Ogallala Aquifer Technical Support Study by the Kansas Geological Survey for the Kansas Water Plan – Summary of FY 2007 Activities

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Kansas Geological Survey staff participating in the studies in alphabetical order:
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Assistance to All Groundwater Management Districts for Use in Subunit Development

Development of ArcReader Map Collection

The Kansas Geological Survey (KGS) developed customized map layers for water levels, water rights, water use, aquifer extents, and other spatial data in the form of an ArcReader file for use by the groundwater management districts in subunit development as well as in other management activities. The initial motivation for this work was for Groundwater Management District No. 1 (GMD1) because it allows the GMD1 to easily examine data layers in maps without having the full ESRI ArcGIS software suite and someone proficient in the software. The ArcReader file was also developed for Groundwater Management Districts No. 3 (GMD3) and No. 4 (GMD4). ArcReader is a free, easy-to-use desktop mapping application that allows users to view, explore, and print "published" map collections. Links were included for the monitoring well and water-right map layers to allow real-time inquiry of database information from the KGS websites by clicking on the features within each layer. The ArcReader map collection also contains multiple years of aerial photographs and 24K scale topographic maps. An example of a computer screen image of ArcReader for an area within GMD1 is shown in Figure 1. The KGS spent an afternoon at the GMD1 office introducing the capabilities and functions on the software.

Assistance to GMD1 for Use in Subunit Development

Overview of Municipal Ground-Water Resources

The KGS assisted GMD1 with a review of the water rights and water levels within a five mile radius of the points of diversions for selected municipal water-right holders within the district. This review included establishing trends in saturated thickness, reported water use, and the distribution and measurement history of monitoring wells. A report (Appendix A) described the available data and data needs, included maps of each area showing the municipal water rights, and addressed issues relevant to water supplies and their sustainability – saturated thickness, rate of water-level change, water use density, data problems, enhancement opportunities.

Assistance to GMD3 for Use in Subunit Development

Analysis of water appropriations within two-mile circles around wells

The KGS worked with the Groundwater Management District No. 3 (GMD3) manager in the development of an approach to budget and prioritize water-right development with the

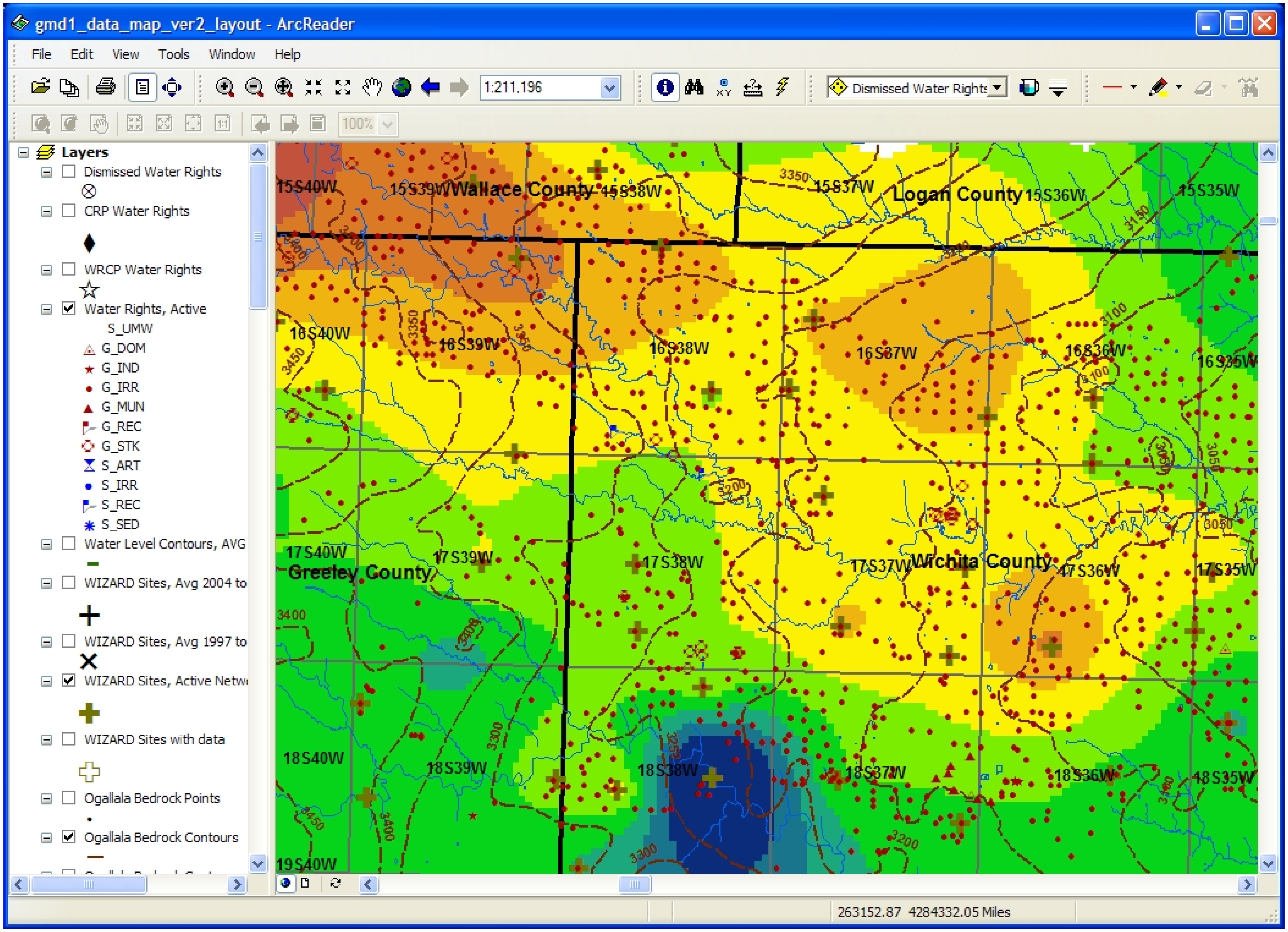


Figure 1. Example of a computer screen image for an area of west-central Kansas from the ArcReader map collection developed for GMD1. The checked boxes on the left of the image show the active map layers. The colored shading is for contours of water-use density (displayed farther down in the list of map layers so that it is not visible in the image displayed).

District. After several iterations, the process currently centers on matching ground-water extraction with some target volume while sharing any reductions across all water rights but still recognizing the priority dates of those rights. This review process is a moving analysis in that it is focused on the two-mile area around every water right/ground-water well combination. To facilitate these intensive computations, the KGS developed a customized ArcGIS-based program. The KGS met with the Research and Development Committee of GMD3 in Topeka to present the results of the project to date. The approach is still in the developmental phases and is being reviewed by GMD3 for possible future modifications and adaptations.

Assistance to GMD4 for Use in Subunit Development

Cross-validation analysis of water level measurement reliability in priority areas

The KGS used geostatistical methods to determine and examine the uncertainties in the water-level surface from the annual water-level measurements in priority areas of Groundwater Management District No. 4 (GMD4). The analysis resulted in figures for 1) contoured average residuals (difference between modeled and measured water levels) for GMD4, 2) contoured average residuals after removal of the outliers (greater than one standard deviation from the mean), 3) a plot of cross-validation of the dataset with the outlier values removed, and 4) a contour plot of residuals obtained by a spline fit technique (Appendix B). The KGS provided a description of the methods and results along with the figures. The results indicated that a specific area-by-area review of the well logs and well construction would be valuable to determine whether the high statistical residuals for some wells can be explained by aquifer and well characteristics. The results also suggest that a trial program of measuring additional wells, and of periodic measurements between the first of the year and the onset of large-scale pumping would be valuable for reducing uncertainties within a range acceptable for GMD4 management needs in priority areas. Cross-validation tests of these data can help pinpoint the steps needed to for such a measurement program.

Assessment of quick response area in Thomas County, GMD4

During FY 2006, the KGS worked with GMD4, the Kansas Water Office, and the Division of Water Resources on an assessment of a proposed subunit area of the Ogallala/High Plains aquifer in south-central Thomas County. This was one of the "Quick Response" areas proposed by the GMDs, the DWR, and the KWO as a priority area related to Ogallala subunit identification. The assessment included an examination of ground-water levels, water use, hydrogeologic characteristics, and climate data, and determination of an approximate water budget. The results were used during FY 2007 in selecting an appropriate location for the index/calibration monitoring well within the Quick Response area in GMD4.

Assistance for Proposed CREP in Upper Arkansas Basin

The KGS prepared presentations and printed handouts, gave testimony, and was available for questions at the briefings and hearings related to the legislation being develop on the proposed Kansas Conservation Reserve Enhancement Program (CREP) during the 2007 session of the Kansas Legislature (House Agriculture and Natural Resources Committee and Senate

Natural Resources Committee). The subject of the presentations and printed documents was hydrologic responses to pumping in the Upper Arkansas basin and effects of the Kansas CREP. The presentations were combined into one document and placed as a pdf file on the web site for High Plains/Ogallala aquifer information at the end of a section entitled "WRAPS and CREP Education (http://www.kgs.ku.edu/HighPlains/wraps_crep/index.shtml)

Volunteer Water-Level Entry Web Page

During FY 2006, the KGS met with the groundwater management districts (GMDs), the Division of Water Resources (DWR), and the KWO to discuss a new web page for entry of volunteered water-level data. The web page allows depth to ground water measurements to be added into the WIZARD oracle database, KGS' water-level repository, by outside agencies and the participating public. During the developmental phase, the site is password protected with the understanding that the primary use of the site will occur through the western GMDs in support of aquifer subunit delineation efforts. The URL for the volunteer web site is http://hercules.kgs.ku.edu/geohydro/wizard/vol_start.cfm. During the testing phase of the volunteer water-level web page in FY 2007, no volunteer depth-to-water measurements were entered by outside agencies. Only one comment was received and the website was adjusted accordingly. In FY2008, the KGS believes that further outside testing of the site will be valuable for achieving an eventual goal of linking the site to the main public WIZARD website. The implementation of the volunteer water-level program would be especially useful in the areas of the index/calibration monitoring wells to establish a set of local observations for comparisons and calibration tests.

Investigations Enhancing Index/Calibration Well Project

The KGS is conducting studies additional to the work in the Index/Calibration Well project for the Ogallala – High Plains aquifer in western Kansas. These enhancements include generating lithologic cross sections in the area of the index/calibration well sites (cross sections have been started for the Haskell County site). Other enhancements involve more detailed characterization of the lithology of the aquifer sediments through additional geophysical logs and sampling and analysis of subsurface sediments at the well site in GMD3 in northeast Haskell County. The sediment characterization will be used to "calibrate" the lithology recorded by drillers in WWC-5 forms to better interpret the information in these forms for the Ogallala – High Plains aquifer. Chemical analyses of the sediments will be applied to improving an understanding of the chronological succession of sediments and the depositional processes leading to the succession.

High Plains/Ogallala Aquifer Information Web Pages

The Kansas Geological Survey (KGS) revised and updated the web pages containing information on the Ogallala-High Plains aquifer. Sections added to the web site include Numerical Model of the Middle Arkansas River Subbasin and activities related to WRAPS and CREP Education. We conducted this effort in conjunction with continued development and integration of the HIPLAIN web site into the KGS web site. The online data and analysis are available through the web site http://www.kgs.ku.edu/HighPlains/ of the KGS.

General Assistance

The KGS provided general assistance to the GMDs on the hydrogeologic characteristics and water use of the Ogallala - High Plains aquifer for use in subunit development and other management approaches. For example, the KGS provided updated reported water-use density values based on the latest water-use data, by section, to GMD4.

The KGS matched or inserted new well records in the WIZARD database to coincide with water-level monitoring records from all the sub-programs of the Kansas Department of Agriculture, Division of Water Resources. These include the Subbasin Management Program wells in the Upper Arkansas Basin in GMD3 and the Ogallala fringe wells primarily around GMD4. With the well matching complete, database routines were developed that allow seamless data uploads to occur throughout the year to WIZARD which in turn provides expanding measurement coverage across the aquifer.

Appendix A

GMD1 Municipal Water Supplies: An Informal Overview

D. P. Young, B. B. Wilson, and R. W. Buddemeier

This summary data compilation is provided to review the information available "off the shelf" at KGS. Additional detail can be developed by further focused analysis and by additional data assembly (for example, by addition of records from the city water departments). This initial description is intended to support the Manager and Board in decisions about priorities and actions with regard to water supply protection and management.

Maps of each area containing the municipal water rights are shown, and brief summary pages address the following issues relevant to water supplies and their sustainability.

Saturated thickness (ST): Average 2004-2006 saturated thickness (ft). Saturated thickness is a first-cut indicator of water in storage, although assessment of the practical saturated thickness (relative yield) and/or specific yield is needed to refine this information.

Rate of water table (WT) elevation change: Change in water table elevation from 1996 to 2006 (ft). The average annual change in ft can be computed by dividing the number by 10. Negative numbers indicate water-level declines and positive numbers indicate water-level increases.

Density of use (pumping): 1996 to 2004 water use averaged over a 5-mile block, in acre-feet per square mile (AF/sq mi). This density of use indicates how much water is being pumped from the aquifer in the vicinity of the municipal wells, or in the upgradient area.

Data needs or problems: The annual monitoring network is known to provide regional data of lower resolution (in terms of both time and location) than is desirable for local supply studies. Additional problems arise because many of the GMD1 municipal supplies are close to the edge of the aquifer, and therefore are at or beyond the limits of good water level interpolations.

Enhancement opportunities: In addition to the rather standard opportunities (pooling data from various sources, adding more well measurements in the area of interest), there is the potential for installing a few dedicated continuous-measurement monitoring (index) wells – at least one per Ogallala GMD. The quantity and quality of additional information obtainable from such an installation depends on the hydrologic setting and the specific site.

In addition to these water quantity considerations, water quality (present and possible future) needs to be taken into account, especially in situations where new or relocated wells might be part of the overall plan. This assessment is best done cooperatively on a location-by-location basis, with consideration of both hydrologic conditions (e.g., depth to water, permeability) and possible sources of contaminants (natural ground-water constituents; municipal, industrial, or animal facility waste; petroleum or chemical storage; fertilizer and biocide use, etc.).

The following ten pages (Figures A1-A10) are two-page overviews for each of the county seats in the five counties within GMD1: Sharon Springs, Tribune, Leoti, Scott City and Dighton. On the first page of the overview for each county seat, conditions are summarized and a map shows the locations of water rights within the zone of interest for each municipality. Additional maps of saturated thickness, water-table change and density of use are shown on the second page of each overview.

Discussion and Summary

None of the cities in or near the District appear to be in a completely comfortable situation with regard to long-term water supply. The recent decline rates and estimated supplies suggest problems within time scales ranging from a very few to many decades. However, these are large-scale approximations and need to be supplemented by more detailed local consideration of the geology, hydrology, and pumping experience.

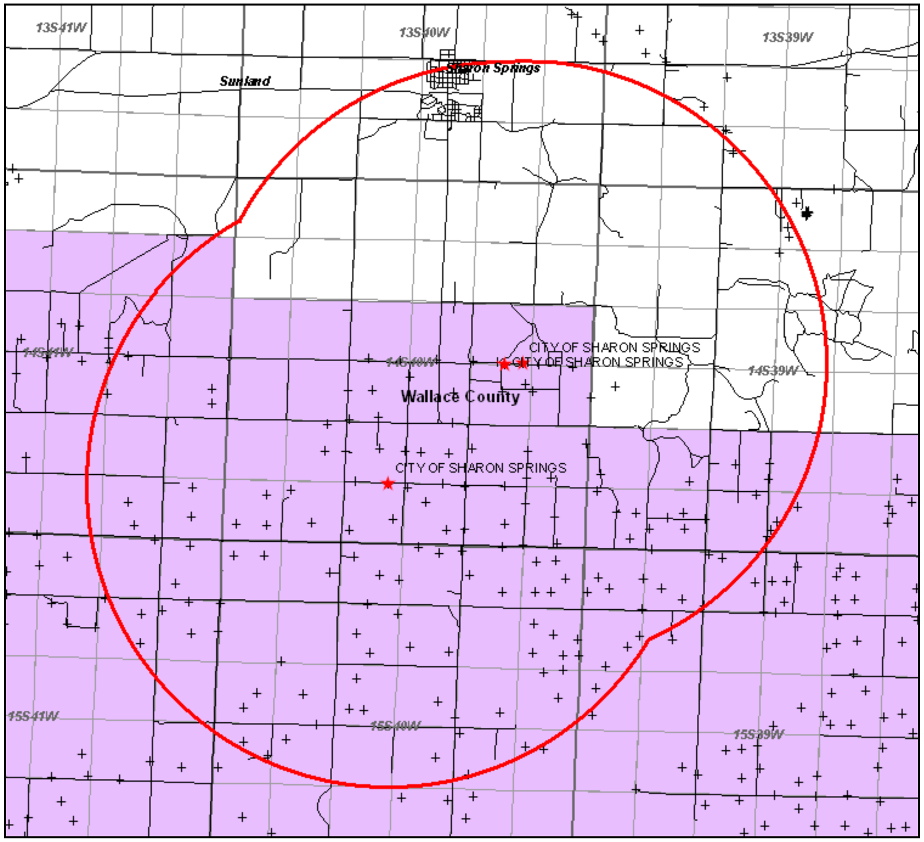
In terms of saturated thickness remaining around at least some of the municipal water-right locations, the ranking is approximately Scott City>Sharon Springs>Tribune>Leoti>Dighton. However, in terms of the rate of decline, the order is Sharon Springs>Scott City>Leoti> Dighton>Tribune. This tends to level the comparisons, since the areas with the greatest present reserves are experiencing the fastest declines. Use densities in most of the areas are relatively low (for comparison, the high use area of Wallace county has township-size areas with average pumping >300 AF/sq. mi.), although Scott City is an exception to this.

Because of the differing characteristics of the various supplies, approaches to sustainability will be different – ranging from identifying additional sources (that is, harvesting water at greater distances or over a wider area) to reducing depletion rates in the areas currently used for supply.

Detailed recommendations cannot be made on the basis of the general information currently available, but more extensive assessments (involving the municipalities and a more thorough review of the available information) can improve the information base fairly quickly and easily. Additional information is also needed, and data collection can be enhanced (in most of the areas) by initiating more, and more frequent, well measurements in the vicinity of the municipal wells.

Construction of dedicated monitoring wells (index/calibration wells) for tracking general water resource conditions in an area appears likely to be most useful in the Scott City area – the "depression" is a limited but well-connected (and heavily used) water resource, which currently lacks detailed monitoring in the vicinity of the municipal wells. Based on saturated thickness and decline rates, the other areas can be given an initial ranking of the possible utility of data from a dedicated monitoring well: Sharon Springs > Tribune ~ Leoti > Dighton.

Figure A1: Sharon Springs



Crosses indicate the locations of water rights, red stars are the locations of municipal water rights, and the red outlines are the outer limit of a set of 5-mile circles around each of the municipal water rights. The lavender color indicates the extent of GMD1.

Saturated thickness: Assumed low in two north wells (outside of our section-level dataset). Less than 50 ft of water remains in the north wells as of January 2005 (based on nearest measured monitoring well). 60-90 ft around south well, increases slightly to the south.

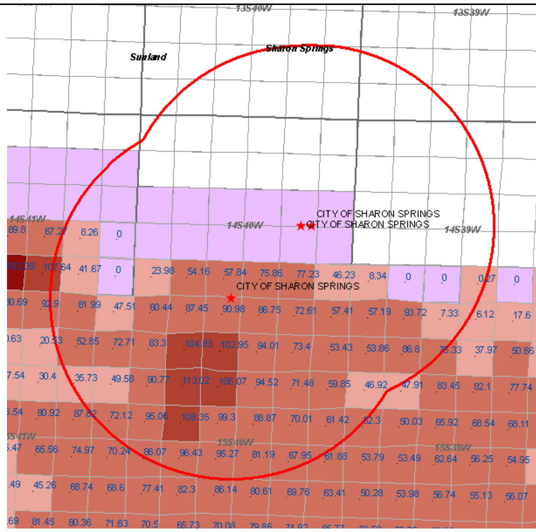
Rate of WT elevation change: Reflects of use density (see next page). High (15-20 ft; 1.5-2 ft/yr) decline surrounding south well and even higher (20-25 ft) decline in a concentrated area south of south well. 5-15 ft decline surrounding north wells.

Density of use (pumping): Very high (>300 AF/sq mi) less than 1 mile south of south well. High (250-300 AF/sq mi) around south well. Presumed intermediate near north wells.

Data needs or problems: The annual network does not provide good estimates of water level in the vicinity of the southern well.

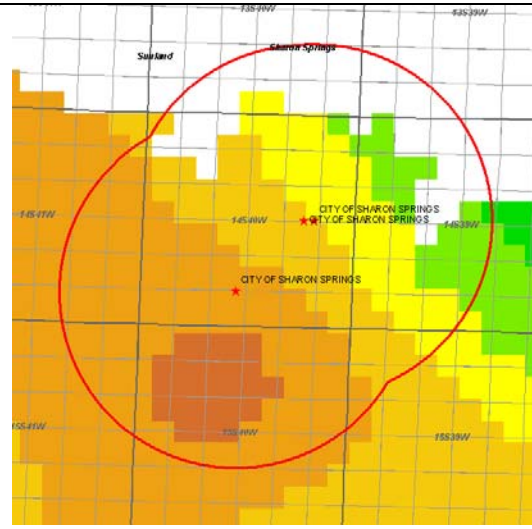
Enhancement opportunities: Well log reviews plus more frequent measurements of more wells near the municipal wells can improve estimates of both remaining water and rate of change. An index well would provide additional knowledge of the trends and conditions affecting the south well, but would not be useful across the whole area or in the thinly saturated region.

Figure A2: <u>Sharon Springs</u>



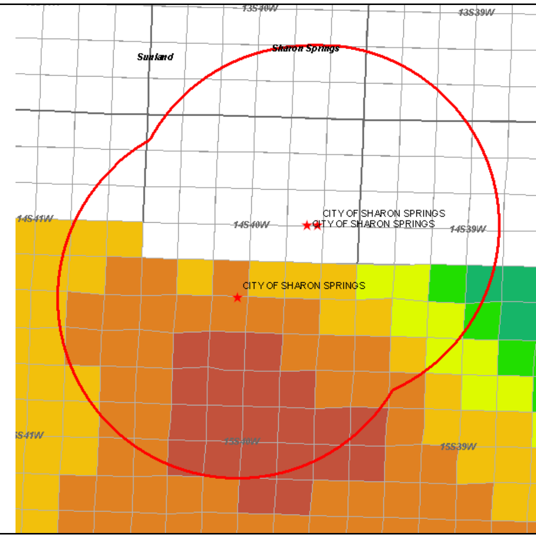
Sharon Springs water supply – saturated thickness (Avg 04-06), in ft. Blue numbers are estimated saturated thickness values at the section center.

ST
- 0
- 0 to 50
- 50 to 100
- 100 to 150
- Over 150



Sharon Springs water supply – change in saturated thickness 96-06, in ft.

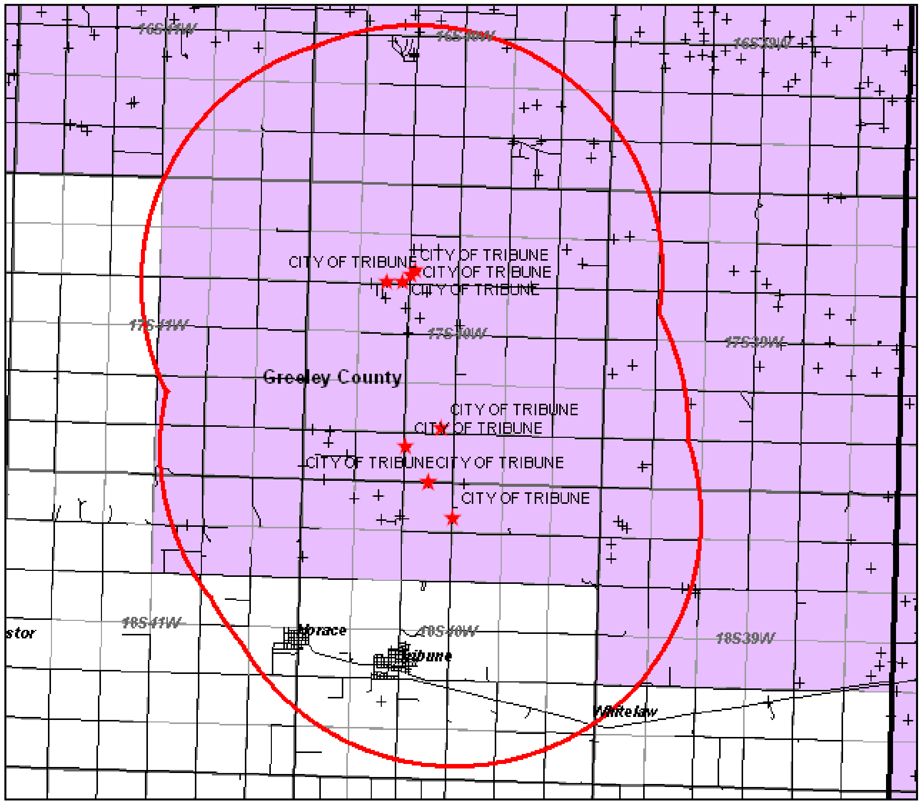
Value
- < -25
- -25 to -20
- -20 to -15
- -15 to -10
- -10 to -5
- -5 to -1
- -2 to -1
- -1 to 0
- 0 to 1
- 1 to 2
- > 2



Sharon Springs water supply – average density of use (5-mile smoothing radius), in acre-ft per square mile (AF/sq mi).

- 0.0
- 0.1 - 50.0
- 50.1 - 100.0
- 100.1 - 150.0
- 150.1 - 200.0
- 200.1 - 250.0
- 250.1 - 300.0
- 300.1 - 337.0

Figure A3: <u>Tribune</u>



Crosses indicate the locations of water rights, red stars are the locations of municipal water rights, and the red outlines are the outer limit of a set of 5-mile circles around each of the municipal water rights. The lavender color indicates the extent of GMD1.

<u>Saturated thickness</u>: 30-60 ft in the immediate vicinity of both groups of wells. Values are similar to the east, but drop off gradually to the west and rapidly to the north and south.

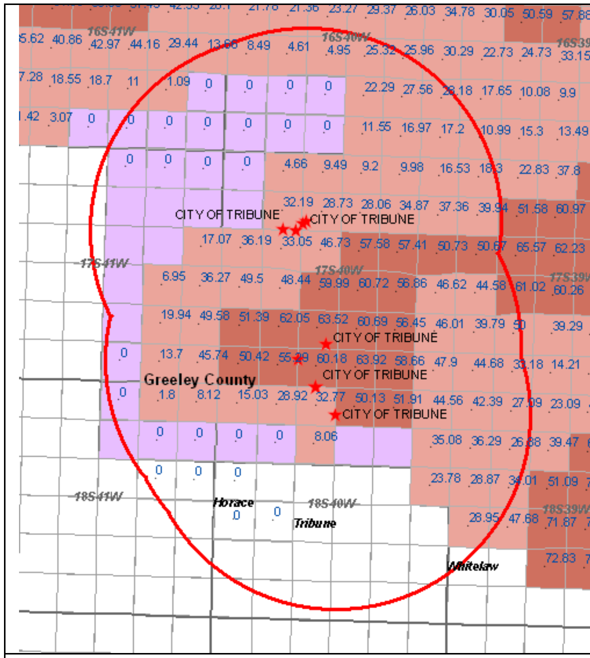
<u>Rate of WT elevation change</u>: Averaged +1 to -2 feet (≤ -0.2 ft/yr). Changes up to -5 ft occurred a short distance to the NE of the municipal wells, but values >+2' occurred to the SE, and immediately to the SW of the northern group.

<u>Density of use (pumping)</u>: Less than 50 AF/sq mi around the southern group of wells and to 1 mi north of the northern group. Farther to the north, use density rose to 50-100 AF/sq. mi to 3 mi north of the northern group, and to 100-150 to the 5 mi limit.

<u>Data needs or problems</u>: The annual network does not provide good estimates of water level in the vicinity of the southern group of wells.

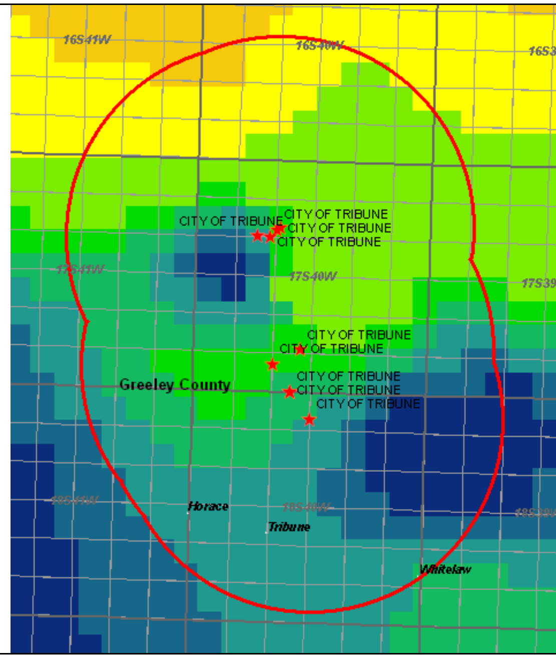
<u>Enhancement opportunities</u>: Well log reviews plus more frequent measurements of more wells near municipal can improve estimates of both remaining water and rate of change. An index well might provide some additional knowledge for the northern group, but would not be useful across the whole area or in the thinly saturated region.

Figure A4: <u>Tribune</u>



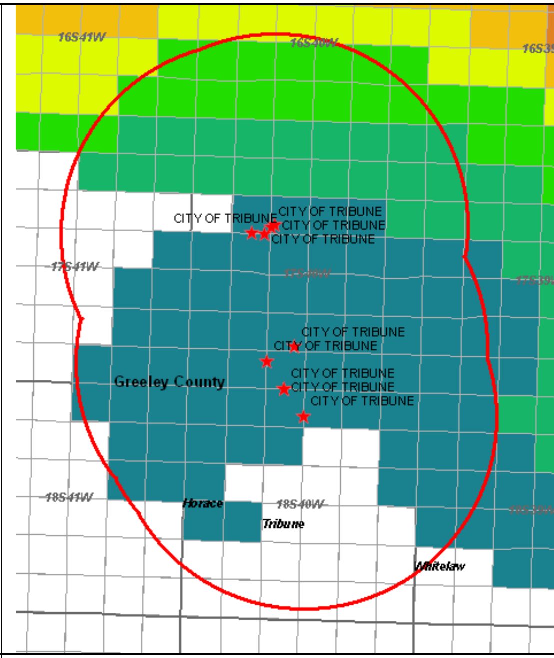
Tribune water supply – saturated thickness (Avg 04-06), in ft. Blue numbers are estimated saturated thickness values at the section center.

ST
- 0
- 0 to 50
- 50 to 100
- 100 to 150
- Over 150



Tribune water supply – change in saturated thickness 96-06, in ft.

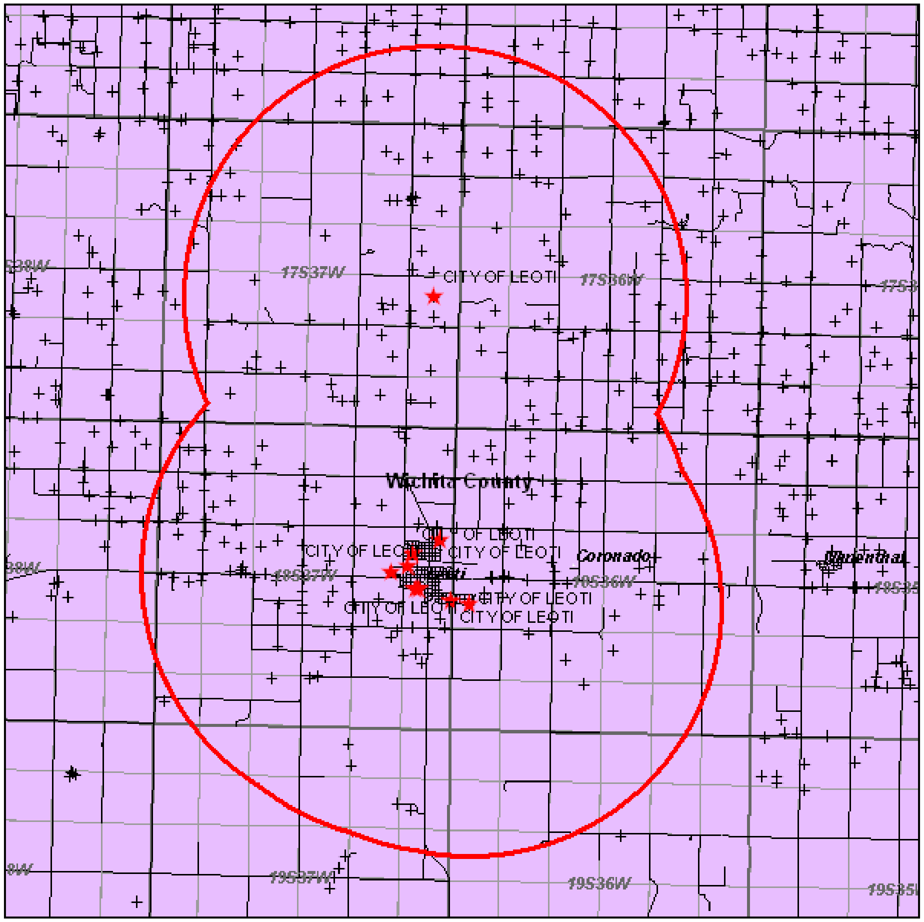
Value
- < -25
- -25 to -20
- -20 to -15
- -15 to -10
- -10 to -5
- -5 to -1
- -2 to -1
- -1 to 0
- 0 to 1
- 1 to 2
- > 2



Tribune water supply – average density of use (5-mile smoothing radius), in acre-ft per square mile (AF/sq mi).

- 0.0
- 0.1 - 50.0
- 50.1 - 100.0
- 100.1 - 150.0
- 150.1 - 200.0
- 200.1 - 250.0
- 250.1 - 300.0
- 300.1 - 337.0

Figure A5: Leoti



Crosses indicate the locations of water rights, red stars are the locations of municipal water rights, and the red outlines are the outer limit of a set of 5-mile circles around each of the municipal water rights. The lavender color indicates the extent of GMD1.

Saturated thickness: Low, typically less than 50 ft, and commonly less than 40 ft. Declines rapidly to the south of the southern wells – aquifer fringe.

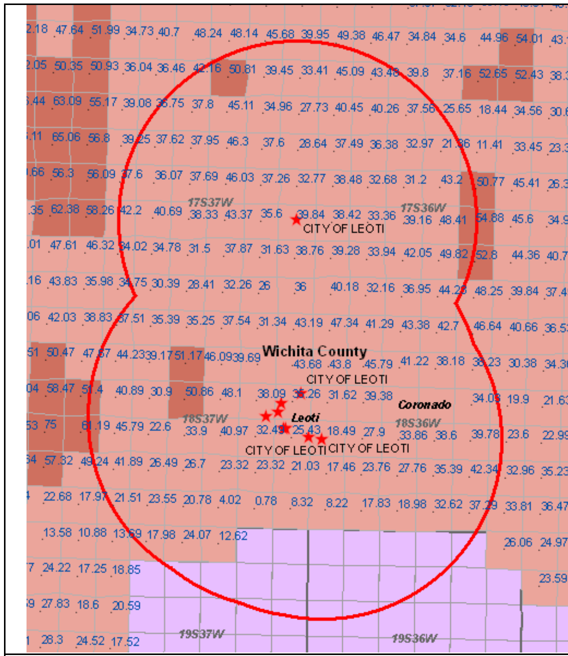
Rate of WT elevation change: 1-5 ft decline around south wells. 5-10 ft decline for north well. An area of higher (10-15 ft) decline a mile east of north well.

Density of use (pumping): 100-150 AF/sq mi for most of the south wells. Decreases to the south and increases to the north. Close to 200 AF/sq mi for north well. Patches exceeding 200 AF/ sq mi within a few miles north, east and west of the north well.

Data needs or problems: The annual network does not provide good estimates of water level in the vicinity of the southern group of wells. One Wizard well is located within about 3 miles north of the north well.

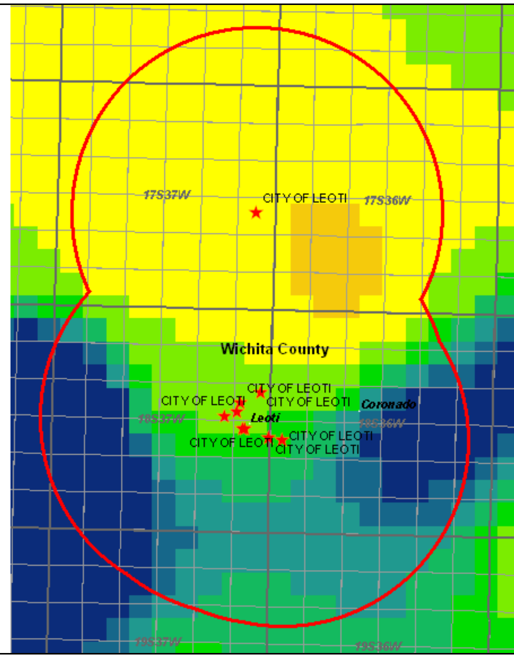
Enhancement opportunities: A reasonable density of wells near all of the municipal wells suggests that additional water table measurements could be obtained and applied to the municipal water supply monitoring and projection. Low saturated thickness values and rapid N-S changes in hydrologic conditions in the vicinity of the city would limit the usefulness of a monitoring (index) well.

Figure A6: Leoti



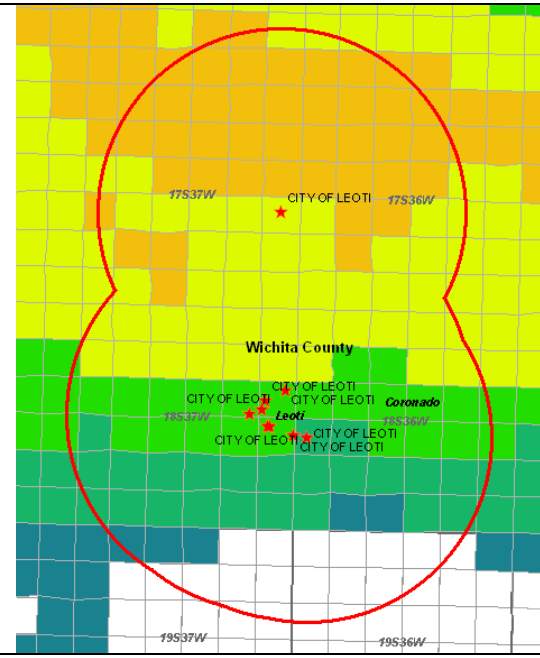
Leoti water supply – saturated thickness (Avg 04-06), in ft. Blue numbers are estimated saturated thickness values at the section center.

ST
- 0
- 0 to 50
- 50 to 100
- 100 to 150
- Over 150



Leoti water supply – change in saturated thickness 96-06, in ft.

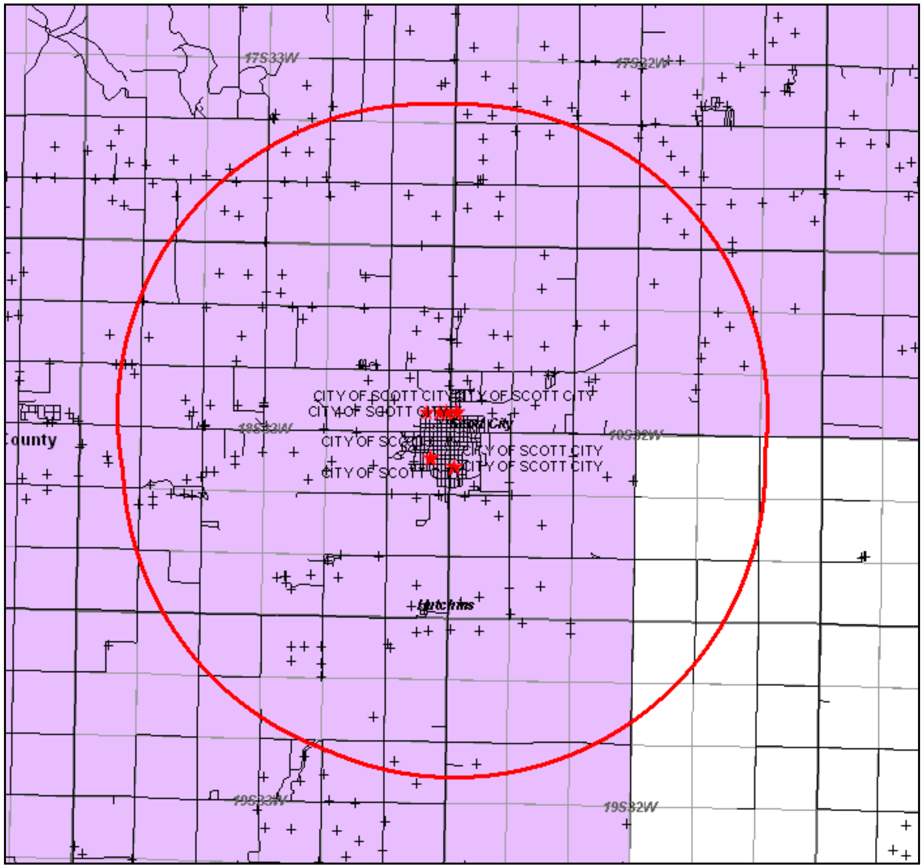
Value
- < -25
- -25 to -20
- -20 to -15
- -15 to -10
- -10 to -5
- -5 to -1
- -2 to -1
- -1 to 0
- 0 to 1
- 1 to 2
- > 2



Leoti water supply – average density of use (5-mile smoothing radius), in acre-ft per square mile (AF/sq mi).

- 0.0
- 0.1 - 50.0
- 50.1 - 100.0
- 100.1 - 150.0
- 150.1 - 200.0
- 200.1 - 250.0
- 250.1 - 300.0
- 300.1 - 337.0

Figure A7. Scott City



Crosses indicate the locations of water rights, red stars are the locations of municipal water rights, and the red outlines are the outer limit of a set of 5-mile circles around each of the municipal water rights. The lavender color indicates the extent of GMD1.

Saturated thickness: The Scott-Finney depression is a narrow north-south band of higher ST and lower bedrock elevation passing beneath Scott City. ST > 100 ft in the narrow band, approximately 1 mile wide. Near the municipal wells, ST is currently in the 50-100 ft range. ST drops to essentially zero a few miles east of the city wells, and to less than 50 ft a few miles west of the city wells.

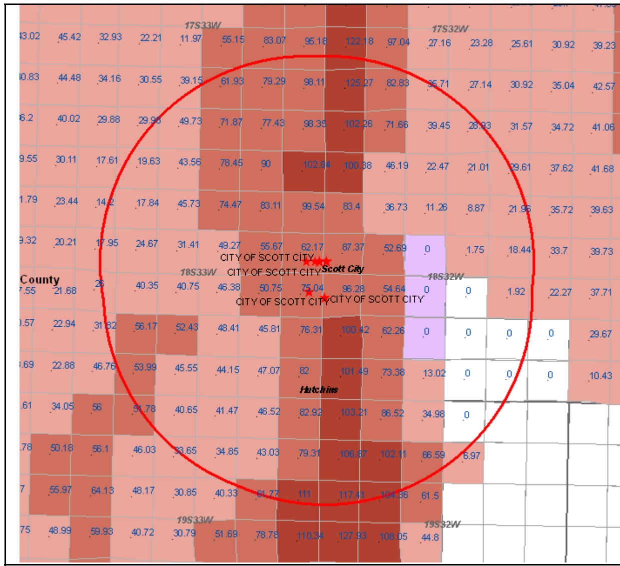
Rate of WT elevation change: 5-10 ft decline in an area roughly centered on the city wells, and extending north and northeast. Less change farther away.

Density of use (pumping): High. 250-300 AF/sq mi surrounding and north of city wells. Greater than 100 AF/sq mi in essentially the entire 5-mile radius, and generally greater than 150 AF/sq mi.

Data needs or problems: The annual network does not provide resolution adequate for the abrupt changes in local hydrology and geology, or measurements in the depression near the municipal wells .

Enhancement opportunities: Well log reviews plus more frequent measurements of more wells near municipal can improve estimates of both remaining water and rate of change. An index well in the major groundwater body supplying the city (the southern part of the depression) would substantially improve local understanding of the water resource and prospects for the municipal supply.

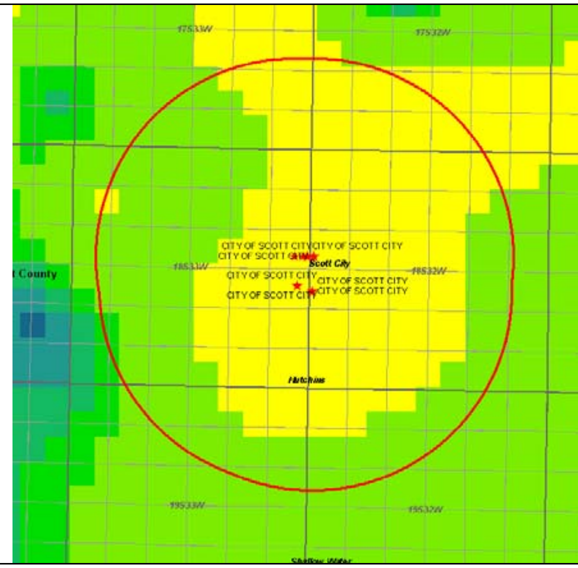
Figure A8. <u>Scott City</u>



Scott City water supply – saturated thickness (Avg 04-06), in ft. Blue numbers are estimated saturated thickness values at the section center.

ST

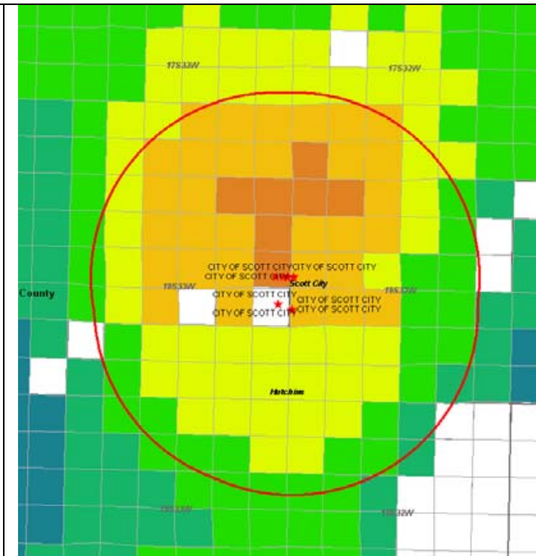
- 0
- 0 to 50
- 50 to 100
- 100 to 150
- Over 150



Scott City water supply – change in saturated thickness 96-06, in ft.

Value

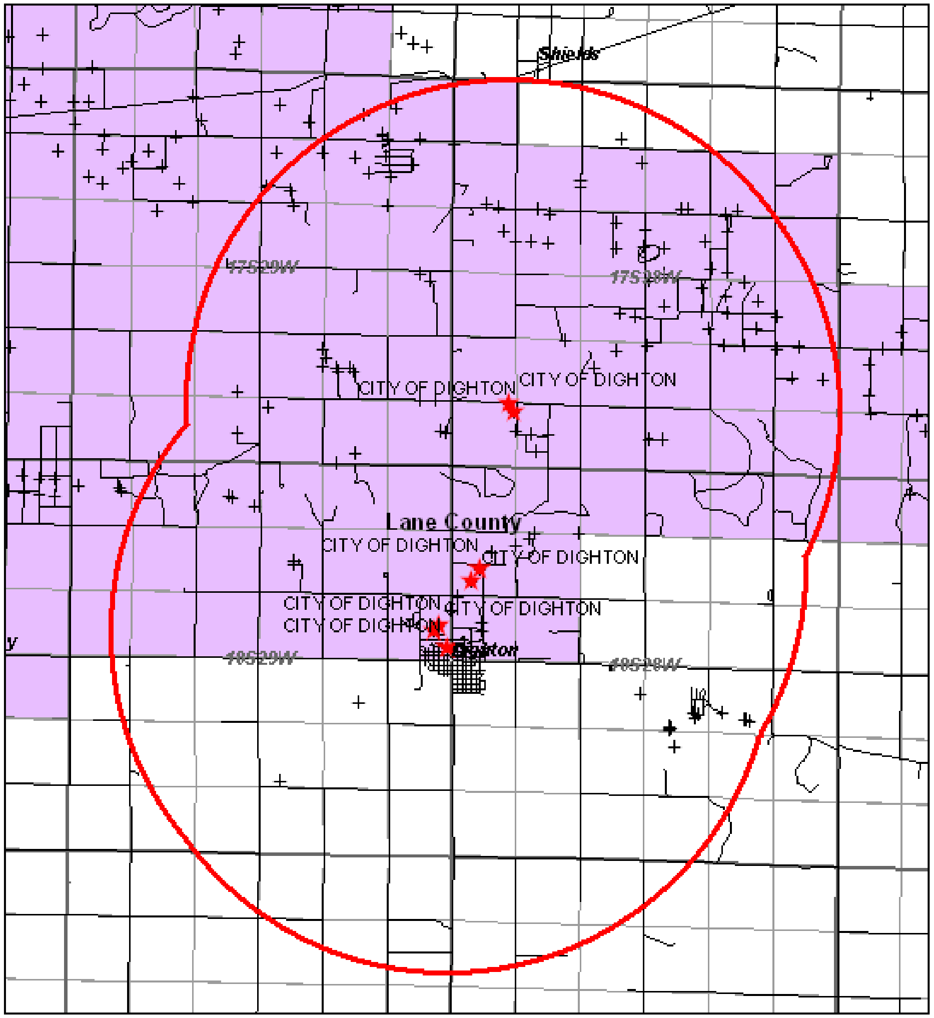
- < -25
- -25 to -20
- -20 to -15
- -15 to -10
- -10 to -5
- -5 to -1
- -2 to -1
- -1 to 0
- 0 to 1
- 1 to 2
- > 2



Scott City water supply – average density of use (5-mile smoothing radius), in acre-ft per square mile (AF/sq mi).

- 0.0
- 0.1 - 50.0
- 50.1 - 100.0
- 100.1 - 150.0
- 150.1 - 200.0
- 200.1 - 250.0
- 250.1 - 300.0
- 300.1 - 337.0

Figure A9. Dighton



Crosses indicate the locations of water rights, red stars are the locations of municipal water rights, and the red outlines are the outer limit of a set of 5-mile circles around each of the municipal water rights. The lavender color indicates the extent of GMD1.

Saturated thickness: Typically less than 30 ft. Increases north and west of the northern wells. Essentially zero within a couple of miles south and east of the southern wells. An area with little or no ST separates the northern and southern wells.

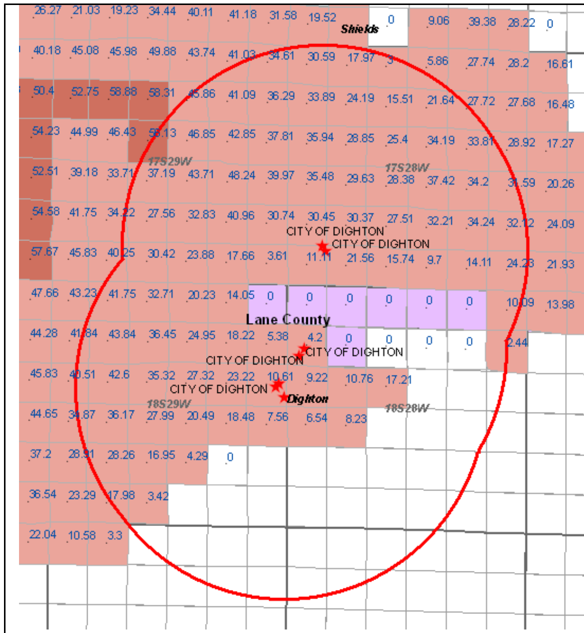
Rate of WT elevation change: 1-5 ft declines.

Density of use (pumping): Less than or around 50 AF/sq mi for south wells. 100-150 north and west of north wells, less to the east.

Data needs or problems: The annual network does not provide good estimates of water level in the vicinity of the wells because of extremely low ST values around the pumping and measurement wells (particularly for the northern wells which are presumably the ones that are pumped).

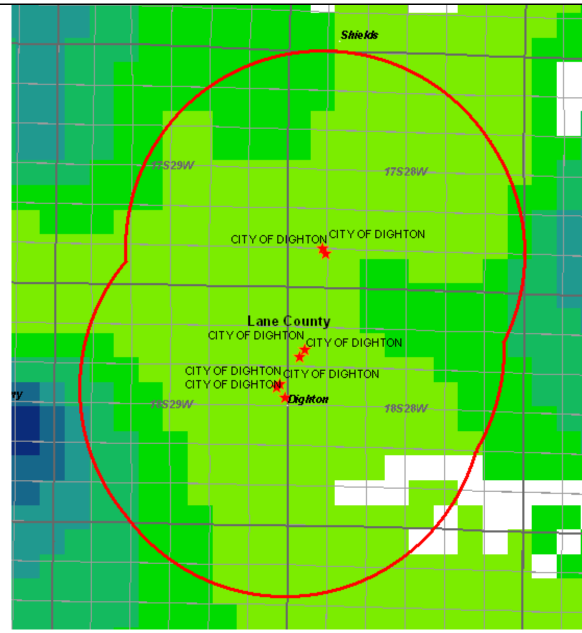
Enhancement opportunities: Low well density and low saturated thickness limit the amount of improvement possible. A detailed local assessment appears desirable to get a better picture of the actual problems and opportunities.

Figure A10. Dighton



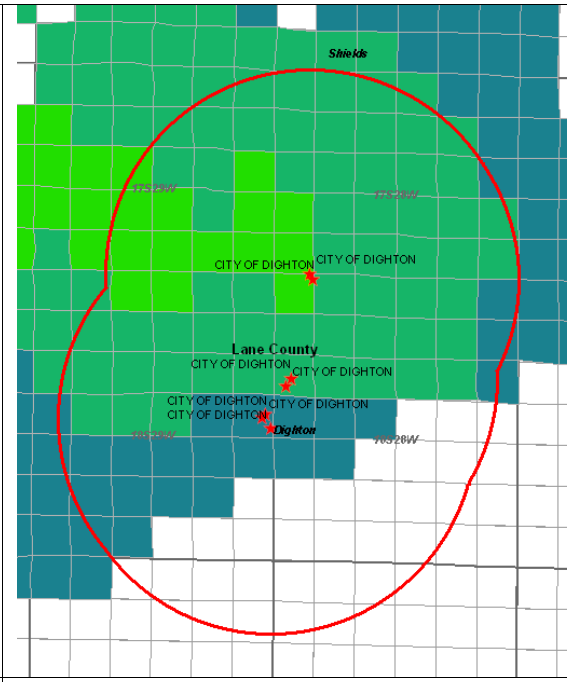
Dighton water supply – saturated thickness (Avg 04-06), in ft. Blue numbers are estimated saturated thickness values at the section center.

ST
- 0
- 0 to 50
- 50 to 100
- 100 to 150
- Over 150



Dighton water supply – change in saturated thickness 96-06, in ft.

Value
- < -25
- -25 to -20
- -20 to -15
- -15 to -10
- -10 to -5
- -5 to -1
- -2 to -1
- -1 to 0
- 0 to 1
- 1 to 2
- > 2



Dighton water supply – average density of use (5-mile smoothing radius), in acre-ft per square mile (AF/sq mi).

- 0.0
- 0.1 - 50.0
- 50.1 - 100.0
- 100.1 - 150.0
- 150.1 - 200.0
- 200.1 - 250.0
- 250.1 - 300.0
- 300.1 - 337.0

Appendix B

Cross-Validation Analysis of Water-Level Measurement Reliability in GMD4 Priority Areas

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Kriging cross-validation analysis

We applied the same cross-validation analysis for the GMD4 wells as used in the general statistical report on annual water levels for previous years, except that we estimated a variogram for just the GMD4 wells. First we computed an empirical variogram in the "trend-free" direction (about N 15 W) for each year, and then averaged that variogram over all years. We fit a variogram model to the averaged variogram by eye. The estimated variogram model is Gaussian with a nugget of 100 ft^2, a sill of 4200 ft^2 (total sill of 4,300 ft^2), and a (practical) range of 197,000 feet or 37 miles. The fit is reasonably good. We ran the GSLIB kriging program in cross-validation mode for each year. The cross-validation analysis leaves each well out of the dataset in turn, estimates the water-table elevation at that well location by interpolating elevations from surrounding wells, and compares the measured and estimated elevation at each well location.

We generated a spreadsheet (available as a separate electronic file) that includes columns of measured elevations from 1996-2007 (Elev96, etc.), estimated (kriged) elevations for 1996-2007 (WTEst96, etc.) -- the value at each well is the kriged value at that location when that well is withheld from the dataset -- and then columns of residuals, as (actual minus estimated) (worksheet Export_Output_1 in the spreadsheet). A positive residual means the actual is higher than the estimated, or that the water level in that well is higher than the weighted average of water levels at surrounding wells, and vice versa. The residuals are fairly consistent over time, especially for the wells with large (positive or negative) residuals. Thus, a well that is really "out of keeping" with its neighbors tends to be so consistently. This means that there are factors influencing the variation between wells for which a 2D interpolation approach cannot account.

Figure 1: Contoured average residuals (difference between modeled and measured water levels) for GMD4. Priority areas (taken from map on GMD 4 website) are included in dashed lines. The contour intervals are very uneven. Uncertainties of more than a few feet are a problem for detailed management or assessment efforts, thus, we combined positive and negative values greater than 10 ft into single categories.

An important point concerning this analysis is that many of the residuals, at the least the moderate to large ones, are not as much related to "error", in the sense of statistical error in the measurements or the interpolation process, as they are to violations of the conceptual model implicitly underlying the interpolation, i.e., that the measurements represent a single smoothly-varying surface, varying solely as a function of the geographic coordinates. This model underlies any 2D interpolation process, not just kriging. Therefore, any significant violations of that conceptual model, such as significant vertical gradients between wells screened at different depths, or more or less discrete variations between different units, could manifest themselves as large residuals.

The spreadsheet includes the concatenated geological unit codes; which help in the explanation of some of the results. To compare differences, data in the spreadsheet could be sorted to determine which wells are the nearest neighbors of a given well. For example, a column added to the spreadsheet representing distance to any selected well could be sorted to aid in determining variations around that well.

If the clear outliers were entirely removed from the dataset, the agreement among the remaining wells would be better because the measurements at these outlier wells influence the estimates at neighboring wells (worksheet EO_no_outliers in the spreadsheet).

Figure 2: A replot of the Figure 1 contour intervals after the outliers >1 standard deviation from the mean have been removed.

Reanalyzing the data after removal of the outliers >1 standard deviation from the mean residual creates quantitative differences, but very little qualitative difference, i.e., the priority areas are still largely associated with high (negative) deviations.

Smoothing spline cross-validation analysis

Figure 3: A plot of a new cross-validation run involving a smoothing spline fit on the dataset after the outlier values have been removed.

We used a smoothing spline fit to the water table elevations, rather than the leave-one-out kriging residuals, as a different approach to the cross-validation problem (worksheet spline in the spreadsheet). Unlike kriging, which is an exact interpolator, the smoothing spline does not try to exactly match the data. Instead, it fits a smooth surface, with the degree of smoothing optimized (behind the scenes) through a kind of cross-validation process. The optimization is done prior to the final fitting, so the predicted water-table elevation values in this spreadsheet are the actual predictions -- the values of the smooth surface -- at each well location, rather than the value that would be obtained if the well were removed.

Kriging (or any other exact interpolation algorithm) can sometimes behave "pathologically" because we ask it to give us a smooth surface that exactly reproduces the data, and these two goals (smoothness and exact interpolation) cannot both be achieved in a satisfactory fashion when the data do not nicely fall on a smooth surface. Thus we get bull's-eyes, the bane of all exact interpolation algorithms. In areas of high variability, the interpolated surface contorts itself to match all the contradictory data points, no matter the cost in terms of sensibility. The smoothing spline will produce a compromise surface in these areas, which is probably a more sensible approach in many cases. However, in terms of the wells with very large residuals, particularly negative residuals, similar results as the kriging cross validation were obtained. This suggests that there really are systematic differences in the priority areas.

Figure 4: Contour plot of residuals obtained by the spline fit technique**.**

Discussion

In our first approach, including the outliers, we came up with a standard deviation of 15. This was a first cut review. We could probably find justification to throw out a few of the measurement years for the wells based on observations such as recent pumping, spotty tape readings, etc. In the second approach, we dropped all of the wells with very large residuals (those outside the 15 foot window), resulting in a standard deviation of 8.5.

Historically, the goal of the entire water-level network was to achieve an uncertainty within a 10 foot standard deviation. Although there are some differences in the present goals, the network generally appears to be performing as intended.

More data and monitoring in the priority areas should reduce uncertainties. Having more wells at strategic locations would reduce the residuals given that one of the most sensitive parameters in the kriging process (like all interpolation methods) will be the density and spacing of the input points. However, even with a very large number of points, high residuals could still occur as a result of geologic boundaries and vertical gradients as they interact with well screen depths.

It is interesting to note that all of the priority areas have some of the highest levels of use and ground-water declines in GMD4 – as well as a tendency to overlie the areas of high residuals in the cross-validation. Those areas predominately have large negative residual values. Most likely, the large residuals do not represent errors in the water-table measurements; instead they represent systematic deviations from the fitted surface due to factors that cannot be represented in a two-dimensional interpolation analysis. It may be that because of the higher use/higher declines, the water-level elevations are lower than the statistical estimates – perhaps a recovery problem that could be partly solved with later (or continuous) measurements. There is also the possibility that the reason that these areas have problems is that they have less favorable hydrogeologic characteristics (lower specific yield or regional permeability), and the residuals are reflecting some combination of geology and sampling (characteristics of the sampled wells).

The results suggest that what is needed includes:

1. A specific area-by-area review of the well logs and well construction to see if the high-residual wells can be explained.
2. A trial program of measuring additional wells, and of periodic measurements between the first of the year and the onset of large-scale pumping. Cross-validation tests of these data could help to pinpoint the steps needed to bring uncertainties in water-level changes within a range acceptable for management needs.

Figure 1. Cross-validation Residuals (measured minus estimated), 1996 to 2007, Outliers Included

Outlier wells (those over 1std) are shown by red stars

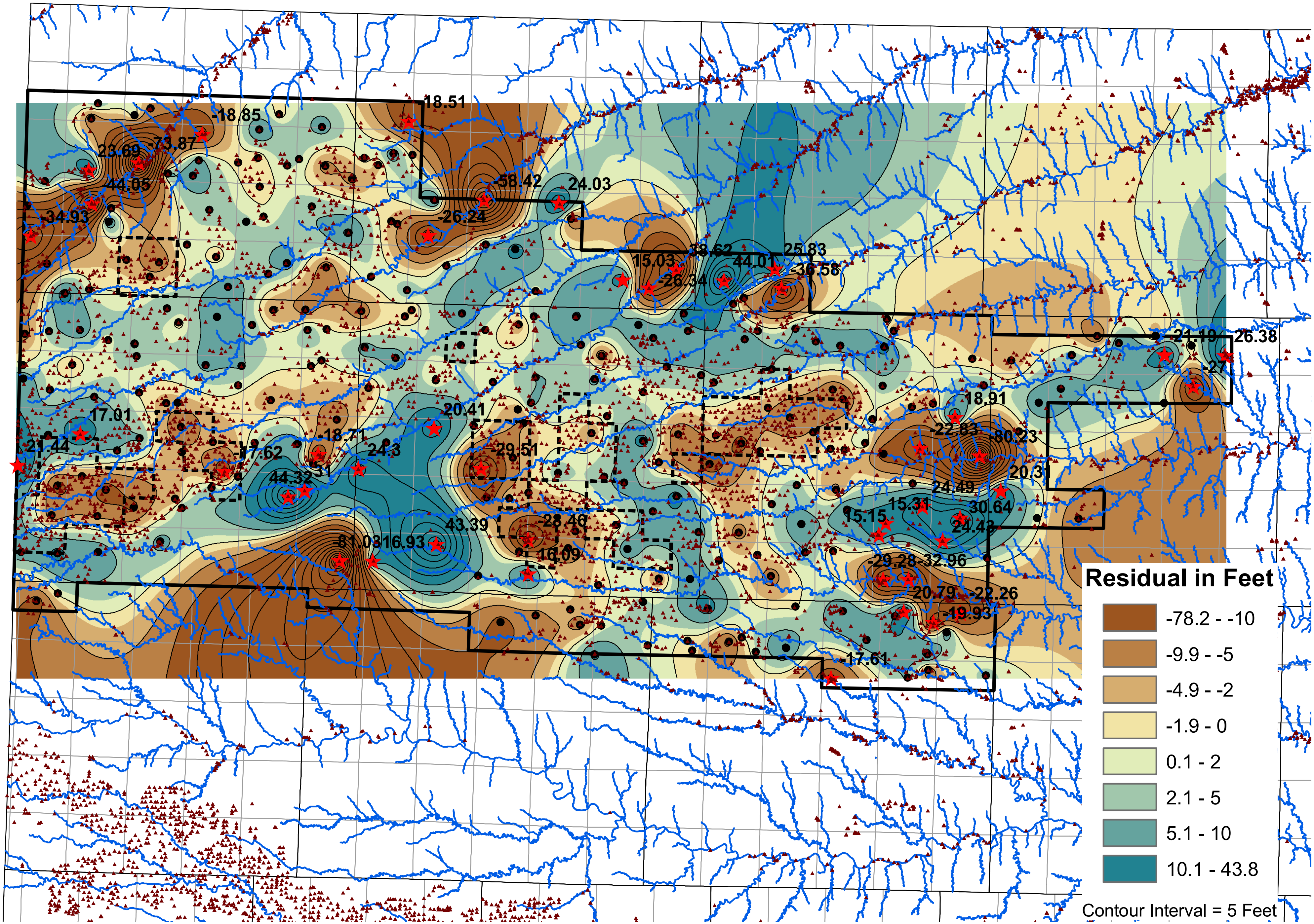

Figure 2. Cross-validation Residuals (measured minus estimated), 1996 to 2007, Outliers Excluded

Outlier wells (those over 1std) are shown by red stars

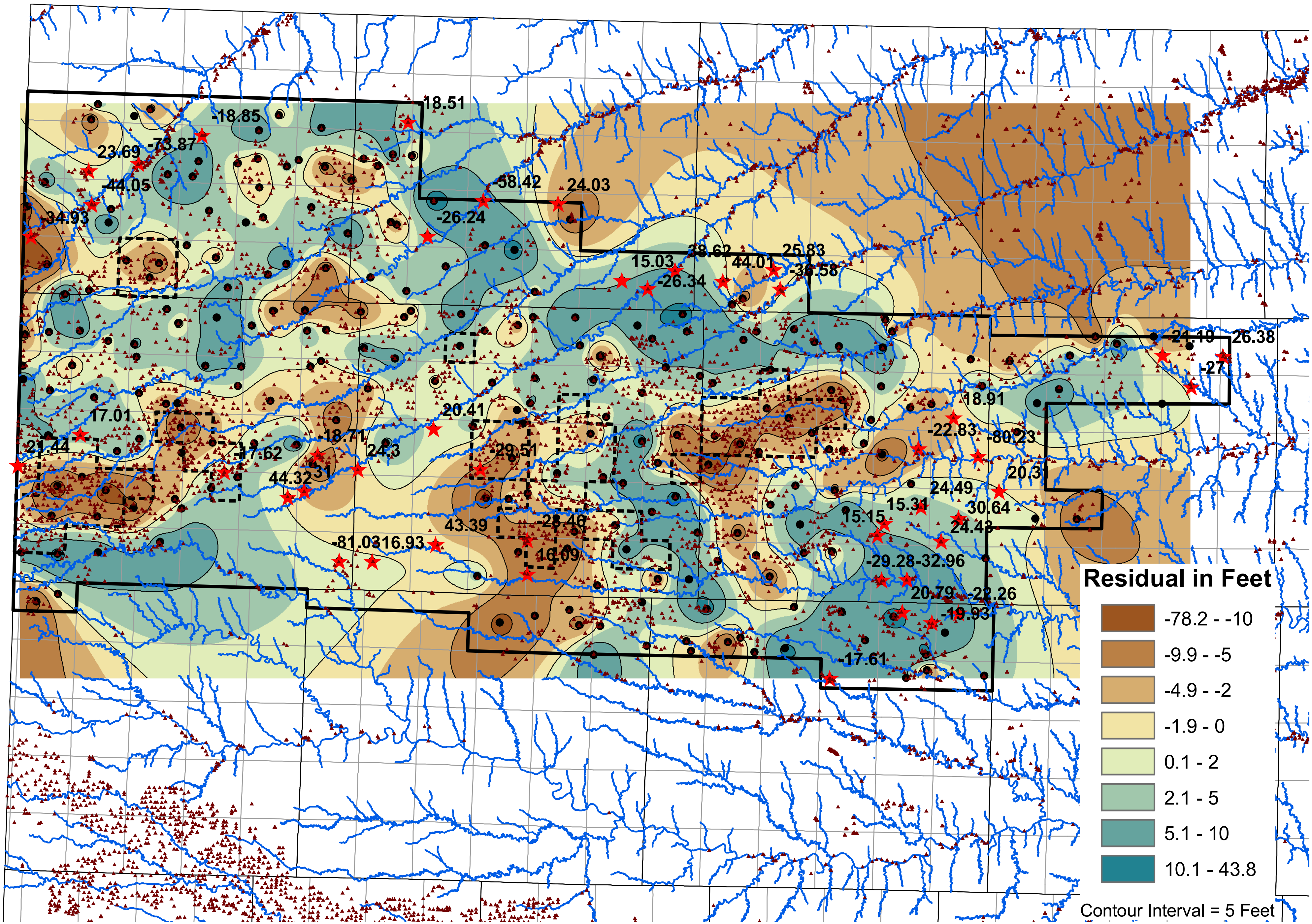

Figure 3. Cross-validation Residuals (measured minus estimated), 1996 to 2007, Outliers Excluded, Version 2

Outlier wells (those over 1std) are shown by red stars

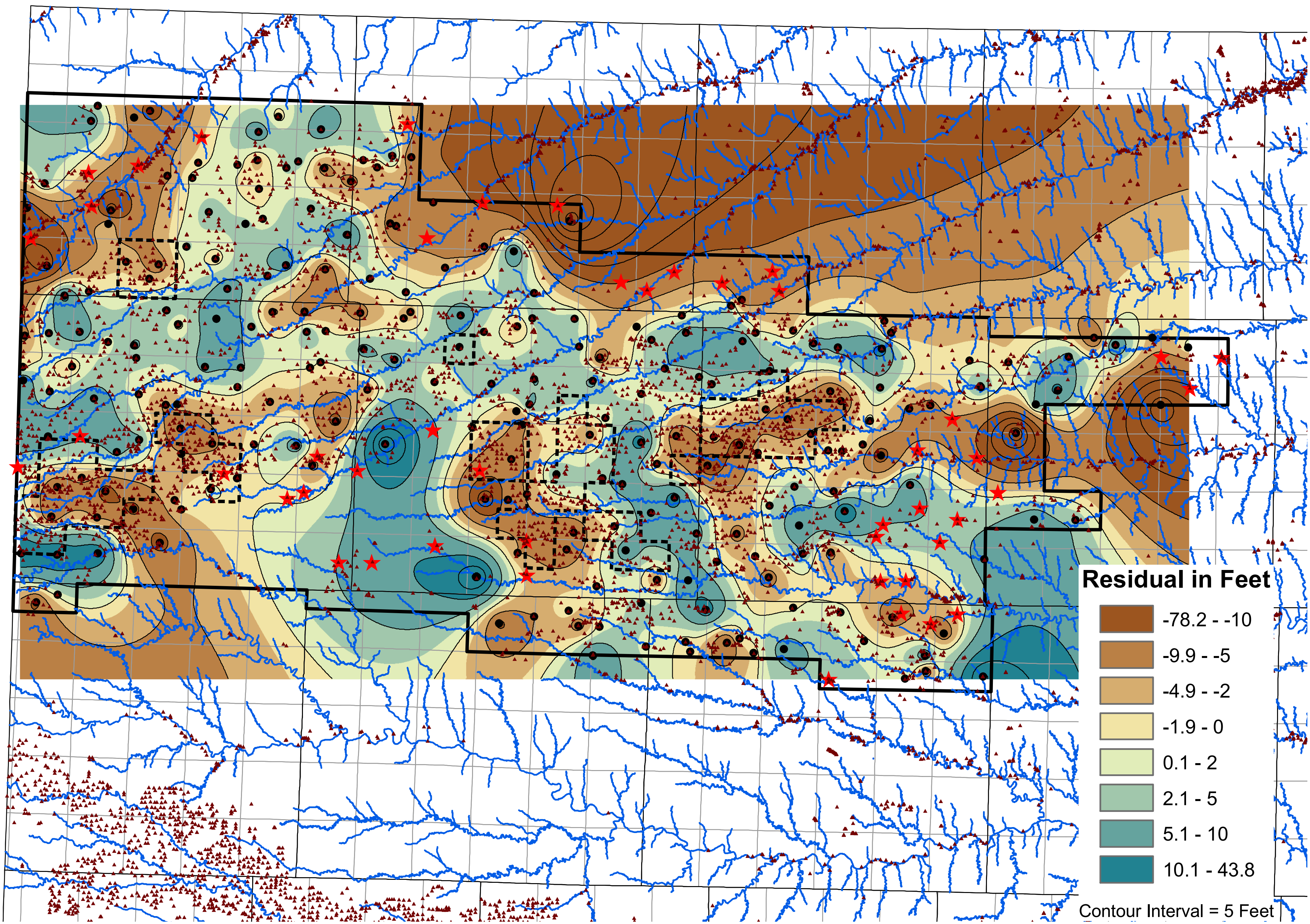

Figure 4. Smoothed Spline Residuals (measured minus estimated), 1996 to 2007