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Winter 2022–2023 Water-Level Elevation Map and Estimation of Water in Storage for a Region Northwest of Clovis, New Mexico

Prepared for the Ogallala Land & Water Conservancy

Geoffrey Rawling

OPEN-FILE REPORT

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New Mexico Bureau of Geology and Mineral Resources
A research and service division of New Mexico Institute of Mining and Technology

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Cover Photograph: Abandoned irrigation sprinklers near Clovis, NM. *Photo by Scott Christenson*

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EXECUTIVE SUMMARY

New water-level measurements collected from wells in winter 2022–2023 were combined with compiled data on the elevation of the base of the High Plains aquifer to estimate the quantity of groundwater in storage in a region northwest of Clovis, New Mexico. Standard geostatistical methods were used to map the water-level elevation surface and the base of the aquifer. Groundwater in storage was estimated using three independent approaches, with different rigor and tolerance for uncertainty. The estimated storage amounts are 304,000 acre-feet, 370,000 acre-feet, and 485,000–873,000 acre-feet. The first two estimates are considered high confidence and are the preferred results. Projected lifetimes of the aquifer in the study area based on water-level changes over the past 8 years vary spatially, from less than 5 years to over 50 years. These projections are based on water-level changes affected by groundwater pumping for irrigation, which has now ceased, so the true lifetime will likely be longer.

Hydrogeological Field Technician Scott Christenson uses a steel tape to measure the water level in an abandoned irrigation well.
Photo by Geoff Rawling

WINTER 2022–2023 WATER-LEVEL ELEVATION MAP AND ESTIMATION OF WATER IN STORAGE FOR A REGION NORTHWEST OF CLOVIS, NEW MEXICO

Geoffrey Rawling

INTRODUCTION

The purpose of this study was to measure water levels in wells, create a water-level elevation map, and estimate the quantity of water in storage in a portion of the High Plains aquifer north and northwest of Clovis, New Mexico (Fig. 1). The Ogallala Land & Water Conservancy (OLWC) has signed lease agreements with multiple landowners in this area to cease pumping of groundwater for 3 years starting June 30, 2022, with the goal of banking the remaining groundwater for future use.

GEOLOGY OF THE STUDY AREA

The study area (Fig. 1) encompasses a paleochannel in the Miocene- to early Pliocene-age (~20 to ~5 million years old) Ogallala Formation. The Ogallala Formation is much thicker in this area because the streams that deposited it had eroded the underlying bedrock more deeply than in adjacent areas (Fig. 1). The High Plains aquifer, which occurs within the Ogallala Formation, thus has a greater potential saturated thickness in the paleochannel areas. In addition, the sediments that make up the Ogallala Formation tend to be coarser-grained in the paleochannel areas (coarse sand and gravel) than in the intervening paleoupland areas (silt and sand; Pazzaglia and Hawley, 2004). This results in higher permeability and a higher-quality aquifer.

PREVIOUS WORK

Studies addressing water-level declines and changes in groundwater storage within the High Plains aquifer are numerous. Work addressing the High Plains aquifer as a whole includes Gutentag et al. (1984), Weeks et al. (1988), McGuire (2011), McGuire et al. (2012), Scanlon et al. (2012), and Haacker et al. (2016).

The present study area was targeted for cessation of groundwater pumping and banking of remaining water in storage based on previous hydrogeology studies. The geometry of the bedrock surface at the base of the Ogallala Formation was mapped in the 1960s by the U.S. Geological Survey (USGS; Cronin, 1969). Numerous subsequent studies of the hydrogeology of the High Plains aquifer in eastern New Mexico and western Texas have used this bedrock surface map (Hart and McAda, 1985; Mulligan et al., 2008, Tillery, 2008a, 2008b; Rawling, 2016; Rawling and Rinehart, 2018). These studies all include water-level elevation maps and discussion of water-level changes over time.

METHODS

Study Area Extent

The study area was defined to enclose the wells and properties under lease agreements with the OLWC and Cannon Air Force Base. The extent shown in red in Figure 1 was drawn by hand to generally follow the topography of the margins of the paleochannel based on the contours of the base of the aquifer from Hart and McAda (1985), and to completely encompass the properties of the landowners who have signed water right lease agreements.

Base of the High Plains Aquifer

Estimating the water in storage in the High Plains aquifer in the study area requires calculating the saturated thickness of the aquifer. The accuracy of this calculation depends on the accuracy of the mapped water-level elevation surface and the mapped surface of the base of the aquifer. The difference in elevation between these two surfaces at any point is the saturated thickness. Weeks and Gutentag (1981) noted how the complexity and curvature of contours defining the base of the High Plains aquifer on their regional map is strongly dependent on the number of data (most commonly well logs in which the base of the aquifer can be identified). In other words, in areas with few data, the topography of the base of the aquifer cannot be resolved in great detail, and the contoured surface is necessarily a simplification of reality.

The maps of Cronin (1969) do not show the wells used to map the base of the High Plains aquifer. Contour lines on his map are drawn as solid where they are "more reliable" and dashed where inferred; in the present study area, both types are present. Given the more than 50-year age of Cronin's (1969) map and the relatively small size of the present study area (<150 mi^2), the base of the High Plains aquifer was remapped for the present study using logs of water wells obtained from the New Mexico Office of the State Engineer (OSE). Logs and construction information for 369 wells within the study area were examined, 33 of which were wells with water-level measurements made in this study (Fig. 2, Table 1[1]). Where possible, the locations of wells recorded by the OSE were checked against aerial photographs, and in some cases the location of the well was moved to match the imagery. The elevation of the base of the High Plains aquifer is easily identified in most water well logs by the occurrence of "redbeds" or similar terms used to describe the Triassic rocks present below the Ogallala Formation.

Water wells rarely extend more than 10 ft into the Triassic rocks. A total of 179 wells had logs from which the elevation of the base of the aquifer could be reliably determined. The difference between the redbed elevation and the elevation of the bottom of the well was calculated for these 179 wells. The median value of these data is 7 ft, meaning that the typical well extended 7 ft below the base of the High Plains aquifer as defined by the occurrence of redbeds. Seven feet were then added to the elevation of the base of wells without logs as a "best estimate" of the elevation of the redbeds/base of the High Plains aquifer (these two terms are assumed equivalent in this report). The elevation of the base of the aquifer was then spatially interpolated using geostatistical methods as described below.

Water-Level Elevation Surface

Ninety-eight wells were recommended for measurement by the OLWC. All were visited in the field in December 2022 and January 2023. Water-level measurements were successful in 60 wells; the remainder could not be measured (Fig. 3, Table 2). In old, unused wells, this was likely due to casing collapse. Note that the depth-to-water data in Table 2 are reported relative to the ground surface because the measuring point height is not reported for the USGS water-level data. Water levels were measured using either a steel tape or an electric probe (if the well was unequipped) following standard methods of the USGS (e.g., Falk et al., 2011; Galanter and Curry, 2019, and references therein).

Well information and water levels from March 2023 were provided for 11 wells on Cannon Air Force Base (Jeffrey Davis, personal communication, July 2023). Well information and water levels from February 2023 for four wells measured by the USGS were accessed from the National Water Information System (USGS, 2023). All water-level elevations were calculated from measured depth to water relative to the ground surface using a 4.5-m resolution digital elevation model (DEM; Fig. 3). Water in storage was calculated using the saturated thickness results combined with the mapped specific yield of the High Plains aquifer from Cederstrand and Becker (1998).

Geostatistical Interpolations

A two-step procedure was followed to construct the surfaces defining both the base of the aquifer and the water-level elevation in the study area. First, a trend surface was fit to the water-level or redbed elevation data. In both cases, second-degree polynomial functions of the easting and northing coordinates of the well were used. This simple model captures the general trough shape of both surfaces, declining to the southeast. Eleven wells whose redbed elevations

1 Data tables are available at https://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=626

were identified as outliers from the trend model using the criteria defined by Rawling (2022) were not used in further analysis. Three outliers from the water-level trend model were identified using the same criteria, but these were retained because of the much fewer number of water-level elevation data points (75 vs. 358).

The residuals from the trend surface models are the differences between the model predictions at the well sites and the actual data values. The spatial correlation of the residuals was determined by calculating the sample variogram for both datasets (Fig. 4). Mathematical models were fit to the variograms, and these models were then used to interpolate the trend surface residuals across the study area with spatial kriging. Anisotropic variogram models were chosen for both datasets; a two-component model with zonal anisotropy (maximum semivariance varies with direction) for the redbed elevation data, and a single-component model with geometric anisotropy (correlation length varies with direction) for the water-level elevation data. In addition to the structure of the sample variograms, use of anisotropic models was suggested by the elongate study area, the strong northwest–southeast trend in the paleochannel surface topography and water-level elevations, and the geometry of the network of wells used for water-level measurements. Final variogram models were chosen to minimize the mean-squared error (MSE) of both the model fit to the sample variogram and the residuals of leave-one-out cross-validation (Rawling, 2022).

The residuals predicted from kriging were then added to the trend surface predictions, both on a 1,640-ft (500-m) square grid, to yield the final interpolated redbed and water-level elevation surfaces (Figs. 5 and 6). This two-step geostatistical interpolation is known as regression kriging, residual kriging, or kriging with external drift (Hengl et al., 2007; Montero et al., 2015; Rawling, 2022, 2023). The procedure is the same regardless of terminology. Derivative maps from the water-level elevation and redbed elevation surfaces are the saturated thickness (Fig. 7) and depth to water (Fig. 8). The latter was found by subtracting the water-level elevation surface from a 4.5-m resolution DEM. Water in storage was found by multiplying the saturated thickness by the specific yield from the map of Cederstrand and Becker (1998).

Uncertainty Assessments

The trend surface model and kriging of trend–surface residuals both yield maps of the prediction variance of each type of calculation, usually presented as standard deviation (s.d.; the square root of the variance, with the same units as the input data). The total uncertainty of either the redbed surface or the water-level elevation surface is the sum of the two sources of variance. In terms of standard deviation, this is (Chilès and Delfiner, 2012; Figs. 5 and 6):

(1) $$total\ s.d. = \sqrt{kriging\ variance + trend\ surface\ variance}$$

The 95% confidence interval is the first of three approaches used to assess the uncertainty of the storage calculations. Then 95% confidence intervals about each predicted surface can be calculated as (Cressie, 2015):

(2) $$95\%\ confidence\ interval = predicted\ surface \pm 1.96\ \times total\ s.d.$$

If we were to make a new water-level measurement in the study area, we can be 95% confident that it will fall between the extremes of the 95% confidence interval (Cumming et al., 2007). The range in estimated saturated thickness, and thus water in storage, was illustrated by using the four possible extreme combinations of the predicted redbed elevation and predicted water-level elevation surfaces, plus or minus their respective confidence intervals.

A second criterion to assess the saturated thickness and groundwater storage calculations is the confidence factor defined by Rawling and Rinehart (2018). This is a map derived from the kriging variance maps of the redbed elevation and water-level elevation interpolations, and provides a quantitative ranking (0 to 1) of the spatial variability of the uncertainty (Fig. 9). It is calculated as:

(3) $$1 - 0.5\left[\frac{variance\ of\ older\ surface}{maximum\ variance\ of\ older\ surface} + \frac{variance\ of\ younger\ surface}{maximum\ variance\ of\ younger\ surface}\right]$$

Third, the ranges of the variogram models used for the redbed and water-level elevation interpolations provide important guidance in the interpretation of the spatial extent of the predictions. The range, or spatial correlation length, is the distance at which the variogram first reaches its peak value (Fig. 4). Data points (i.e., wells) separated by a distance larger than the range have uncorrelated measurements, and a measurement at one point provides no information about the other. Results within the range around each well are much more robust—beyond this distance, the interpolated surfaces are based on the trend models only. Note that the range is isotropic for the redbed data, but varies with direction for the water-level elevation data (Fig. 4). Virtually all of the study area is within the combined range of the redbed wells (Fig. 5). The fewer wells with water-level data, their much more limited spatial distribution, and the shorter and anisotropic range for the water-level data results in much of the study area being outside of the combined range (Fig. 6). These last three points are the most important constraints of this study and must be considered when interpreting the results.

Water-Level Changes and Projected Lifetime

Some of the data and results of Rawling and Rinehart (2018) were reanalyzed to estimate water-level changes since the mid-2010s and to project the usable lifetime of the aquifer in the study area. The 2010s and 2000s water-level surfaces of Rawling and Rinehart (2018) were created using similar geostatistical interpolation methods, but the data were median water-level values for each decade from a different set of wells. In the present study area, there are 22 wells for the 2000s decade and 31 wells for the 2010s decade from the Rawling and Rinehart (2018) dataset. In both decades, six wells were also in the new dataset for this study.

Saturated thickness calculations in Rawling and Rinehart (2018) used the base of the aquifer surface from Hart and McAda (1985) and excluded areas these authors identified as "discontinuous saturation." Saturated thickness for the present study area in the 2000s and 2010s was recalculated using the water-level surfaces for those decades and the new redbed surface prepared in this study. The areas of "discontinuous saturation" of Hart and McAda (1985) were not excluded. From these new results, the saturated thickness change in the study area since the 2010s (Fig. 10) and the rate of change since the 2010s (Fig. 11) were calculated. An estimate of the remaining usable lifetime of the full saturated thickness of the aquifer was made based on the 8-year change rate from the 2010s to 2023 (i.e., 2015 to 2023; Fig. 12).

RESULTS AND DISCUSSION

It is important to understand the limitations of the data and the uncertainties in this analysis when considering the results and the derived quantity of water in storage. The limited number of wells with water-level data, and especially their locations in two spatial clusters, rather than being more evenly or randomly distributed across the study area, are the main limitations of this study. The structure of the sample variograms, in particular the range, is controlled by the spatial arrangement of the data points. The exact same water-level elevations, but with a different, more dispersed spatial arrangement, would result in a very different variogram.

This is often unavoidable in hydrogeology studies. We are usually limited to "wells of opportunity" rather than a planned network that would generate statistically robust results across the area of interest. The water wells are where they are for a reason: they follow the axis of the paleochannel—the deepest, thickest part of the aquifer. The systematic offset of the water wells from the paleochannel axis, as mapped by Cronin (1969; Fig. 3), was an additional motivation to remap the base of the aquifer. The greater number of wells with data on the base of the aquifer, and their less-clustered, broader spatial distribution, made the remapping of the base of the aquifer practicable. The paleochannel axis of the revised redbed surface more closely matches the main trend of wells extending to the northwest (Fig. 5).

Note how the confidence factor map relates to the variogram range buffer about the water wells (Fig. 9). The highest confidence factor values are within the extent of the buffer. This is to be expected; the highest values of uncertainty (variance or standard deviation) are at values greater than the range of spatial correlation of the water-level data (see Fig. 6B). The confidence factor is highest where both interpolated surfaces used in the saturated thickness calculation have low uncertainty. The wells used to create the redbed surface are more numerous and spread more evenly over a larger area, and the redbed variogram model has a larger and isotropic range, so the variogram range buffer for these data covers almost the whole study area (Fig. 5B). The high saturated thickness (Fig. 7) and shallow depth to water (Fig. 8) predicted at the east and west margins of the southern portion of the study area are largely artifacts of projecting the water-level trend model far beyond the data points. *They are not well-supported by data and should be viewed with caution.*

The saturated thickness changes, rates of change, and projected lifetime maps (Figs. 10–12) should be interpreted with the same caution in mind, and for the same reasons. *Areas of saturated thickness increase and rising water levels are largely outside of the variogram range buffer around the water-level wells and are not well-supported by the data.* The projected lifetime is based on the water-level change rate from approximately 2015 to early 2023. Assuming that most groundwater pumping for irrigation has ceased in the study area, this can be viewed as a "worst-case" scenario. With little or no pumping presently occurring in the study area, the lifetime will be much longer than is shown on the map. Future water-level monitoring will likely show increases in water levels in some wells due to the recovery of cones of depression and possibly an overall flattening of the water-level surface.

Figure 13A shows how the base estimate of water in storage is partitioned across values of the confidence factor (Fig. 9). About 370,000 acre-ft of water are stored in areas with confidence factor values of 0.7 or higher. Figure 13B shows the range of estimates of water in storage as determined by calculating saturated thickness using the confidence intervals about the interpolated redbed elevation and water-level elevation surfaces. The bounds of the 95% confidence intervals about each surface are given by equation 2. For example, the minimum case uses the redbed elevation surface plus 1.96 × total standard deviations with the water-level elevation surface minus 1.96 × total standard deviations. The effect is to raise the base of the aquifer and lower the water-level elevation. Conversely, the maximum case is just the opposite—the water-level elevation is raised and the base of the aquifer is lowered.

The base estimate of water in storage in the entire study area, without considering confidence intervals, is 666,000 acre-ft. The base case and the other two intermediate cases probably encompass the realistic range of estimates of water in storage (485,000–873,000 acre-ft) using this method. The most conservative estimate of water in storage is only that contained within the bounds of the variogram range buffer about the water-level wells: 304,000 acre-ft. Recall that this area is the region where water levels at wells have some spatial correlation with each other; outside this region, the water-level elevation is determined by the trend surface model. Limiting storage estimates to only this area is the approach that was used by Rinehart et al. (2016, 2017).

The various approaches to assessing the uncertainty in the quantity of water in storage can be ranked as follows, in decreasing order of confidence:

1. ***304,000 acre-ft.*** This is the quantity contained within the extent of the variogram range buffer for the water-level data. This estimate is the most conservative and most strongly supported by the data. Regions of large uncertainty and poor data support are completely excluded.
2. ***370,000 acre-ft.*** This is the quantity contained in areas with a confidence factor of 0.7 and higher (Figs. 9 and 13A). This region extends outside the area of the variogram range buffer for the water-level data, but still excludes the regions of largest uncertainty and poorest data support.
3. ***485,000–873,000 acre-ft.*** This is the range of quantities spanning the three intermediate combinations of confidence intervals shown in Figure 13B. These estimates cover the entire study area and include the regions of largest uncertainty and poorest data support

Results 1 and 2 are considered the "best" estimates. For comparison, Magnuson et al. (2019) estimated that 71,060 acre-ft of groundwater were pumped for irrigated agriculture in 2015 across the entirety of Curry County.

MONITORING RECOMMENDATIONS

Figure 14 shows wells recommended for yearly monitoring of water levels. All of the wells on the Wall property that are currently measured yearly by the OLWC are included. Twelve other wells that were successfully measured in January 2023 are shown in light green. These wells were selected to give well coverage at a spacing less than or near to the water-level variogram range in the 135° direction (about 9,000 ft; Fig. 4B). The wells are listed in Table 3. Note that unlike Table 2, the depth to water in Table 3 is reported relative to the measuring point to allow easy comparison of future field measurements with the data from January 2023.

SUMMARY

Saturated thickness and water in storage were estimated for a region of the High Plains aquifer northwest of Clovis, New Mexico. Elevations of the base of the aquifer from 369 wells and water-level elevations from 75 wells were used as inputs for geostatistical interpolations of the aquifer base elevation and the water-level elevation. Estimates of the groundwater in storage range from 304,000 acre-ft in the region within the spatial correlation of water-level measurements, to 370,000 acre-ft in areas with a reasonably high confidence factor (≥0.7), to 485,000–873,000 acre-ft using the intermediate range of confidence intervals around the interpolated surfaces. The first two estimates are considered higher-confidence and are preferred. Projected lifetimes of the aquifer based on water-level change over the past 8 years vary spatially, from less than 5 years to over 50 years. These projections are based on water-level changes affected by groundwater pumping for irrigation, and so the true lifetime will likely be longer.

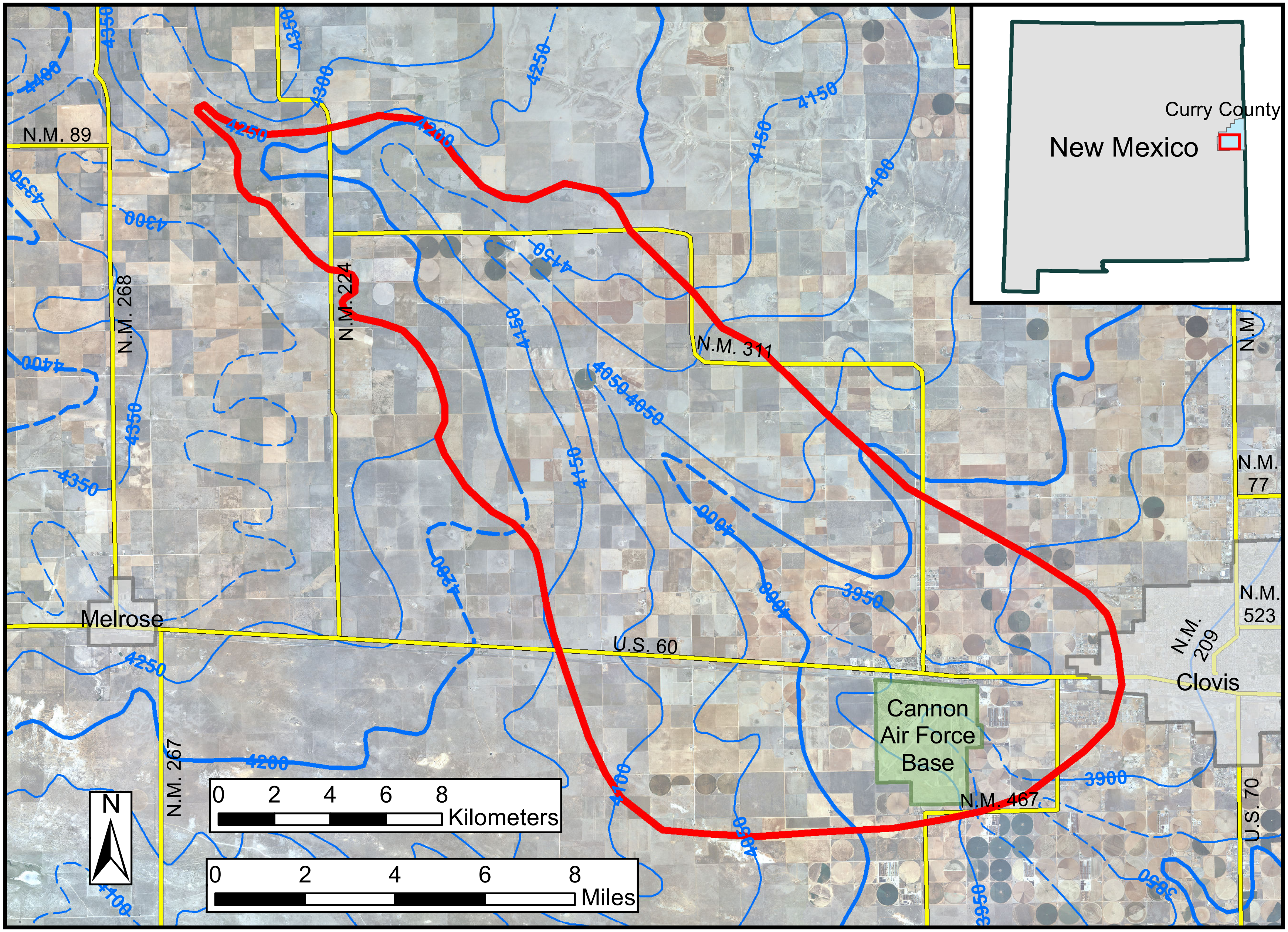


Figure 1. Map of the study area in Curry County, New Mexico. Study area outlined in red. Location of main map in red in the inset. Blue contours are the elevation of the base of the High Plains aquifer (in ft) from Hart and McAda (1985), after Cronin (1969).

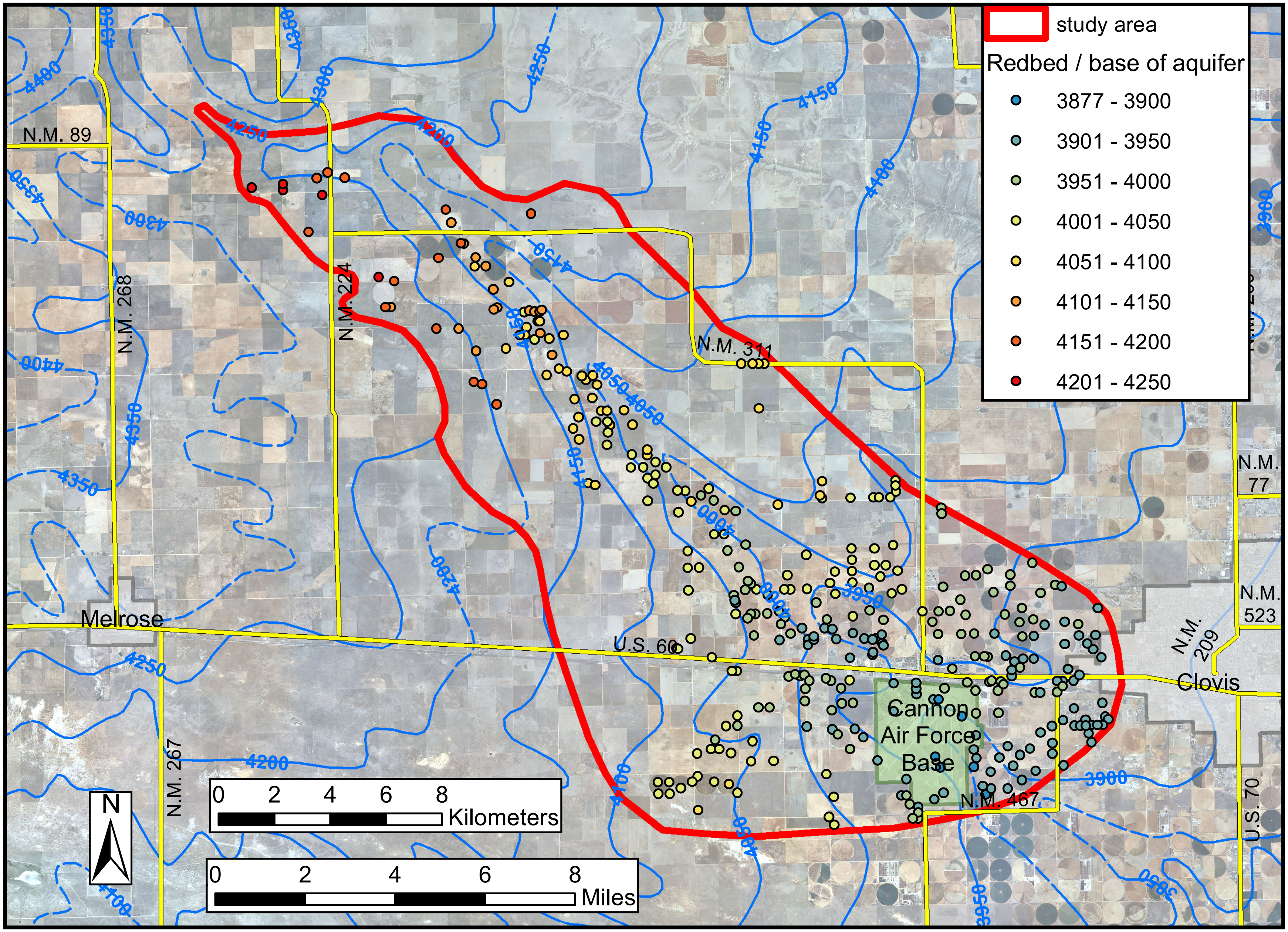


Figure 2. Wells with elevations (in ft) of the base of the High Plains aquifer/redbeds compiled for this study. Blue contours are the elevation of the base of the High Plains aquifer from Hart and McAda (1985), after Cronin (1969).

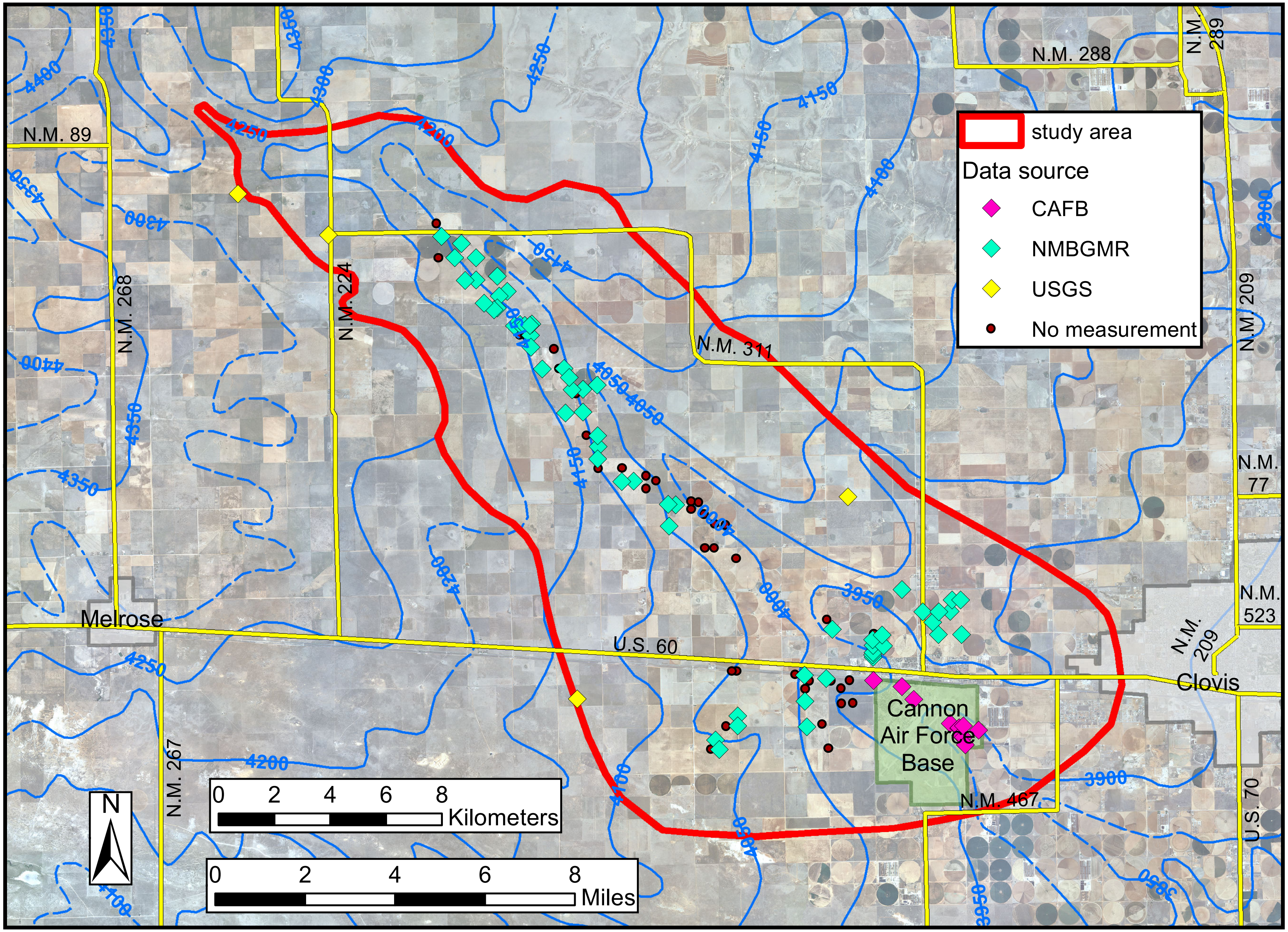
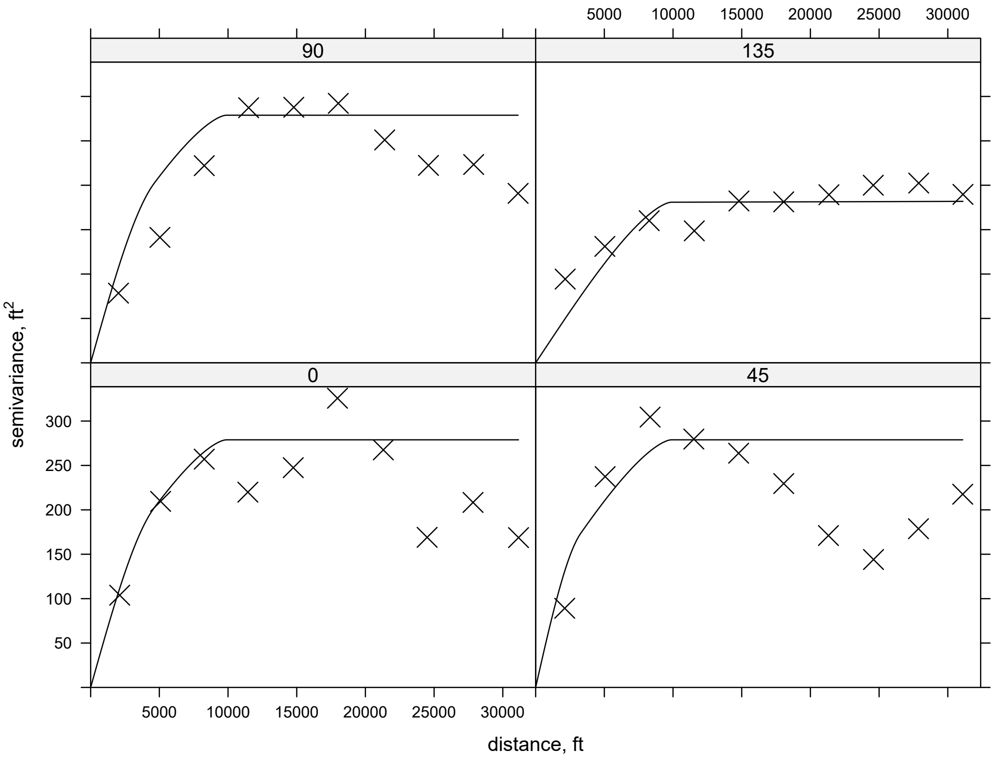


Figure 3. Wells with water-level elevations measured and compiled for this study. Blue contours are the elevation of the base of the High Plains aquifer from Hart and McAda (1985), after Cronin (1969). Data sources are Cannon Air Force Base (CAFB), New Mexico Bureau of Geology and Mineral Resources (NMBGMR), and U.S. Geological Survey (USGS). "No measurement" identifies wells recommended by the OLWC that could not be measured.

A



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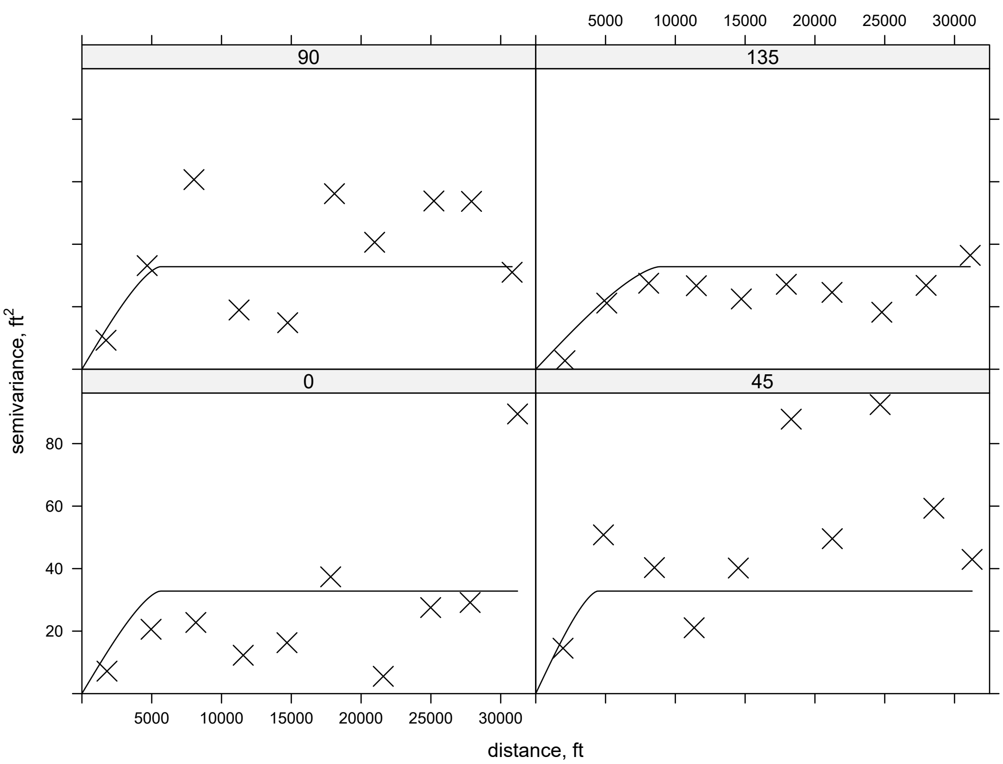

Figures 4A and 4B. Directional sample variograms of trend surface residuals (X) and fitted anisotropic models (solid line). By symmetry, the variograms in directions at 180° to those shown are identical. (A) Redbed elevation with zonal anisotropic model. Spatial correlation is highest (lowest semivariance) in the 135° direction (SE) along the axis of the paleochannel, but the model reaches its maximum semivariance (range value) at the same distance in every direction. (B) Water-level elevation with geometric anisotropic model. The range of the spatial correlation is larger in the 135° direction (SE) along the axis of the paleochannel, but the spatial correlation (highest semivariance) is the same in every direction.

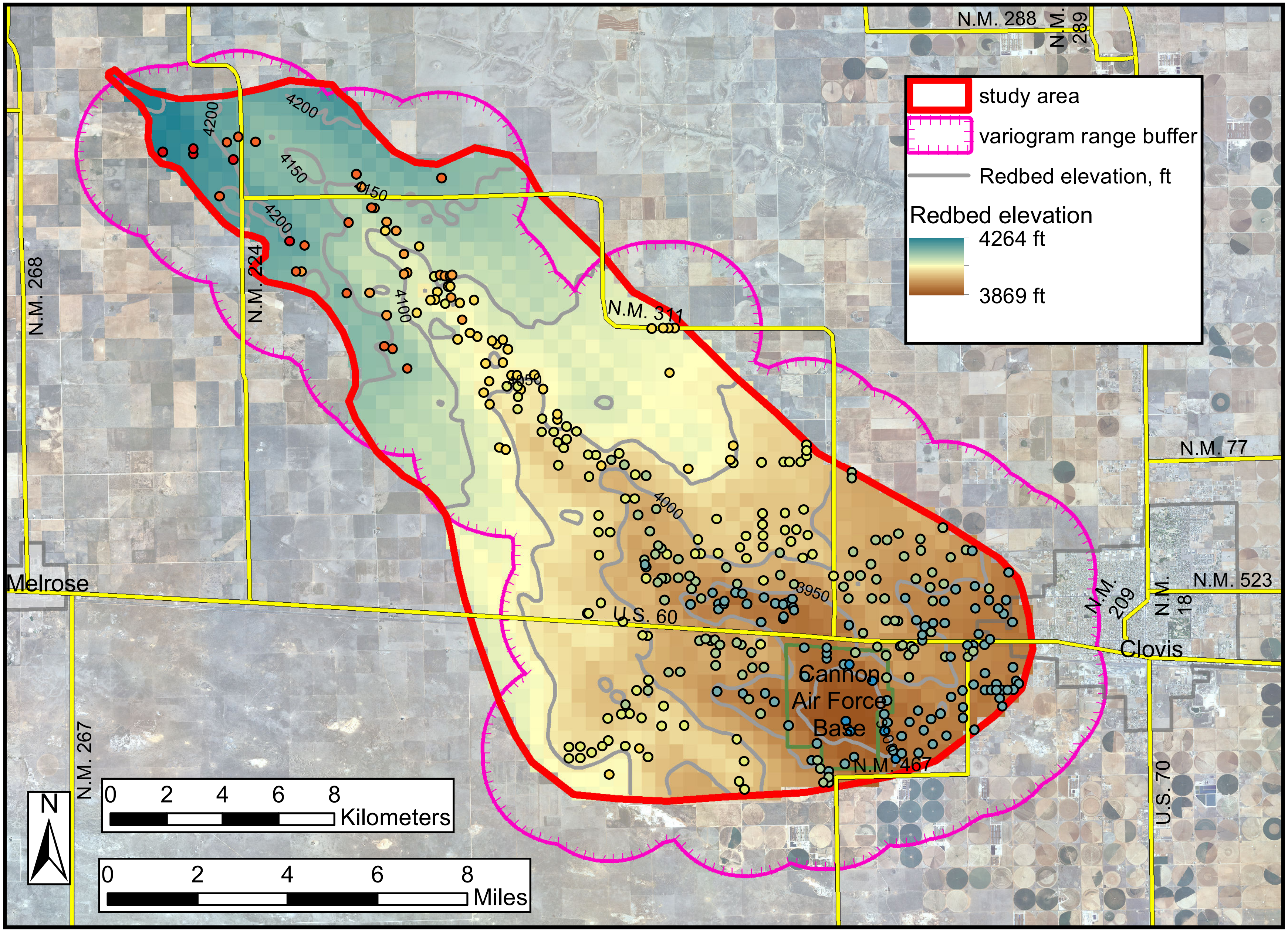

Figure 5A. Revised base of the High Plains aquifer/redbed elevation map. Colored circles are wells with redbed elevation compiled for this study, symbology as in Fig. 2. Circles with a radius equal to the redbed variogram range (9,842 ft; Fig. 4A) around each well were merged to create the variogram range buffer (in pink).

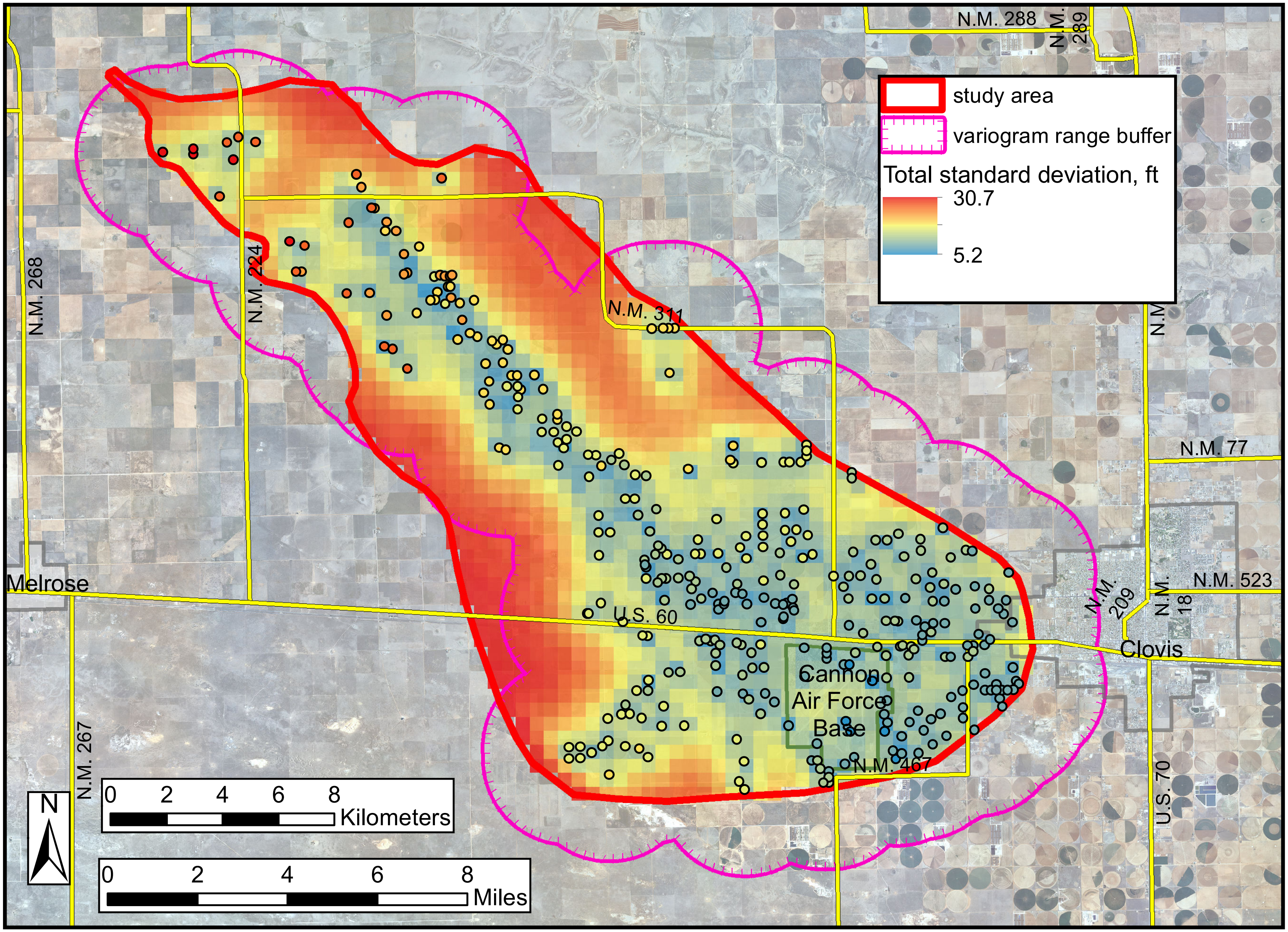

Figure 5B. Total standard deviation of the redbed elevation predictions (from eq. 2).

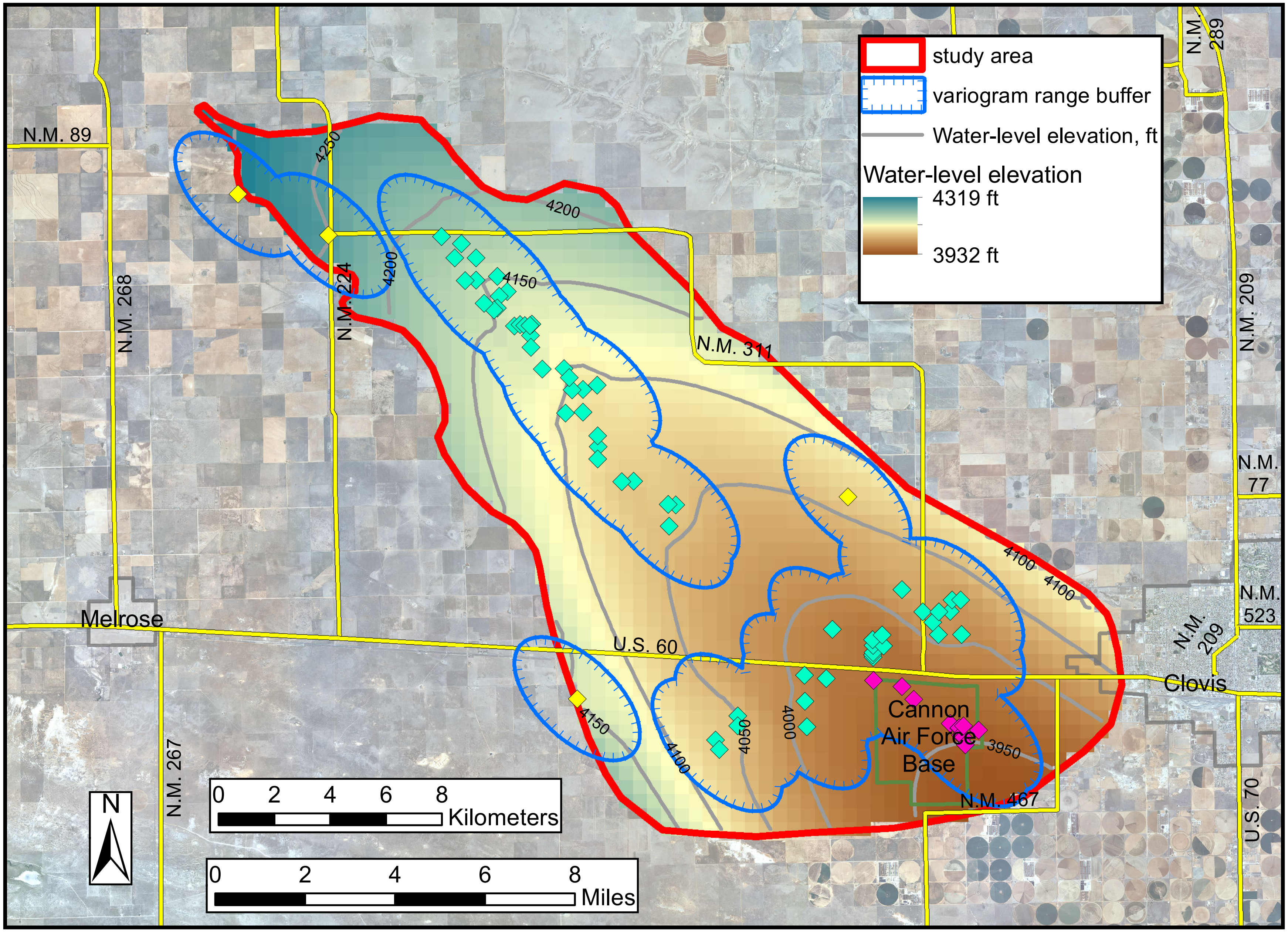

Figure 6A. Water-level elevation map. Wells symbolized as in Fig. 3. Ellipses with major and minor axes equal to the anisotropic variogram range (8,860 and 4,430 ft; Fig. 4B) around each well were merged to create the variogram range buffer (in blue).

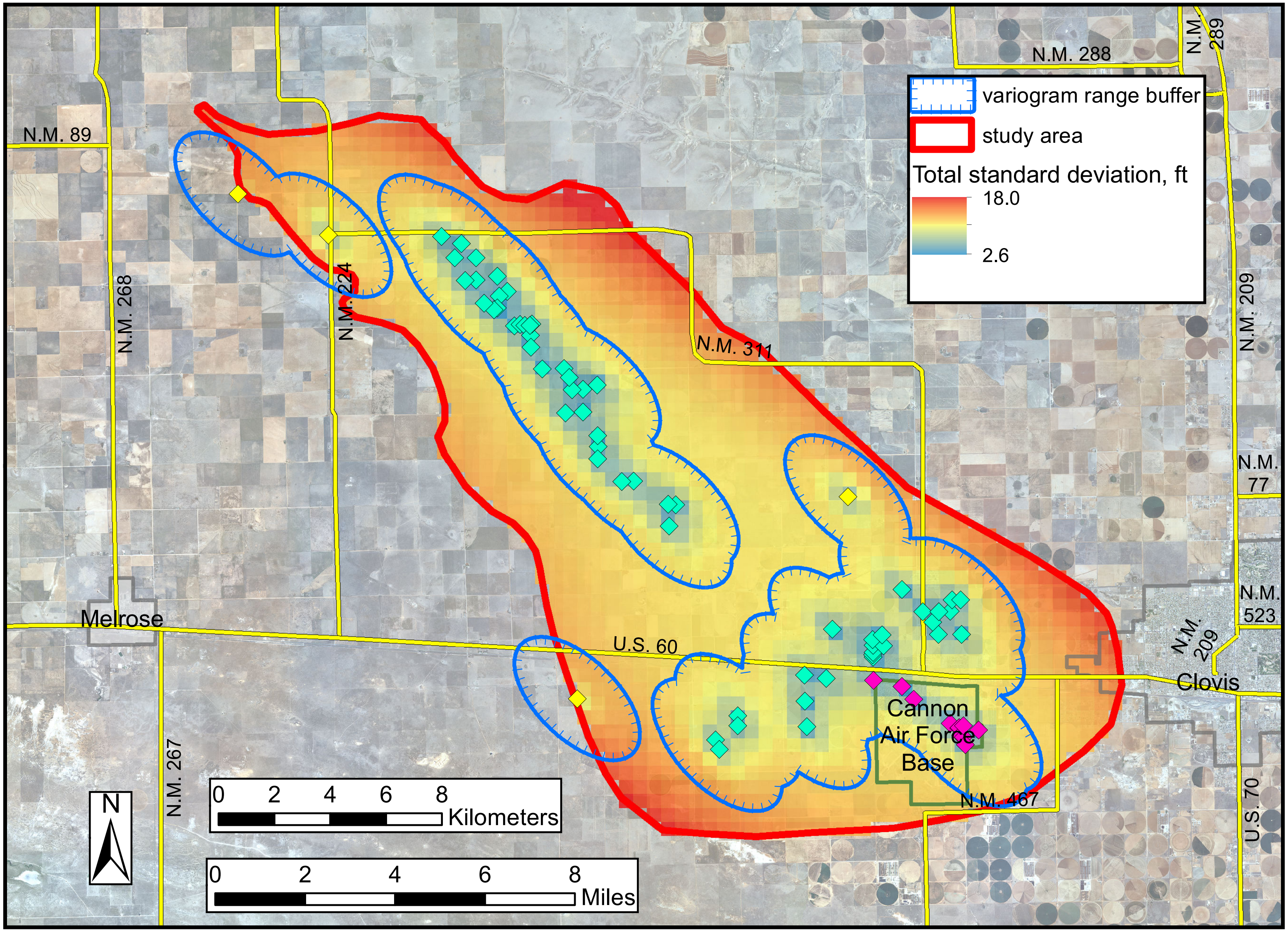

Figure 6B. Total standard deviation of the water-level elevation predictions (from eq. 2).

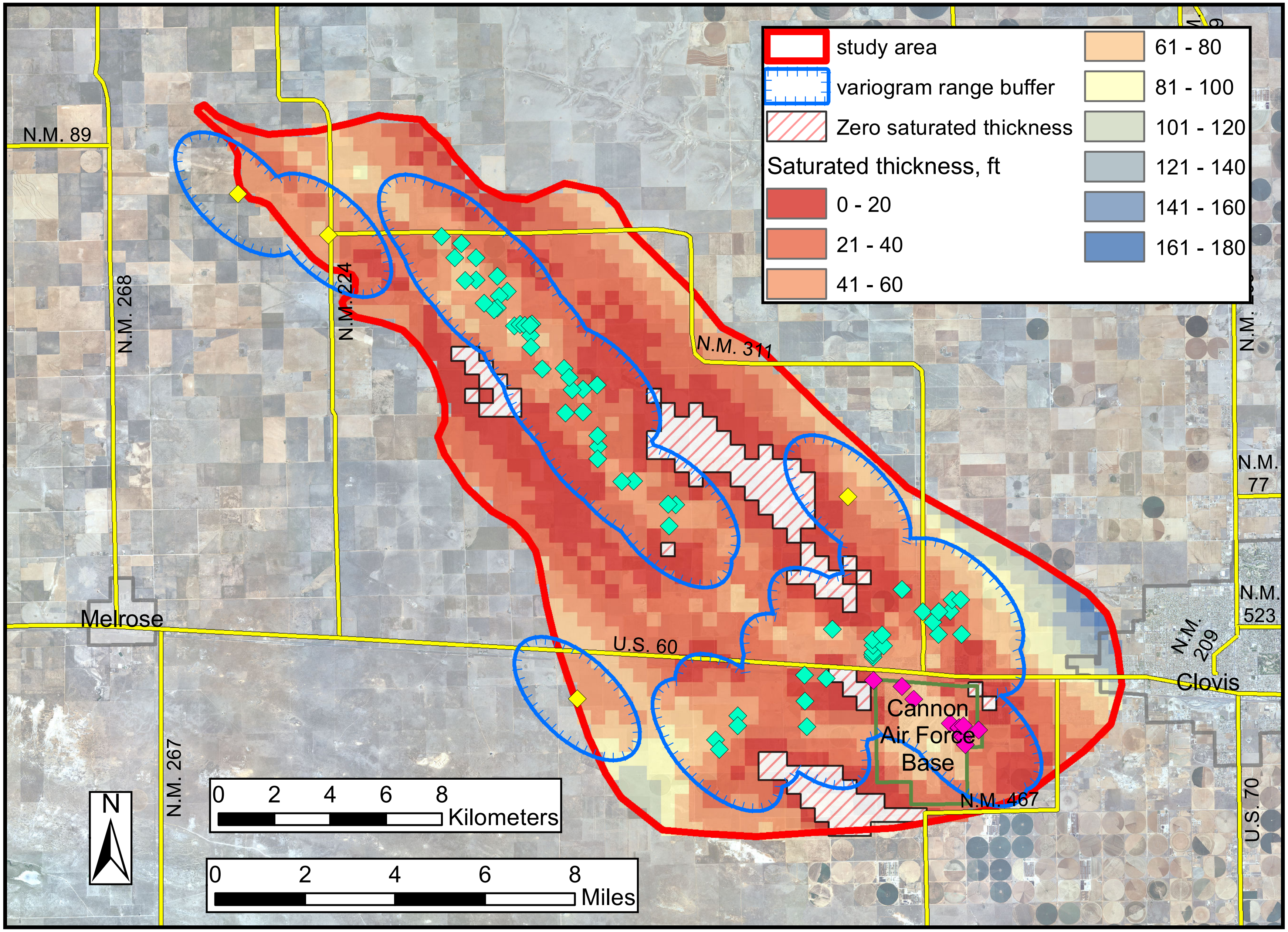

Figure 7. Saturated thickness map. Wells symbolized as in Fig. 3. Results outside of the variogram range buffer are less reliable and should be viewed with caution.

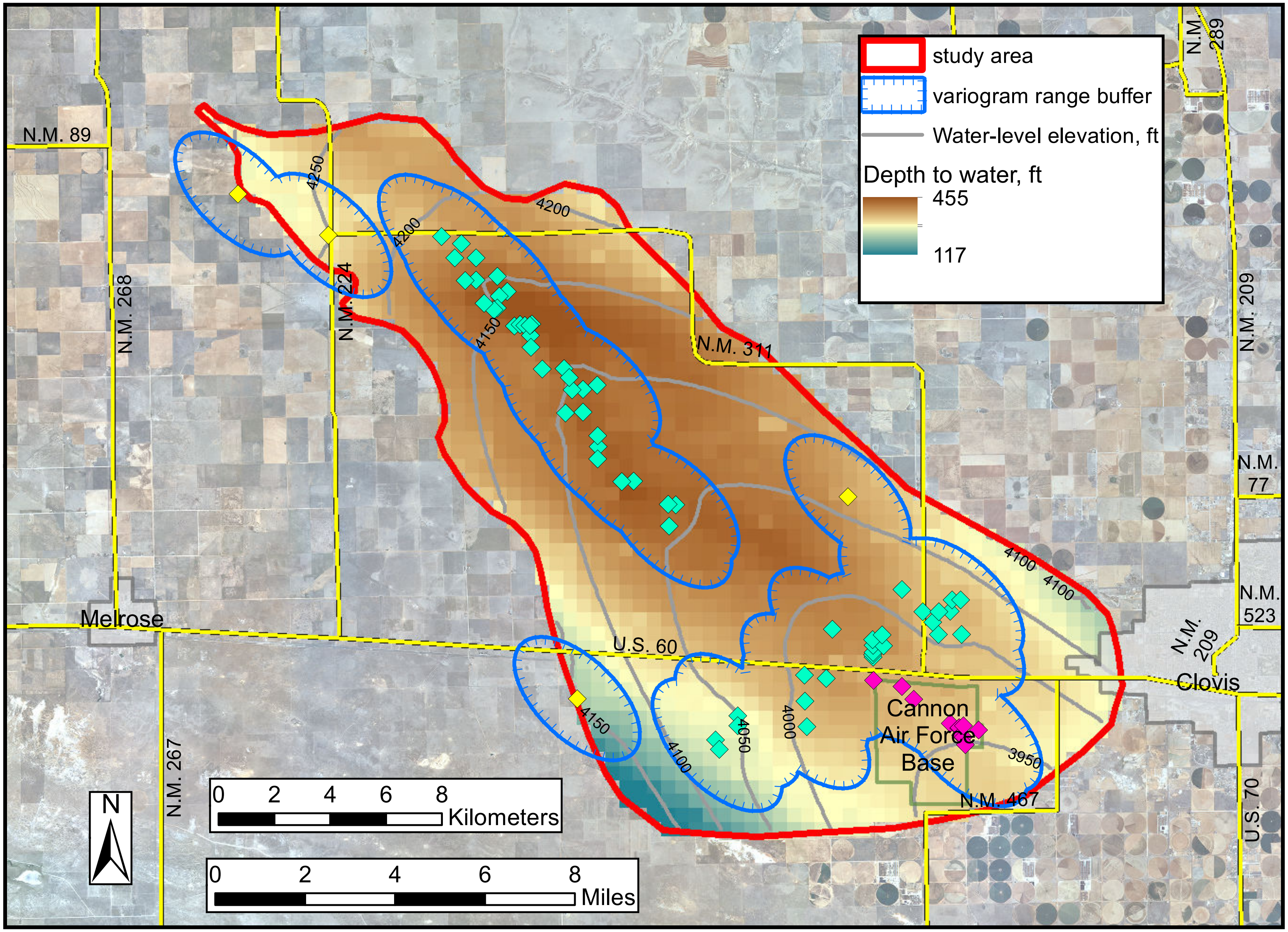

Figure 8. Depth-to-water map. Wells symbolized as in Fig. 3. Results outside of the variogram range buffer are less reliable and should be viewed with caution.

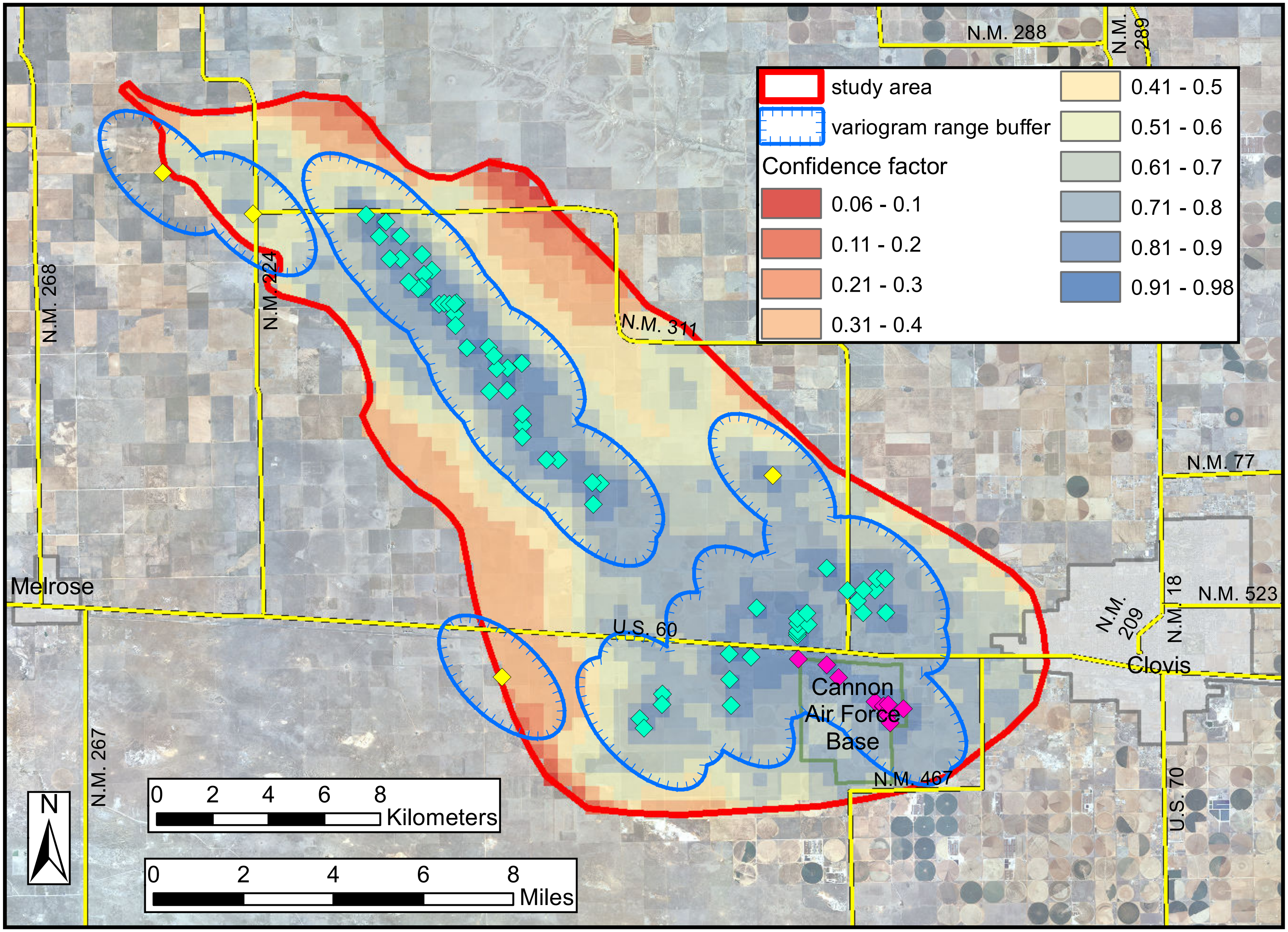

Figure 9. Confidence factor map. Wells symbolized as in Fig. 3. Results outside of the variogram range buffer are less reliable and should be viewed with caution.

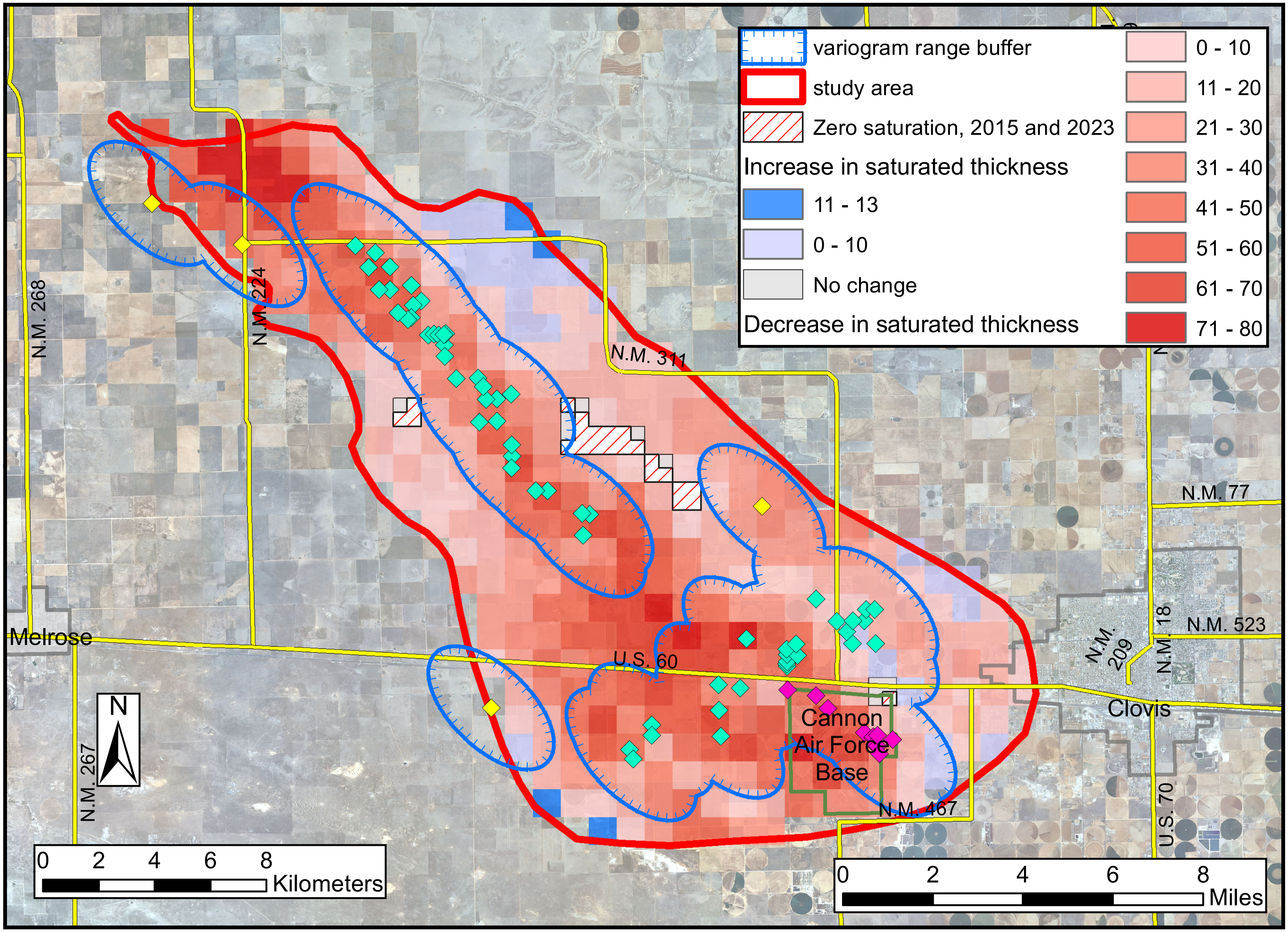

Figure 10. Change in saturated thickness from mid-2010s (2015) to 2023. Wells symbolized as in Fig. 3. Results outside of the variogram range buffer are less reliable and should be viewed with caution.

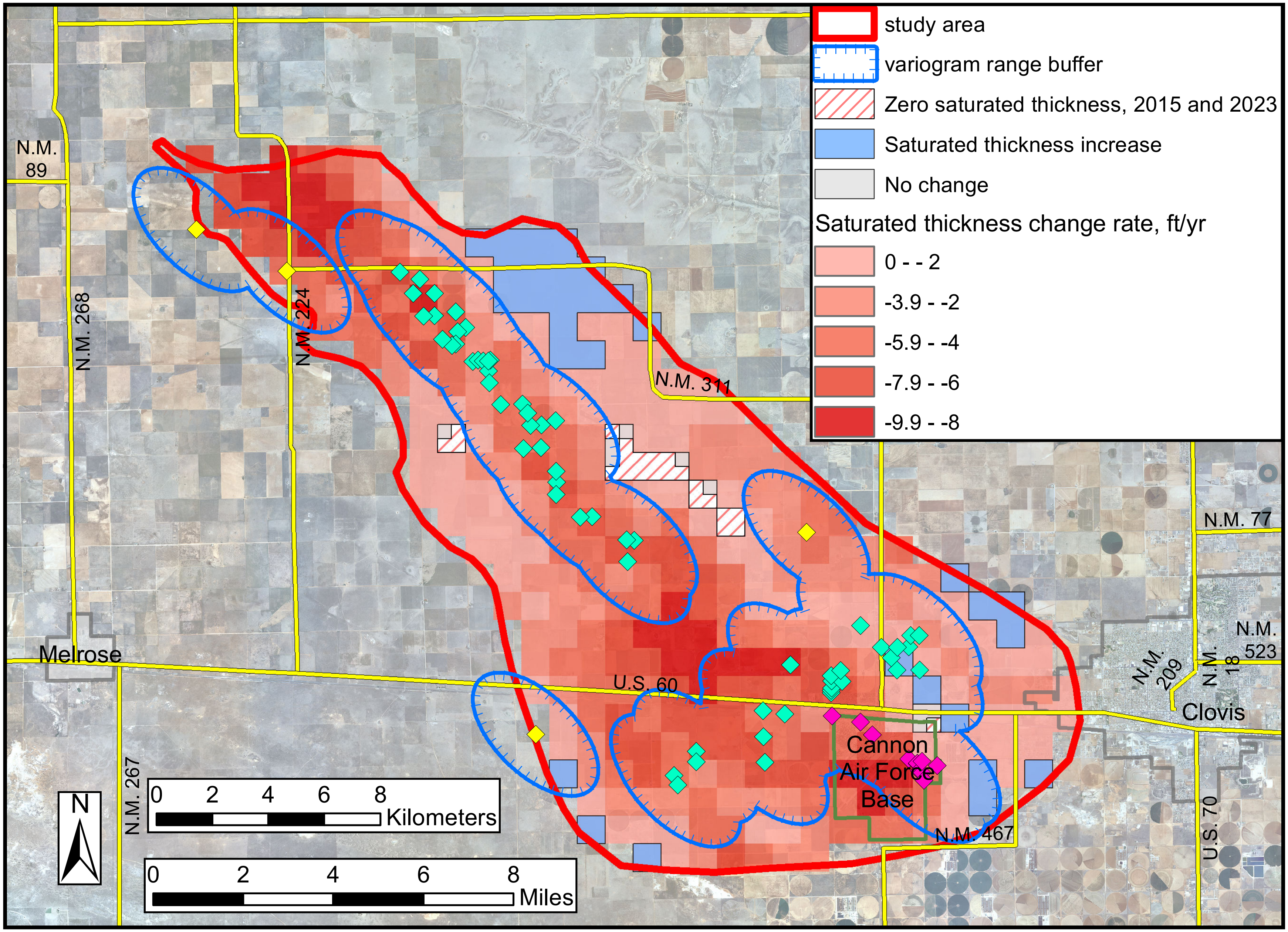

Figure 11. Rate of change of saturated thickness from mid-2010s (2015) to 2023. Wells symbolized as in Fig. 3. Results outside of the variogram range buffer are less reliable and should be viewed with caution.

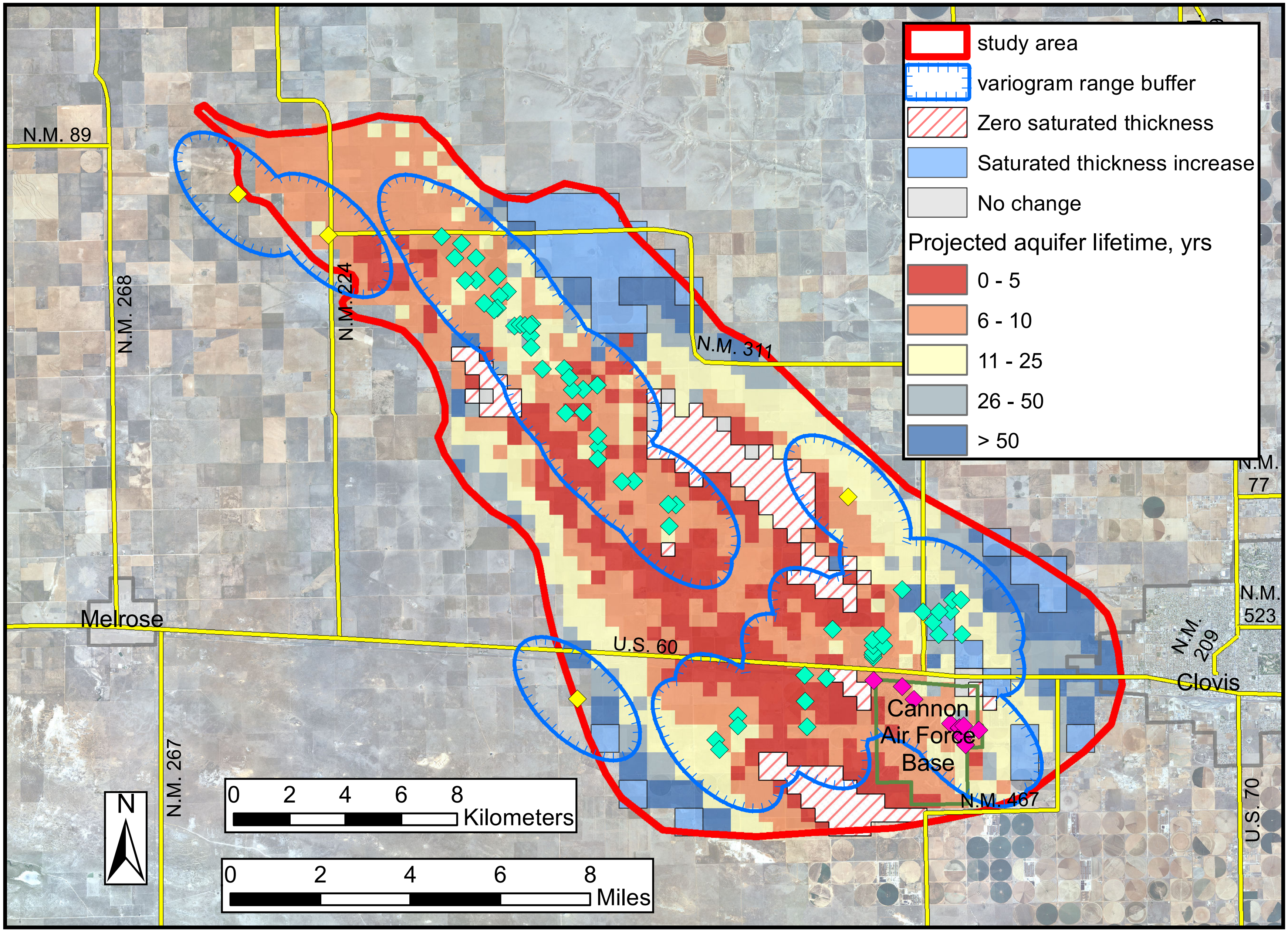

Figure 12. Projected lifetime from 2023 saturated thickness and 8-year change rate from mid-2010s (2015) to 2023. Wells symbolized as in Fig. 3. Results outside of the variogram range buffer are less reliable and should be viewed with caution.

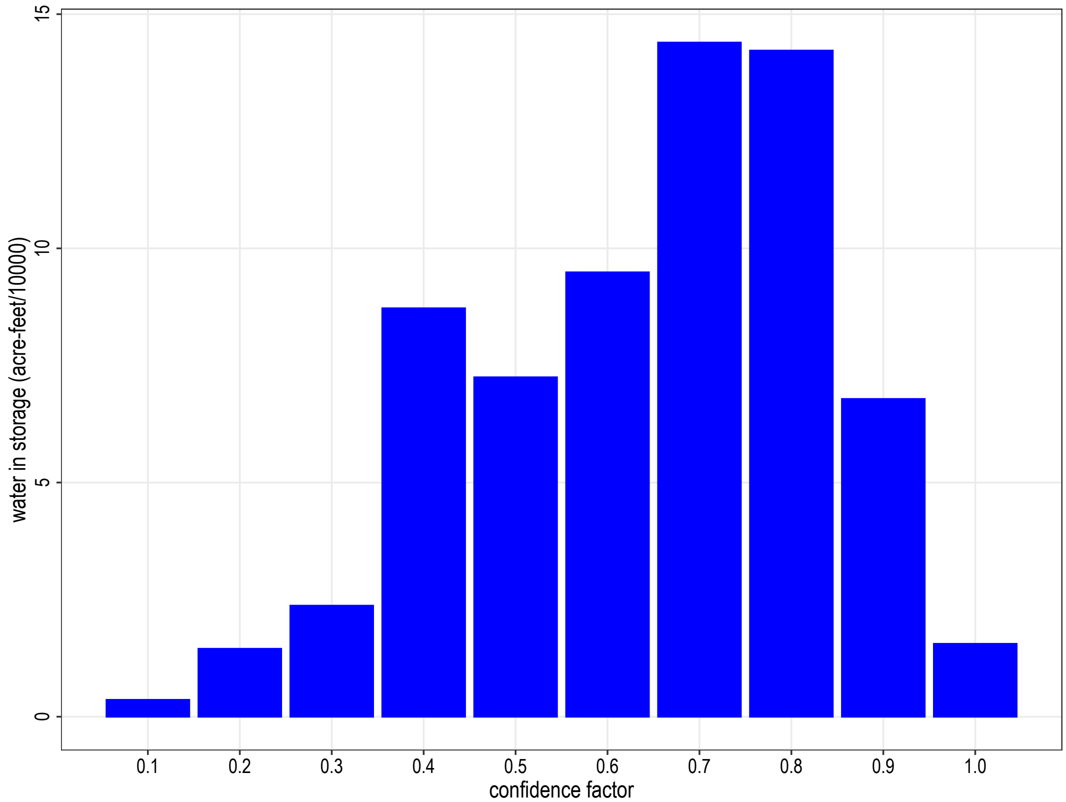

Figure 13A. Total groundwater in storage (666,000 acre-ft, base value with no confidence intervals) partitioned across regions of different confidence factor values (Fig. 9).

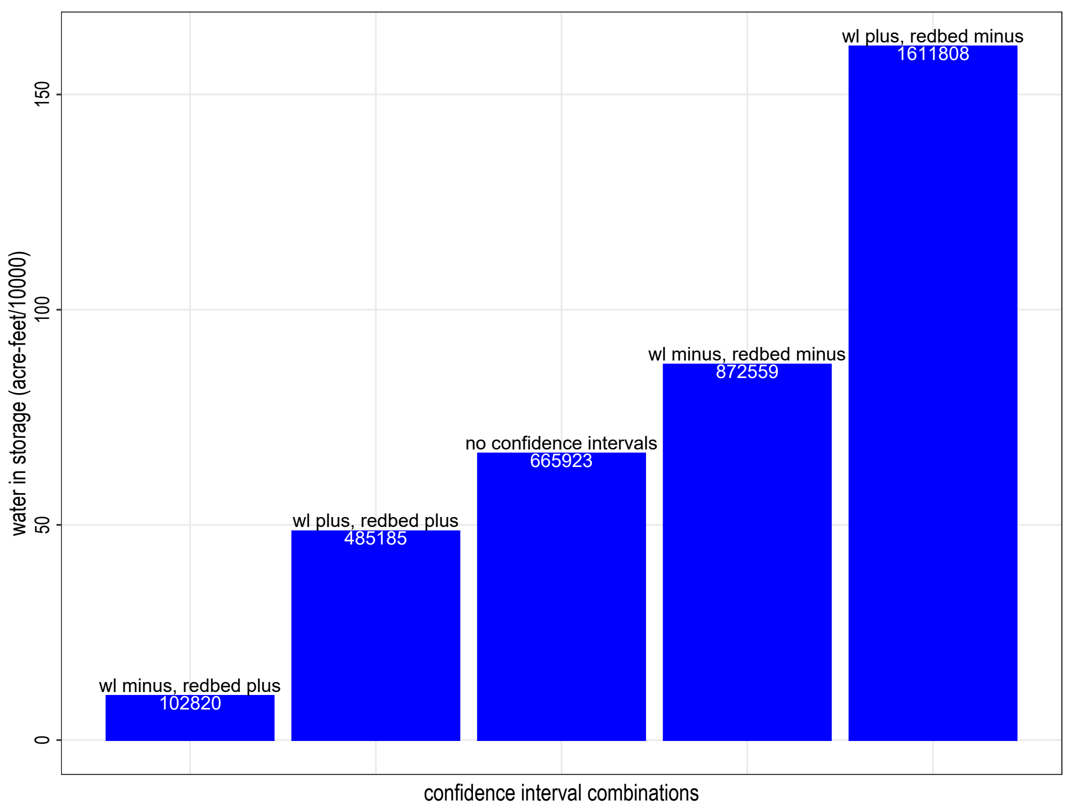

Figure 13B. Groundwater in storage calculated from saturated thickness using different combinations of confidence intervals about the base case with no confidence intervals. See the *Results and Discussion* section of the text for details. "wl" is water level. Minus indicates that lower confidence interval was used, plus indicates that upper confidence interval was used.

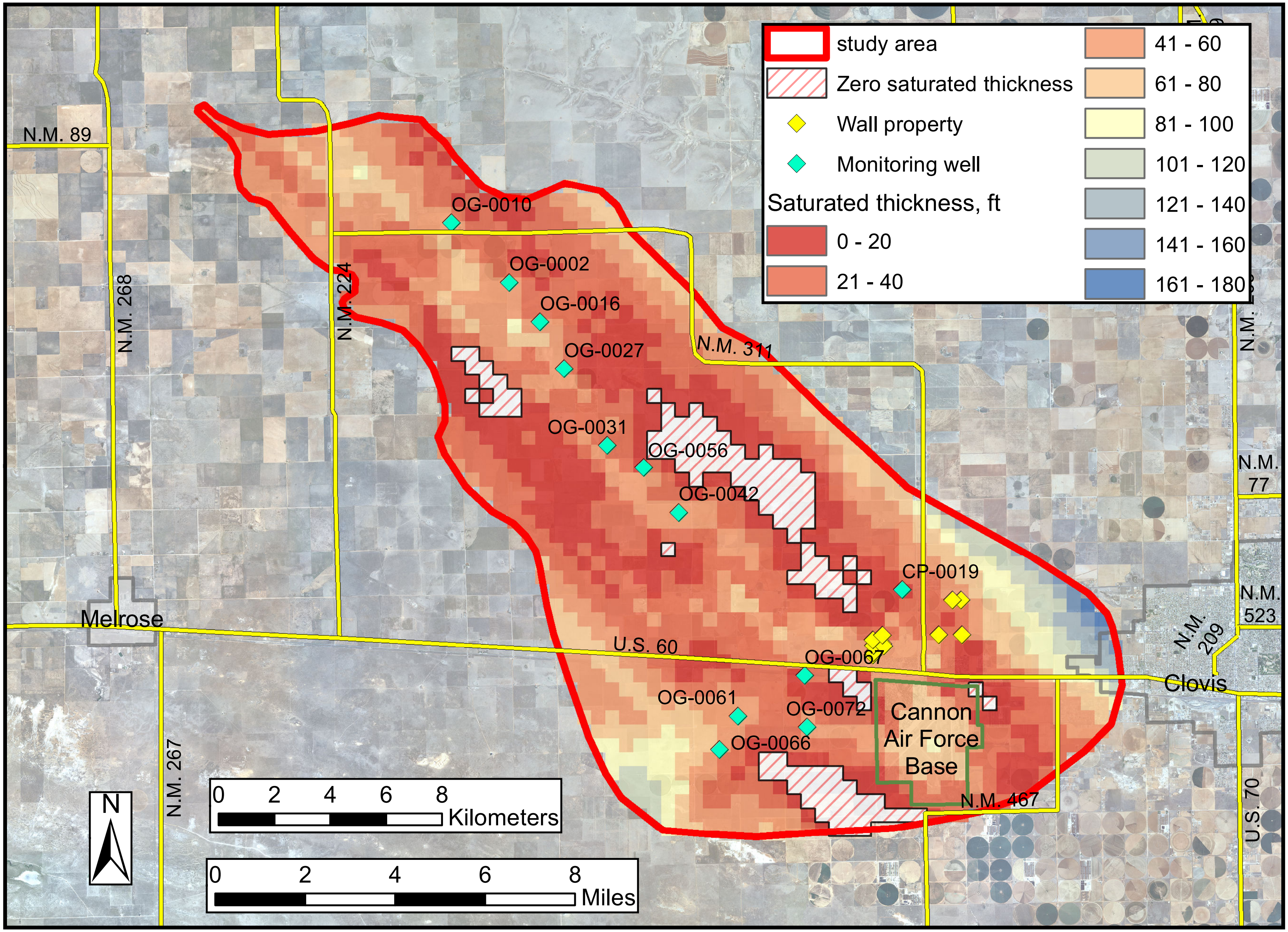

Figure 14. Wells recommended for future water-level monitoring.

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