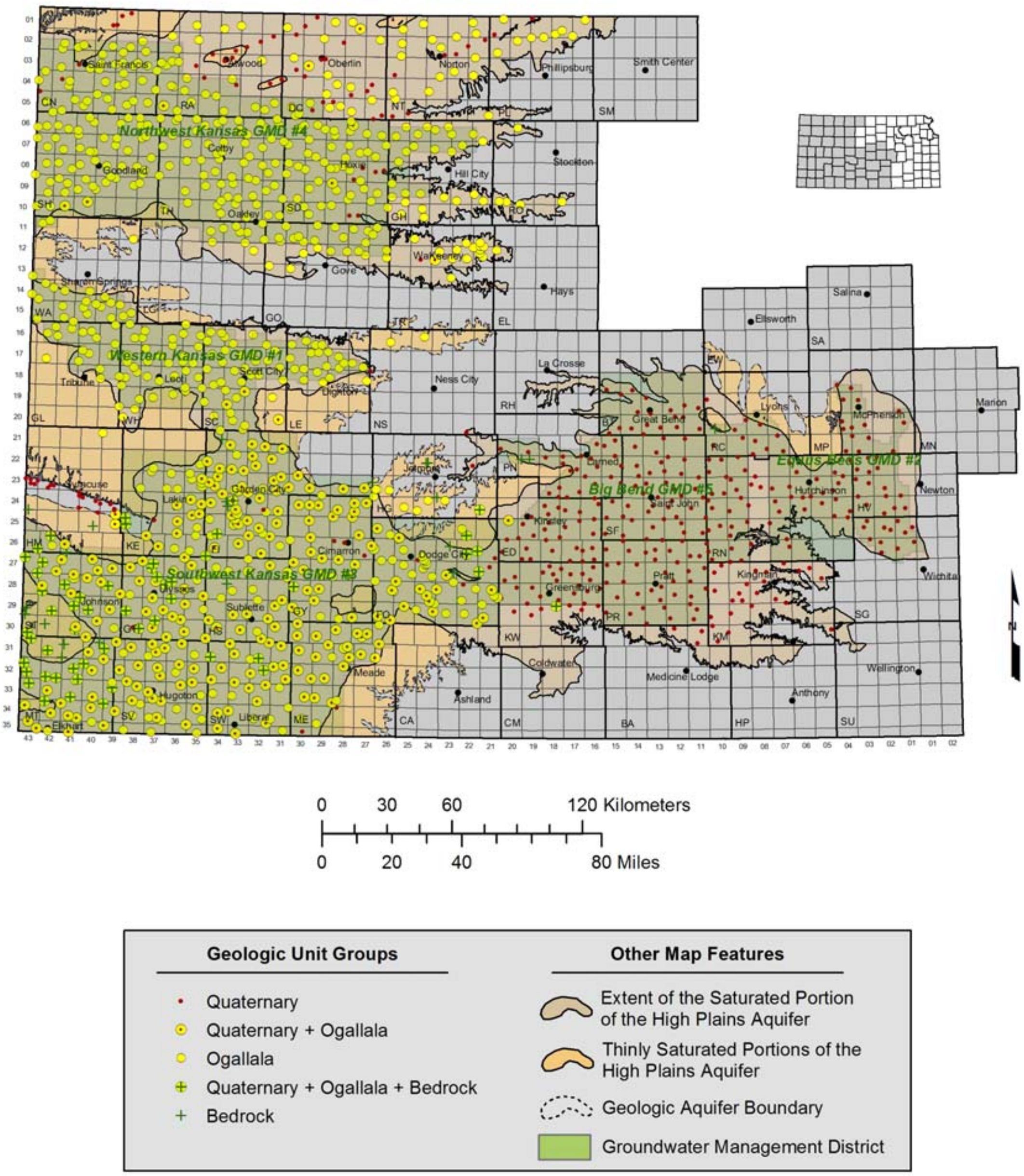

Figure 2. Five-part aquifer groupings by well

Figure 3 shows the sequence of measurement times for the wells within the HPA extent. There are 1450 total measurements, including repeat measurements at 124 wells. Traditionally, the vast majority of measurements each year are taken in the first week of January. The measurements in February 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.

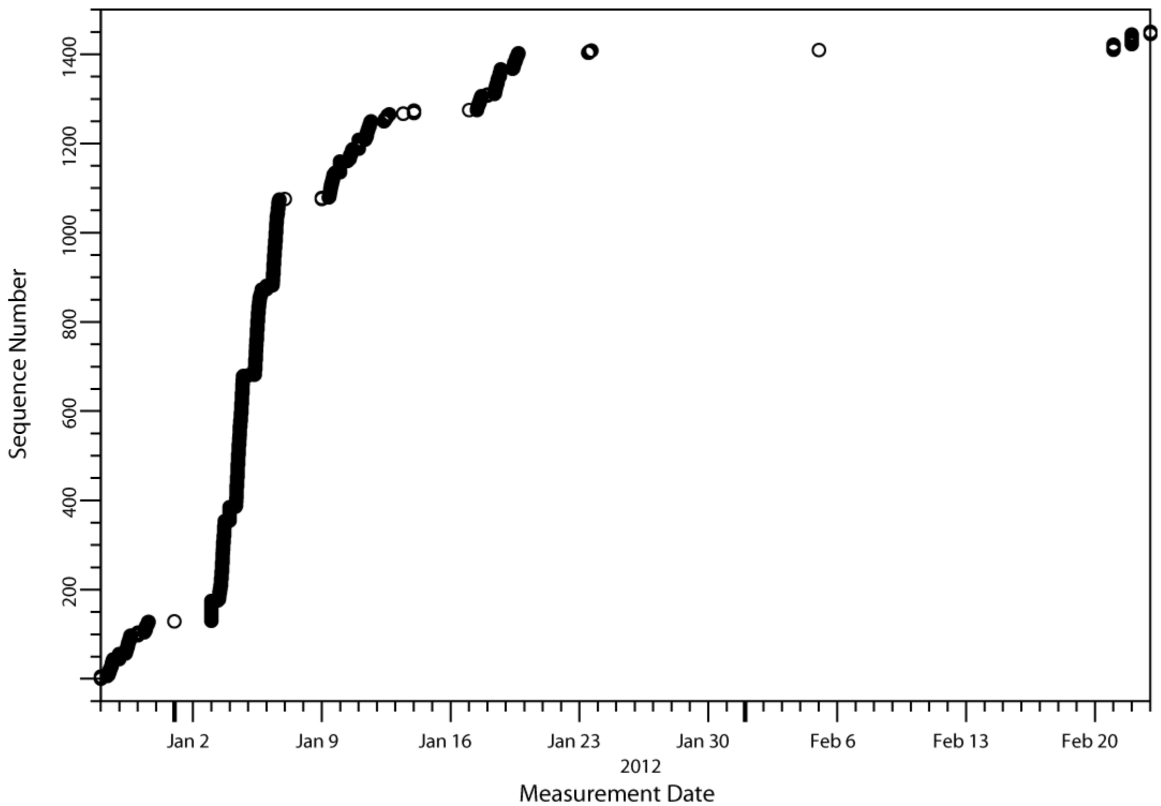

Figure 3. Sequence of measurement dates for water-level measurements at wells within the High Plains aquifer extent, 2012 measurement campaign.

3. Repeat Measurements

The 2012 water-level data include repeat measurements at 124 wells within the High Plains aquifer extent. The majority of these repeat measurements are performed for quality control purposes in the field. Other return visits are made to verify unexpected, out-of-trend measurements or if a particular well was difficult to access (e.g., spotty tape, down-hole restrictions). For wells with repeat measurements, Figure 4 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.

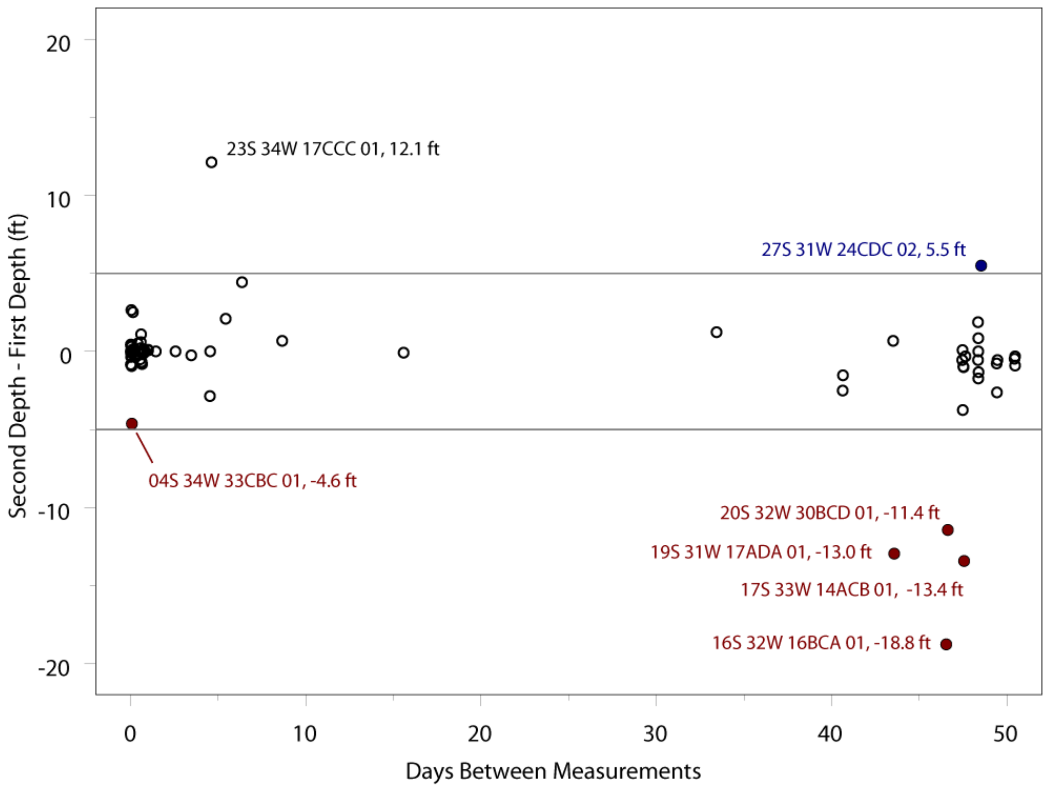

Figure 4. Difference between second and first measured depths to water versus time span between measurements for 124 wells with repeat measurements in the 2012 measurement campaign. Horizontal lines represent differences of -5 and 5 feet.

Eighty-five of the wells have repeat measurements taken within 24 hours of the first measurement. For 82 of these, the differences fall between -1 and 1 foot (and many are zero). The differences for the remaining four wells are 1.1 feet (26S 21W 25CCC 01), 2.5 feet (31S 40W 29ABB 01), 2.7 feet (08S 38W 24AAB 01), and -4.6 feet (04S 34W 33CBC 01). For this last well, the first measurement is considered anomalous and it is one of the five wells highlighted in red on Figure 4. The remaining four wells highlighted in red, with time differences of 43 to 48 days between repeat measurements, also have first measurements that are considered anomalous. None of these anomalous measurements is used in the remaining analyses. Well 27S 31W 24CDC 02, highlighted in blue, has a second measurement that is considered anomalous due to nearby pumping at the time it was taken. There is no apparent reason to question either measurement for well 23S 34W 17CCC 01, which exhibited a 12.1-foot increase in depth to water over the five days between the two measurements.

4. Summary Statistics of Primary Variables

Summary statistics for the 2012 depth to water (from ground surface) and water-table elevation, along with the declines since 2011 and 2007, are shown in Table 1. The average water-level decline between 2011 and 2012 was 2.01 feet, notably higher than the 1.18-foot average decline between 2010 and 2011 and representing the largest single-year decline since the KGS started administration of the cooperative water level program in 1996 – a reflection of the extreme drought conditions seen throughout Kansas in 2011. Summary statistics for the 1- and 5-year declines for each of the five groundwater management districts are presented in Section 9.

Table 1. Summary statistics for 2012 water-level measurements and prior 1- and 5-year water-level declines.

	2012 Depth (feet)	2012 Elevation (feet a.s.l.)	2011 to 2012 Decline (feet)	2007 to 2012 Decline (feet)
Minimum:	2.01	1323.21	-13.63	-17.70
1st Quartile:	35.90	2180.02	0.30	-0.51
Mean:	118.02	2592.19	2.28	4.50
Median:	109.31	2644.44	1.32	1.39
3rd Quartile:	174.94	3009.53	3.44	5.94
Maximum:	414.55	3832.57	23.68	60.01
Std. Dev.:	87.35	576.05	3.35	9.17
Count:	1327	1327	1297	1219

Figures 5 and 6 show two different displays of the distribution of water-level declines between 2011 and 2012, 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.

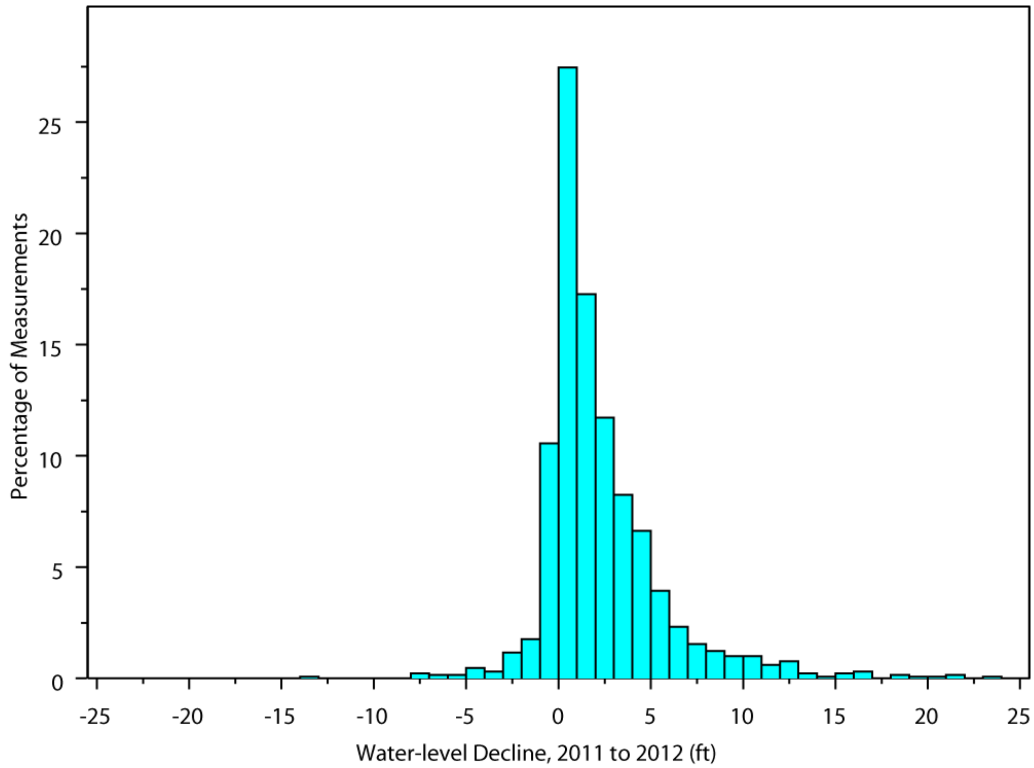

Figure 5. Histogram of water-level declines between 2011 and 2012 campaigns.

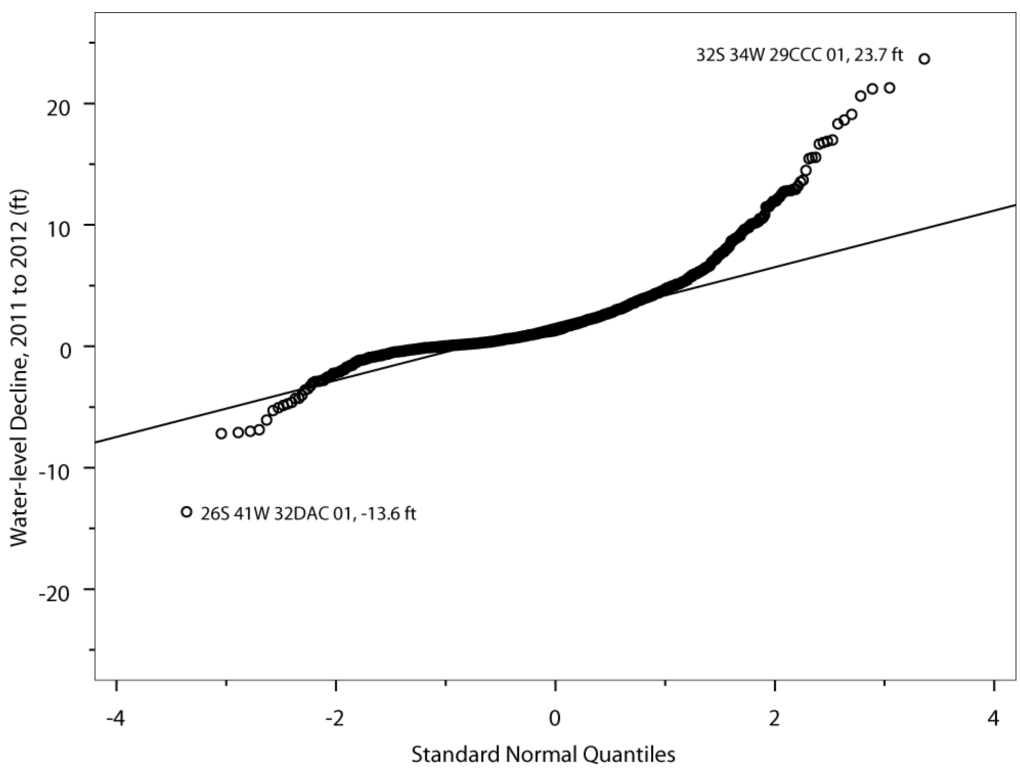

Figure 6. Normal QQ plot of water-level declines between 2011 and 2012 campaigns.

Well 32S 34W 29CCC 01 (USGS ID 371339101025302), a QUTO well, had the single largest 2011 to 2012 measured decline of 23.68 feet. The well is located northwest of Liberal in an area that traditionally exhibits large water-level declines. Several wells in this area of the state showed single-year water-level declines of 10 feet or more.

Well 26S 41W 32DAC 01 (USGS ID 374421101490902), a KJ (undifferentiated Cretaceous/Jurassic) well in southern Hamilton County, showed the largest measured 2011 to 2012 water-level increase. It is 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 fourth annual water-level change observed for the well. It is likely that the 2011 measurement is anomalous.

Figures 7 and 8 show the histogram and normal QQ plot of the 5-year declines, between 2007 and 2012. The two wells with the most extreme 5-year changes are flagged in Figure 8. Neither of these values appears to be particularly anomalous. Well 30S 34W 15BAA 01 (USGS ID 372642101013501), with a 60-foot decline starting in 2008, is a QUTO well in southwest Haskell County. Well 29S 35W 07CBD 01 (USGS ID 373214101114301), with a 17.7-foot increase, is an abandoned QUTO well in east-central Grant County that has exhibited significant fluctuations in water level since it was first measured in 1979.

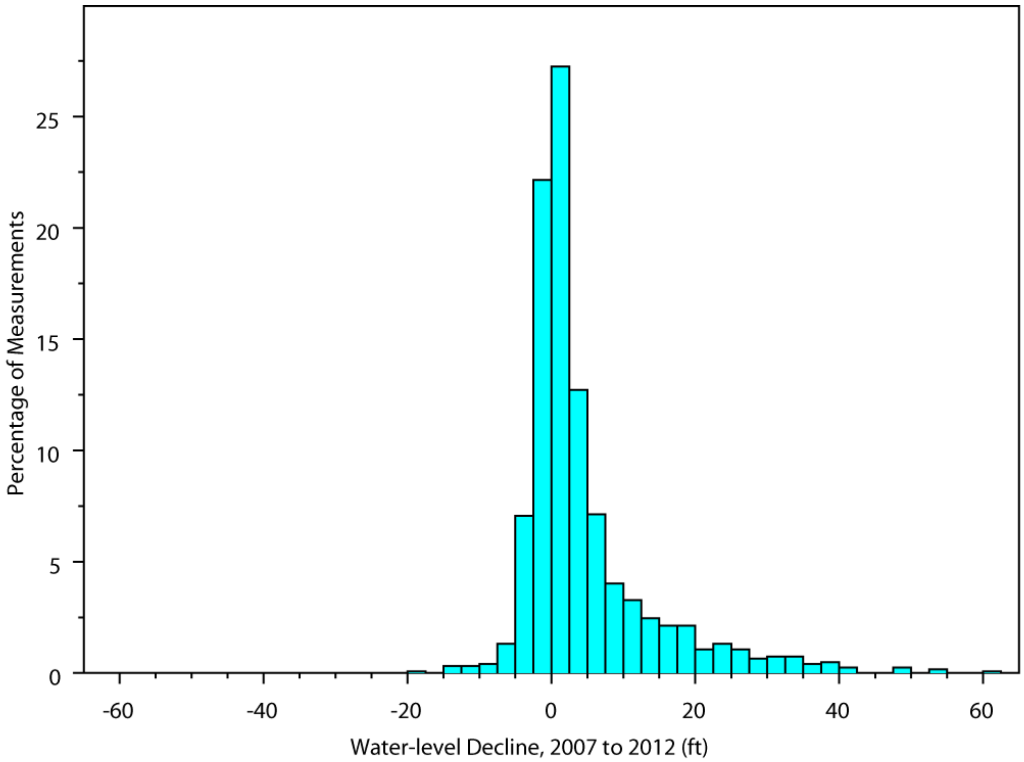

Figure 7. Histogram of water-level declines between 2007 and 2012 campaigns.

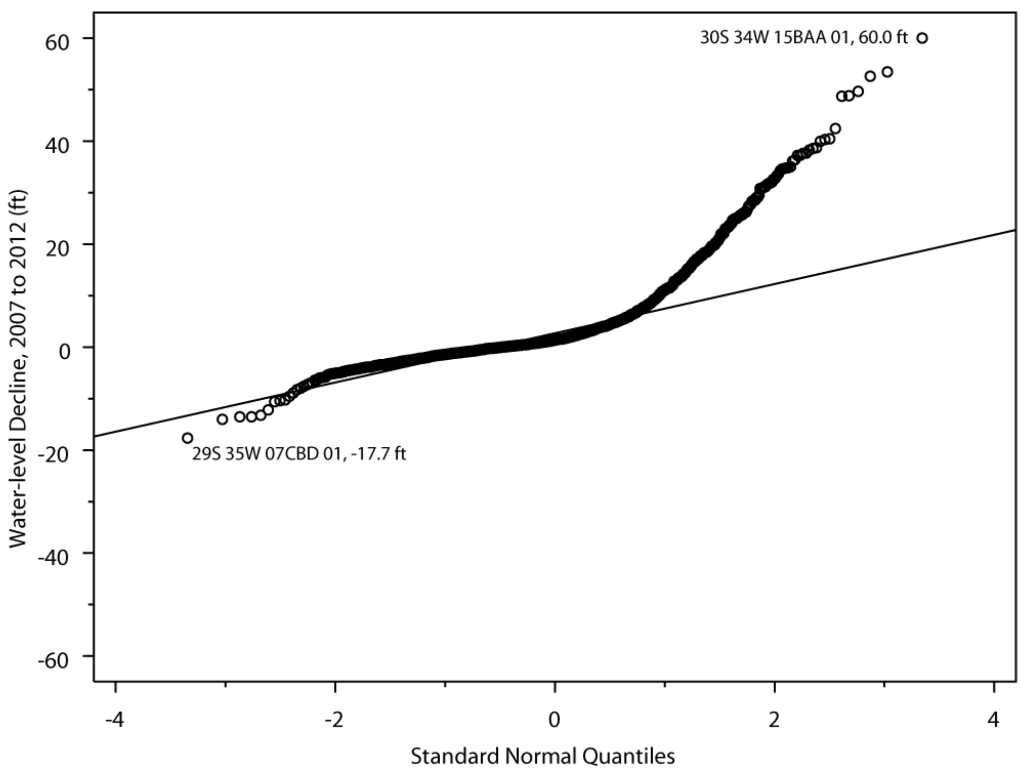

Figure 8. Normal QQ plot of water-level declines between 2007 and 2012 campaigns.

5. Geostatistical Analysis of 2012 Water-Table Elevations

For the geostatistical analysis of 2012 water-table elevations, we employed the measurements from both the DWR and KGS at 1327 wells located within the High Plains aquifer extent, using the first measured value for those wells with repeat measurements (except for the five wells with anomalous first measurements, discussed in Section 3).

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; 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 2012 measurements, the direction N 11° E appeared to be slightly more trend free, so that direction has been used this year. Figure 9 shows the empirical semivariogram for the 2012 water-table elevation measurements in the direction N 11° 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 69 square feet, an overall sill of 12735 square feet, and a range of 65.8 km.

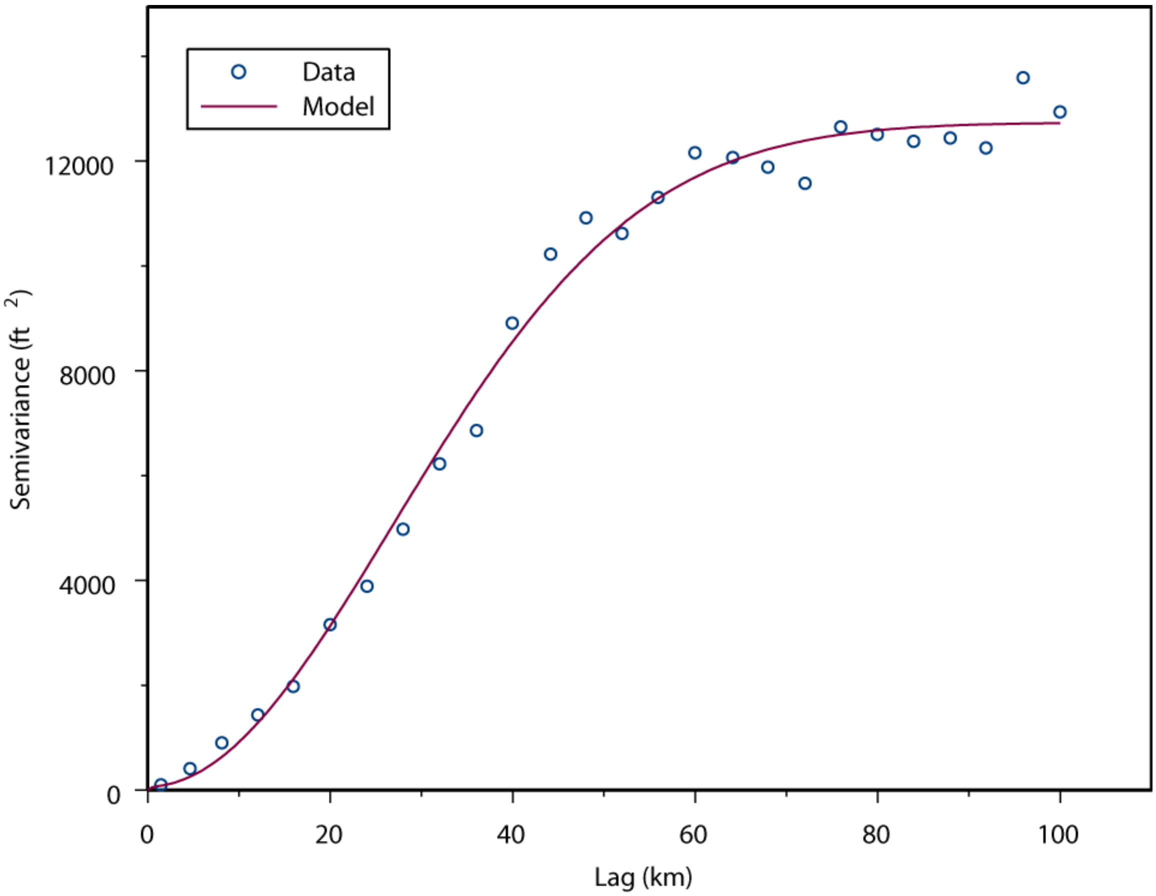

Figure 9. Semivariogram of 2012 water-table elevation measurements in direction N 11° E along with fitted Gaussian model (line).

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. Figure 10 shows the resulting map of kriged water-table elevations. By and large, ground-water elevations mirror land-surface elevations with highs along the Kansas-Colorado border running to lower elevations in the eastern portions of the aquifer.

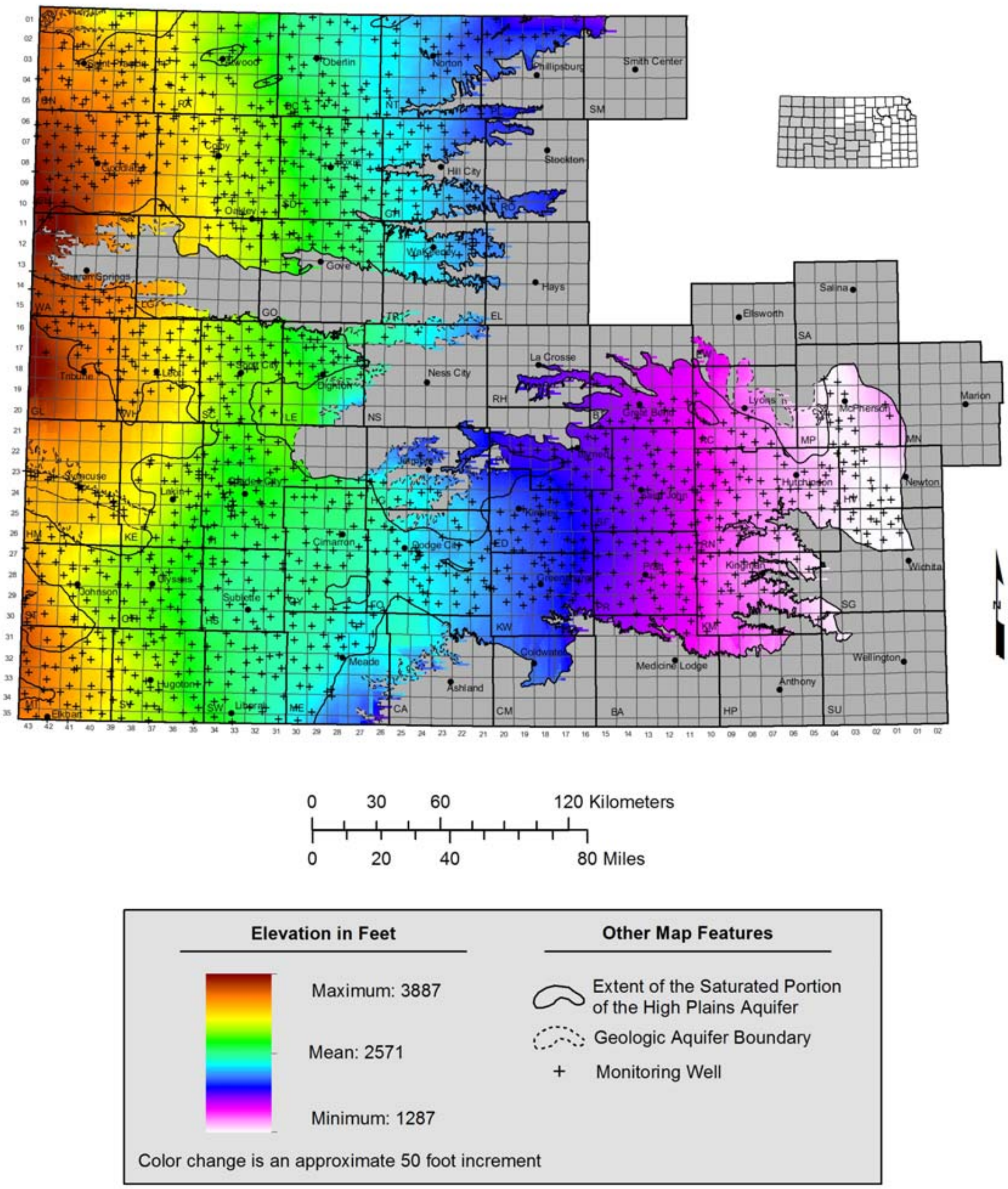

Figure 10. Kriged 2012 water-table elevation.

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 2012 water levels is shown in Figure 11. This map is used in the identification of holes or gaps in the measurement network, as described in Section 10. For 2012, most of the 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 2012 is 8.3 ft (square root of 69 ft^2). The nugget of the 2012 semivariogram model is somewhat higher than that for the 2011 semivariogram model (44 ft^2) but significantly lower than that estimated in the 2000's; 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 ("nests" of wells) 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, which resulted in the exclusion of only nine of the 1327 wells from the semivariogram computation, the estimated nugget for the 2012 semivariogram model was 195 ft^2, and the resulting kriging standard deviations were above 10 feet throughout most of the HPA extent.

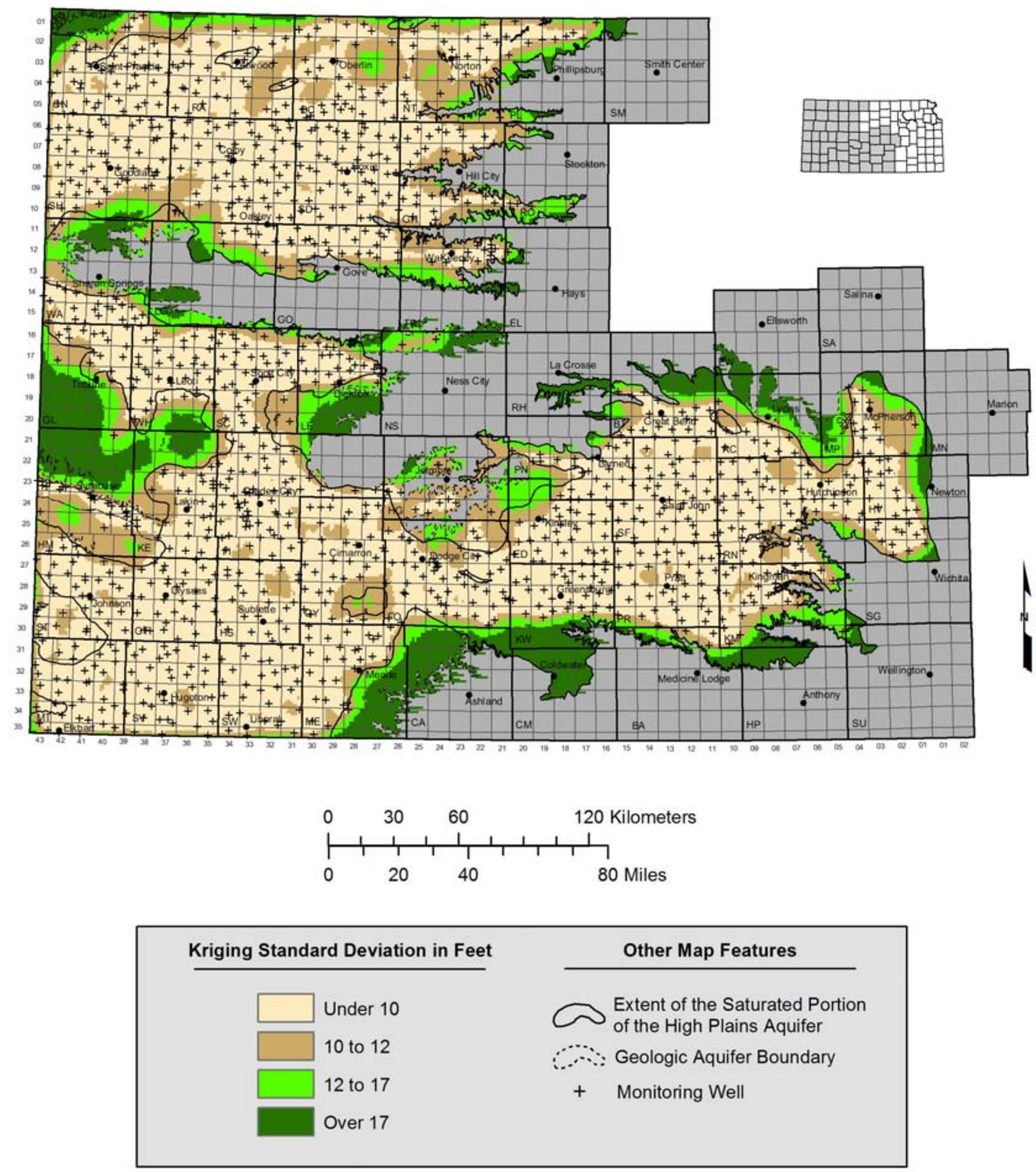

Figure 11. Kriging standard deviation for the 2012 water-table elevation.

Figure 12 shows the results of a kriging crossvalidation analysis for the 2012 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 12 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 24.1 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.

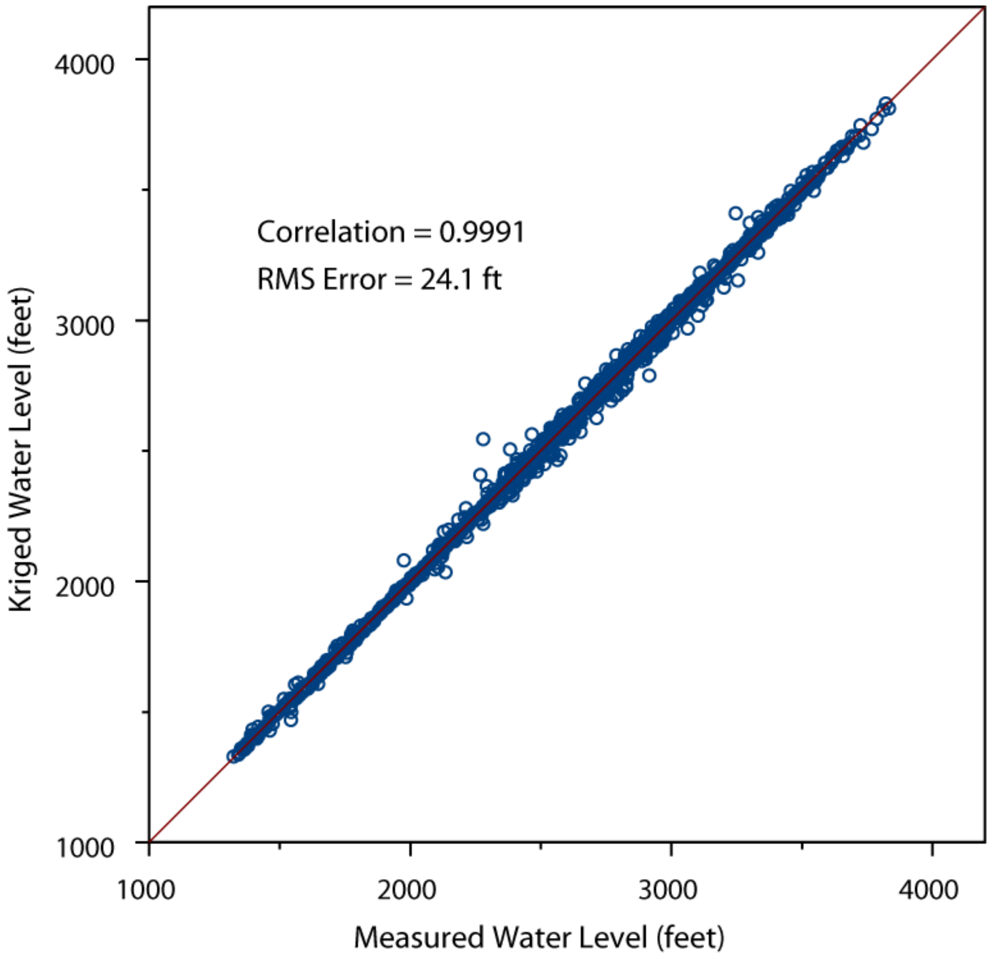

Figure 12. Kriging crossvalidation results for 2012 water-table elevations.

Figure 12 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.

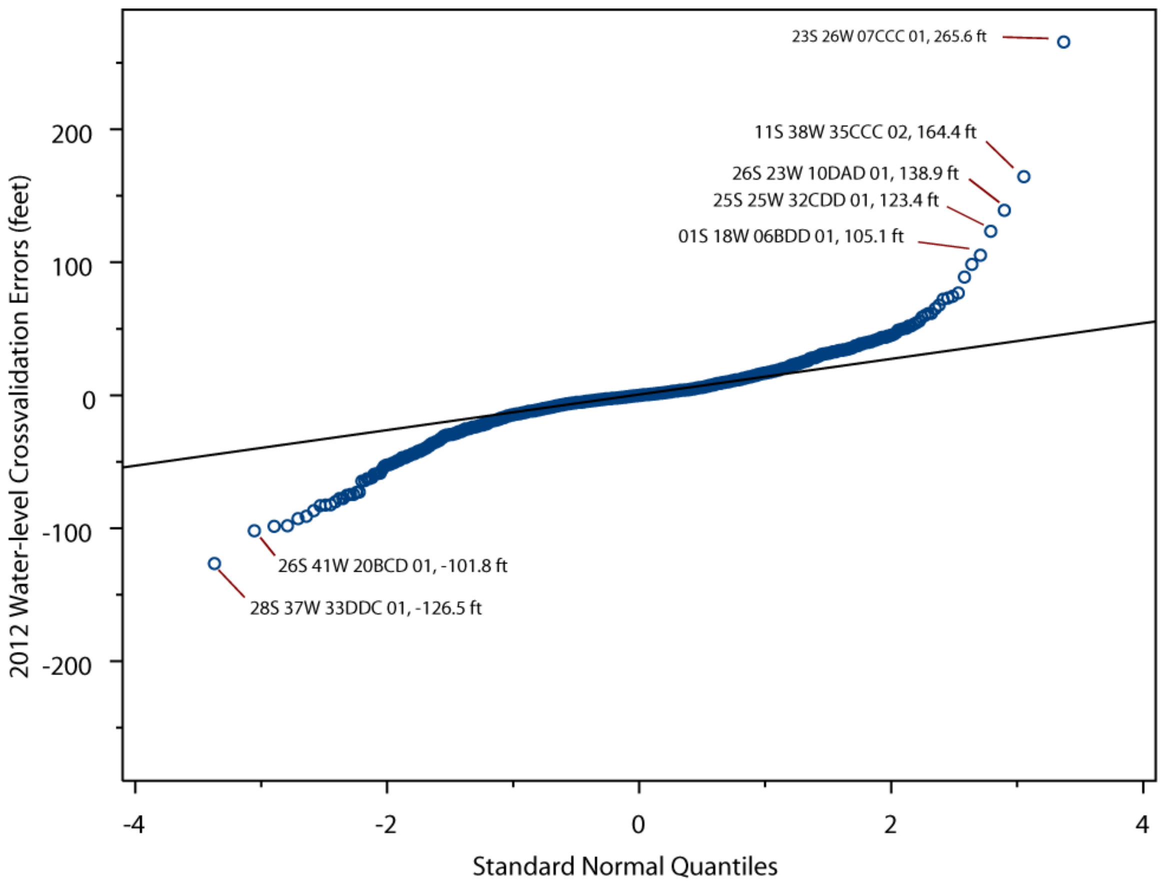

Figure 13: Normal QQ plot of kriging crossvalidation errors for 2012 water-table elevations.

Figure 13 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 13, and Table 2 contains additional information for these wells.

Table 2. Wells with kriging crossvalidation errors larger than 100 feet in magnitude.

KGS ID	USGS ID	2012, 2011 kriging residual (feet)	GeolUnits
23S 26W 07CCC 01	380335100132701	266, 251	KD
11S 38W 35CCC 02	390254101305402	164, 171	TO
26S 23W 10DAD 01	374725099485601	139, 109	KD
25S 25W 32CDD 01	374936100052801	123, 123	KD
01S 18W 06BDD 01	395944099234201	105, 95	QA
26S 41W 20BCD 01	374638101495001	-102, -110	QUTO
28S 37W 33DDC 01	373346101215801	-126, -137	QUTO

For comparison, the errors from the kriging crossvalidation analysis performed in 2011 are also included in Table 2. Note that these errors are quite similar to the 2012 errors and in fact 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 2012 water-table elevation was 2279 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 2544 feet at well 23S 26W 07CCC 01. The two other Dakota (KD) wells listed in Table 1 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 the relatively rugged landscape of 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. The measured water-table elevation in this QUTO well is 2915 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 2788 feet at well 28S 37W 33DDC 01, 126 feet below the measured water level. Well 28S 37W 33DDC 01 was constructed in the summer of 1994 and is not screened within the lower Cretaceous material.

Well 26S 41W 20BCD 01, in south-central Hamilton County, is a shallow QUTO well along the edge of the High Plains aquifer with a measured water-table elevation of 3254 feet in 2012. Its nearest neighboring well is a KJ well with a measured 2012 water level of 3109 feet. The next two nearest wells are a much deeper TO well and a QUTO well with measured levels of 3162 and 3143 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 3152 feet, due to the strong influence of the three nearest wells.

Well 01S 18W 06BDD 01, in northern Phillips County, close to the Nebraska state line and thus on the edge of the mapped region, is a well screened in Quaternary alluvium whose nearest neighboring wells (primarily to the south) are screened in the Ogallala.

6. Geostatistical Analysis of 5-Year Water-Level Declines

Figure 14 shows the omnidirectional semivariogram for the water-level changes over the 5-year period from 2007 to 2012, along with the fitted semivariogram model. The model is exponential in form, with a range of 129 km, nugget of 12.3 ft^2, and overall sill of 72.6 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. For comparison, the semivariogram for the 2006 to 2011 declines was also exponential in form, with a range of 115 km, nugget of 8.9 ft^2, and overall sill of 65.5 ft^2. Thus, the 2007-2012 declines exhibit a somewhat higher level of overall variation (sill) and short-scale variation (nugget) than the 2006-2011 declines.

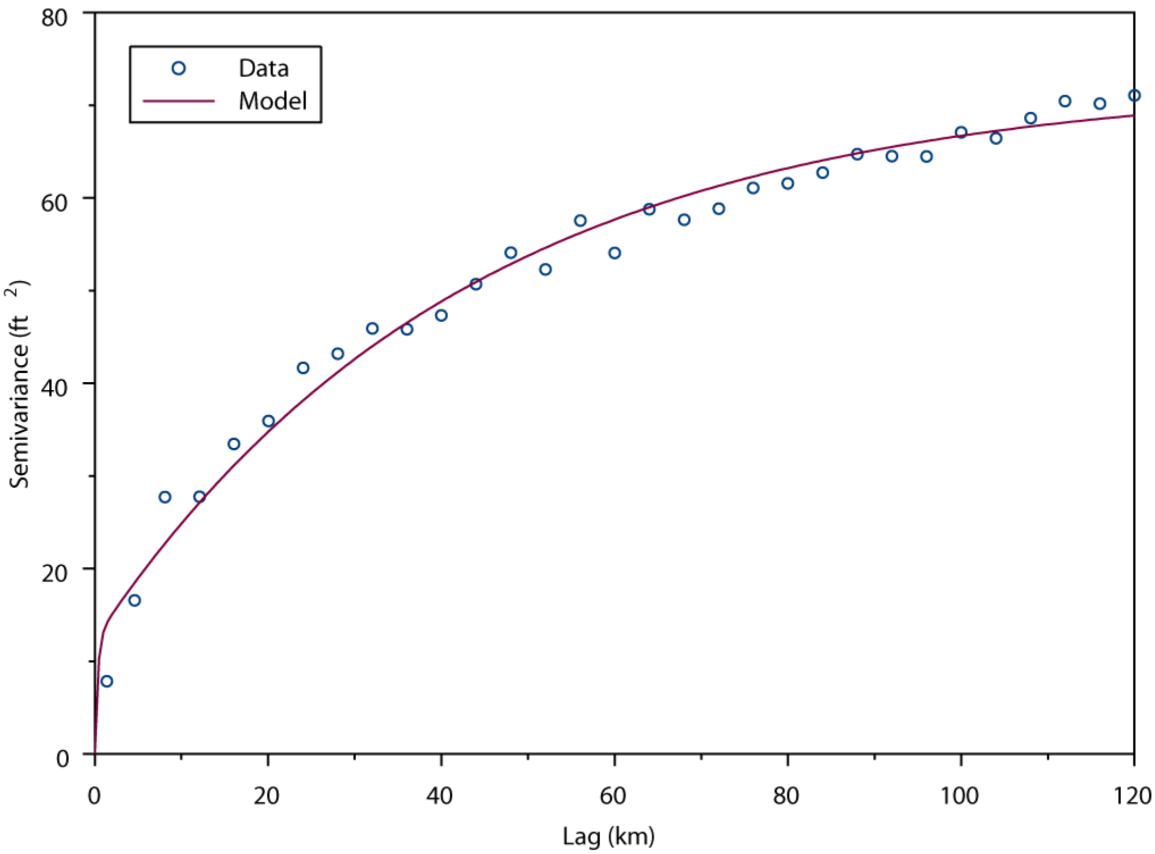

Figure 14. Omnidirectional semivariogram for changes in water level over the 5-year period from 2007 to 2012.

Figure 15 is a map of the kriged water-level declines between 2007 and 2012. The average interpolated decline within the extent of the High Plains aquifer region is 3.8 feet. 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. These two areas traditionally have the largest decline in the state with the declines from 2007 to 2012 reaching 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, increases in the water table can be seen in northwest Kansas in both the alluvial and Ogallala wells. Hydrograph investigations of the Thomas County Index Well indicate significant water inflows independent of previous season ground-water withdrawals and precipitation amounts (Butler et al., 2012). The determination of this inflow has yet to be fully understood but may help explain the water-level changes occurring here.

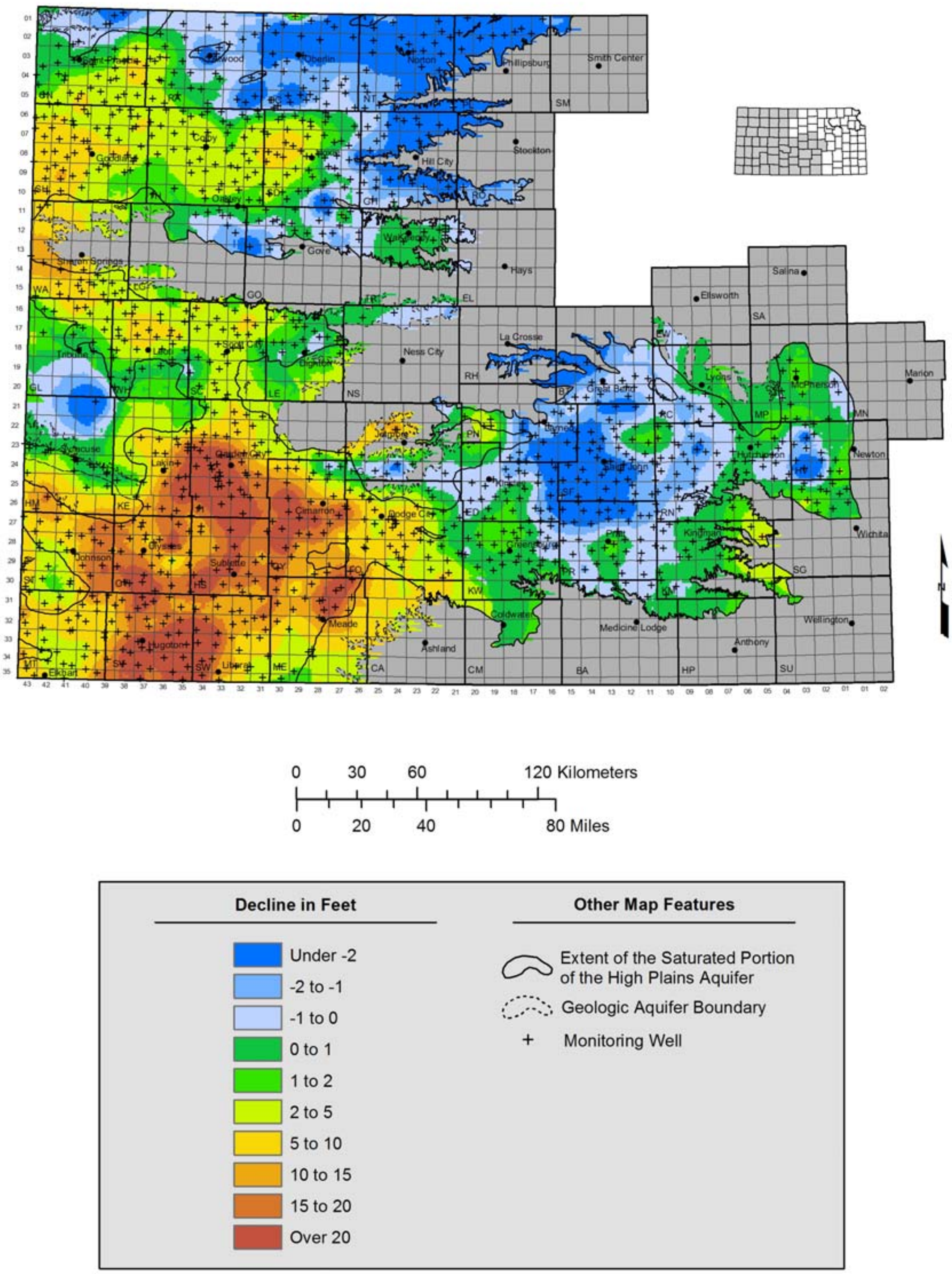

Figure 15. Kriged water-level declines for the 5-year period from 2007 to 2012.

Figure 16 shows the results of the kriging crossvalidation analysis for the water-level declines between 2007 and 2012. The correlation between the true and estimated declines is 0.79 and the root mean squared (rms) error is 5.6. feet.

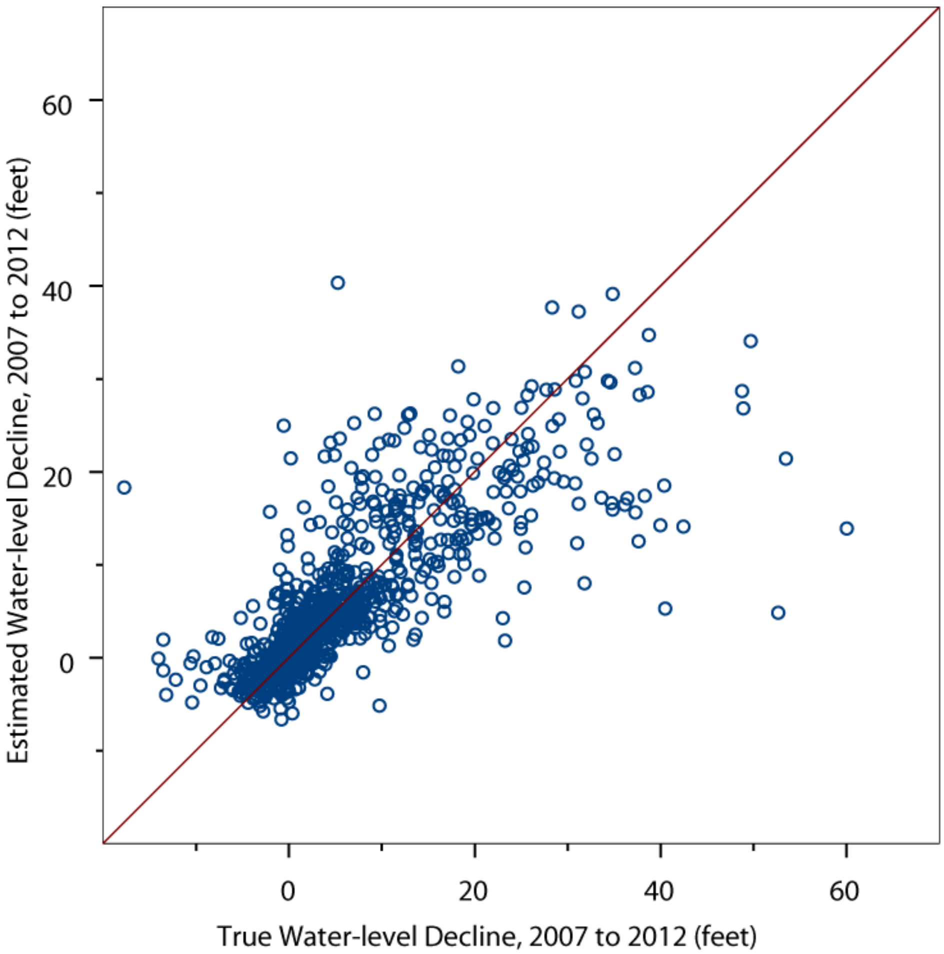

Figure 16. Kriging crossvalidation results for 5-year water-level changes.

Figure 17 is a normal QQ plot of the kriging crossvalidation errors (residuals) for the water-level declines between 2007 and 2012. 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).

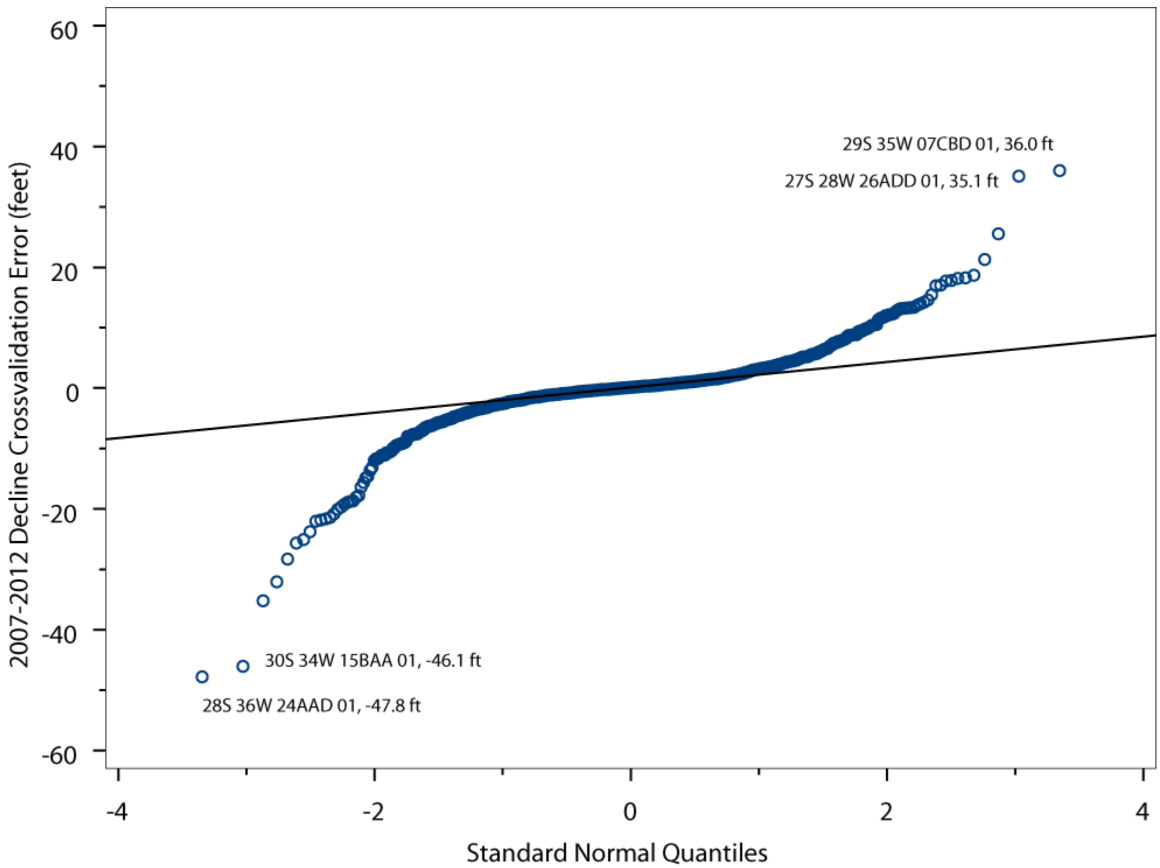

Figure 17. Normal QQ plot of kriging crossvalidation residuals for water-level declines between 2007 and 2012.

Four wells whose 5-year decline values are particularly out of keeping with those at surrounding wells are flagged in Figure 17. Well 29S 35W 07CBD 01 (USGS ID 373214101114301) is a QUTO well in east-central Grant County that exhibited a water-level increase of 17.7 feet (or a decline of -17.7 feet) between 2007 and 2012. This is the largest observed 5-year increase (Figure 8, and discussion in Section 4 of this report). The surrounding wells (primarily QUTO wells) show 5-year declines of a few feet to about 15 feet, except for the second nearest well (7100 meters away), which shows a decline of 52.7 feet. The interpolated 5-year decline value at the location of 29S 35W 07CBD 01 is 18.2 feet, resulting in a crossvalidation error of 36.0 feet.

Well 27S 28W 26ADD 01 (USGS ID 374022100203601) is a TO well in central Gray County with a 5-year decline of 5.2 feet. Its nearest neighboring well is a Dakota well a mere 3.7 meters away with a 5-year decline 40.5 feet. The next nearest well (a QUTO well with a 5-year decline of 5.4 feet) is 5600 meters away, so, in the crossvalidation analysis, the Dakota well decline value dominates the interpolated decline at the location of 27S 28W 26ADD 01, which turns out to be 40.3 feet. It would not be unreasonable to question whether this particular Dakota well should be included in the statistical analysis, because it is in such close proximity to an Ogallala well, unlike the other bedrock wells in "fringe" areas that essentially substitute for High Plains / Ogallala wells.

Well 30S 34W 15BAA 01 (USGS ID 372642101013501), a QUTO well in southwestern Haskell County with a 5-year decline of 60.0 feet, the largest observed 5-year decline (Figure 8 and discussion in Section 4 of this report). Its four nearest neighboring wells, with distances ranging between 3 and 6 miles, are QUTO wells with declines ranging from 13 to 15 feet. In the crossvalidation analysis, the interpolated 5-year decline value at the location of 30S 34W 15BAA 01 turns out to be 13.9 feet. However, 30S 34W 15BAA 01 is at the south end of a region of high declines extending northward through central Haskell County up into Finney County.

Well 28S 36W 24AAD 01, a QUTO well in east-central Grant County, with an observed 5-year decline of 52.7 feet (41.6 feet of that decline occurring between 2008 and 2009), happens to be the second nearest neighbor of 29S 35W 07CBD 01, the abandoned well with the 17.7 foot 5-year increase (and 29S 35W 07CBD 01 is also the second nearest neighbor of 28S 36W 24AAD 01). Thus, a well with one of the largest observed declines is quite close to the well showing the largest 5-year water-level increase. As mentioned in the discussion of 29S 35W 07CBD 01, other wells in the vicinity show 5-year declines of a few feet to about 15 feet, which, when combined with the -17.7 foot decline at 29S 35W 07CBD 01, results in an interpolated 5-year decline of 4.86 feet at the location of 28S 36W 24AAD 01 and a crossvalidation error of -47.8 feet.

7. Geostatistical Analysis of 2011 to 2012 Water-Level Declines

Figure 18 shows the omnidirectional semivariogram for the water-level changes from 2011 to 2012, along with the best-fit semivariogram model. The fitted model is exponential with a range of 70 km, a nugget of 3.4 ft^2, and an overall sill of 10.0 ft^2. The fitted model for the 2010-2011 declines was exponential with a range of 63 km, a nugget of 2.8 ft^2, and an overall sill of 6.4 ft^2.

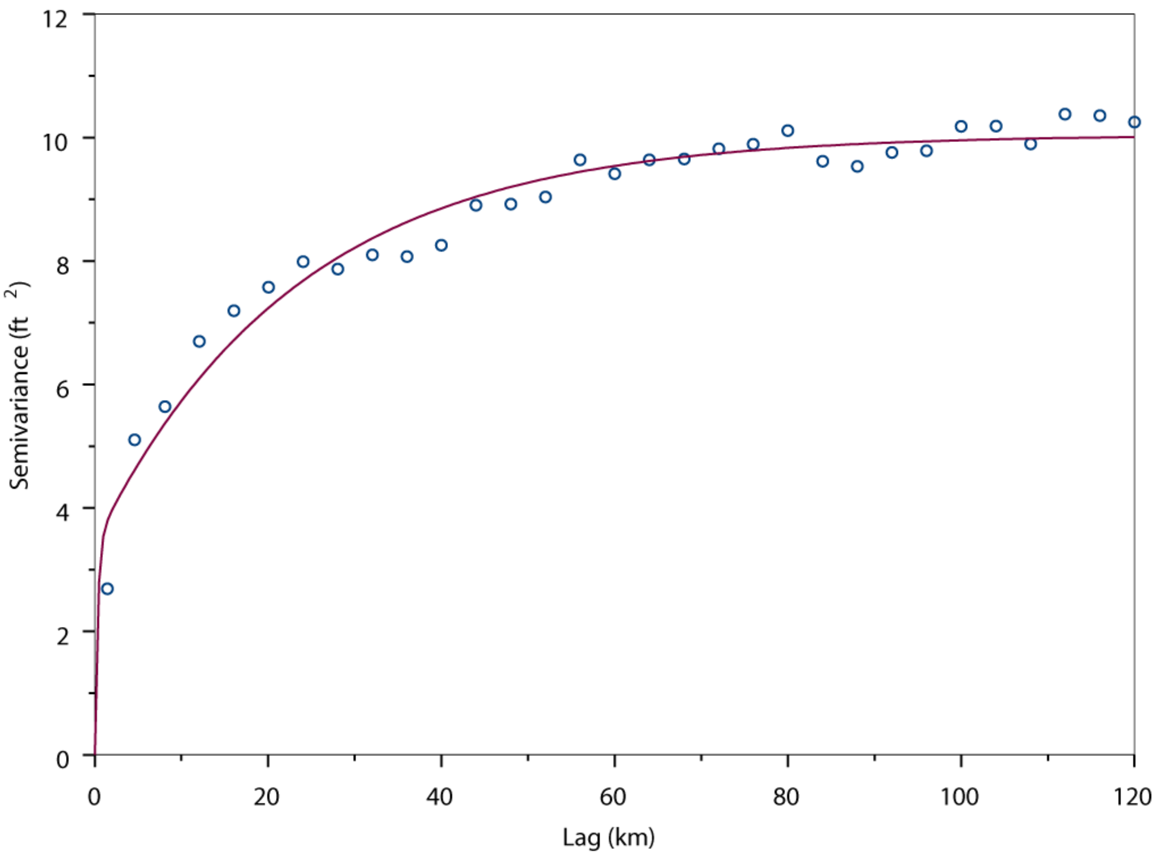

Figure 18. Omnidirectional semivariogram for changes in water level between 2011 and 2012 measurement campaigns.

Figure 19 is a map of the kriged water-level declines between 2011 and 2012. The average interpolated decline within the HPA extent is 2.0 feet, the highest estimated single-year decline since the State began administration of the cooperative water-level program. As such, most of the High Plains aquifer region saw ground-water declines over this period. The greatest declines were in the continued drought-stricken southwest Kansas, particularly in the area northwest of Liberal along the Stevens and Seward county line. Declines here were over 15 feet. Notable declines also occurred in a line from the sand hills south of the Arkansas River to Meade, KS, and along the Stanton/Grant county line, where declines of 5 to 10 feet were common.

South-central Kansas also saw declines almost exclusively across the area, with an average water-table drop of almost 3 feet. Between 2011 and 2012, the greatest declines in south-central Kansas occurred along the Stafford/Pratt county line and in northeast Reno and central Harvey counties. This is in stark contrast to the regional increase in the water-table elevations seen from 2007 to 2012, an indication the High Plains aquifer here should recover as precipitation levels return to more normal levels.

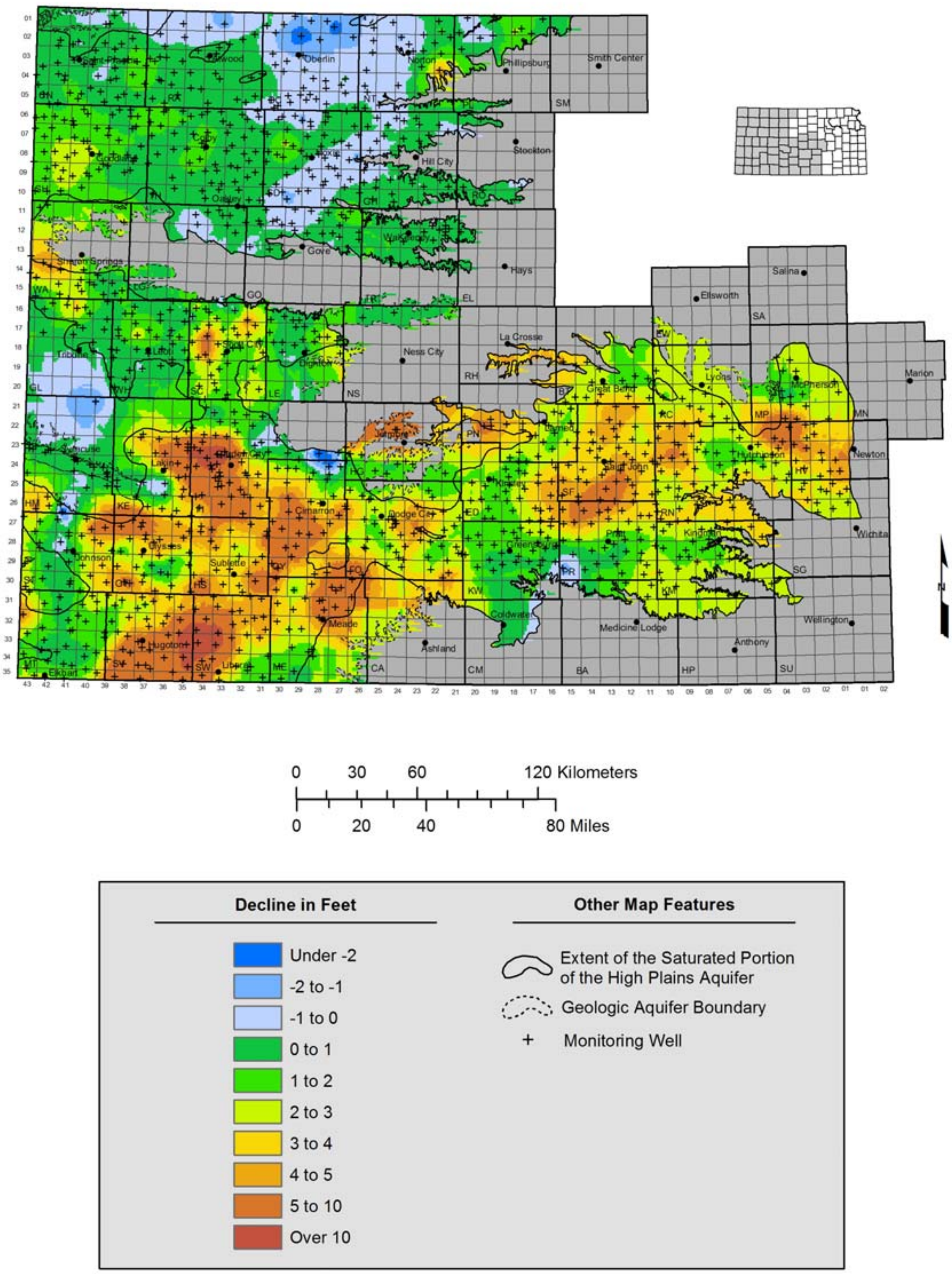

Figure 19. Kriged water-level declines for 1-year period from 2010 to 2011.

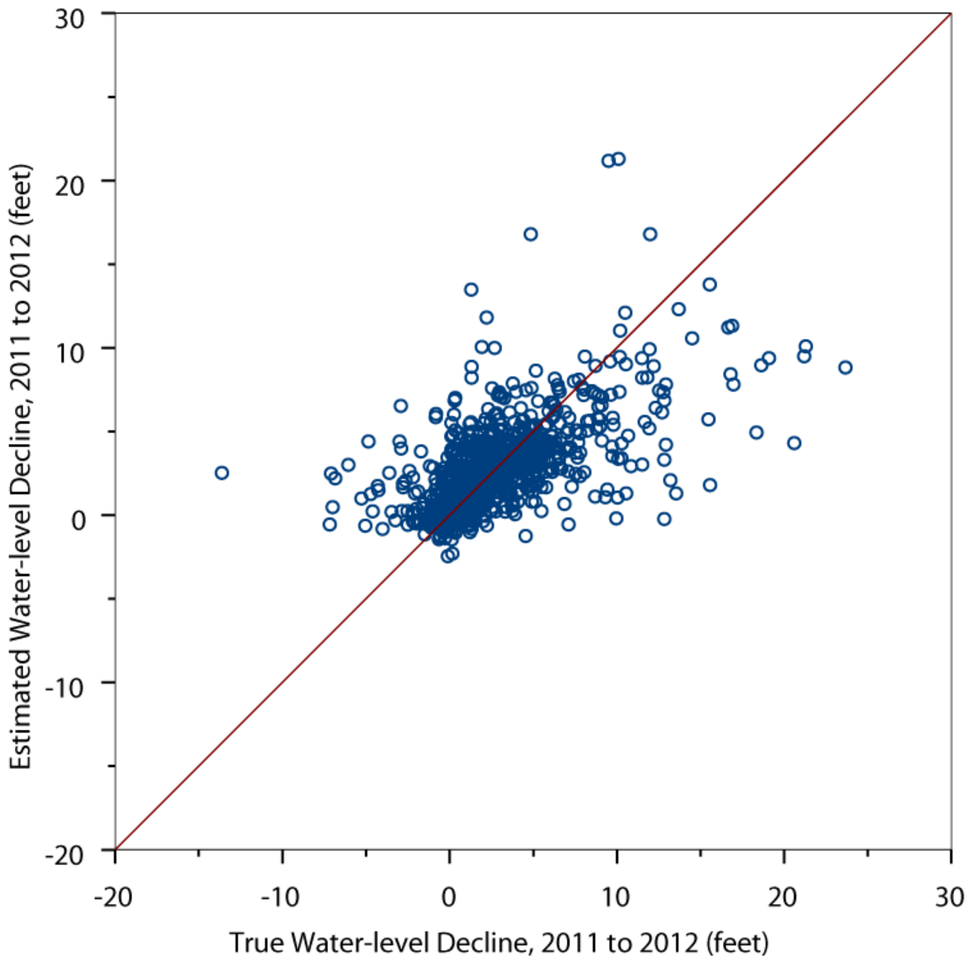

Figure 20. Kriging crossvalidation results for changes in water level between 2011 and 2012.

The kriging crossvalidation results for the 1-year declines, shown in Figure 20, 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 0.64 and the rms error is 2.6 feet.

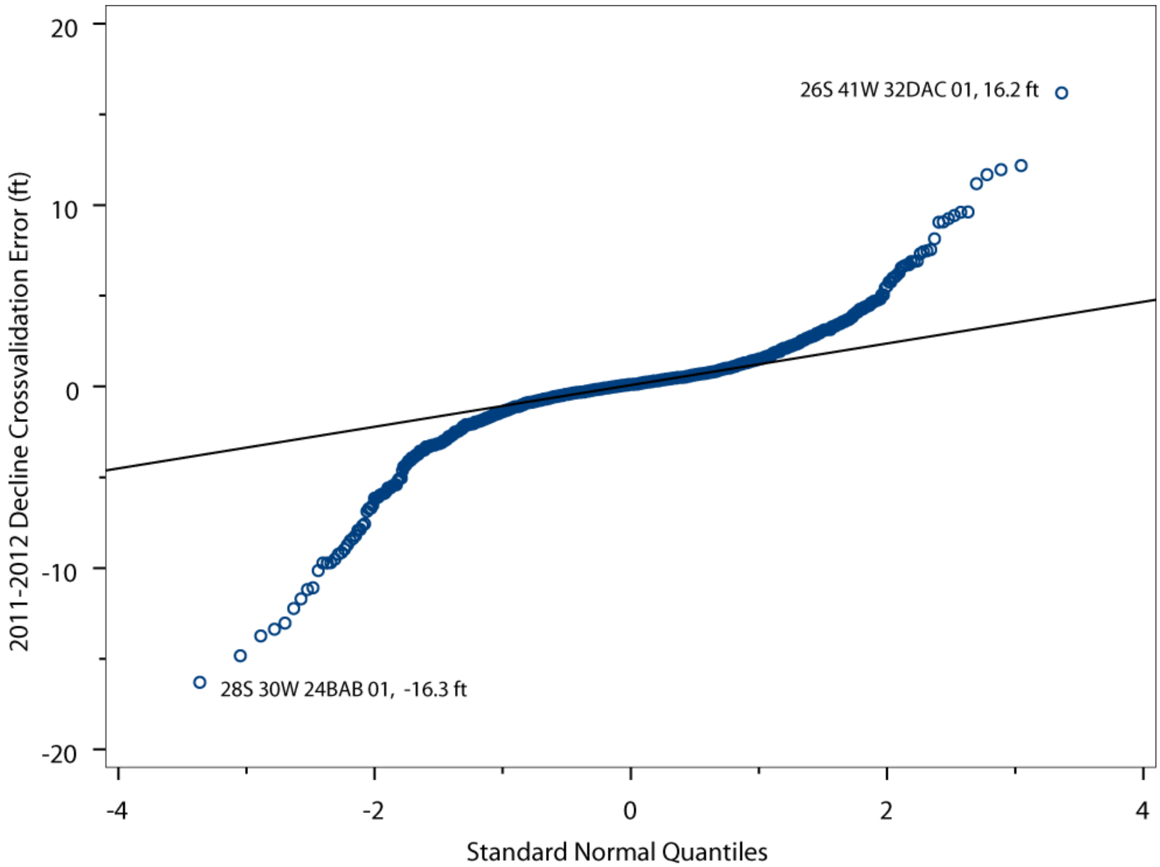

Figure 21. Normal QQ plot of kriging crossvalidation errors for 2011-2012 water-level declines.

Figure 21 is a normal QQ plot of the kriging crossvalidation errors for the 1-year declines, with the most extreme errors flagged. Well 26S 41W 32DAC 01 (USGS ID 374421101490902), a KJ well in southern Hamilton County, is the well with the largest 1-year increase (13.6 feet, or a decline of -13.6 feet, Figure 6). As noted in Section 4 of this report, this well is surrounded by Quaternary and Ogallala wells showing declines of a few feet, leading to an interpolated decline of 2.5 feet at the location of 26S 41W 32DAC 01 and a crossvalidation error of 16.2 feet. The water levels in well 28S 30W 24BAB 01 (USGS ID 373614100331601), a QUTO well in southwestern Gray County, have shown significant declines since about 2002. Its observed 2011-2012 decline is 20.6 feet. The surrounding wells, also primarily QUTO wells, showed 2011-2012 declines of a few to around 10 feet, leading to an interpolated decline of 4.3 feet at the location of 28S 30W 24BAB 01 and thus a crossvalidation error of -16.3 feet.

8. Analysis of Variance

Here we present 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 1-year declines. Because the declines themselves exhibit spatial correlation that could contribute variation that might be incorrectly attributed to one or more exogenous variables, we base the analysis of variance on the kriging residuals for the 1-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 residuals (errors) for the 2011 to 2012 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 (categories listed on page 4). 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.

Table 3. Analysis of variance of kriging crossvalidation errors for 2011 to 2012 declines.

Source	Df	Sum of Sq	Mean Sq	F Value	Pr(F)
Measurer	21	85.85	4.09	0.67	0.86
Downhole.Access	1	1.25	1.25	0.20	0.65
Weighted.Tape	1	46.09	46.09	7.52	0.0062
Well.Use	3	41.98	13.99	2.28	0.078
Oil.On.Water	1	1.21	1.21	0.20	0.66
Chalk.Cut.Quality	2	76.94	38.47	6.28	0.0020
Aq.Group5	4	58.37	14.59	2.38	0.050
Residuals	970	5945.46	6.13		

Residual standard error: 2.48 feet

Factors with potentially significant effects are those associated with small values of Pr(F) (probability of obtaining observed F statistic by chance). Two variables associated with the process of making a measurement, use of a weighted tape and chalk cut quality, appear to be potentially significant. An analysis of variance for weighted tape alone deems this factor to be highly significant (Pr(F) = 0.0007). There is some evidence that use of an unweighted tape results in an overestimate of depth to water and thus an overestimate of the 2011-2012 decline (assuming the 2011 measurement is accurate). However, it is difficult to assess the true impact of this factor because the “experiment” is extremely unbalanced: Only 178 measurements used in the analysis involved unweighted tape, as opposed to 1086 measurements using weighted tape.

An analysis of variance for chalk-cut quality alone indicates marginal significance for this factor (Pr(F) = 0.1, or a 10% chance of getting the observed effect by chance). The “experiment” for this effect is also extremely unbalanced, with only 26 measurements with a chalk-cut quality of “Fair”, compared to 269 “Good” and 969 “Excellent”. Again, there is some evidence that the measurements with fair chalk-cut quality are associated with overestimates of depth to water in 2012. However, they also appear to be associated with underestimates, rather than overestimates, of the 2011-2012 declines, so the connection is not as clear as for the use of weighted tape. Nevertheless, this factor is beyond human control.

An analysis of variance for aquifer group alone does not deem this factor to have a significant effect on the 2011-2012 decline residual values. Nevertheless, because the multivariate analysis of variance deems it just significant at the 5% level and because it is a factor of some interest, we present boxplots of the crossvalidation residuals (errors) by aquifer group in Figure 22. One conclusion that might be drawn from this plot is that the bedrock-only (KK) wells tend to exhibit more negative crossvalidation errors than wells in the other groups. This means that the KK wells tend to have higher declines than expected based on declines observed at nearby wells. (The KK wells also tend to have higher actual decline values than the other groups, but this is due at least in part to the fact that they are concentrated in the southwest portion of the state, where declines are generally high. As mentioned earlier, we examine the decline crossvalidation errors here in an attempt to factor out the “confounding” influence of the overall spatial variation in the decline values themselves.)

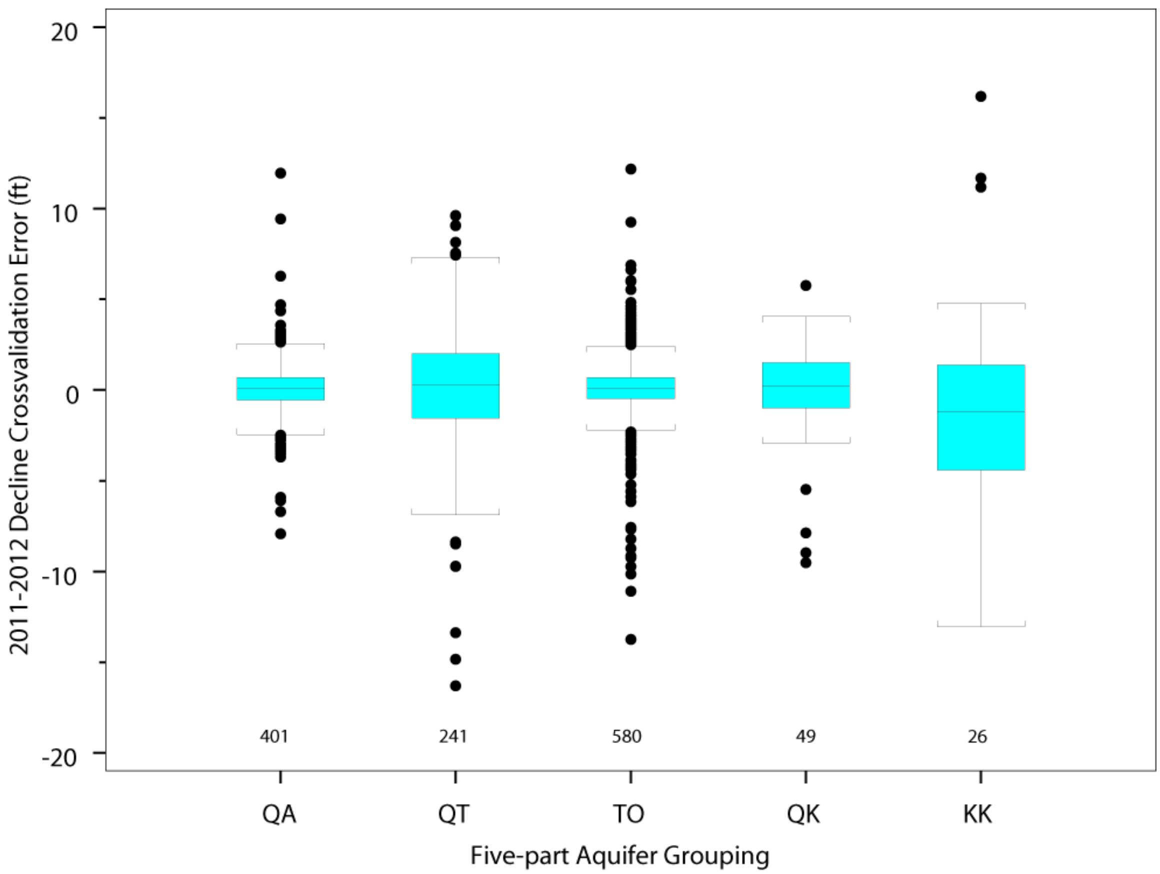

Figure 22. 2011 to 2012 water-level decline crossvalidation errors by five-part aquifer grouping (see page 4). Numbers above aquifer group labels represent number of wells in each group with 1-year decline values. Lower and upper box limits are 25th and 75th percentiles, line in box is median, whiskers extend to most extreme points within 1.5 times the interquartile range (75th percentile minus 25th percentile) beyond box limits, and more extreme points are plotted individually.

9. Decline Statistics by Groundwater Management District

Tables 4 and 5 provide summary statistics for the 1- and 5-year declines separated out by Groundwater Management District and Figures 23 and 24 show the distributions of the decline values by GMD.

Table 4. Summary statistics for 2011 to 2012 water-level declines, in feet, by Groundwater Management District. Column order of districts is north to south in the western portion of the state and then eastward in the southern portion of the state.

	GMD 4	GMD 1	GMD 3	GMD 5	GMD 2
Minimum:	-4.60	-4.85	-13.63	-5.28	-2.91
1st Quartile:	-0.03	0.25	1.18	1.67	1.63
Mean:	0.57	1.58	4.05	2.96	3.12
Median:	0.40	0.76	2.96	2.68	2.50
3rd Quartile:	1.12	2.18	6.05	4.10	4.42
Maximum:	5.48	15.57	23.68	9.72	11.67
Std. Dev.:	1.22	2.70	4.58	1.86	2.73
Count:	284	124	395	215	64

Table 5. Summary statistics for 2007 to 2012 water-level declines, in feet, by Groundwater Management District. Column order of districts is north to south in the western portion of the state and then eastward in the southern portion of the state.

	GMD 4	GMD 1	GMD 3	GMD 5	GMD 2
Minimum:	-10.61	-4.53	-17.70	-7.02	-14.04
1st Quartile:	0.21	1.00	4.29	-2.36	-0.51
Mean:	2.32	3.63	13.24	-1.02	0.11
Median:	1.99	2.76	10.92	-1.07	0.47
3rd Quartile:	4.11	5.32	19.61	0.32	1.27
Maximum:	15.32	18.89	60.01	6.53	4.51
Std. Dev.:	3.35	4.03	11.74	2.04	2.99
Count:	269	109	367	210	61

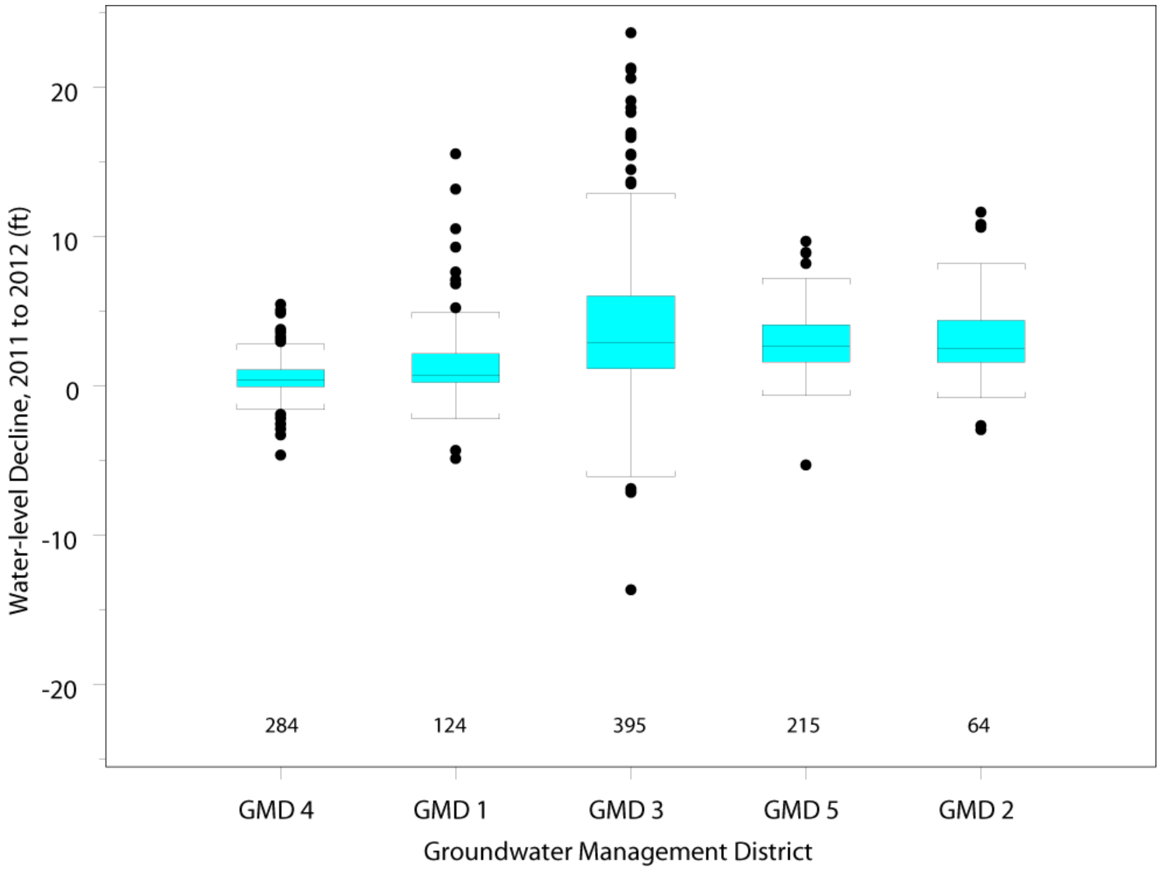

Figure 23. 2011 to 2012 water-level declines by Groundwater Management District. Numbers above GMD labels represent number of wells in each district with 1-year decline values. See Figure 22 for boxplot conventions. Districts are ordered north to south in the western portion of the state and then eastward in the southern portion of the state.

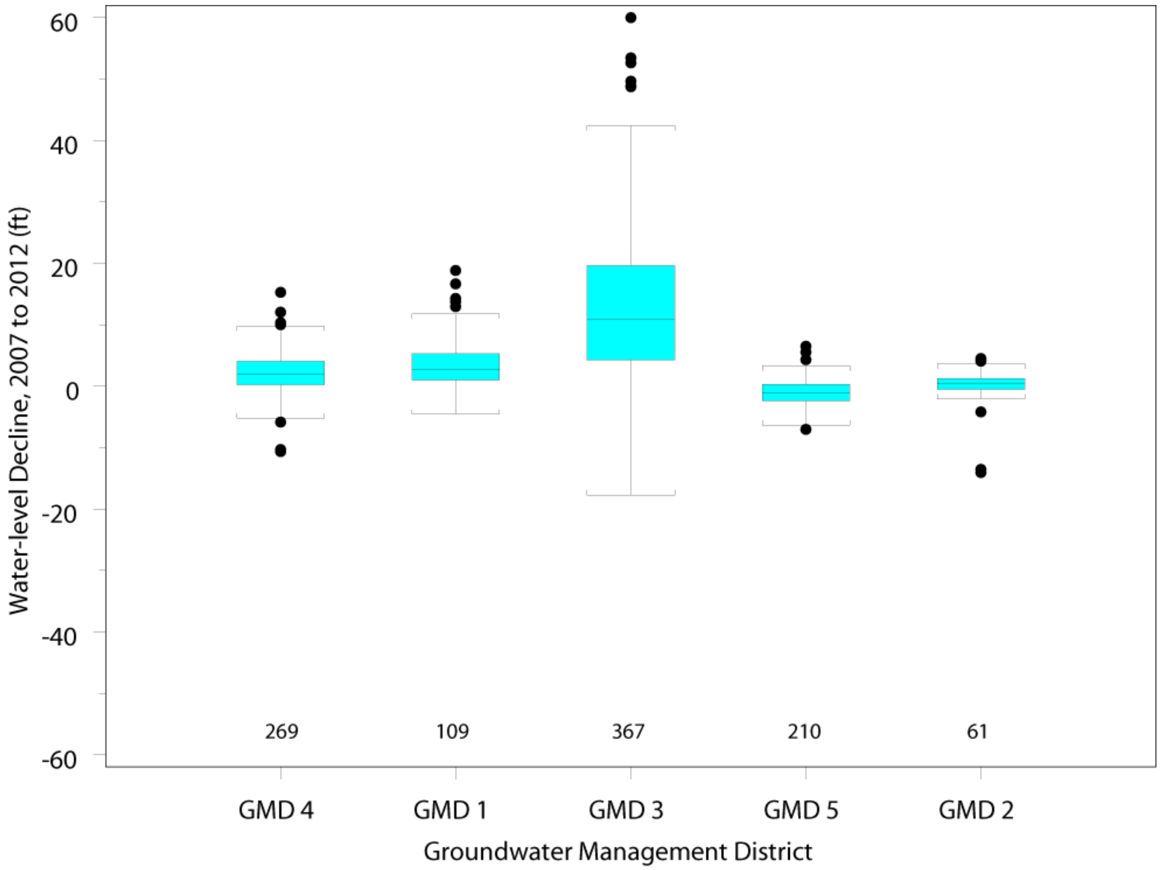

Figure 24. 2007 to 2012 water-level declines by Groundwater Management District. Numbers above GMD labels represent number of wells in each district with 5-year decline values. Districts are ordered north to south in the western portion of the state and then eastward in the southern portion of the state.

10. Identification of Network Holes

The kriging error (standard deviation) map for the 2012 water-table elevations (Figure 11) 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.

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 25 shows the 35 potential network hole centers that were identified based on the 2012 measurement campaign.

For each hole center, a list of well candidates is selected from the Master Well Inventory (MWI). The MWI is a central repository that imports and links together the State's three primary ground-water well data sets—KDHE's Water Well Completion Records, KDA-DWR's Water Rights Information Management and Analysis System, and the KGS' Water Information Storage and Retrieval Database. 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.

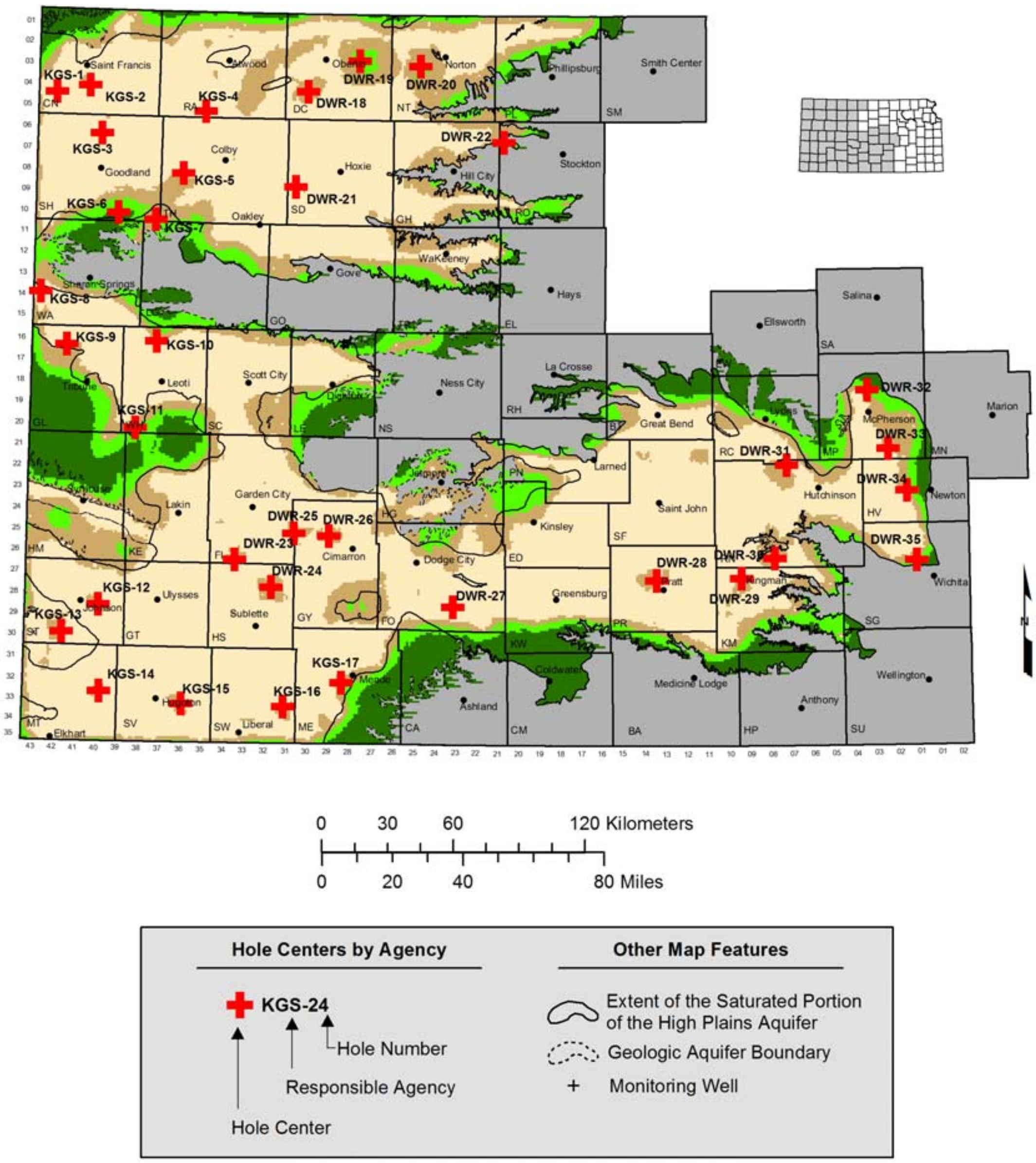

Figure 25. Network holes from the 2012 measurement campaign.

11. Concluding Remarks

The purpose of this report is to present statistical and geostatistical analyses of water-level measurements taken over the winter months of 2012. We also present an overview of water-level changes occurring primarily in the High Plains aquifer, the region's primary water source.

The drought conditions of 2011 are readily apparent in the declines from 2011 to 2012, both in the increase in average decline values compared to the 2010 to 2011 declines and in the spatial pattern of declines. The map of 5-year water level changes between 2007 and 2012 shows increases in water levels or moderate declines in the Great Bend Prairie and Equus Beds aquifers, reflecting timely growing season precipitation (if not flooding conditions) in 2008, 2009, and 2010. In contrast, declines prevailed throughout the High Plains region in 2011. At the time of this report (summer 2012), all 105 counties in Kansas were placed into some category of drought and all but two Ogallala counties of the western third of Kansas were in a "Drought Emergency" classifications while the rest of the High Plains aquifer region in "Drought Warning" stages. If these conditions continue, the significant water-level declines seen from 2011 to 2012 will likely continue going into 2013.

References

Bohling, G. C., and B. B. Wilson, 2004, Statistical and geostatistical analysis of the Kansas High Plains water table elevations, 2004 measurement campaign: Kansas Geological Survey, Open-file Report 2004-57.

Bohling, G. C., and B. B. Wilson, 2005, Statistical and geostatistical analysis of the Kansas High Plains water table elevations, 2005 measurement campaign: Kansas Geological Survey, Open-file Report 2005-6.

Bohling, G. C., and B. B. Wilson, 2006, Statistical and geostatistical analysis of the Kansas High Plains water table elevations, 2006 measurement campaign: Kansas Geological Survey, Open-file Report 2006-20.

Bohling, G. C., and B. B. Wilson, 2007, Statistical and geostatistical analysis of the Kansas High Plains water table elevations, 2007 measurement campaign: Kansas Geological Survey, Open-file Report 2007-32.

Butler, J. J, Jr., R. L. Stotler, D. O. Whittemore, E. Reboulet, G. C. Bohling, and B. B. Wilson, 2012, High Plains Aquifer Calibration Monitoring Well Program: Fifth Year Progress Report: Kansas Geological Survey, Open-file Report 2012-2.

Goovaerts, P., 1997, *Geostatistics for Natural Resources Evaluation*: Oxford University Press, New York, 483 p.

Isaaks, E. H., and R. M. Srivastava, 1989, *An Introduction to Applied Geostatistics*: Oxford University Press, New York, 561 p.

Olea, R. A., and J. C. Davis, 2003, Geostatistical analysis and mapping of water-table elevations in the High Plains aquifer of Kansas after the 2003 monitoring season: Kansas Geological Survey, Open-file Report 2003-13, 22 p, 11 plates.

Olea, R. A., 1984, Sampling design optimization for spatial functions: Mathematical Geology, v. 16, no. 4, p. 369-392.

Appendix A: Network Hole Centers

COUNTY	AGENCY	HOLE NUMBER	UTM X	UTM Y
Cheyenne	KGS	1	246552.3537	4394225.9032
Cheyenne	KGS	2	261765.9258	4397083.4089
Sherman	KGS	3	267189.8949	4375175.8651
Rawlins	KGS	4	314550.4063	4385097.7599
Thomas	KGS	5	304231.6357	4356787.2866
Sherman	KGS	6	274489.5563	4338898.7751
Sherman	KGS	7	291528.7570	4335723.7687
Wallace	KGS	8	239101.4646	4303047.6617
Greeley	KGS	9	250928.3633	4278838.2383
Wichita	KGS	10	291966.6433	4280122.5725
Wichita	KGS	11	282011.6755	4240605.8702
Stanton	KGS	12	265144.7821	4159983.6419
Stanton	KGS	13	248167.5189	4147625.5887
Morton	KGS	14	265311.2303	4120472.6698
Stevens	KGS	15	302698.2530	4114523.5017
Seward	KGS	16	349332.4816	4112990.2382
Meade	KGS	17	376002.5350	4123785.2598
Decatur	DWR	18	361276.4470	4393909.6881
Decatur	DWR	19	384880.6093	4407887.5719
Norton	DWR	20	412377.7245	4405441.7643
Sheridan	DWR	21	355547.6758	4350397.5864
Rooks	DWR	22	450418.4231	4370437.3926
Finney	DWR	23	327460.5684	4180196.9646
Haskell	DWR	24	343902.7798	4167632.3180
Gray	DWR	25	354509.8587	4192248.7596
Gray	DWR	26	370345.2028	4190912.6111
Ford	DWR	27	427027.5329	4158366.3706
Pratt	DWR	28	520002.3022	4170404.9363
Kingman	DWR	29	558915.3123	4171374.0189
Reno	DWR	30	574036.9415	4180730.3216
Reno	DWR	31	579239.3217	4223266.5872
McPherson	DWR	32	616085.9318	4257763.9132
McPherson	DWR	33	625769.7012	4231093.8598
Harvey	DWR	34	634209.9264	4211946.8076
Sedgwick	DWR	35	638850.0659	4180170.2858