APPRAISAL OF GROUNDWATER IN STORAGE IN THE OGALLALA AQUIFER BENEATH THE DUNCAN RANCH, HUTCHINSON AND ROBERTS COUNTIES, TEXAS

Letter Report

prepared for

Canadian River Municipal Water Authority

and

E. B. Duncan Family Limited Partnership, A. A. Gustafson, and D. D. Weathers

by

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QAe7166

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SUMMARY

This study makes an assessment and appraisal of groundwater in storage in the Ogallala aquifer beneath Duncan Ranch in Hutchinson and Roberts Counties, Texas. Data used as a basis for mapping the base and the water table of the Ogallala aquifer included results from 10 boreholes drilled on Duncan Ranch, water-level readings at nearby wells, data on the elevation of the top of red beds in the vicinity of Duncan Ranch, and parameters mapped in the regional computer model of the Ogallala aquifer. Gamma and resistivity logs from the 10 Duncan Ranch boreholes were used as a basis for estimating water quality.

A best estimate of the volume of water in place in sands and gravels of the Ogallala aquifer beneath Duncan Ranch is 380,000 acre-feet. Different estimates of porosity give a range in water volume from ~320,000 to ~440,000 acre-feet. The best estimate is the midpoint of this range, calculated within each section on Duncan Ranch. Chloride (*Cl*) concentration estimated for a subset of this volume averages 85 mg/L. Because the resistivity method overestimates *Cl* concentration of <15 mg/L, the true average is probably <85 mg/L. All of this water volume might not be recoverable. Hydrogeologic modeling would provide a technical basis for evaluating the performance of various well-field scenarios but was beyond the scope of this study.

INTRODUCTION

The purpose of this analysis is to make an assessment and appraisal of the groundwater in storage in the Ogallala aquifer beneath specified sections of Duncan Ranch in Hutchinson and Roberts Counties, Texas (fig. 1). The appraisal was undertaken at the request of the Canadian River Municipal Water Authority (CRMWA) and Mr. Ronnie Cox, acting as representative of the E. B. Duncan Family Limited Partnership, A. A. Gustafson, and D. D. Weathers, as part of a contract of sale of the groundwater beneath the ranch property.

We approached the analysis as follows:

- Discuss field-sampling plan with Lee Wilson and Associates, Inc. (LWA);
- Analyze field data collected by LWA consisting of information from 10 boreholes drilled on Duncan Ranch;
- Prepare and digitize maps representing the base and the water table of the Ogallala aquifer in the area around Duncan Ranch;
- Calculate saturated thickness and volume of water in the Ogallala aquifer beneath Duncan Ranch, taking these and other data into account; and
- Estimate the weighted average quality of groundwater in the Ogallala aquifer beneath Duncan Ranch.

This Letter Report documents the data and methods that were used in the analysis and reports the findings.

DATA

Sources of Data

Four sets of data were used as a basis for mapping the base and the water table of the Ogallala aquifer:

(1) results from 10 boreholes drilled on Duncan Ranch,

(2) water-level readings at 26 wells reported by the Panhandle Groundwater Conservation District (PGCD),

(3) data on the elevation of the top of red beds in the vicinity of Duncan Ranch as interpreted by PGCD staff, and

(4) parameters mapped in the regional computer model of the Ogallala aquifer (Dutton and others, 2001).

First, LWA drilled 10 boreholes on Duncan Ranch, ran geophysical logs, recorded logs of drill cuttings, observed water levels in two boreholes completed as monitoring wells, surveyed well locations, and collected related information. The field program followed a drilling plan that had been reviewed prior to the start of the investigation. Naming of boreholes was divided informally between north and south parts of Duncan Ranch (fig. 1). Borehole data were significant for providing an estimate of the elevation of the base of the Ogallala aquifer and a representation of how water quality varies vertically within the aquifer at tested locations.

A second data set was provided by Mr. Ray Brady (PGCD) listing approximately 26 water-level readings in wells between October 2003 and March 2004 in the vicinity of Duncan Ranch. Most of these wells are thought to be completed in the Ogallala aquifer, and the water-level elevations derived from these data were assumed to be a reasonable estimate of the top of the saturated column in the Ogallala aquifer.

A third set of data included estimates of the elevation of Permian red beds recorded from various water wells and compiled by PGCD. The top of these red beds is taken as the base of the Ogallala aquifer.

The fourth data set was taken from the regional computer model of the Ogallala aquifer adopted by the Panhandle Water Planning Group and the Texas Water Development Board (Dutton and others, 2001). This computer model provided a regional framework for mapping the base, water table, and specific yield of the Ogallala aquifer, supplementing the site-specific field data.

Base of the Ogallala Aquifer

Three of the four data sets (water-level data were not used here) were merged to make a map of the elevation of the top of Permian red beds, assumed to be equivalent to the base of the Ogallala aquifer. Merging these data allowed data from the 10 Duncan Ranch boreholes to be interpreted in a regional geological context.

The geophysical and driller's logs are consistent and show mainly two lithologies: (1) fine- to coarse-grained sand and gravel and (2) red or brown shale (fig. 2). In two of the boreholes (DS-1 and DS-2), drilling proceeded through an 85- to 140-ft-thick section of red shale and into an additional thick section of sand. Both of these boreholes ended in red shale underlying deeper sand deposits. Borehole logs for three other locations on the south part of Duncan Ranch (DS-3, DS-4, and DS-5-1) all contained reports of Alibates-like material in red shale. The Alibates is an Upper Permian Formation ~250 to 255 million years old. These three boreholes were not drilled deeper than the red shale. It was assumed for this analysis that this pick of the top of the Permian section was correctly made. Picks of the base of the aquifer used in the analysis on the basis of geophysical and driller's logs are listed in table 1.

Differences in elevation of the top of red beds or base of the Ogallala Formation within the 8,800-acre area are consistent with the geological setting of Duncan Ranch. It is well known that dissolution of Permian salt and subsidence of the ground surface were contemporaneous with deposition of the Ogallala Formation (Gustavson and Finley, 1985). Data from Duncan Ranch boreholes DS-3, DS-4, and DS-5-1 might represent an area with less salt dissolution and less ancient ground-surface subsidence. Boreholes DS-1 and DS-2 show thicker deposits and may lie within a local collapse basin of Miocene-Pliocene age (timing of deposition of the sediments making up the Ogallala Formation in the study was approximately 4.6 to 5.3 million years ago).

To supplement the site-specific well data, values for the base of the aquifer were extracted from the regional computer model of the Ogallala aquifer (Dutton and others, 2001). Most of the values for model cells in the vicinity of Duncan Ranch match the red-bed data compiled by PGCD because both data were derived from the same source. For contouring the elevation of the base of the aquifer, model values were not used in the cells where they were superseded by Duncan Ranch data or by PGCD red-bed data. Data used in contouring are shown in figure 3.

Making a reasonable map of these data requires some level of geological interpretation. It was assumed that locally thick areas represent deposition in ancient salt-dissolution-zone subsidence basins. The basins were assumed to have some paleostructure or paleotopographic relationship to one another. In this analysis they were connected as if they lay along ancient stream courses.

Steps in making the elevation map of the base of the aquifer were as follows:

(1) Interpret depth to red beds from Duncan Ranch geophysical and driller's logs and convert to elevation above sea level.

(2) Hand contour merged elevation data, honoring Duncan Ranch and PGCD data and using groundwater model data as an envelope around the other data.

(3) Digitize traces of the hand-contoured lines of elevation.

(4) Merge digitized elevation-contour traces with original well and model data, then use Surfer (version 7), a digital contouring program, to grid and remap the elevations. It was found that using default settings for the kriging algorithm (linear model, slope=1, no anisotropy, no drift) resulted in the gridded map that matched the hand-drawn map.

(5) Generate a grid of regularly spaced coordinates in rows and columns spaced at a distance of 0.1 mile at which to sample the digital elevation map.

(6) Use Surfer (version 7) to calculate the value of the base elevation at each 0.1-mile sampling point.

Elevations at the 0.1-mile sampling points coinciding with the 10 boreholes gave a match in elevation within ~1 percent of the range in measured elevations.

Water-Table Elevation

Calculated water-table elevations from the PGCD data set, boreholes DS-1 and DS-2, and a nearby windmill were superposed on (a) a digital elevation model (DEM) map of ground-surface elevation and (b) a map of simulated water levels representing

December 2003 in the regional groundwater model (Dutton and others, 2001). DEM data were obtained from the U.S. Geological Survey National Elevation Dataset (http://seamless.usgs.gov/viewer.htm). Water-table elevation contours were drawn across the Duncan Ranch area on the basis of the following assumptions:

- Water-levels in the PGCD data set were correct.
- Water-level elevations should be higher beneath upland areas and lower beneath valleys, draws, and creeks. This is a reasonable assumption in this area except in the vicinity of pumping. Data were honored for wells, for example, in well 6-16-904, which might show pumping-related drawdown.
- The strike of water-level contours simulated using the regional model (Dutton and others, 2001) was representative of the trend near Duncan Ranch; simulated water-level elevations at individual model cells were not used.

Steps in making the water-table elevation map were similar to those for making the map of the base elevation:

(1) Hand-contour merged water-table elevation data on the basis of the just-stated assumptions.

(2) Digitize traces of the hand contoured lines of elevation.

(3) Merge digitized elevation-contour traces with original PGCD and Duncan Ranch water-level data, then use Surfer (version 7) to grid and remap elevations. The kriging algorithm again resulted in the best version of the gridded map.

(4) Use Surfer (version 7) to calculate the value of the elevation at each 0.1-mile sampling point.

The resulting map of the water table is shown in figure 4. Elevations at the 0.1-mile sampling points coinciding with the reported data gave a match of ~1 percent of the range in measured elevations. Water-table elevations were interpolated for the 6.4-acre grid areas that represent Duncan Ranch borehole locations (table 1). Depth to water (beneath ground surface) was determined for these locations by subtracting the interpolated water-table elevation from ground surface. Water levels at DN-1 and DN-3 are expected to be shallow; depth to water of nearby well 6-15-902, for example, is 26 ft.

Other Mapping

Driller's logs report 85- to 140-ft thick deposits of red shale in boreholes DS-1 and DS-2. These were assumed to have been derived as sediment eroded off paleo-topographic highs, topped by Permian red shale, and shed into the valleys as they were being filled by sands and gravels carried in from mountains to the west. These thick deposits of reworked shale might not contribute nearly as much groundwater to production wells as sands and gravels will. These red beds were assumed not to contribute to available groundwater supplies. To exclude thickness of these deposits in calculations of saturated thickness, we assumed that there was an abrupt increase in thickness of Ogallala Formation south of boreholes DS-3, DS-4, and DS-5-1 and north of boreholes DS-1 and DS-2. The assumed location of this boundary is shown in figure 3; red beds lie south of the dashed line representing the edge of the subsidence basin or paleovalley. Thickness of these red beds within the Ogallala section was assumed to increase from east to west. Thickness was extrapolated from the two boreholes, and contours were traced and digitized following steps similar to those of the aquifer-base and water-table maps.

Geophysical Log Interpretation

Interpretation of water quality from geophysical logs focused on gamma and deep-resistivity logs. Analysis and transformation of geophysical logs were done using Landmark Stratworks® and Petroworks®.

We used the ratio method (Schlumberger, 1989, eqn. 4-6) to estimate apparent resistivity of the groundwater. The equation for the ratio method is

$$\frac{R_{xo}}{R_t} = \left(\frac{S_w}{S_{xo}}\right)^2 \bullet \frac{R_{mf}}{R_{wa}} \tag{1}$$

where R_{xo} is resistivity of the formation flushed with drilling water, R_t is true formation resistivity, S_w is water saturation of the formation, S_{xo} is water saturation of the flushed zone, R_{mf} is resistivity of the mud filtrate, and R_{wa} is apparent resistivity of groundwater in the formation. Because there are no nonaqueous phase liquids (such as hydrocarbons) in the aquifer, the ratio S_w/S_{xo} is 1, and equation 1 can be rearranged as

$$R_{wa} = R_{mf} \bullet \left(\frac{R_{xo}}{R_t}\right)^{-1} \tag{2}$$

R_{mf} was estimated from a report that the drilling fluid used water with a specific conductance of 682 μS/cm (R. Goodwin, email to K. Satterwhite, June 2004), or a resistivity of ~15 ohm-m. The ratio R_{xo}/R_t was estimated from an empirical relationship observed for resistivity logs (Schlumberger, 1989, eqn. 8-18b):

$$\frac{R_{xo}}{R_t} = 1.85 \bullet \left(\frac{FEFE}{RILD}\right) - 0.85 \tag{3}$$

where *FEFE* and *RILD* are two deep-resistivity logs run in the Duncan Ranch boreholes. The value of R_{wa} (in ohm-m) from equation 2 was converted to specific conductance (SC_w in μS/cm) using

$$SC_w = 10{,}000 / R_{wa} \qquad (4)$$

Finally, dissolved chloride (*Cl*) concentration (in mg/L) was calculated from specific conductance using an empirical relationship (R. Miller, written communication, 2004) of

$$Cl = 0.28 \bullet SC_w - 120.83 \qquad (5)$$

Equation 5 was applied where SC_w was >450 μS/cm. Where SC_w calculated from the logs was <450 μS/cm, dissolved *Cl* was assumed to be 15 mg/L. Equation 5 is a reasonable estimate of the linear relation between *Cl* and SC_w for water samples from the Ogallala aquifer listed for Roberts and Hutchinson Counties (fig. 6).

Equations 2 through 5 were applied to each of the 10 boreholes. Average *Cl* concentration was calculated by eliminating several intervals of the logs. The following intervals were excluded:

(1) above the projected or measured water table at each borehole,

(2) beneath the pick for the base of the Ogallala aquifer or top of Permian red beds,

(3) within red-bed zones within the Ogallala aquifer at boreholes DS-1 and DS-2 (fig. 2), and

(4) where gamma-log values exceeded a specified threshold (V_{sh}).

The gamma-log threshold of 15 (dimensionless) was calculated as follows, following procedures developed for Campbell Ranch by LWA (R. Miller, written communication, 2004):

$$V_{sh} = 0.083 \bullet (2^{3.7 I_{sh}} - 1) \tag{6}$$

where

$$I_{sh} = \frac{\gamma_i - \gamma_{\min}}{\gamma_{\max} - \gamma_{\min}} \tag{7}$$

and γ_i is the gamma-log reading at a given depth and γ_{min} and γ_{max} are the smallest and largest gamma values, respectively, in the entire logged section. Equation 6 is a form of the Larionov equation. Equation 7 scales gamma-log values between 0 and 1 for the entire logged section of the well. Where gamma-log values exceed the specified threshold, the clay content of the aquifer matrix may contribute significantly to resistivity and interfere with applying equations 2 and 3 to estimating water quality from resistivity logs. To estimate the sensitivity of results to the selected threshold value, the value of the gamma-log threshold was varied by ±2 and ±5, and average *Cl* concentrations were recalculated with different included intervals of the resistivity logs.

We considered using another approach for calculating dissolved chloride from resistivity logs that was used previously by LWA as part of studies on Campbell Ranch. In this approach, apparent water resistivity is calculated from

$$R_{wa} = \phi \bullet R_t \bullet R_m / (R_m - \phi \bullet R_t) \tag{8}$$

where R_m is matrix resistivity and ϕ is effective porosity (R. Miller, written communication, 2004). Matrix resistivity is specified for different texture and composition of the aquifer matrix (for example, 54 ohm-m for fine-grained intervals, 81 ohm-m for medium sand, and 580 ohm-m for coarse sand and gravel). Equation 8 would be applied in place of equation 2. We did not apply this approach in this study because we found calculated SC_w logs to be too irregular, perhaps because of how we applied R_m correction factors.

CALCULATION OF SATURATED THICKNESS AND VOLUME OF GROUNDWATER

Values for aquifer base, water-table elevation, red-bed thickness, and specific yield were determined for the 0.1-mile sample points and were tallied in an Excel worksheet. Results were then summed for the 0.01-square-mile sample areas within the footprint of Duncan Ranch (table 2). Calculations for each 0.1-mile sample point included

- Total saturated thickness (T) = Water-table elevation (WLE) minus aquifer-base elevation (B)
- Saturated thickness less red beds (T*) = Total thickness (T) minus red-bed thickness (rbt)
- Water volume (V*) = Saturated thickness less red beds (T*) × sample area (0.01 square miles) × assumed effective porosity.

One estimate of effective porosity was specific yield, as mapped by Knowles and others (1984) for the Ogallala aquifer and used in the regional groundwater model (Dutton and others, 2001). The specific-yield values reported by Knowles and others (1984) probably give a good estimate of effective porosity (J. Ashworth, written communication, June 2004). Specific yield averages ~16 percent in both Duncan Ranch and Campbell Ranch areas; 16.4 is an average for Duncan Ranch sections. Another value for effective porosity was assumed to be 23 percent, which was used previously in calculations for Campbell Ranch (R. Miller, personal communication, 2004). Effective porosity and specific yield at this step were assumed to be an average for the entire saturated thickness.

Tallied values of saturated thickness and water volume on the 0.1-mile sample spacing were imported as a table into ArcView (version 3.3). Sample points were linked to a uniform grid of cells with an area of 0.01 square mile in an Albers equal-area projection. The shapefile with the uniform grid of cells was then "intersected" (an ArcView geoprocessing wizard routine) with the shapefile for Duncan Ranch sections. The result is a shapefile with a grid of sample cells having an area of ≤0.01 square mile; cells along section edges have a smaller area. Average saturated thickness and volume of water were summed over the sample-cell estimates for each section to be calculated (table 2). Figure 5 shows the spatial variation in saturated thickness at Duncan Ranch.

Effective porosity, for which there are very few data, has the greatest uncertainty in the analysis. Error in digitizing the various maps is ~1 percent, and geological interpretation and contouring of data probably have an error of <5 percent. Uncertainty in effective porosity (16 versus 23 percent), however, results in uncertainty in volume estimate of as much as 40 percent.

The high estimate of groundwater volume is ~440,000 acre-feet (assuming 23 percent porosity), and the low estimate is ~320,000 acre-feet (assuming Knowles and others [1984] specific-yield values that average 16.4 percent) (table 2). A compromise between the range of 16.4 to 23 percent porosity is to split the difference. Accordingly the best estimate might be that there is 380,000 acre-feet of water in storage in sands and gravels of the Ogallala aquifer. This volume estimate discounts the presence of groundwater in thick red shale within the Ogallala saturated section that was logged at boreholes DS-1 and DS-2 and assumes that the red beds would not contribute to water production.

The following simple calculation provides a check on the previous results:

(1) Average saturated thickness of 237 ft = average of point estimates for elevation of the water table (2,765 ft) minus average elevation at the base of aquifer (2,528 ft);

(2) area of Duncan Ranch is ~8,830 acres;

(3) effective porosity is between 16.4 and 23 percent; and

(4) calculated volume for porosity of 16.4 percent = ~340,000 acre-feet and for a porosity of 23 percent is ~480,000 acre-feet;

where the water-table elevation includes measurements within and outside of Duncan Ranch and the base elevation includes data only from Duncan Ranch boreholes. The 340,000- to 480,000-acre-foot range does not discount water content of the red shale logged at DS-1 and DS-2. Nonetheless, this range is roughly consistent with the 320,000- to 440,000-acre-foot range derived from more precise geological mapping.

ESTIMATED WEIGHTED-AVERAGE GROUNDWATER QUALITY

Calculated chloride profiles vary with depth and across the Duncan Ranch area (fig. 7). Several features may be observed:

(1) High *Cl* concentration is seen in several boreholes above the water table near ground surface but also beneath the water table in DN-1 and DN-3. The hydrological meaning of these features was not studied.

(2) *Cl* concentration appears to increase with depth in some boreholes, for example, in DS-1, DS-6, and DN-3, although this was not statistically tested.

(3) After excluding (a) intervals with red beds (in DS-1 and DS-2 [fig. 2]), (b) sections above the projected water table and beneath the base of the Ogallala aquifer, and (c) intervals in which the calculated V_{sh} exceeded 15, we included the interval that in the calculation of average *Cl* concentration ranged from as little as 29 ft (DS-3) to as much as 322 ft (DS-6).

(4) Average *Cl* concentration ranges from 32 to 157 mg/L at the 10 Duncan Ranch boreholes.

(5) Water samples had been collected from DS-2 and DS-5-1 during field testing. The *Cl* concentrations calculated for these two boreholes are higher than they are in reported analyses (table 3). The geophysical log method might poorly estimate *Cl* concentrations <15 mg/L, because equation 5 does not apply at SCw values of <450 μS/cm. The two samples are not enough to determine whether there is a systematic bias in resistivity-based equations.

(6) Calculated *Cl* concentration was only somewhat sensitive to the value of the gamma-log threshold, except for borehole DN-1 and to a lesser extent borehole DS-1. When the gamma-log threshold was varied by ±2 (i.e., from 13 to 17), *Cl* concentration changed by <4 percent; DN-1 changed by 13 percent. When the

gamma-log threshold was varied by ±5 (i.e., from 10 to 20), *Cl* concentration changed by <7 percent, except for DN-1, which changed by 21 percent, and DS-1, which changed by 11 percent.

To determine an average *Cl* concentration for the entire study area on Duncan Ranch, we weighted average *Cl* concentration by the percent of the area represented by each borehole. Equal-weighting (Thiessen) polygons were calculated in ArcView for the 10 boreholes. Using this method, we find that weighting factors for boreholes vary from 8.1 to 12.7 percent (table 4). These weighting factors give an average *Cl* concentration of 85 mg/L for Duncan Ranch. Average *Cl* concentration is insensitive to the selected gamma-log threshold values; increases at one borehole appear to cancel out decreases in another. For comparison, it is noted that the 10 boreholes are approximately evenly spaced across Duncan Ranch, so each borehole's *Cl* concentration could have an equal weight of 0.1. Equal weighting also gives an average *Cl* concentration of ~85 mg/L for included intervals.

ADDITIONAL WORK THAT COULD BE DONE

Additional work could be done for this and other properties in the vicinity of Duncan Ranch in which the Buyer or Seller have an interest.

(1) Geophysical methods have the potential of identifying the base of the Ogallala aquifer, depth to the water table, and resistivity profile in the subsurface. In particular, time-domain electromagnetic surveys (TDEM) have been shown to be successful in similar settings, for example, in Carson County. At Duncan Ranch, a greater number of TDEM surveys might have been performed at a cost lower than

for drilling 10 boreholes. One advantage is that information might be gained at a greater number of locations for the same overall cost. A disadvantage is that the accuracy of picked contacts at the base of the aquifer and water table would be less than from drilling results. TDEM survey results could have formed the basis for drilling a fewer number of boreholes for the purpose of checking and validating results. Accuracy of estimating the base of aquifer and the water table, however, accounted for only a small part of the uncertainty in this study's analysis of water volume.

(2) Effective porosity, or its lack of measurement, is the greatest source of uncertainty for estimating water volume in the Ogallala aquifer in general and at Duncan Ranch in particular. It is expensive and difficult to obtain quality whole-core material with which to measure effective porosity at the depths of interest in the Ogallala aquifer. Additional sets of geophysical borehole logs might be used to estimate porosity. There is some concern about running neutron and density logs in uncased exploratory boreholes. Sonic logs might provide additional information for estimating porosity. Additional effort beyond the scope of this study could be made to estimate porosity by comparing responses from various geophysical logs.

(3) Thick red-bed sections in DS-1 and DS-2 were excluded in this analysis from the calculation of water in storage and average *Cl* concentration. These red beds within the Ogallala aquifer are thought to be perhaps locally derived from erosion of Permian shale formations. It was assumed for this analysis that the red beds within the Ogallala aquifer act as a low-permeability confining layer and would

contribute no appreciable water to withdrawal at wells. If the megafabric of the red beds is like a coarse conglomerate, however, the red beds may be capable of contributing some groundwater. Additional studies might be performed to evaluate hydrogeological properties of the red beds within the Ogallala aquifer.

DISCUSSION

This study estimated that a best estimate of the volume of water in place in sands and gravels of the Ogallala aquifer beneath Duncan Ranch is 380,000 acre-feet, a compromise number between two different estimates of effective porosity. Chloride concentration estimated for a subset of this volume is 85 mg/L or less.

Different estimates of porosity give a range in water volume of from ~320,000 to ~440,000 acre-feet. Porosity accounts for much more uncertainty in volume estimate than in picks for the base of the aquifer or elevation of the water table.

Water quality is estimated on the basis of geophysical log interpretation. Resistivity-based methods work better in formations that have salinity greater than what is found in this part of the Ogallala aquifer, where water quality is good. Parts of the boreholes have groundwater with an estimated specific conductance of <450 μS/cm. *Cl* concentration in these intervals may be less than the minimum value of 15 mg/L assigned in our method. Truncating estimated *Cl* concentration results in average estimates that are higher than would be measured in water produced from a well.

An estimate of water volume in the ground is not the same as that of recoverable groundwater for several reasons. PGCD has a depletion rule that states that half of the 1998 saturated thickness shall remain in 2048. Dutton and Reedy (2000), however, found that as much as half of the produced groundwater from the Campbell Ranch property over a 50-yr period might come from drainage of water from outside its property boundaries. The hydrogeologic setting of Duncan Ranch is expected to be slightly different from that of Campbell Ranch because

(1) Duncan Ranch lies closer to the pinch-out of the Ogallala aquifer to the north in the Canadian River valley. The radius of capture of groundwater may be limited to the north by the pinch-out of the Ogallala aquifer.

(2) Duncan Ranch lies on the axis of deposition of the fluvial channel and fan deposits mapped by Seni (1980), which were shown by Dutton and others (2001) to also mark an axis of higher hydraulic conductivity in the Ogallala aquifer. Average hydraulic conductivity of wells completed on Duncan Ranch is expected to be higher than average hydraulic conductivity of wells on Campbell Ranch. A higher hydraulic conductivity may negatively interact with the close boundary of the aquifer at the Canadian River valley, resulting in more rapid depletion of the aquifer at Duncan Ranch. This hypothesis can be tested by application of the regional groundwater flow model for the Ogallala aquifer.

ACKNOWLEDGMENTS

It is appropriate to acknowledge the contributions of Mr. Tom Parker of Lee Wilson and Associates, Inc., in managing the field-data collection program and providing organized field data. Also, Mr. Roger Miller, of Lee Wilson and Associates, Inc., provided helpful description of the procedures used previously to estimate water quality from geophysical logs for Campbell Ranch. In addition, Mr. Jeffrey Kane at the Bureau of Economic Geology made helpful suggestions and assisted in the analysis of the Duncan Ranch borehole geophysical logs. The Bureau of Economic Geology, The University of Texas at Austin, acknowledges support of this research by Landmark Graphics Corporation via the Landmark University Grant Program.

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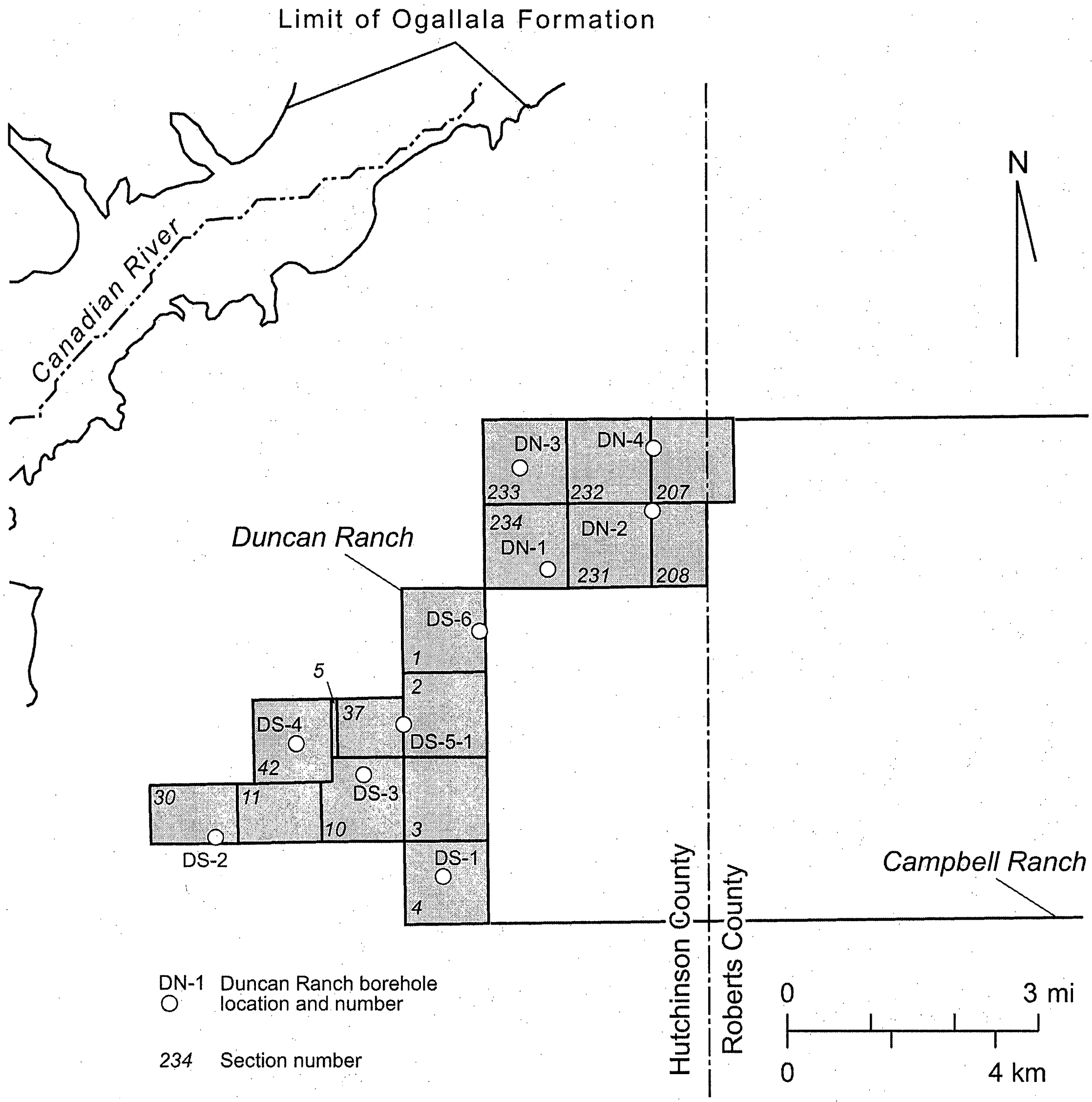

Figure 1. Location of the Duncan Ranch in Hutchinson and Roberts Counties, Texas.

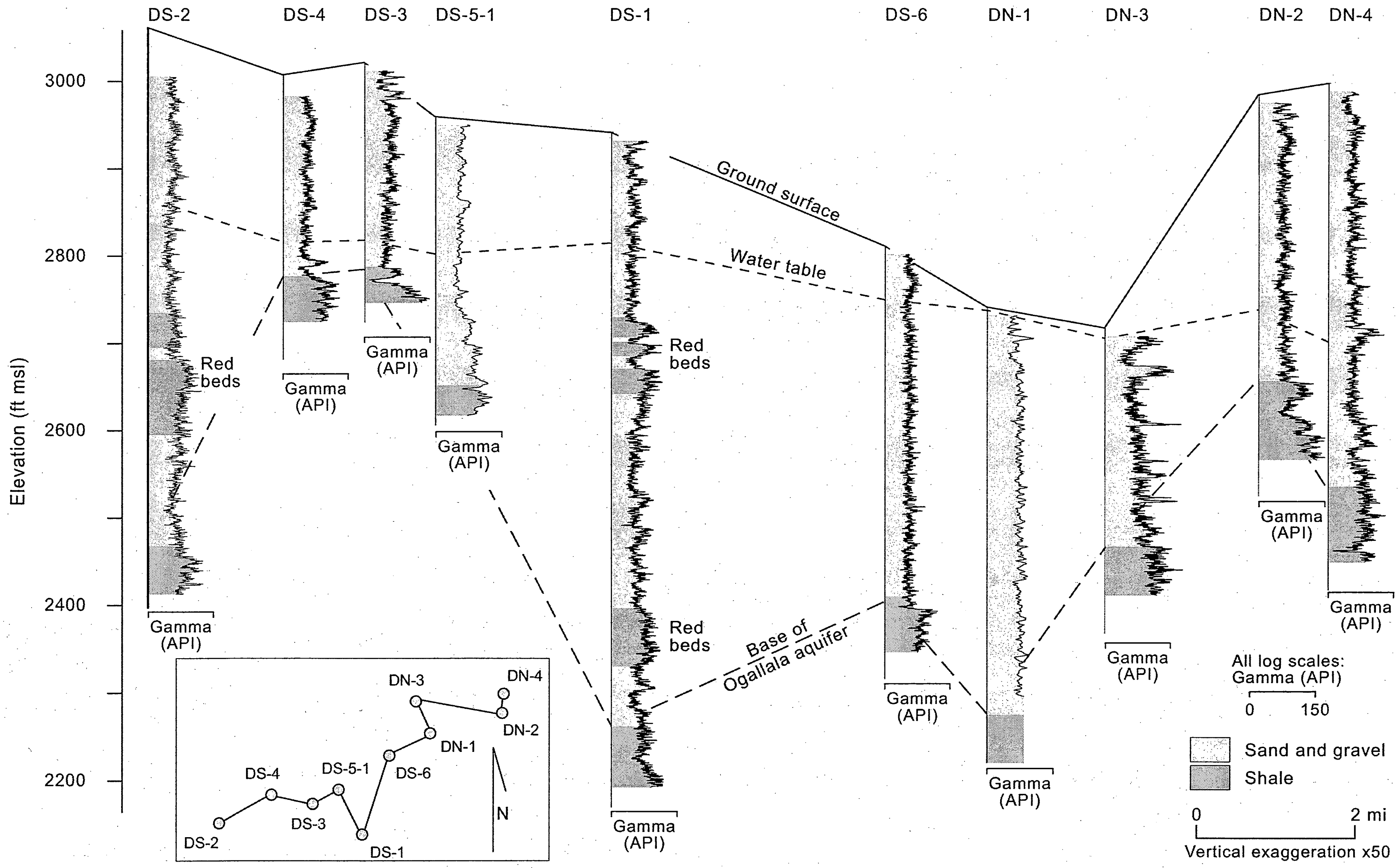

Figure 2. Cross section of geophysical (gamma) and lithologic logs of boreholes at Duncan Ranch with inferred base and water table of the Ogallala aquifer.

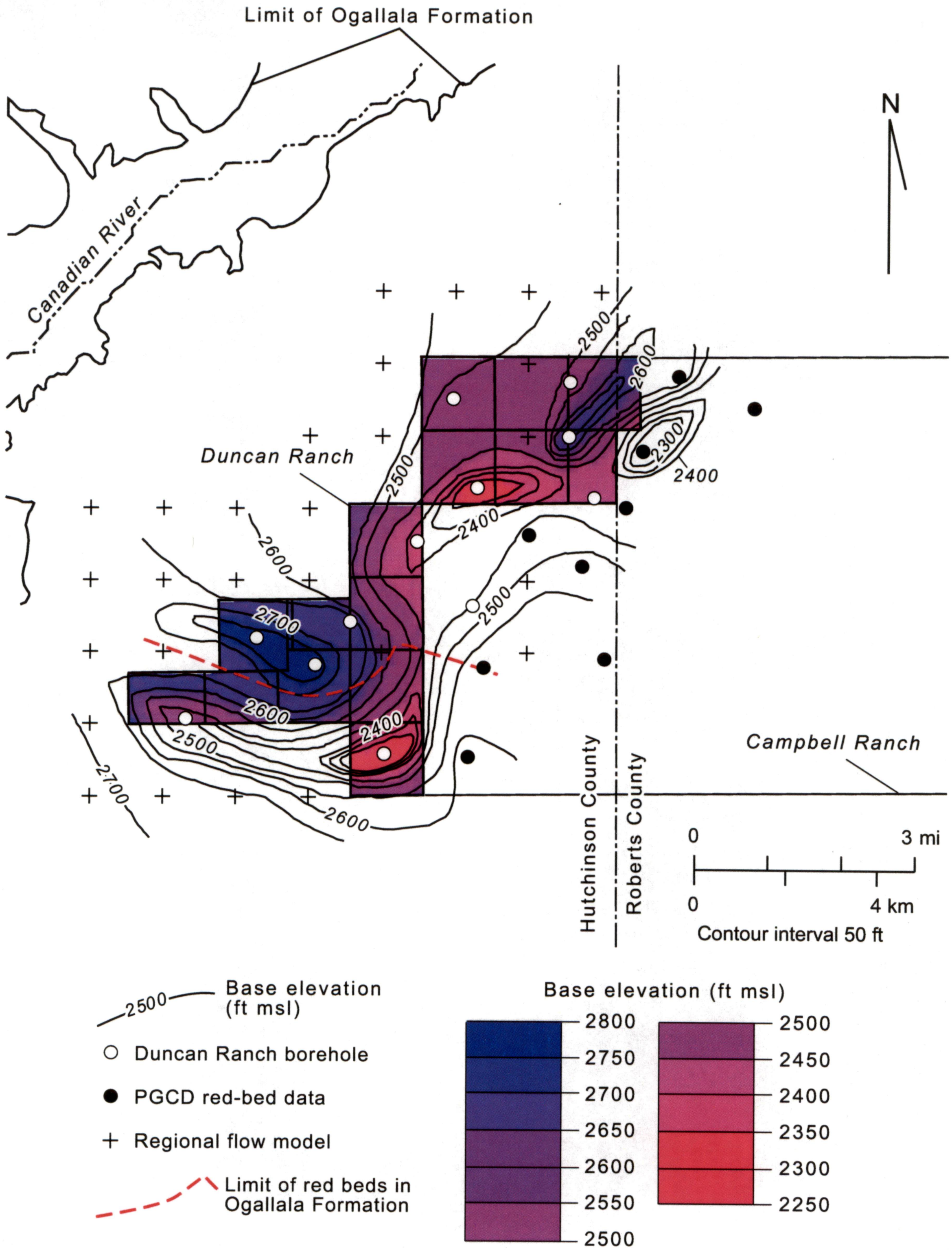

Figure 3. Elevation of the base of the Ogallala aquifer in the vicinity of Duncan Ranch.

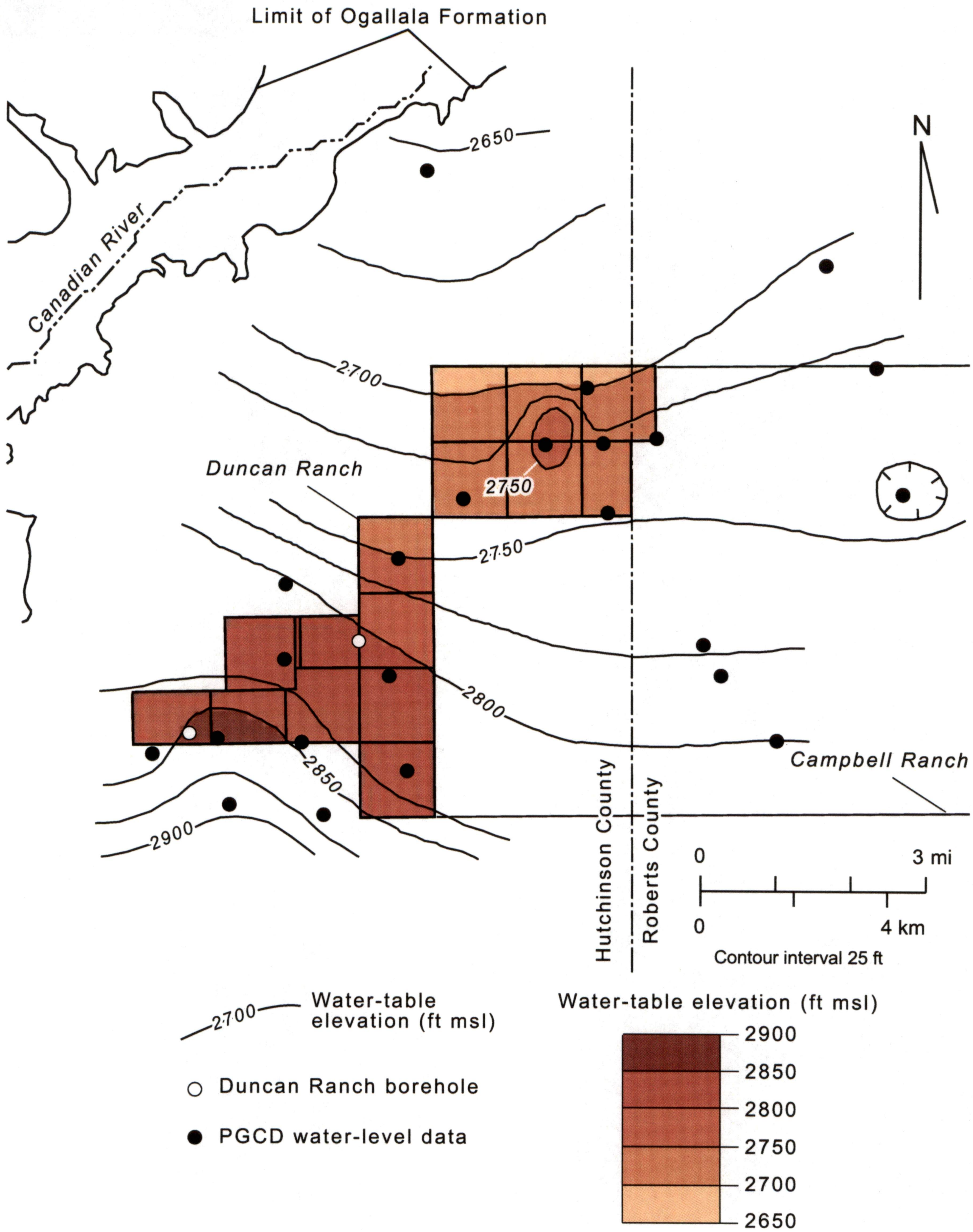

Figure 4. Elevation of the water table in the Ogallala aquifer in the vicinity of Duncan Ranch.

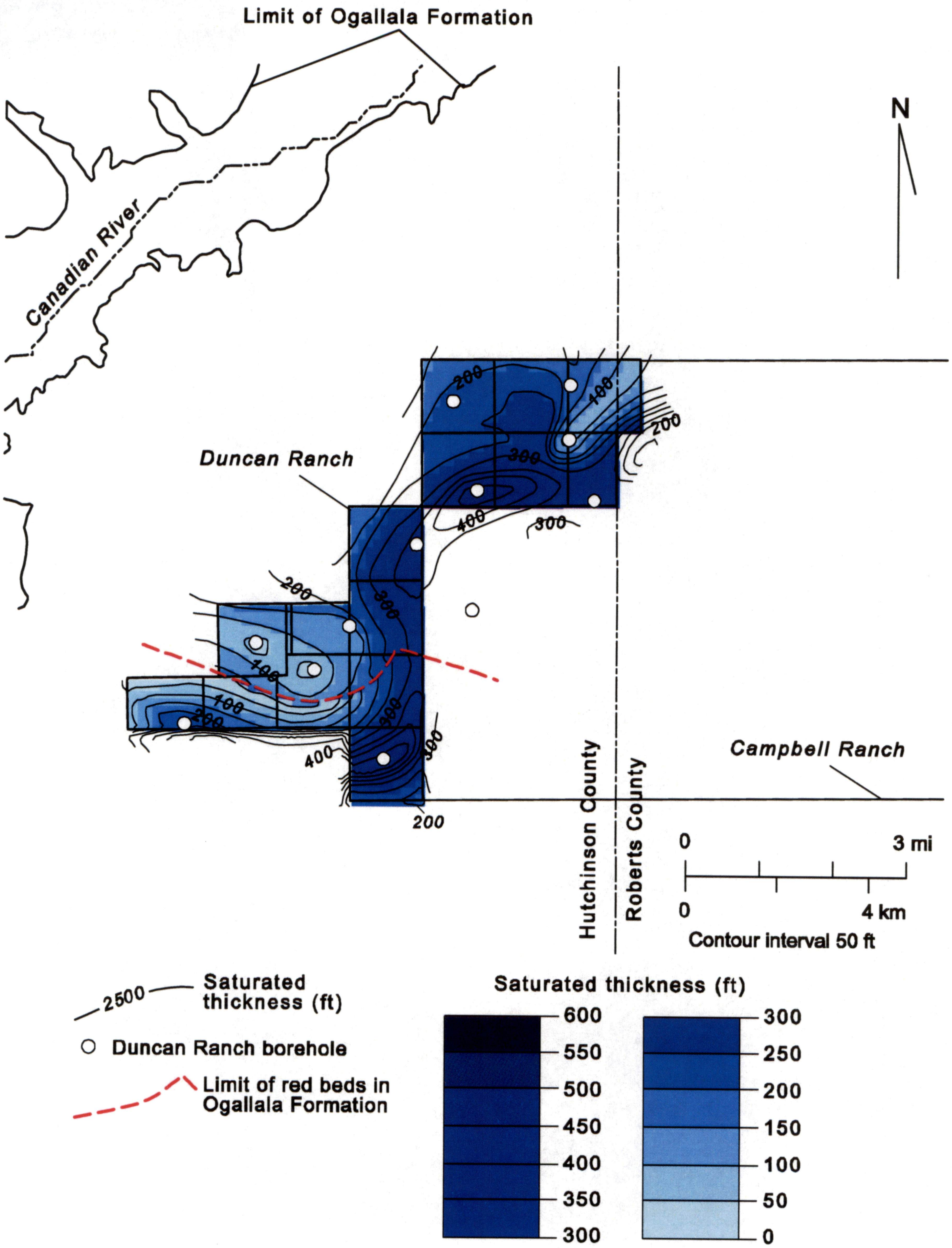

Figure 5. Saturated thickness calculated for Duncan Ranch.

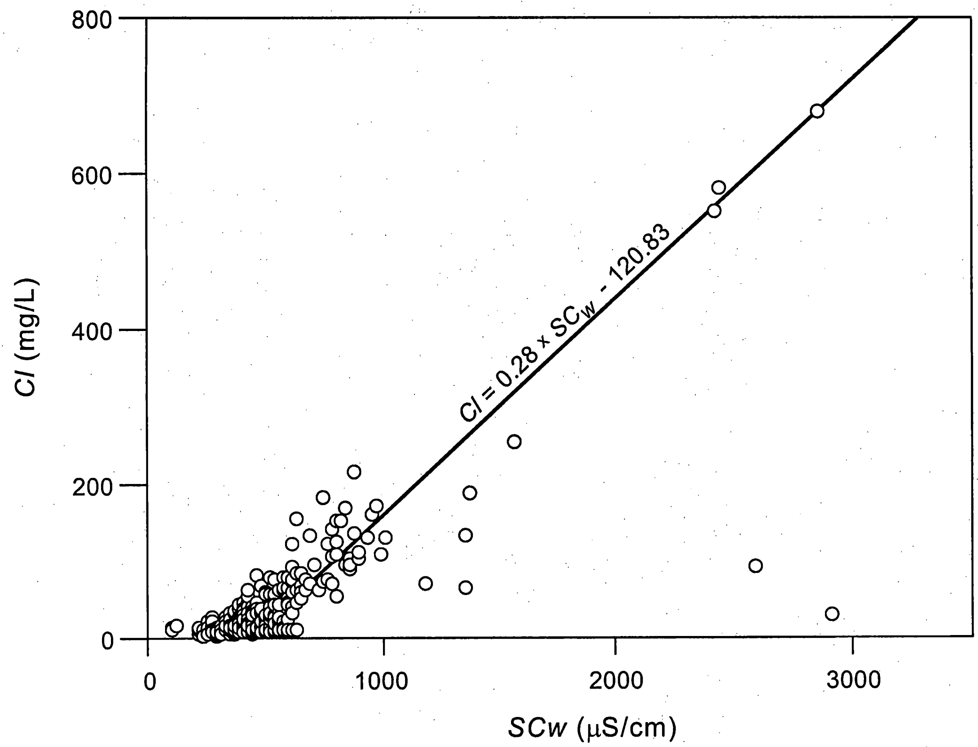

Figure 6. Relation between *Cl* and SC_w for water samples from the Ogallala aquifer in Roberts and Hutchinson Counties. Data from TWDB online data base (www.twdb.state.tx.us).

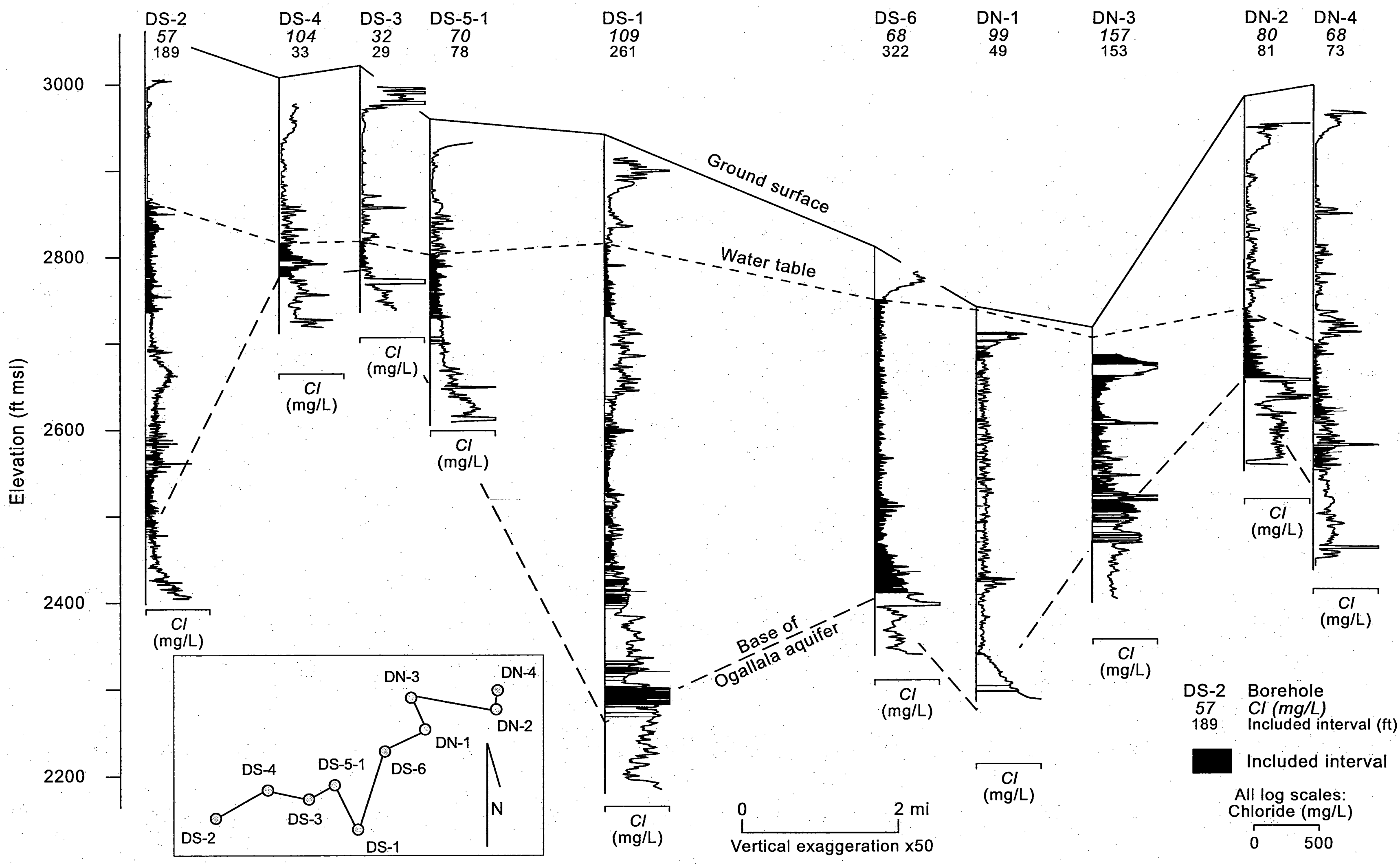

Figure 7. Cross section of chloride (*Cl*) profiles calculated from geophysical logs in boreholes at Duncan Ranch. Numbers at the top of each log show borehole name, average *Cl*, and total footage of interval included in the calculation.

Table 1. Picks and estimates of depths, elevations, and thicknesses for Duncan Ranch boreholes.

Borehole	Ground-surface elevation (ft)	Depth to base of Ogallala Formation (ft)	Elevation of base of Ogallala Formation (ft)	Thickness of red-bed section (ft)	Depth to water (ft)	Water-level elevation (ft)	Saturated thickness (ft)	Saturated thickness discounting red-bed thickness (ft)
DN-1	2,742	469	2,273	0	3*	2,739*	466*	466*
DN-2	2,985	325	2,660	0	245*	2,740*	80*	80*
DN-3	2,718	249	2,469	0	11*	2,707*	238*	238*
DN-4	2,998	467	2,531	0	296*	2,702*	171*	171*
DS-1	2,942	680	2,262	85	126*	2,816*	554*	469*
DS-2	3,062	587	2,475	140	197	2,865	390	250
DS-3	3,022	234	2,788	0	204*	2,818*	30*	30*
DS-4	3,008	231	2,777	0	192*	2,816*	39*	39*
DS-5-1	2,960	308	2,652	0	156	2,804	152	152
DS-6	2,812	416	2,396	0	62*	2,750*	354*	354*

*Extrapolated from map of water table

Table 2. Estimates of saturated thickness and water volume in sand and gravel of the Ogallala aquifer beneath Duncan Ranch.

Section	Area (acres)	Total saturated thickness (ft)	Saturated thickness – red-bed thickness (ft)	Water volume @ ~16.4 % specific yield (acre feet)	Water volume @ 23 % porosity (acre feet)	Best estimate of water volume (acre feet)*
1	652	271	271	30,000	42,000	36,000
2	649	279	279	29,000	41,000	35,000
3	645	305	262	26,000	37,000	32,000
4	647	415	329	36,000	51,000	44,000
5	32	102	102	1,000	1,000	1,000
10	620	149	97	9,000	13,000	11,000
11	462	229	112	8,000	11,000	10,000
30	478	265	121	10,000	14,000	12,000
37	361	132	132	8,000	11,000	9,000
42	599	101	97	10,000	13,000	11,000
207	642	143	143	14,000	20,000	17,000
208	430	274	274	20,000	28,000	24,000
231	654	321	321	34,000	48,000	41,000
232	654	229	229	25,000	35,000	30,000
233	656	207	207	23,000	32,000	27,000
234	648	302	302	32,000	46,000	39,000
Total/Average	8,830	243	216	315,000	443,000	379,000

* Calculated in worksheet by prerounding section averages of total volume using specified specific yield (average ~16.4 percent) and 23-percent porosity

Table 3. Comparison of measured and calculated chloride (*Cl*) concentration (mg/L) in two boreholes at Duncan Ranch.

Borehole	Measured *Cl*	Calculated *Cl*
DS-2	10	57
DS-5-1	17	70

Table 4. Calculated chloride (*Cl*) concentration (mg/L) in boreholes at Duncan Ranch.

Borehole	Thiessen polygon area (acre)	Percent of total area	Calculated *Cl*
DN-1	784	8.9	99
DN-2	1,122	12.7	80
DN-3	938	10.6	157
DN-4	821	9.3	68
DS-1	982	11.1	109
DS-2	719	8.1	57
DS-3	903	10.2	32
DS-4	791	9.0	104
DS-5-1	1,047	11.9	70
DS-6	722	8.2	68
Sum:	8,830	Average:	85