GROUNDWATER RECHARGE IN THE CENTRAL HIGH PLAINS OF TEXAS: ROBERTS AND HEMPHILL COUNTIES

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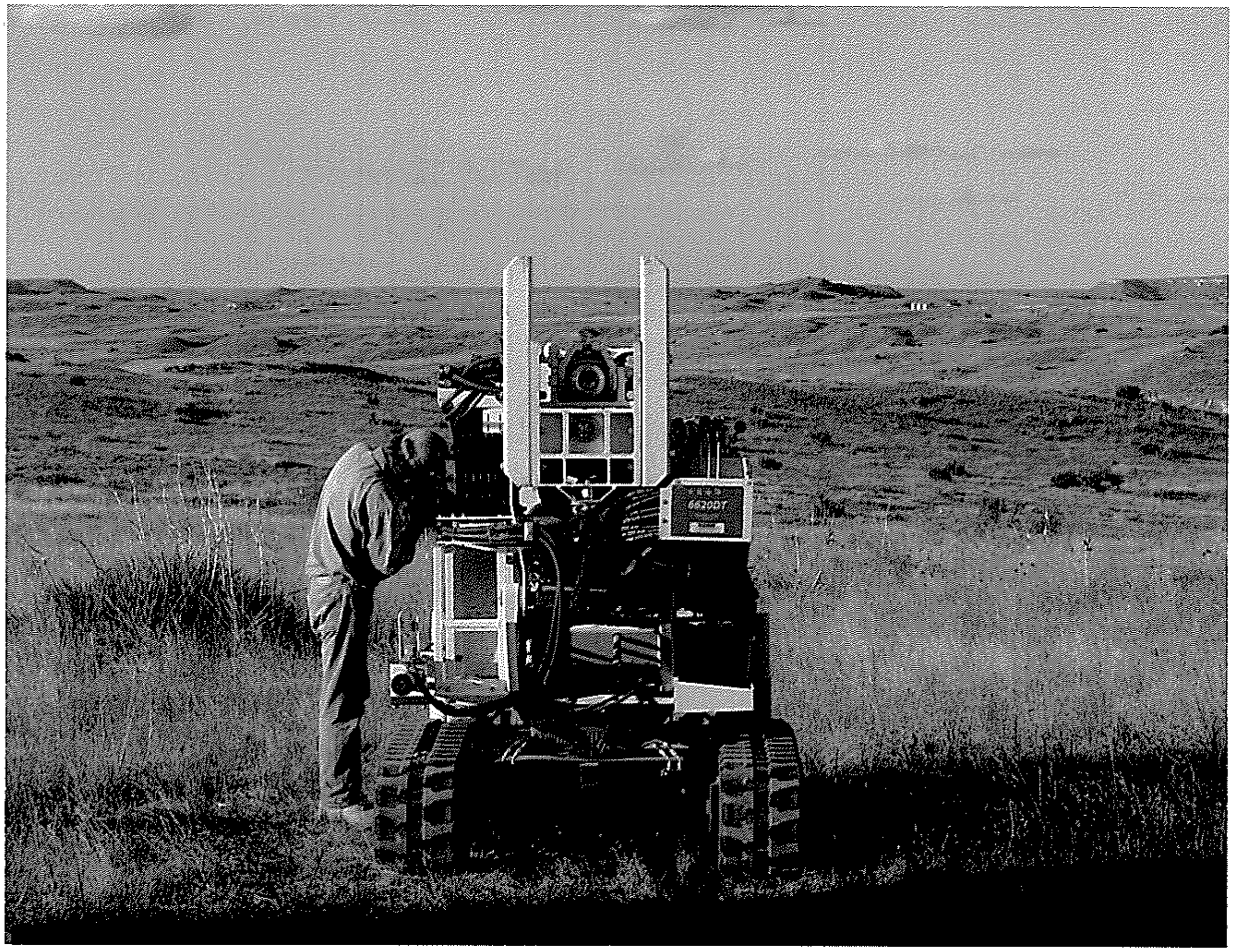

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Task 1.1 Quantify Recharge Rates Using the Chloride Mass Balance Approach

Purpose:
The spatial variability in natural groundwater recharge will be estimated using the chloride mass balance approach.

Relation to Regional Planning:
By more precisely identifying the natural recharge rates in the study's focus area, the Panhandle Water Planning Group will be better able to design models that account for more precise recharge rates. These models will then be used for more precise Managed Available Groundwater and Groundwater Availability Model numbers.

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Purpose:
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Relation to Regional Planning:
Identifying recharge rates in areas of different land usage in Roberts and Hemphill Counties provides the Panhandle Water Planning Group with detailed data that will be useful in identifying future water conservation and water management strategies. Rangeland, dryland, irrigated, and dry stream soils are all tested to ensure that a variety of land usage options are considered. The results of this study will affect regional water planning from both the perspective of recharge resources and recommended land use strategies.

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Purpose:
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Relation to Regional Planning:
In previous plans, the Panhandle Water Planning Group has identified that the management of the Ogallala Aquifer is the management of an ultimately finite resource. Task 1.3 will allow the Planning Group to better understand how declining volume in the aquifer may affect water quality. The impact that declining volume has on water quality may ultimately lead the Planning Group to consider alternative conservation strategies. It is highly important for regional plans to consider not only water volume, but also water quality.

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Purpose:
To conduct coordination activities with Region O regarding the findings of the Ogallala recharge study. The changed conditions for this area are the reduced availability from the CRMWA regarding total available yeild from the CRMWA system and refined groundwater availability.

Relation to Regional Planning:
The Canadian River Municipal Water Authority provides municipal drinking water to 11 cities that lie in Region A and Region O. CRMWA has expanded into groundwater in Roberts County in order to continue providing services. The effects of this research will be seen in localities in Region O as well as Region A. The 2011 Regional Plans will need to account for the findings of this research.

Location of Task 1.4 in the Report:
A. Supplemental document entitled *"Plan Consistency and Interregional Coordination".*

EXECUTIVE SUMMARY

Reliable estimates of recharge are important for assessing and managing groundwater resources. Declining groundwater resources in the High Plains aquifer of Texas as a result of large scale pumping make recharge estimation even more critical for this region.

The purpose of this study was to estimate groundwater recharge in the vicinity of Roberts County. Three basic approaches were used to estimate recharge: (1) chloride mass balance in groundwater, (2) chloride mass balance in the unsaturated zone, and (3) numerical modeling of recharge in the unsaturated zone. Groundwater chloride concentrations were used to evaluate regional recharge rates based on the chloride mass balance approach in Roberts County. A limited number of groundwater well samples were analyzed for tritium-helium ages to supplement the regional groundwater chloride mass balance analysis. The chloride mass balance approach was also applied to the unsaturated zone to provide point recharge estimates in different land use settings. A total of 19 boreholes were drilled from 2006 through 2008 in different locations (14 in Roberts and 5 in Hemphill counties) to depths ranging from **18.5 to 88 ft** (5.6 to 26.8 m). Natural rangeland represents the dominant land use in these counties and nine boreholes were located in this setting. Two boreholes were located beneath dryland agriculture and three boreholes beneath irrigated agriculture. One borehole was drilled in a dry drainage channel and four boreholes were drilled adjacent to stock impoundments that pond water in Roberts County. Soil samples were collected in the field for laboratory measurement of soil physics (water content and matric potential head) and environmental tracers (chloride, fluoride, nitrate, and sulfate). Groundwater recharge was estimated using the chloride mass balance or chloride front displacement approach. Groundwater recharge in Roberts County was also estimated using unsaturated zone modeling based on meteorological data from 1961 through 1990, representative online soils data from SSURGO, and representative vegetation types. Sensitivity analyses were conducted to estimate maximum recharge based on bare sand and to evaluate soil texture and vegetation controls on recharge.

Previous studies throughout the central High Plains estimated a regional recharge rate of 0.43 in/yr (11 mm/yr) based on groundwater chloride concentrations (Wood and Sanford, 1995). This regional estimate was based on chloride concentrations in precipitation (0.58 mg/L) from wet and dry deposition for 1 yr (1984-1985). Most of the recharge was attributed to focused recharge beneath playas in the region. However, playa density in Roberts County is extremely low, with all playas located in the southeastern part of the county where the Blackwater Draw Formation is found. More detailed analysis of groundwater chloride concentrations in Roberts

County and surrounding counties was conducted in this study. Results show that there are saline plumes in the southern part of Roberts and northern Gray counties and also along the Canadian River in Roberts and Hemphill counties. However, a region of low chloride groundwater (≤50 mg/L) in the central part of Roberts County that extends into Hemphill County was used to provide a lower bound on recharge using the chloride mass balance method. Chloride input was estimated to be 0.24 mg/L from 20 yr of data on wet deposition from the National Atmospheric Deposition Program and estimates of dry deposition from chlorine-36 data. This value of chloride input is considered more reliable than the previous estimate used by Wood and Sanford (1995) which was based on only one year of data. The lower chloride input results in lower regional recharge estimates by about 50% relative to those from Wood and Sanford (1995). This study found a median recharge rate of **0.26 in/yr** (6.6 mm/yr) for this region in Roberts County based on groundwater chloride concentrations, with 90% of the log-normal recharge distribution between 0.13 and 0.60 in/yr (3.3 and 15.2 mm/yr). The highest recharge rates, representing only about 2% of the Roberts County area, range from 0.67 to 0.91 in/yr (17 to 23 mm/yr) and are consistent with high recharge rates (≥0.67 in/yr; ≥17 mm/yr) estimated from an unsaturated zone profile sampled beneath a drainage in Roberts County. These results indicate that stream drainages in Roberts County may be functioning similarly to playas in other regions by focusing recharge to the Ogallala aquifer.

Results of tritium-helium age dating analysis indicate that a detectable component of young water (≤50 yr) is only present in two of four wells sampled. All wells are located within presumably favorable areas as indicated by the regional groundwater chloride distribution analysis (i.e. low-slope areas within lower-elevation reaches of the drainage network). The results are consistent with the results from groundwater chloride analysis and indicate that the volume of recent recharge has generally not significantly impacted current groundwater storage.

The chloride mass balance approach applied to the unsaturated zone resulted in a range of recharge estimates for different land use settings. Most of the profiles in rangeland settings (6 out of 9) are generally characterized by large chloride accumulations (peak chloride concentrations 477 to 2,593 mg/L) corresponding to accumulation times ranging from 3,601 to 19,758 yr. These data indicate that there is essentially no recharge in these regions and that the profiles have been drying out over these long time periods. Matric potentials are generally low in these profiles, with mean matric potentials below the root zone ranging from -68 to -108 m. These low matric potentials generally support the lack of recharge from the chloride data. Two of the remaining profiles (one in Roberts County and one in Hemphill County) have much lower chloride concentrations (mean 108 and 250 mg/L), indicating low, but measurable, recharge rates of **0.11 and 0.14 in/yr** (2.8 and 3.6 mm/yr). These boreholes are located along the breaks near the Canadian River, where soils are coarser grained. Recharge rates could not be estimated in the third profile because only cuttings, not cores, were collected. Matric potentials were measured in two of the three profiles and are slightly higher than others, with mean values of -38 and -67 m. Lack of recharge in most rangeland profiles is attributed to low permeability soils and the ability of natural grasslands/shrublands to remove all infiltrated water through evapotranspiration. Low recharge in two of the rangeland profiles is attributed to their location along the Canadian breaks and associated coarser soil textures.

Conversion of rangeland to dryland agriculture did not increase recharge below the root zone in a profile in Roberts County but did increase recharge in a profile in Hemphill County to **0.41 in/yr** (10.4 mm/yr). The lack of increased recharge in the Roberts County dryland profile is attributed to the low permeability soils (Pullman clay loam) in this region. Evidence of increased recharge in the Hemphill County profile is provided by low chloride concentrations (mean 15 mg/L; peak 26 mg/L).

There is increased recharge under all of the irrigated sites. The chloride bulge has been displaced to 32.2 ft (9.8 m) depth in an irrigated profile in Roberts County. This site has been irrigated since the 1950s, ~55 yr, resulting in a water velocity of 0.52 ft/yr (0.16 m/yr, assuming a root zone of ~3 ft, (1 m) and a recharge rate of **1.9 in/yr** (48 mm/yr) based on an average water content of 0.30 m^3/m^3. Recharge in the other irrigated profile in Roberts County is **2.2 in/yr** (56 mm/yr), which is based on the chloride mass balance approach because a chloride front could not be identified. The recharge rate is based on an irrigation application rate of 1.5 ft/yr (0.5 m/yr) and chloride concentration in irrigation water (26 mg/L; well 616651, 1992–2005). The irrigated profile in Hemphill County is characterized by high chloride concentrations (mean 176 mg/L, peak 1005 mg/L) and high matric potentials (mean -6 m). There is also no recognizable chloride front in this profile and an irrigation application rate of 1.5 ft/yr (0.5 m/yr) and measured chloride concentration in a sample of the irrigation water (14.5 mg/L) results in an estimated recharge rate of **4.5 in/yr** (115 mm/yr) for this site.

One borehole was drilled in a dry drainage channel in Roberts County. Extremely low chloride concentrations (mean 16 mg/L) and very high matric potentials (mean -2 m) indicate high recharge rates. It is difficult to estimate recharge rates beneath the drainage because we do not know the chloride input (runon rate and chloride concentration in runon). A lower bound on the recharge rate of **0.68 in/yr** (17 mm/yr) can be estimated by assuming no runon. Assuming a runon depth of 2 ft/yr (0.6 m/yr) and chloride concentrations in runon water of 1 mg/L results in a recharge rate of 3.8 in/yr (96 mm/yr). Increasing runon and chloride in runon would linearly increase calculated recharge rates.

Four boreholes were drilled beneath or adjacent to three stock impoundments that pond water frequently. All profiles are characterized by low chloride concentrations and high matric potentials throughout, indicating high recharge rates. Minimum recharge rates based on precipitation and chloride in precipitation only ranged from **0.64 to 1.4 in/yr** (16 to 36 mm/yr). Assuming ponded depths of 2 ft/yr (0.6 m/yr) and chloride concentrations in ponded water of 1 mg/L results in recharge rates of 3.4 to 7.3 in/yr (86 to 185 mm/yr). Although recharge rates are locally high, the areal extent of such ponds is < 1%; therefore, volumetric recharge rates are low.

Unsaturated zone modeling using bare sand provides a maximum estimate of recharge that is based on climatic forcing in Roberts County. Simulated mean (30-yr) annual recharge for bare sand is high, 6.9 in/yr (174 mm/yr), representing 35% of mean (30-yr; 1961-1990) annual precipitation. Simulated mean (30-yr) annual, areally averaged recharge for Roberts County is 2.0 in/yr (52 mm/yr) for texturally variable soil profiles, representing 10% of mean annual precipitation. This recharge rate is 3.4 times lower than that based on the monolithic sand profile, indicating the importance of soil textural variability in controlling recharge. To assess the impact of vegetation without the influence of soil textural variability, simulations of recharge were conducted in vegetated, monolithic sands. Vegetation reduces simulated mean annual recharge (0.18 in/yr, 4.5 mm/yr; 0.9% of mean annual precipitation) by a factor of 11.4 relative to recharge for the nonvegetated sands. Texturally variable soils with vegetation are the most realistic representation of actual conditions and should provide the most reliable recharge estimates for the different regions. Simulated mean (30-yr) annual, areally averaged recharge is low, 0.004 in/yr (0.1 mm/yr), and represents 0.02% of mean annual precipitation. However, this recharge estimate does not incorporate the effects of stream drainages in Roberts County or increased water input through drainage systems.

The regional recharge rate of 0.26 in/yr (6.6 mm/yr), based on groundwater chloride concentrations, is probably the most reliable estimate for Roberts County and is similar to previous regional estimates (0.24 in/yr, 6 mm/yr) for the central High Plains using chloride input based on long-term data (20 yr from NADP). The groundwater chloride data indicate that stream drainages in Roberts County and playas in the central High Plains may function similarly, focusing recharge. Results from unsaturated zone sampling and modeling are consistent with the regional recharge estimates that are based on groundwater chloride and indicate that there is little recharge outside of stream drainages or stock impoundments in the region.

1.0 INTRODUCTION

Quantifying and understanding controls on groundwater recharge are important for developing strategies to optimally manage groundwater resources. Groundwater resources are critical in the High Plains in Texas because of large-scale depletion. The objective of this work was to estimate recharge in Roberts and Hemphill counties in the central High Plains, using a variety of approaches including chloride mass balance in groundwater and in the unsaturated zone and unsaturated zone modeling. Previous studies of recharge in the central High Plains of Texas provide a regional estimate of recharge of 0.43 in/yr (11 mm/yr) that is based on average groundwater chloride concentration data (Wood and Sanford, 1995). Estimates of recharge rates based on unsaturated zone sampling in Carson County range from 2.4 to 4.7 in/yr (60 to 120 mm/yr) beneath playas that are based on tritium concentrations and no recharge in adjacent interplaya rangeland settings that are based on chloride concentrations (Scanlon and Goldsmith, 1997). Similar recharge rates (3.0 in/yr; 77 mm/yr) were estimated beneath playas in the southern High Plains on the basis of the distribution of bomb tritium (Wood and Sanford, 1995). Previous studies in the southern High Plains also show that recharge is related to land use: in general, there is no recharge in interplaya rangeland settings, higher recharge beneath dryland agriculture (median 1 in/yr, 24 mm/yr), and variable recharge beneath irrigated sites (Scanlon et al., 2005, 2007). Higher recharge beneath dryland agriculture is attributed to shallower rooting depths of crops relative to perennial grasses and shrubs and to long winter fallow periods when there is no vegetation (Scanlon et al., 2007). Information is limited on recharge beneath irrigated sites because specific data on irrigation water application rates and chloride concentrations in irrigation water are generally not available. Tritium analyses in two irrigated soil profiles in Cochran County resulted in recharge rates of 0.67 and 1.26 in/yr (17 and 32 mm/yr) (McMahon et al., 2006).

This study focuses on recharge in the area of Roberts and Hemphill counties (Fig. 1). The primary source of groundwater is the High Plains aquifer which consists primarily of the Ogallala Formation and minor overlying alluvial sediments in this region (Fig. 1). The Blackwater Draw Formation overlies Ogallala sediments in parts of extreme southern Roberts County and in counties to the south and west. The dominant land use/land cover in Roberts County is rangeland (91%), which consists of grasslands (78%) and shrublands (22%) (Fig. 2). Cultivated croplands represent 7% of the county area, consisting of dryland (75%) and irrigated (25%)

crops. Developed (urban) areas combined with all other land use categories (open water, wetlands, forest, etc) represent the final 2%.

2.0 METHODS

Recharge is defined as addition of water to an aquifer, generally from precipitation that infiltrates downward through the unsaturated zone. Unsaturated zone sample analysis results provide estimates of downward water fluxes (drainage rates) below the root zone; however, in many cases the water has not reached the water table. If climate, vegetation, and soil conditions remain the same, we assume that the water fluxes calculated below the root zone (i.e. drainage rates) will ultimately reach the aquifer and become groundwater recharge. In this report, the term recharge refers to calculated drainage fluxes below the root zone that will reach the water table, assuming that current climatic conditions prevail.

Recharge rates in this study are based on (1) the chloride mass balance approach applied to groundwater and unsaturated zone sample measurements, (2) on the chloride front displacement method applied to unsaturated zone sample measurements, and (3) on unsaturated zone modeling results. Additional supporting information is provided by soil physical parameters in the unsaturated zone and by non-invasive electromagnetic induction surveys. The methods are described according to saturated zone studies that were based on groundwater chloride concentrations, unsaturated zone field studies, and unsaturated zone numerical modeling.

2.1 Meteoric Chloride

Chloride concentrations in groundwater or in unsaturated zone pore water have been widely used to estimate recharge (Allison and Hughes, 1978; Scanlon, 1991, 2000; Phillips, 1994). Precipitation contains low concentrations of chloride. Chloride in precipitation and dry fallout is transported into the unsaturated zone with infiltrating water. Chloride concentrations increase through the root zone as a result of evapotranspiration because chloride is nonvolatile and is not removed by evaporation or by plant transpiration. Below the root zone, chloride concentrations should remain constant if recharge rates have not varied over time. Qualitative estimates of relative recharge rates can be determined using chloride concentrations in groundwater or unsaturated zone pore water if precipitation and dry fallout are the only sources of chloride to the subsurface. In this case, chloride concentrations are inversely related to recharge rates: low chloride concentrations indicate high recharge rates because chloride is flushed out of the system, whereas high chloride concentrations indicate low recharge rates because chloride accumulates as a result of evapotranspiration. For example, low chloride concentrations beneath playas in the central and southern High Plains indicate high recharge, whereas high chloride concentrations in natural interplaya settings indicate low recharge (Scanlon and Goldsmith, 1997; Scanlon et al., 2007). The chloride mass balance (CMB) approach can be applied to chloride concentrations in groundwater:

$$PCl_p = RCl_{gw}, \qquad R = \frac{PCl_p}{Cl_{gw}} \tag{1}$$

which balances chloride input (precipitation, P, times the chloride concentration in precipitation and dry fallout, Cl_P) with chloride output (recharge rate, R, times chloride concentration in groundwater Cl_{gw}). The CMB approach can similarly be applied to unsaturated zone pore water:

$$PCl_p + ICl_I = RCl_{uz}, \quad R = \frac{PCl_p + ICl_I}{Cl_{uz}} \tag{2}$$

where chloride concentration in unsaturated zone pore water (Cl_{uz}) replaces Cl_{gw} and includes an additional term to account for irrigation (I) and chloride concentration in irrigation water (Cl_I) where applicable. The age of pore water at any depth in the unsaturated zone can also be estimated by dividing cumulative total mass of chloride from the surface to that depth by the chloride input rate.

Recharge rates can also be estimated using the chloride front displacement (CFD) method at sites with insufficient data to apply the CMB approach (Walker et al., 1991). Large chloride bulges that accumulated under rangeland conditions are displaced downward by increased recharge rates following land use conversion to cultivation (Scanlon et al., 2005). The transition from low chloride concentrations at shallower depths (typical of cultivated areas) to higher chloride concentrations at greater depths (typical of rangeland areas) forms a chloride front at sites where rangeland was converted to cultivated land. Recharge is estimated from the velocity (v) of the (downward) chloride front displacement:

$$R = \theta v = \theta \frac{z_2 - z_1}{t_2 - t_1} \tag{3}$$

where θ is average volumetric water content over the displacement depth interval and z_1 and z_2 are depths of the chloride front corresponding to times t_1 and t_2 related to new (dryland or irrigated) and old (rangeland) land uses.

2.1.1 Data Sources

Average annual precipitation was estimated spatially by interpolation of data from the National Climate Data Center (NCDC) using the period-of-record means for 1,397 weather stations in Texas and surrounding states (www.ncdc.noaa.gov). The period of record for all stations ranges from 30 to 149 yr and from 41 to 74 yr for the 17 stations in the nine-county area centered on Roberts County. Mean annual total precipitation in the nine-county area shows an eastward to southeastward increasing trend ranging from ~19.7 in/yr (500 mm/yr) in the west to ~23.6 in/yr (600 mm/yr) in the east, with values approaching 27.6 in/yr (700 mm/yr) near McLean in southeast Gray County (Fig. 3). Precipitation in Roberts County ranges from ~20.9 in/yr (530 mm/yr) in the northwest to ~23.2 in/yr (590 mm/yr) in the southeast and averages about 22.4 in/yr (570 mm/yr).

Average annual net chloride input was estimated spatially from chloride concentrations in precipitation measured by the National Atmospheric Deposition Program (NADP) at 190 monitoring locations in the US (http://nadp.sws.uiuc.edu/). Monitoring began at most sites in 1982. The closest monitoring location is approximately 70 mi NE of Roberts County at the Goodwell Research Station in Texas County, OK. There are seven additional monitoring locations within 200 mi of Roberts County. Chloride concentrations reported by NADP represent wet deposition only and do not include dry deposition. To account for dry deposition, chloride concentrations were increased by a factor of two, as suggested by previous work in this region (Scanlon and Goldsmith, 1997). Resultant chloride concentrations exhibit a southeastward increase in concentration ranging from 0.22 mg/L in Hansford County to 0.28 mg/L in Wheeler County, and a mean of 0.24 mg/L in Roberts County (Fig. 4).

Groundwater chloride concentrations were obtained from the Texas Water Development Board database (www.twdb.state.tx.us). A total of 422 analyses of groundwater chloride concentrations representing samples from 1947 through 2006 (mean 1983) were used in the analysis (Fig. 5).

Other information required for various aspects of the analysis and interpretation of recharge in Roberts County included maps of the Ogallala water table elevations and aquifer base elevations obtained from Houston et al. (2003), detailed soil clay content map (1.5–2.0 m depth) compiled from county survey data from the State Soil Geographic (SSURGO) database (http://soils.usda.gov/survey/geography/ssurgo/), and a digital elevation model (DEM) map of ground surface elevations and other surface feature maps (http://www.tnris.state.tx.us/).

2.2 Field Methods

Results of the field study rely primarily on analytical results of soil and sub-soil core samples. Noninvasive electromagnetic induction measurements were also obtained at many borehole locations to evaluate local spatial variability at a given borehole location and for comparison among borehole locations within and between different land use settings.

2.2.1 Soil Cores

Core samples were obtained at 19 locations in the central High Plains (Roberts and Hemphill counties) using a track-mounted, direct push drilling rig (Model 6620DT, Geoprobe, Salina, KS) without any drilling fluid (Fig. 1, Table 1). Boreholes are designated on the basis of abbreviated county name, year sampled, and sequence number. For example, ROB07-02 is Roberts County, 2007, borehole no. 2. Cores were obtained in different land use settings: nine in rangeland (grassland/shrubland), two in nonirrigated (dryland) agriculture (cropland), three in irrigated agriculture, one beneath a dry drainage channel, and four beneath stock impoundments (Fig. 1). Rangeland sites are vegetated with grasses and sparse shrubs. Irrigation began in the 1950s at both sites in Roberts County and in the 1970s at the Hemphill irrigated site.

Continuous cores were obtained using core tubes (4.0 ft. [1.22 m] long, 1.1 inch [29 mm] inside diameter) from the ground surface to depths ranging from 18.5 to 88 ft (5.6 to 26.8 m). Core sample tubes were cut into various lengths, capped and sealed to prevent evaporative loss, and kept in cold storage. Two boreholes were drilled in Roberts County using a commercial drilling rig with air-rotary technology. Samples consisting of cuttings circulated to the ground surface using forced air pressure were collected from these two boreholes. One of the air-rotary boreholes was drilled at the same location as borehole ROB06-02 (Fig. 1) in an attempt to obtain samples from greater depth. This air-rotary drilling approach could not drill deeper than the Geoprobe; therefore, the air-rotary samples for this borehole were not analyzed.

2.2.2 Electromagnetic Induction

Noninvasive measurements of near-surface apparent electrical conductivity (EC_a) were performed at 16 borehole locations using an EM31 instrument (Geonics, Mississaugua, ON). The EM31 has a nominal depth of investigation of 20 ft (6.1 m) when operated in the vertical dipole mode, as in this study. Survey measurements were obtained at nominal 10-ft (3-m) intervals along transects up to 200-ft (61-m) in length at various compass orientations, depending on site characteristics. Where possible, two transect lines were oriented at ~ 90° centered on the borehole location. Instrument readings in the vertical dipole mode were obtained at each point.

Electromagnetic (EM) induction instruments measure a depth-weighted average of the electrical conductivity of the soil, termed *apparent electrical conductivity* (EC_a). Apparent electrical conductivity of the subsurface varies with clay content, water content, salinity, and temperature. The theoretical basis for EM induction measurements was described by McNeill (1992). Rhoades et al. (1989) developed a linear model to describe subsurface variations in EC_a that generally applies to solution conductivities ≤ 400 mS/m:

$$EC_a = EC_w \theta \tau + EC_s \tag{4}$$

where EC_w is pore water conductivity, θ is volumetric water content, τ is tortuosity, and EC_s is surface conductance of the sediment (Rhoades et al., 1976). This model applies when water content is above a certain threshold value. Laboratory studies show that threshold water contents range from 0.05 m^3/m^3 for sand to 0.12 m^3/m^3 for clay (Rhoades et al., 1976). Below this threshold water content, EC_w is 0 and EC_a is controlled by surface conductance (EC_s), which is primarily determined by the cation exchange capacity of the clays. Measurements from EM surveys conducted in west Texas, which were related to variations in soil texture, salinity, and water flux in different regions, were useful in interpolating between borehole measurements (Scanlon et al., 1999). Temporal variability in water content was monitored using EM induction calibrated using neutron probe monitoring at another site in west Texas (Reedy and Scanlon, 2003).

2.2.3 Groundwater Tritium-Helium Age Dating

The tritium-helium ($^3H/^3He$) age-dating method is reliable in providing ages for the component of sampled groundwater that has recharged an aquifer following the onset of atmospheric thermonuclear bomb testing during the 1950s and utilizes measurements of the isotopic ratio of tritium, ^3H, to that of its daughter product, ^3He. Historical tracers or event markers, such as bomb-pulse tritium have been used widely in the past to estimate recharge (Egboka et al., 1983; Robertson and Cherry, 1989). Tritium is used to trace water movement because it is part of the water molecule. Tritium is a radioactive isotope of hydrogen with a half life of 12.32 yr. Tritium occurs naturally in the atmosphere and enters the subsurface primarily through precipitation. Tritium fallout increased as a result of atmospheric nuclear testing that began in the early 1950s and peaked in 1963. The presence of bomb pulse tritium in groundwater indicates that a component of the groundwater is young (< ~ 50 yr old). Bomb-pulse tritium concentrations have been greatly reduced as a result of radioactive decay; therefore, the use of tritium to date groundwater is generally being replaced by the use of $^3H/^3He$. Tritium and (tritiogenic) ^3He combined behave as a non-decaying tracer and the ratio of ^3H to ^3He can be used to estimate the age of the groundwater (age being defined as the time since water entered the saturated zone) by:

$$t = -\frac{1}{\lambda}\ln\left[1+\frac{^{3}He_{trit}}{^{3}H}\right] \qquad (5)$$

where λ is the decay constant (ln $2/t^{1/2}$; 0.05626), $t^{1/2}$ is the ^3H half life (12.32 yr), and $^3He_{trit}$ is tritiogenic ^3He. Use of this equation assumes that the system is closed (does not allow ^3He to escape) and is characterized by piston flow (no hydrodynamic dispersion). The method involves determining the concentration of tritium in water as well as precise measurements of dissolved atmospheric and noble gas concentrations, including N_2, ^3H, ^4He, and ^{20}Ne to differentiate non-tritogenic helium sources, including the radioactive decay of U/Th present in sediments and from excess air entrained during recharge.

Four wells, three located in Roberts County and one in Hutchinson County, were sampled for $^3H/^3He$ age-dating in early March 2009. Wells were selected based on availability and on location generally within or near lower elevation drainage areas. Samples were collected in 3/8-inch ID copper tubing approximately 0.5 m in length and were sealed under pressure from the well pump. The samples were analyzed at the University of Utah Dissolved and Noble Gas Laboratory.

2.3 Laboratory Methods

Chemical parameters included anions in water leached from 351 core samples (70 from 2006, 236 from 2007, and 45 from 2008) from the unsaturated zone. The primary anion of interest in this study was chloride, which is used to estimate rate of water movement through the unsaturated zone using the chloride mass balance approach. The pore water was also analyzed for nitrate, sulfate, and fluoride. Approximately 40 mL of double deionized water (≥18.2 MOhm) was added to about 25 g of moist soil. The mixture was placed in a reciprocal shaker for 4 hr and then centrifuged at 7,000 rpm for 20 minutes. The resulting supernatant was filtered to 0.2 µm and was analyzed for anion concentrations using ion chromatography at the Bureau of Economic Geology. Soil samples were then oven dried at 105°C for 48 hr to determine gravimetric water content.

Anion concentrations in the supernatant were converted to pore water concentrations by dividing by gravimetric water content and multiplying by density of pore water, assumed to be 1.00 Mg/m^3. Concentrations are expressed as milligrams of ion per liter of pore water.

Soil samples were also analyzed in the laboratory for pressure head to determine direction of water flow in the soil. The term *pressure head* is generally equivalent to the term *matric potential*, which refers to potential energy associated with the soil matrix. Matric potentials ≥-26.2 ft (-8 m) were measured using tensiometers (Model T5, UMH, Munich), whereas matric potentials ≤-26.2 ft (-8 m) were measured using a dew-point potentiometer (Model WP4-T, Decagon Devices Inc., Pullman, WA).

2.4 Unsaturated Zone Modeling

The method used to model the water balance of Roberts County is based on a study by Keese et al. (2005). Unsaturated flow modeling is used to simulate drainage below the root zone, which is equated to groundwater recharge. The code UNSAT-H (Version 3.0; Fayer, 2000) is a one-dimensional, finite difference code that simulates nonisothermal liquid flow and vapor diffusion in response to meteorological forcing. Simulations focus on the water balance:

$$D = P - ET - R_0 - \Delta S \tag{6}$$

where D is deep drainage below the root zone, P is precipitation, ET is evapotranspiration, R_0 is surface runoff, and ΔS is change in water storage. UNSAT-H simulates subsurface water flow using Richards' equation:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} = \frac{\partial}{\partial z}\left(\left(K(\theta)\frac{\partial H}{\partial z}\right)\right) - S = \frac{\partial}{\partial z}\left(\left(K(\theta)\frac{\partial h}{\partial z} - K(\theta)\right)\right) - S(z,t) \tag{7}$$

where θ is volumetric water content, q is water flux, K is hydraulic conductivity, H is hydraulic head, h is matric potential head, and S is a sink term used to describe removal of water by plants.

Input data requirements for the model include meteorological forcing, vegetation parameters, hydraulic parameters for different soil types, and initial conditions. Meteorological data were obtained from the database in the GEM code (Hanson et al., 1994). The 1961–1990 period was chosen because solar radiation data, needed for potential evapotranspiration calculations, are available for this period from the National Solar Radiation Data Base (National Renewable Energy Laboratory, 1992). Meteorological input to the model included daily precipitation, daily average dew-point temperature and wind speed, total daily solar radiation, and minimum and maximum daily temperatures. Meteorological data from the Amarillo

International Airport was used in this study because it is the location nearest to Roberts County for which this information was available.

Distribution of vegetation types was obtained from a GIS coverage of vegetation in Texas (McMahon et al., 1984). Roberts County consisted of three different vegetation types: shrub/grassland (shrub), cottonwood-hackberry-saltcedar brush/woods (brush), and crops. The distribution of crops within Roberts County was determined from the National Agricultural Statistics Survey (U.S. Department of Agriculture, variable); the dominant summer crop, sorghum, was modeled. Vegetation parameters required for UNSAT-H include percent bare area, planting and harvesting dates for crops, time series of leaf area index (LAI) and rooting depth (RD), and root-length density (RLD). These parameters for shrubs and brush were obtained from Keese et al. (2005) and were primarily determined from the literature. Information on sorghum, including sowing and harvesting dates, rooting depth, and leaf area index were obtained from Louis Baumhardt (USDA, Agricultural Research Service, Bushland, Texas, pers. comm., 2008) and Thomas Marek (Texas A&M AgriLife Research and Extension Service, Amarillo, Texas, pers. comm., 2008). Time series for LAI and root growth were specified on particular days of the year and linearly interpolated. Root growth was simulated for crops only; other plant types were modeled as perennial, with a constant rooting depth. The RLD function is based on the assumption that normalized total root biomass is related directly to RLD (ρ_{rL}) and can be related to depth below the surface (z) by:

$$\rho_{rL} = ae^{(-bz)} + c \qquad (8)$$

where a, b, and c are coefficients that optimize fit to normalized biomass data. Dominant vegetation types that represented ~70–80% of the area of each region were simulated.

The Soil Survey Geographic (SSURGO) database (version 2) at a scale of 1:24,000 (USDA, 1995) is available online and includes the following attributes: clay content, organic material, soil water capacity, permeability, infiltration, drainage, slope, and soil water retention data at -10.8 and -492 ft (-3.3 and -150 m) matric potential head. Pedotransfer functions were used to determine soil hydraulic properties using data from the SSURGO database. Rosetta software uses neural network programming and a database of measured texture, water retention, and saturated hydraulic conductivity to provide estimates of van Genuchten water-retention parameters and saturated hydraulic conductivity for input to unsaturated flow models (Schaap et al., 2001).

Simulations were run for 25 soil profiles that represent ~80% of the Roberts County area. Examination of results for all profiles showed that recharge rates could be categorized into distinct groups, resulting in a more manageable number of representative profiles (4).

A soil-profile depth of 16 ft (5 m) was chosen for the simulations because rooting depths of vegetation types used in this study are < 16 ft (5 m) deep. In addition, SSURGO soil textural information is available only for the upper 6.6 ft (2 m). Texture in the 6.6 to 16 ft (2 to 5m) zone was assumed equal to that of the lowest data available. Once water drains below the root zone, there is little chance of it being drawn upward again. Thus, modeled drainage below the 16 ft (5 m) soil profile can be used as an estimate of groundwater recharge. Sensitivity of simulated recharge to profile depth was evaluated.

In UNSAT-H, node spacing can be adjusted to decrease computing time (fewer nodes) or to increase accuracy at input, output, and layer boundaries (more nodes). In monolithic profiles, nodal spacing ranged from 0.08 in (2 mm) at the top and base of the profile and increased by a factor of ~1.2 with depth to a maximum value of 9.1 in (230 mm) within the profile. In layered soil profiles, nodal spacing was also reduced near textural interfaces to a value of ~0.8 in (20 mm).

UNSAT-H requires an initial matric potential profile for the soil column being modeled. Initial conditions were set arbitrarily at a matric-potential head of -33 ft. (10 m). The impact of initial conditions on simulation results was evaluated by reinitializing simulations multiple times with the final conditions of each run; however, rerunning simulations once was found to be sufficient for minimizing the impact of initial conditions.

The lower boundary condition most appropriate for simulating unimpeded recharge is the unit gradient lower boundary condition which corresponds to free drainage or gravitational flow.

The water balance for a 30-yr period (1961–1990) was simulated for Roberts County. To assess the relative importance of different controls on groundwater recharge, four different scenarios were simulated:

1. nonvegetated, monolithic sand
2. nonvegetated, texturally variable soil
3. vegetated, monolithic sand
4. vegetated, texturally variable soil

The simplest simulations of nonvegetated, monolithic sand were used to provide an upper bound on recharge rates. Complex, texturally variable soil profiles were simulated without vegetation to evaluate the impact of soil textural variability on recharge. Vegetation was added to the monolithic and texturally variable soil profiles to determine its impact on simulated recharge. The most realistic scenario is represented by vegetated, texturally variable soils.

Simulated recharge results are represented by a single temporal (30-yr) and spatial average recharge value for each region, using GIS coverages to determine the area represented by each vegetation type, soil type, or combination of vegetation and soil types to spatially weight 1-D results. Thirty-eight simulations were conducted for the final analysis.

3.0 RESULTS AND DISCUSSION

3.1 Recharge Estimates Based on Groundwater Chloride Data

Groundwater chloride concentrations were mapped to evaluate regional trends that may be related to cross-formational flow of elevated salinity groundwater from formations underlying the Ogallala (Fig. 5). The chloride concentration map was generated using local polynomial methods in ArcMap GIS. Kriging methods, which used a directional variogram based on the study area data set produced a map with very similar overall appearance, but failed to capture subtle but significant features of the groundwater chloride spatial distribution in Roberts County. Chloride plumes (defined arbitrarily as areas where chloride concentrations are ≥ 50 mg/L) are found in several regions of the study area, with concentrations averaging ~150 mg/L and ranging up to 1580 mg/L. Plumes located near the southern boundary of Roberts County (southern plume) and along the Canadian River in Roberts County (river plume) are significant for this study. The presence of saline groundwater in the southern plume area was first reported by local residents as early as 1926 (Long, 1961) and was mapped by McAdoo et al. (1964) and Knowles et al. (1984). Mehta et al. (2000) determined that the shape of the southern plume had not changed significantly since 1964, and was considered to exist in a quasi-steady state.

The mechanism of groundwater salinization in this region was speculated by Dutton (1989) to be related to:

1) cross-formational discharge of brines formed by dissolution of underlying Permian evaporites,
2) infiltration from brine pits associated with oil and gas pits, and/or
3) upward movement from poorly plugged oil and gas wells.

Mehta et al. (2000a) concluded that the geochemical signature of the plume water did not support an oil-field origin because of differences in sulfate concentrations and degree of stable isotope enrichment. Salinization was attributed to topographically driven flow of the Middle/Late Wisonsinan (30-20 ka) recharged water mixed with salt-dissolution zone water in the upper part of the underlying evaporite confining unit (Whitehorse Group) (Mehta et al., 2000b). Cross-formational paleowater discharge is primarily controlled by aquifer geometry, and occurs along the down gradient (northeast) side of the structurally high Amarillo Uplift and through preferential flow paths such as fractures and joints created as a result of salt dissolution (Fig. 5).

The river plume results from upwelling of higher salinity paleowater along deep flow paths through underlying formations that mixes with Ogallala water before discharging to the Canadian River.

An analysis of recharge rates using the CMB approach was applied to the interpolated groundwater chloride concentration distribution in Roberts County (Fig. 5). Only chloride values ≤ 50 mg/L (~74% of the county area) were included in the analysis and were assumed not to be significantly influenced by plume water. Using a county-wide mean total precipitation rate of 22.4 in/yr (570 mm/yr) (Fig. 3) and an annual mean chloride concentration in precipitation of 0.24 mg/L (Fig. 4), results indicate a median recharge rate of **0.26 in/yr** (6.6 mm/yr), with 90% of the (log-normal) recharge rate distribution between 0.13 and 0.60 in/yr (3.2 and 15.2 mm/yr). The highest recharge rates, representing only about 2% of the Roberts County area, range from 0.67 to 0.91 in/yr (17 to 23 mm/yr).

Interpretation of the groundwater chloride distribution in Roberts County requires an integrated understanding of groundwater flow and surface hydrology. A map of water table elevations indicates that groundwater flow in Roberts County is generally northwest in the south part of the county, curving gradually northward to discharge along the Canadian River (Fig. 6). Groundwater flow paths in Roberts County south of the Canadian River originate almost completely in the region of the southern plume, yet the groundwater chloride concentrations decrease in the central region of the county south of the river plume. The decrease in concentration along flow paths in Roberts County could be caused by dilution resulting from recharge and dispersion or it could simply be an artifact of sampling bias (i.e., groundwater samples from wells that only partly penetrate the aquifer saturated thickness and thus sample only shallower water potentially having lower salinity). Mehta et al., (2000a) found that total dissolved solids (TDS) increased with depth in a limited number of sampled wells. To test for sampling bias due to stratification, a subset (49 points) of the Roberts County groundwater sample data for which well depth information is available was used. Well depth was compared to a base-of-aquifer elevation map (Houston et al., 2003) and depth to water table measurements from the TWDB database. A penetration factor, P_f, representing the apparent percentage of aquifer sampled, was calculated for each well as

$$P_f = \frac{E_{WT} - E_{BW}}{E_{WT} - E_{BA}} \times 100\% \qquad (8)$$

where E_{WT} is water table elevation, E_{BW} is bottom-of-well elevation, and E_{BA} is base-of-aquifer elevation. Values of P_f were regressed on groundwater chloride concentrations (Fig. 7). Results indicate that there is generally very poor correlation between P_f and chloride (r = 0.36).

Eliminating questionable data points (10 wells with either < 10 ft [3 m] of water or $P_f > 1$) results in a marginal increase in the correlation (r = 0.41). Although salinity stratification may occur locally, evidence that salinity stratification is pervasive is not compelling, and groundwater samples in Roberts County appear to be generally representative of spatial chloride concentrations.

Spatial distribution of chloride concentrations was also compared with soil clay distribution (Fig. 8). Two regions of elevated chloride concentration (~25 to 50 mg/L) extend as fingers down-gradient and generally along flow lines away from the south plume; one extends generally northward from south-central Roberts County and a second extends generally northeastward from northeastern Gray County across Hemphill County (Figs. 5 and 8). These fingers coincide generally with areas where clay content is higher than that of surrounding areas that also tend to be where surface elevation is higher than surrounding areas (Fig. 9). Conversely, areas of lower chloride concentrations tend to be centered near drainage areas, particularly in areas where the drainage channels are wide with small (<2%) slope (Fig. 10). This relationship is obscured in the lowest drainage reaches by the river plume. Approximately 900 mi (1450 km) of drainage channels are in Roberts County, as defined on USGS 7.5-min quadrangle maps (not including the Canadian River). Lower reaches of major stream drainages south of the Canadian river, where surface slopes are ≤2%, represent about 2.6% (24 mi^2) of the county area.

Given the totality of evidence, a conceptual model of recharge in Roberts County can be developed. Chloride concentrations in Ogallala groundwater are affected by cross-formational flow from underlying units having elevated salinity, complicating application of the chloride mass balance method. Apparent stability of the southern plume, presence of lower chloride concentration groundwater down gradient from the southern plume, and lack of significant evidence of sampling bias indicate that recharge must be occurring. Spatial distribution of groundwater chloride concentrations down gradient from the southern plume indicates that recharge is most likely focused primarily in the lower reaches of drainage areas where drainage from steeper-sloped upper reaches of the drainage networks has coalesced and sufficient runoff is focused to allow deep infiltration below the root zone. Lower reaches of the drainage networks tend to have wider channels, coarser textured soils, and gentler slopes, all of which would enhance recharge, relative to their upper reaches.

3.2 Groundwater Tritium-Helium Age-Dating Results

The results of the $^3H/^3He$ sample analysis indicate that only two of the four wells sampled have a component of water that has recharged within the past 50 yr, while the remaining two samples no component of water that is younger than 50 yr (Table 2). The Gill well (map reference 4) displays the youngest component with an estimated age of about 30 yr and is located in the lowest groundwater chloride concentration region in Roberts County beneath the Red Deer Creek drainage in the southeast corner of the county (Fig. 5). The Duncan well (map reference 3), located in eastern Hutchinson County, has a component of water with about a 50 yr age. Both the Pickens and Morton wells (map reference 1 and 2, respectively), located in west-central Roberts County within the lower reaches of different drainages about 5 miles south of the Canadian River, have no measureable component of water younger than 50 yr.

These results are generally consistent with groundwater chloride mass balance results in that younger water tends to be associated with lower chloride concentrations (indicating higher recharge rates) while older water tends to be associated with higher chloride concentrations (indicating lower recharge rates). Results highlight that though the sampled wells are presumably located in areas most favorable to recharge, that there is very little recent recharge.

3.3 Recharge Estimates Based on Unsaturated Zone Field Studies

3.3.1 Rangeland Setting

General soil texture information for different profiles was estimated from SSURGO data (USDA-NRCS, 2007) (Fig.8). Most of the profile soils at the rangeland sites have moderate clay contents (mean clay content in the upper 2 m of 25 to 33%) with the exception of HEM07-02, located on the breaks near the Canadian River in Hemphill County which contains only 18% clay (Table 3, Figs. 11 and 12). Rangeland profiles have variable water contents. Three of the 5 rangeland profiles in Roberts County for which measurements are available have high mean water contents (0.20 to 0.24 m^3/m^3) whereas the other two profiles have low mean water contents (0.06 to 0.09 m^3/m^3) (Table 3, Figs. 11 and 12). One of the profiles in Roberts County was drilled with air rotary and only cuttings were available; therefore, water content or recharge rates could not be calculated for this profile. Rangeland profiles in Hemphill County also have variable water contents, ranging from 0.06 to 0.22 m^3/m^3. Mean water content below the root zone in rangeland profiles is moderately correlated with SSURGO soil texture (r=0.58), indicating that average surface soil clay content is a controlling factor in deeper profile water content.

Apparent electrical conductivity (EC_a) values measured using the EM 31 meter near rangeland profiles are generally correlated with mean water contents (r=0.89). EC_a varies with water content, soil texture, salinity, and temperature. Relationships between EC_a and water content also reflect soil textural effect on water content and EC_a. Generally low EC_a values are found in drier sediments that are coarser grained whereas higher EC_a values are found in wetter sediments that are associated with more clay-rich sediments.

Matric potentials are low in rangeland sites (mean -38 to -117 m). Variations in matric potential do not seem to be related directly to water content variability.

Chloride concentrations in rangeland profiles are generally high (Table 3, Figs. 11 and 12). Mean chloride concentrations in rangeland profiles range from 161 to 1,115 mg/L in profiles with high water content (0.14 to 0.24 m^3/m^3). These profiles generally have low chloride concentrations in the upper 3 ft (1 m), with the exception of profile ROB07-07 which has low chloride concentrations to a depth of 14.1 ft (4.3 m). Depth of chloride flushing in this profile may reflect local runon, although this was not obvious from the local topography. Peak chloride concentrations in profiles with high mean chloride concentrations range from 477 to 2593 mg/L (6 to 24 ft; 1.8 to 7.3 m depth) (Table 3, Fig. 11). These large chloride accumulations require 3,747 to 19,758 yr to accumulate, indicating that soils in these settings have been drying out over these time periods. There has been no recharge in these settings over these time periods. Profiles with lower mean chloride concentrations (49 and 78 mg/L) correspond to lower mean water contents (0.06 m^3/m^3) and coarser textured soils near the Canadian breaks. Estimated mean water fluxes below the root zone in these profiles range from **0.11 to 0.14 in/yr** (2.8 to 3.6 mm/yr) (Table 3, Fig. 12). Higher water fluxes are attributed to generally coarser textured soils.

Concentrations of other ions, including nitrate, sulfate, and fluoride are variable (Table 4, Figs. 17 and 18). Concentrations of nitrate-N are generally low (median 1.5 mg NO_3-N/L; range 0.8 to 9.5). The only profile with moderately high nitrate-N concentrations is ROB06-02 with a mean nitrate-N concentration of 9.5 mg/L and peak concentration of 32 mg NO_3-N/L at 20.3 ft (6.2 m) depth. Higher nitrate concentrations in this profile are attributed to low water contents and coarse textured soils, because nitrate concentrations on a mass basis are low in this profile, similar to those in other rangeland profiles.

Sulfate profiles are quite variable, with mean concentrations ranging from 174 to 3,647 mg/L and peak concentrations of 459 to 11,738 mg/L. Peak sulfate concentrations are so high in some profiles that they suggest a lithogenic source, such as gypsum and/or anhydrite. Lower concentrations (peaks <1,000 mg/L) may be derived from precipitation and dry fallout, similar to chloride. Correlations between sulfate and chloride are variable (r=0.48 to 0.90). High correlations may reflect similar processes affecting the two ions, such as evapotranspirative enrichment, regardless of the source. Peak chloride and sulfate peaks are also coincident in some profiles (ROB07-06 and HEM07-04).

Fluoride profiles are variable, with mean concentrations from 3 to 129 mg/L and peak concentrations that range from 16 to 459 mg/L at depths of 1.2 to 7.1 m. Fluoride peaks in most profiles are found in the shallow subsurface (5 profiles $\leq$ 1.8 m; 3 profiles 3.0, 3.7, and 7.1 m). Fluoride may be derived partly from precipitation and dry fallout. Although information on fluoride concentrations in precipitation is limited, existing data indicate that concentrations are generally low (Edmunds and Smedley, 2005). Fluoride may also be derived from dissolution of fluorite and/or apatite. Regardless of source, peak fluoride concentrations may be related to evapotranspirative enrichment near the root zone. Profiles with deeper peaks may be related primarily to a lithogenic source.

3.3.2 Dryland Setting

Only two boreholes were drilled in dryland agricultural settings, one in Roberts County and one in Hemphill County. The Roberts County profile is in fine-grained sediments (mean clay content 43%) whereas the profile in Hemphill County is in coarser textured soils (mean clay content 29%) (Table 3, Fig. 13). The difference in mean water content below the root zone at the two sites (Roberts County: 0.21 m^3/m^3, Hemphill County: 0.10 m^3/m^3) reflects the difference in soil texture. Apparent electrical conductivity (EC_a) measured using the EM31 meter at the Roberts site is moderately high (median 55 mS/m).

Matric potential profiles are generally low (-213 and -338 ft; -65 and -103 m). These values are similar to those found in rangeland profiles.

Chloride profiles at the two dryland sites are quite different. High chloride concentrations in the Roberts County site (mean 417 mg/L, peak 1,295 mg/L at 9.8 ft [3.0 m] depth) are similar to the rangeland profiles and represent 10,867 yr of accumulation (Table 3, Fig. 13). This large chloride accumulation represents long-term drying over this time period and indicates that there has been no recharge in this region. The lack of impact of cultivation on recharge at this site may reflect high clay content of the soils in this region. The profile in Hemphill County has low chloride concentrations between the root zone and a depth of 18 ft (5.5 m) (mean 15 mg/L, range 7 to 26 mg/L). Calculated mean water flux for this zone is **0.41 in/yr** (10.4 mm/yr) (Table 3). The time represented by chloride in this section of the profile is 87 yr, which generally corresponds to the time since cultivation began at this site (early 1900s). At depths $\geq$18 ft (5.5 m) chloride concentrations increase to 152 mg/L, which may reflect buildup of chloride under rangeland settings that is mobilized by higher water fluxes under dryland agriculture. The profile is not sufficiently deep (31 ft, 9.4 m) to show much of the rangeland chloride.

Concentrations of nitrate, sulfate, and fluoride are variable (Fig. 19). Concentrations of nitrate-N are generally low in both profiles below the root zone (mean 5.5 and 5.7 mg NO_3-N/L). Highest nitrate-N concentrations in the Hemphill County profile are restricted to the root zone (peak 133 mg NO_3-N/L, depth 0.08 m), which is accessible to crop roots.

Sulfate concentrations are high in the Roberts County dryland profile (peak 3,427 mg/L at 1.5 m depth) and much lower in the Hemphill County profile (peak 399 mg/L at 1.3 m depth). These variations in sulfate concentrations are consistent with chloride concentrations, which are also much higher in the Roberts County profile than in the Hemphill County profile. High sulfate concentrations in the Hemphill County profile are found in the chloride flushed zone, indicating that sulfate is much less readily mobilized by increased drainage beneath dryland agriculture relative to chloride.

Fluoride concentrations are higher in the Hemphill County profile (mean 78 mg/L, peak 120 mg/L at 5.0 m depth) than in the Roberts County profile (mean 20 mg/L, peak 26 mg/L at 7.3 m). Fluoride concentrations within the chloride flushed zone in Hemphill County indicate that fluoride, like sulfate, has not been mobilized as effectively as chloride by the change in land use.

3.3.3 Irrigated Setting

A total of three boreholes were drilled in irrigated sites (two in Roberts County and one in Hemphill County) (Fig. 1). Soil textures at the Roberts County profiles are 25 and 43% clay and the Hemphill profile is much lower, with only 13% clay (Table 3). Mean water contents are low at one of the irrigated sites in Roberts County (0.14 m^3/m^3) and at the Hemphill County irrigated site (0.14 m^3/m^3), but are much higher at the other irrigated site in Roberts County (0.30 m^3/m^3) (Table 3, Fig. 14). Median EC_a values measured using the EM31 meter vary with water content and are much higher (76 mS/m) for the Roberts County profile, which has high water content than for the other two irrigated profiles with lower water content (16 and 18 mS/m).

Matric potentials are uniformly high below the root zone in all irrigated profiles, with mean values ranging from -6 to -10 m, indicating wet conditions (Table 3, Fig. 14). Matric potential is a much more accurate indicator of wet conditions than water content because soil water content varies with soil texture.

Chloride profiles are variable in irrigated settings (Table 3, Fig. 14). Chloride concentrations in the ROB06-01 profile are moderately high and variable with depth (mean 263 mg/L, range 69 to 527 mg/L). Estimated drainage for this site is **2.2 in/yr** (56 mm/yr) using the chloride mass balance approach (equation 2), with an irrigation application rate of 1.5 ft/yr (0.5 m/yr) (meter no. 01-08-2010N; 2002–2004), and chloride concentration in irrigation water of 26 mg/L (well

616651, 9 yr, 1992–2005) (Table 3). The chloride profile beneath the other irrigated site in Roberts County (ROB07-02) has low concentrations in the upper 32 ft (9.8 m) (86 to 264 mg/L), underlain by a zone of high chloride with a peak concentration of 1,140 mg/L at 44 ft (13.4 m) depth (Fig. 6). The upper 32 ft (9.8 m) zone corresponds to the depth interval impacted by irrigation return flow. High chloride concentrations below this zone are attributed to chloride accumulation under previous rangeland conditions; this chloride bulge represents ~8,750 yr of accumulation. The profile is not deep enough to sample the entire chloride profile that developed under rangeland conditions. Water flux can be calculated using the chloride front displacement method (equation 2), which is based on downward displacement of the chloride front from 3 ft (1 m, base of root zone in typical rangeland profiles) to 32 ft (9.8 m) (distance 29 ft, 8.8 m) over ~55 yr irrigation time. This calculation results in a velocity of 0.53 ft/yr (0.16 m/yr) and a recharge rate of **1.9 in/yr** (48 mm/yr) when multiplied by the average water content of 0.30 m^3/m^3 (Table 3). The irrigated profile in Hemphill County has high chloride concentrations in the upper 12 ft (3.7 m) with peak chloride concentration of 1005 mg/L at a depth of 5 ft (1.5 m). High chloride concentrations in this zone are also associated with high sulfate concentrations (peak 449 mg/L at 1.2 m depth) and high fluoride concentrations (peak 66 mg/L at 1.8 m depth). Concentration of salts in this zone is attributed to evapotranspirative enrichment of irrigation water. Estimated recharge for this site is **4.5 in/yr** (115 mm/yr) using the chloride mass balance approach (equation 2) and an irrigation application rate of 1.5 ft/yr (0.5 m/yr) and chloride concentration of 14.5 mg/L measured in a sample of the irrigation water (Table 3).

Concentrations of nitrate, sulfate, and fluoride are variable (Table 4, Fig. 20). Concentrations of nitrate-N are generally low in two profiles below the root zone (means 5.9 and 7.3 mg/L). Much higher nitrate concentrations in ROB07-02 profile extend below the root zone (peak 174 mg /L, depth 1.8 m). A secondary bulge of nitrate near the base of the profile and associated with the displaced chloride bulge may represent organic matter originally in the soil profile that was mineralized and displaced downward following conversion from rangeland.

Sulfate concentrations are high in 2 of the 3 irrigated profiles (peak 449 mg/L at 1.2 m depth; 1,969 mg/L at 7.3 m depth) and low in the third profile, ROB06-01 (46 mg/L at 1.9 m depth. Variations in peak sulfate concentrations generally follow variations in chloride concentrations. However, the peak sulfate concentration in ROB07-02 is much shallower (7.3 m depth) than that of the chloride peak (13.4 m depth), indicating that sulfate is not as readily mobilized by increased drainage beneath irrigated sites as chloride. The difference in peak depths of chloride and sulfate is not as great in the Hemphill County irrigated profile (0.6 m for sulfate and 0.9 m for chloride).

Fluoride concentrations are moderately low in all profiles with peak concentrations ranging from 22 mg/L (1.2 m depth) to 69 mg/L (4.3 m depth). Fluoride profiles do not seem to bear any relation to chloride profiles as the highest peak fluoride concentration is found in the profile with the lowest peak chloride concentration (ROB06-01). Fluoride does not seem to be mobilized under increased drainage resulting from irrigation return flow.

3.3.4 Drainage Setting

One borehole was drilled in a dry drainage channel in Roberts County (Fig. 1). Soil texture at the site is coarse with only 8% clay content in the upper 2 m (Table 3). Mean water content is relatively high (0.17 m^3/m^3) for such coarse soil and matric potential is also high (mean -2 m) (Table 3, Fig. 15). Median EC_a measured using the EM31 was low (15 mS/m) reflecting the coarse soil texture. It is difficult to estimate recharge rates beneath the drainage because we do not know the chloride input (runon rate and chloride concentration in runon). A lower bound on the recharge rate of **0.67 in/yr** (17 mm/yr) can be estimated by assuming no runon. Assuming a runon rate of 2 ft/yr (600 mm/yr) and chloride concentrations in the runon water of 1 mg/L, the estimated recharge rate is 3.8 in/yr (95 mm/yr). Increasing runon and chloride concentration in runon would linearly increase calculated recharge rates.

Mean concentrations of nitrate-N (0.7 mg/L), sulfate (17 mg/L), and fluoride (5 mg/L), are very low and concentration profiles are very uniform (Table 4, Fig. 21). These measurements, along with the chloride profile, indicate that recharge at this site is occurring quickly enough to prevent solutes from building up through evapotranspiration.

3.3.5 Stock Impoundments

Four boreholes were cored beneath or adjacent to stock impoundments in Roberts County (Fig.1). Two boreholes were located in the same impoundment and offset by about 30 ft (9m), with the second borehole being an attempt to obtain greater depth than the first. Both were analyzed for all parameters except matric potential, for which measurements were made for only one profile. Soil texture at the sites is representative of rangeland areas and ranges from 23 to 27% (Table 3). Mean water contents are moderate to high (0.17 to 0.26 m^3/m^3) and matric potentials are very high (mean -4.3 to -15.7 ft; -1.3 to -4.8 m) (Table 3, Fig. 16). Median EC_a measured using the EM31 was high (39 to 56 mS/m) reflecting combined clay and water contents. As with the drainage setting location, it is difficult to estimate recharge rates beneath the impoundments because we do not know the chloride input (ponding rate and chloride concentration). Lower bounds on recharge rates can be estimated by assuming no ponding and a range from **0.64 to 1.4 in/yr** (16 to 35 mm/yr). Assuming a ponding rate of 2 ft/yr (600 mm/yr) and chloride concentrations in the ponded water of 1 mg/L, recharge rates range from 4.3 to 7.3 in/yr (87 to 186 mm/yr). Increasing ponding depth and chloride concentration in pond water would linearly increase calculated recharge rates.

Mean nitrate-N concentrations below the root zone are generally high compared with most rangeland sites and are comparable to cultivated sites (mean 1.3 to 9.8 mg/L) (Table 4, Fig. 22). Peak nitrate-N concentrations below the root zone (12 to 53 mg/L, 1.2 to 6.3 m depth) also follow this pattern, higher than rangeland and comparable to cultivated sites. The highest nitrate-N concentrations in all impoundment profiles occur at the surface or within the root zone, and range from 21 to 480 mg/L, reflecting the high deposition rate of cow manure at these locations.

As with the drainage site profile, mean concentrations of sulfate and fluoride in the impoundment profiles are generally low to very low and concentrations are generally uniform with depth (Table 4, Fig. 22). These measurements, along with the chloride profiles, are similar to stream drainage profile concentrations and indicate that recharge at these sites is also occurring fast enough to prevent solutes from building up through evapotranspiration.

3.4 Recharge Estimates Based on Unsaturated Zone Modeling

Vegetation input parameters required for UNSAT-H simulations are shown in Table 5, and soil water-retention parameters for soil profiles in Roberts County derived from SSURGO data are shown in Table 6. Simulation results are represented for the four basic scenarios to assess relative importance of climate, vegetation, and soils in controlling recharge (Tables 7 and 8). Average final mass balance errors for each simulation ranged from -1.5 to 0.2 mm/yr, with errors for most simulations <0.3 mm/yr. For simulation results with average drainage of >1 mm/yr, the average annual mass balance error was <5% of average annual drainage.

3.4.1 Nonvegetated, Monolithic Sand Simulations

Simulated mean (30-yr) annual recharge for bare sand is high, 6.8 in/yr (174 mm/yr), representing 35% of mean (30-yr) annual precipitation. This recharge estimate provides an upper bound on the actual recharge rate because vegetation and soil textural variability were not included. In addition, simulated runoff from the 1-D model is zero. Lack of simulated runoff was attributed to the high saturated hydraulic conductivity of the sand (9.4 in/hr, 0.24 m/hr) relative to the pre-specified precipitation intensity (4 in/hr, 0.01 m/hr).

Temporal variability in mean annual recharge (coefficient of variation, CV: 0.16) is less than that of precipitation (CV: 0.21, Table 7). Mean 30-yr annual potential ET, 82.5 in/yr (2096 mm/yr), is 6.5 times greater than simulated actual ET (12.7 in/yr, 323 mm/yr). The PET/AET ratio decreases from 12.1 in the arid west of Texas to 2.9 in the humid east of Texas (Keese et al., 2005). In arid regions, most infiltrated water is returned to the atmosphere through evaporation. Roberts County has a semi-arid climate shown by the tracking of precipitation and evaporation (Fig. 24). The high correlation (r^2=0.80) between evaporation and precipitation in this region may be attributed to evaporation rarely being energy limited (high PET). There is some lag between high precipitation and recharge, as shown by the moderate correlation between annual precipitation and recharge (r^2=0.54).

3.4.2 Nonvegetated, Texturally Variable Soil Simulations

Simulated mean (30-yr) annual, areally averaged recharge for Roberts County is 2.0 in/yr (52 mm/yr) for nonvegetated, texturally variable soil profiles, representing 10% of mean annual precipitation (Table 7). This recharge rate is 3.4 times lower than that based on the monolithic sand profile, indicating the importance of soil textural variability in controlling recharge. Lower recharge rates may reflect finer textured soils, or they may be related to reductions in recharge caused by profile layering, both fine over coarse (capillary barrier effect) and coarse over fine layering. Reductions in recharge in the texturally variable soil simulations correspond to increased runoff, evaporation, or both.

Variations in simulated mean (30-yr) annual runoff generally reflect differences in soil texture. Simulated runoff is positively correlated with mean clay content (r^2=0.57) and negatively correlated with mean sand content (r^2=–0.49). Simulated recharge rates in clay-rich soils may not accurately reflect actual recharge rates if preferential flow occurs in these settings because this process is not included in the simulations.

3.4.3 Vegetated, Monolithic Sand Simulations

To assess the impact of vegetation, without the influence of soil textural variability, recharge simulations were conducted for vegetated, monolithic sands (Table 7). Vegetation markedly reduced simulated areally averaged mean annual recharge (0.18 in/yr, 4.5 mm/yr; 0.9% of mean annual precipitation) by a factor of 11.4 relative to recharge for nonvegetated, texturally variable soils.

Simulated runoff was zero for both nonvegetated and vegetated simulations. Vegetation type also affects simulated recharge, as seen in the two orders of magnitude range in simulated recharge for different vegetation types. Shrubs are generally more effective than crops in reducing recharge because of greater rooting depth and longer growing season.

3.4.4 Vegetated, Texturally Variable Soil Simulations

Texturally variable soils with vegetation provide the most realistic representation of actual conditions and should provide the most reliable recharge estimates for the different regions. Simulated mean (30-yr) annual, areally averaged recharge is low, 0.004 in/yr (0.1 mm/yr), and represents 0.02% of mean annual precipitation.

Vegetation markedly reduced recharge relative to that for nonvegetated, texturally variable soils. The reduction factor was greater than 500 and reflects the enhanced ability of vegetation to reduce recharge in this water-limited region.

Simulated runoff was higher in areas with higher clay content relative to lower clay content, as expected. Simulated mean (30-yr) annual, areally averaged runoff is high, 2.9 in/yr (73 mm/yr), and is inconsistent with low runoff estimates based on measured stream gauge data (1961–1990) used to develop a statewide water balance (Reed et al., 1997). Discrepancies between the two estimates can be attributed to predominantly internal drainage to ephemeral lakes or playas and little runoff to gauged stream networks. Runoff is one of the most difficult parameters to simulate because it depends on accurate representation of rainfall intensity and hydraulic conductivity of surficial sediments that may be crusted, as shown by detailed comparisons of simulated and measured runoff at a controlled field experiment (Scanlon et al., 2002).

Relative controls of different vegetation types in vegetated, texturally variable soil simulations are similar to those for vegetated, monolithic sands—recharge rates are lower beneath shrubs and brush than beneath crops (Fig. 25). However, all of the simulations beneath texturally variable soils show extremely low recharge rates. Relative amounts of evaporation and transpiration vary with vegetation type and soil texture. Transpiration is much greater than evaporation for brush, irrespective of texture. Regardless of vegetation type, evaporation is higher than transpiration in finer textured soils than in coarser textured soils, because finer textured soils retain more water near the soil surface for longer periods and therefore allow greater evaporation.

4.0 SUMMARY

A regional recharge rate of **0.26 in/yr** (6.6 mm/yr) was estimated for central Roberts County on the basis of a region of low chloride groundwater (≤50 mg/L) in the central part of Roberts County that extends into Hemphill County. Groundwater chloride concentrations cannot be used in other regions because of saline plumes in the southern part of Roberts and northern Gray counties and also along the Canadian River in Roberts and Hemphill counties.

Approximately 90% of the log-normal recharge distribution was found between 0.13 and 0.60 in/yr (3.2 and 15.2 mm/yr). Highest recharge rates, representing only about 2% of the Roberts County area, range from 0.67 to 0.91 in/yr (17 to 23 mm/yr) and are consistent with high recharge rates (≥0.67 in/yr; ≥17 mm/yr) estimated from an unsaturated zone profile sampled beneath a stream drainage in Roberts County. These results indicate that stream drainages in Roberts County may be functioning in ways similar to playas in other regions by focusing recharge to the Ogallala aquifer. However, tritium-helium age dating of groundwater samples from wells located within the stream drainage network indicates that there has been very little recharge within the past 50 yr.

Unsaturated zone chloride profiles indicate that there is essentially no recharge beneath most rangeland sites in Roberts and Hemphill Counties. Many rangeland profiles (6 out of 9) are characterized by large chloride accumulations that required 3,601 to 19,758 yr to accumulate and indicate that soils have been drying out over these time periods. The remaining rangeland profiles (one in Roberts and one in Hemphill counties) have much lower chloride concentrations (mean 49 to 78 mg/L) indicating low recharge rates of **0.11 and 0.14 in/yr** (2.8 and 3.6 mm/yr) attributed to coarser textured soils and location on the breaks near the Canadian River. Recharge could not be estimated for one rangeland profile in Roberts County because only cuttings could be collected with the air rotary drilling technique. Conversion from rangeland to dryland agriculture did not increase recharge in the Roberts County profile because of fine textured soils but did result in low recharge in the Hemphill County profile **0.41 in/yr** (10.4 mm/yr). Irrigation increased recharge in all 3 irrigated profiles to values of **1.9, 2.2, and 4.5 in/yr** (48, 56, and 115 mm/yr), which is attributed to excess irrigation water leaching below the root zone. Salts are accumulating near the root zone in the Hemphill irrigated profile, which can be attributed to deficit irrigation and evapotranspirative enrichment. A profile beneath a dry stream drainage in Roberts County also showed significant recharge as evidenced by low chloride concentrations; a minimum recharge of rate of **0.68 in/yr** (17 mm/yr) was calculated for this site. The actual recharge rate could not be estimated accurately because the runon amount and chloride concentration in runon were not quantified. Similarly, 4 profiles beneath 3 stock impoundments also showed significant (minimum) recharge rates ranging from **0.64 to 1.4 in/yr** (16 to 35 mm/yr), although actual recharge rates could not be estimated for the same lack of chloride input data.

Unsaturated zone modeling using bare sand for Roberts County resulted in a maximum estimate of recharge of **6.9 in/yr** (174 mm/yr) representing 35% of mean annual precipitation (30-yr; 1961-1990). Simulated mean (30-yr) annual, aerially averaged recharge for Roberts

County is 2 in/yr (52 mm/yr) for texturally variable soil profiles, representing 10% of mean annual precipitation. Vegetation reduces simulated mean annual recharge (0.18 in/yr; 4.5 mm/yr; 0.9% of mean annual precipitation) by a factor of 11.4 relative to recharge for the nonvegetated sands. Texturally variable soils with vegetation provide the most realistic representation of actual conditions. Simulated mean (30-yr) annual, areally averaged recharge is low, 0.004 in/yr; 0.1 mm/yr, and represents 0.02% of mean annual precipitation. However, this recharge estimate does not incorporate the effects of stream drainages in Roberts County or increased water input through drainage systems.

The regional recharge rate of **0.26 in/yr** (6.6 mm/yr) based on groundwater chloride concentrations, probably the most reliable estimate for Roberts County, is similar to previous regional estimates (0.24 in/yr, 6 mm/yr) for the central High Plains using chloride input based on long-term data (20 yr from NADP). Groundwater chloride data indicate that stream drainages in Roberts County may function like playas in the central High Plains, focusing recharge. Results from unsaturated zone sampling and modeling are consistent with regional estimates based on groundwater chloride and indicate that little recharge occurs outside stream drainages and stock impoundments in the region.

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7.0 TABLES

Table 1: Location of sample boreholes, borehole depths, water-table (WT) depths, dates boreholes drilled, and number of samples from each borehole for water content and anion analyses.

Borehole	County	Latitude	Longitude	Depth (ft)	Depth (m)	WT (ft)	WT (m)	Date Drilled	No. of Samples
Rangeland									
ROB06-02	Roberts	35.85093	-101.02675	40.0	12.2	244	74	05/03/06	24
ROB07-01	Roberts	35.65988	-101.03013	38.5	11.7	381	116	07/25/07	18
ROB07-04	Roberts	35.79762	-100.96810	74.0	22.6	233	71	07/27/07	27
ROB07-06	Roberts	35.77688	-100.66328	40.0	12.2	399	122	07/28/07	18
ROB07-07	Roberts	35.87070	-100.73472	30.0	9.1	210	64	07/28/07	16
ROB07-08	Roberts	35.84278	-100.93056	80.0	24.4	227	69	09/29/07	33
HEM07-02	Hemphill	36.00925	-100.34652	40.0	12.2	241	73	07/30/07	18
HEM07-03	Hemphill	35.73182	-100.43177	19.0	5.8	116	35	07/30/07	13
HEM07-04	Hemphill	35.79248	-100.22678	34.8	10.6	181	55	07/31/07	17
Dryland									
ROB07-03	Roberts	35.63493	-100.84613	60.0	18.3	370	113	07/26/07	23
HEM06-01	Hemphill	35.68968	-100.35918	31.0	9.4	144	44	05/02/06	22
Irrigated									
ROB06-01	Roberts	35.86763	-101.02670	38.8	11.8	170	52	05/03/06	24
ROB07-02	Roberts	35.66947	-100.80375	50.0	15.2	371	113	07/25/07	21
HEM07-01	Hemphill	36.01768	-100.34685	34.0	10.4	253	77	07/29/07	17
Drainage									
ROB07-05	Roberts	35.78040	-100.99380	27.5	8.4	71	22	07/27/07	15
Impoundment									
ROB08-01	Roberts	35.66913	-101.03972	88.0	26.8	326	99	08/04/08	17
ROB08-02	Roberts	35.68735	-101.05310	18.5	5.6	284	87	08/05/08	8
ROB08-03	Roberts	35.68745	-101.05310	20.5	6.2	284	87	08/05/08	8
ROB08-04	Roberts	35.76037	-100.67957	49.0	15.0	311	95	08/05/08	12

Table 2. Tritium-helium sample results.

Map Ref.	*Well*	*Latitude*	*Longitude*	*Date Sampled*	*Tritium (TU)*	*R/R_a*	*^{4}He (□μcm^{3}STP /kg)*	*^{20}Ne (□μcm^{3}STP /kg)*	*Age (yr)*	*Cl (mg/L)*
1	Pickens	35.86596	-100.97848	03/03/09	0.21	0.68	74.0	196	>50	29
2	Morton	35.86854	-100.87524	03/03/09	0.02	0.32	176	189	>50	135
3	Duncan	35.78407	-101.12672	03/03/09	0.08	0.88	48.3	181	49.9	15
4	Gill	35.70115	-100.61731	03/04/09	3.25	1.64	46.8	180	30.2	11

TU: tritium units (=molecules of ^{3}H per 10^{18} molecules of ^{1}H)
R: ^{3}He/^{4}He ratio of the sample, R_a: ^{3}He/^{4}He ratio of the air standard
STP: standard temperature and pressure

Table 3. Results from field and laboratory analyses on borehole samples. Electromagnetic field results (median vertical mode ECa); soil texture from SSURGO for the upper 2 m (% clay content), mean water content (WC) and mean matric potential (MP), and chloride concentrations (depth flushed in dryland and irrigated sites, mean, minimum and maximum (peak) chloride concentrations, peak chloride concentration depth, time represented by chloride in rangeland profiles and in flushed zones in agricultural profiles. Recharge rates calculated using the chloride mass balance approach. Mean values represent depth weighted means below the root zone (3.3 ft, 1 m).

						Chloride						
Borehole	Median EC_a (mS/m)	SSURGO clay (%)	Mean WC (g/g)	Mean WC (m^3/m^3)	Mean MP (m)	Flushed Depth (m)	Mean (mg/L)	Min (mg/L)	Max (mg/L)	Peak Depth (m)	Age (yr)	Recharge (mm/yr)
Rangeland												
ROB06-02	4	25	0.04	0.06	-67	—	49	13	108	10.7	187	3.6
ROB07-01	28	27	0.13	0.20	-83	—	447	378	561	3.7	6947	0
ROB07-04	24	26	0.06	0.09	-108	—	938	117	1397	7.3	12706	0
ROB07-06	36	33	0.14	0.23	-96	—	1115	326	2593	1.8	19758	0
ROB07-07	30	25	0.15	0.24	-69	—	161	11	477	7.3	3747	0
ROB07-08	—	25	—	—	—	—	2*	1*	10*	3.4	533	—
HEM07-02	3	18	0.04	0.06	-38	—	78	22	250	3.7	308	2.8
HEM07-03	19	29	0.07	0.11	-117	—	1316	16	2209	5.8	3601	0
HEM07-04	30	29	0.14	0.22	-68	—	533	21	878	3.0	4989	0
Dryland												
ROB07-03	55	43	0.13	0.21	-103	0.9	417	86	1295	3.0	10867	0
HEM06-01	-	29	0.07	0.10	-65	5.6	15	7	26	9.4	87	10
Irrigated												
ROB06-01	16	25	0.09	0.14	-7	11.8	263	69	527	2.2	—	56
ROB07-02	76	43	0.19	0.30	-10	9.8	439	129	1140	13.4	—	48
HEM07-01	18	13	0.09	0.14	-6	10.4	176	14	1005	1.5	—	115
Drainage												
ROB07-05	15	8	0.11	0.17	-2	—	16	3	74	1.2	169	>17
Impoundment						—						
ROB08-01	56	27	0.11	0.17	-2.0	—	12	4.7	38	21.9	—	>16
ROB08-02	39	23	0.11	0.17	—	—	8.4	4.4	11.4	4.9	—	>21
ROB08-03	39	23	0.13	0.20	-1.3	—	7.5	4.1	9.1	4.9	—	>19
ROB08-04	41	27	0.16	0.26	-4.8	—	4.4	2.0	6.3	9.8	—	>35

Water content could not be measured in samples from ROB07-08 because only cuttings were available with the air rotary drilling technique used for this profile. Recharge rates could not be estimated for this profile either. *Chloride concentrations for this profile are in mg/kg of dry sediment, rather than mg/L of soil pore water.

Table 4. Results from laboratory analyses on borehole samples. Values represent concentrations (mg/L soil pore water) for depths below the root zone (3.3 ft, 1 m).

	Chloride			Nitrate-N			Sulfate			Fluoride		
Borehole	Mean (mg/L)	Max (mg/L)	Peak (m)	Mean (mg/L)	Max (mg/L)	Peak (m)	Mean (mg/L)	Max (mg/L)	Peak (m)	Mean (mg/L)	Max (mg/L)	Peak (m)
Rangeland												
ROB06-02	49	108	10.7	9.5	32.2	6.2	174	459	6.2	74	147	7.1
ROB07-01	447	561	3.7	1.3	3.3	1.2	572	1203	2.4	52	210	1.5
ROB07-04	938	1397	7.3	2.2	3.6	11.0	601	1911	3.0	43	287	1.8
ROB07-06	1115	2593	1.8	2.2	5.6	3.0	806	7384	1.8	3	16	1.2
ROB07-07	161	477	7.3	1.5	3.2	3.0	393	742	7.3	129	293	3.7
ROB07-08*	1.80*	10.0*	3.0*	—	—	—	7.7*	16.8*	3.4*	2.8*	8.3*	7.2*
HEM07-02	78	250	3.7	0.9	2.2	1.8	187	866	3.7	40	79	1.8
HEM07-03	1316	2209	5.8	2.2	4.7	4.9	3647	11738	2.4	100	459	1.8
HEM07-04	533	878	3.0	0.8	1.7	1.5	780	1570	4.9	46	88	3.0
Dryland												
ROB07-03	417	1295	3.0	5.7	11.9	4.3	20	3427	1.5	20	26	7.3
HEM06-01	15	26	9.4	5.5	9.3	2.5	136	399	1.3	78	120	5.0
Irrigated												
ROB06-01	263	527	2.2	5.9	17.5	10.7	25	46	1.9	43	69	4.3
ROB07-02	439	1140	13.4	45.5	174.2	1.8	643	1969	7.3	8	22	1.2
HEM07-01	176	1005	1.5	7.3	22.3	7.3	176	449	1.2	29	66	1.8
Drainage												
ROB07-05	16	74	1.2	0.7	2.5	8.4	17	40	1.2	5	7	1.2
Impoundment												
ROB08-01	12	38	21.9	4.5	12	2.4	14	27	4.9	8.3	12	24.4
ROB08-02	8.4	11.4	4.9	8.5	53	1.2	12	69	5.6	11	18	5.6
ROB08-03	7.5	9.1	4.9	9.8	25	6.3	18	30	6.3	7.4	12	3.7
ROB08-04	4.4	6.3	9.8	1.3	6.3	2.4	29	85	14.9	11	18	6.1

*Concentrations for ROB07-08 are in mg/kg of dry sediment because only cuttings were collected for this profile.

Table 5. Vegetation input parameters for UNSAT-H Model from Keese et al. 2005. *Max LAI*: area/area, maximum Leaf Area Index prescribed, defined as the one sided green leaf area per unit ground area in broadleaf canopies, or as the projected needle leaf area per unit ground area in needle canopies; *Max RD*: meters, maximum root depth prescribed; *RLD* parameters, Root Length Density coefficients *a*, *b*, and *c* used to optimize fit to normalized biomass data; *BA*, percentage of area assumed to have no vegetation; *Crop Growing Season*, calendar day on which seeds germinate - calendar day on which plants cease transpiring.

Vegetation Type	*Max LAI*	*Max RD*	*RLD parameters*			*BA*	*Crop Growing Season*	*References*
			a	*b*	*c*			
Shrub	1	1.8	0.64	0.014	0.01	20		1, 2, 3, 4, 5, 6, 7
Brush	1.65	1.8	0.64	0.014	0.01	20		1, 2, 3, 4, 5, 6, 7, 8
Sorghum	3.3	1.5	0.85	0.4	0.01		135-288	9, 10, 11

References: 1. McMahon et al. (1984); 2. Jackson et al. (1996); 3. Ansley et al. (2002); 4. Heitschmidt et al. (1998); 5. James Ansley (pers com); 6. Canadell et al. (1996); 7. Tierny and Fox (1987); 8. Jackson et al. (1999); 9. Howell et al. (1996); 10. Weaver (1926); 11. Dugas et al. (1999)

Table 6. Soil Properties used for UNSAT-H modeling. SSURGO texture and water retention data that were input to Rosetta pedotransfer functions to determine water retention and hydraulic conductivity output. Recharge category (1, highest – 4 lowest), highlighted categories were those selected to represent each respective recharge category; MUID, map unit identification; Component, Map Unit Component; % Area, percent of county or aquifer covered by soil unit; soil profile layer (1-4); Thick; layer thickness, percent gravel, sand, silt, and clay; ρ, bulk density; $\theta_{0.33}$, water content at field capacity; θ_{15}, water content at wilting point; pedotransfer output: θ_s, water content at saturation; θ_r, residual water content, α and n, van Genuchten retention values; K_s, saturated hydraulic conductivity; texture, USDA texture classification.

						SSURGO Input Parameters							*Rosetta Output Parameters*					
Recharge Category	*MUID*	*Component*	*% Area*	*Layer*	*Thick (cm)*	*Gravel %*	*Sand %*	*Silt %*	*Clay %*	ρ *(g/cm³)*	$\theta_{0.33}$ *(m³/m³)*	θ_{15} *(m³/m³)*	θ_s *(m³/m³)*	θ_r *(m³/m³)*	α *(1/cm)*	n	K_s *(cm/hr)*	*Texture*
-	-	Sand[1]	-	-	-	-	-	-	-	-	-	-	0.38	0	0.050	1.774	24.46	
1	18	Tascosa	0.9	1	18	30.0	62.5	26.0	11.5	1.62	0.160	0.085	0.267	0.029	0.042	1.382	1.072	GR-FSL
				2	43	57.5	65.3	23.2	11.5	1.66	0.098	0.045	0.173	0.016	0.054	1.531	1.496	GR-L
				3	66	55.0	65.3	23.2	11.5	1.65	0.103	0.047	0.183	0.017	0.053	1.508	1.517	GR-SL
	19	**Lincoln**	**5.5**	**1**	**30**	**7.5**	**96.8**	**0.7**	**2.5**	**1.50**	**0.076**	**0.019**	**0.375**	**0.020**	**0.064**	**1.558**	**20.03**	**FS**
				2	**122**	**7.5**	**85.0**	**5.0**	**10.0**	**1.52**	**0.131**	**0.067**	**0.375**	**0.035**	**0.055**	**1.463**	**7.988**	**FSCL**
	39	Tivoli	3.1	1	18	1.0	93.2	1.3	5.5	1.50	0.114	0.046	0.396	0.026	0.057	1.455	12.24	FS
				2	147	1.0	93.2	1.3	5.5	1.67	0.112	0.044	0.348	0.026	0.050	1.441	6.450	FS
2	23	Veal	3.4	1	25	5.0	65.4	19.6	15.0	1.55	0.199	0.107	0.365	0.042	0.033	1.338	1.454	FSL
				2	23	5.0	55.1	17.4	27.5	1.55	0.303	0.169	0.385	0.052	0.011	1.308	0.398	SCL
				3	104	10.0	34.7	37.8	27.5	1.60	0.297	0.169	0.356	0.052	0.012	1.296	0.180	CL
	16	Guadalupe	1.3	1	114	2.0	62.5	26.0	11.5	1.55	0.182	0.086	0.358	0.034	0.032	1.350	1.484	FSL
				2	89	2.0	87.0	1.5	11.5	1.60	0.179	0.083	0.372	0.034	0.033	1.341	2.859	LFS
	22/23	**Mobeetie**	**12.4**	**1**	**130**	**5.0**	**66.1**	**19.9**	**14.0**	**1.50**	**0.188**	**0.096**	**0.368**	**0.038**	**0.036**	**1.352**	**2.029**	**FSL**
				2	**73**	**7.5**	**66.1**	**19.9**	**14.0**	**1.55**	**0.187**	**0.097**	**0.349**	**0.038**	**0.035**	**1.348**	**1.590**	**FSL**
	18	Likes	1.5	1	25	5.0	83.5	6.5	10.0	1.65	0.170	0.077	0.342	0.031	0.033	1.346	1.898	LFS
				2	178	5.0	83.5	6.5	10.0	1.68	0.167	0.074	0.334	0.029	0.032	1.346	1.724	LFS
	17	Likes	6.8	1	25	5.0	83.5	6.5	10.0	1.65	0.170	0.077	0.342	0.031	0.033	1.346	1.898	LFS
				2	178	5.0	89.9	0.1	10.0	1.68	0.138	0.075	0.342	0.038	0.049	1.433	4.780	LFS
	4	Amarillo	1.1	1	25	0.0	66.1	19.9	14.0	1.55	0.199	0.104	0.374	0.041	0.032	1.336	1.469	FSL
				2	97	0.0	55.1	17.4	27.5	1.55	0.253	0.175	0.396	0.076	0.038	1.290	1.050	SCL
				3	81	5.0	55.1	17.4	27.5	1.68	0.254	0.183	0.350	0.069	0.038	1.259	0.435	SCL
3	15	Paloduro	2.1	1	38	5.0	35.4	33.6	31.0	1.44	0.323	0.198	0.419	0.067	0.016	1.278	0.387	CL
				2	127	5.0	35.2	38.3	26.5	1.60	0.304	0.169	0.371	0.053	0.010	1.311	0.173	L

[1] Monolithic sand hydraulic and retention parameters from UNSODA database, number 4650 (Leij et al., 1996).

Table 5 (continued)

						SSURGO Input Parameters							*Rosetta Output Parameters*					
Recharge Category	*MUID*	*Component*	*% Area*	*Layer*	*Thick (cm)*	*Gravel %*	*Sand %*	*Silt %*	*Clay %*	*ρ (g/cm^3)*	*$\theta_{0.33}$ (m^3/m^3)*	*θ_{15} (m^3/m^3)*	*θ_s (m^3/m^3)*	*θ_r (m^3/m^3)*	*α (1/cm)*	*n*	*K_s (cm/hr)*	*Texture*
3	**13**	**Estacado**	**2.1**	**1**	**38**	**2.0**	**34.2**	**37.3**	**28.5**	**1.44**	**0.320**	**0.187**	**0.422**	**0.065**	**0.013**	**1.302**	**0.400**	**CL**
				2	**38**	**2.0**	**34.7**	**37.8**	**27.5**	**1.66**	**0.312**	**0.175**	**0.369**	**0.052**	**0.008**	**1.304**	**0.104**	**CL**
				3	**76**	**2.0**	**34.7**	**37.8**	**27.5**	**1.66**	**0.308**	**0.169**	**0.367**	**0.052**	**0.008**	**1.316**	**0.111**	**CL**
				4	**51**	**5.0**	**34.7**	**37.8**	**27.5**	**1.72**	**0.306**	**0.172**	**0.348**	**0.048**	**0.008**	**1.292**	**0.073**	**CL**
	1	Acuff	1.3	1	18	2.5	41.4	37.1	21.5	1.50	0.288	0.141	0.387	0.049	0.009	1.375	0.404	L
				2	89	2.5	35.9	34.1	30.0	1.60	0.321	0.191	0.385	0.058	0.011	1.278	0.139	CL
				3	96	5.0	34.7	37.8	27.5	1.57	0.310	0.178	0.381	0.056	0.011	1.298	0.193	CL
4	23	Potter	3.4	1	25	22.5	37.9	35.6	26.5	1.56	0.261	0.141	0.318	0.044	0.016	1.317	0.311	GR-L
				2	127	50.0	41.6	37.4	21.0	1.68	0.133	0.062	0.141	0.015	0.042	1.402	0.416	CB-L
	15	Estacado	3.6	1	28	2.5	35.4	33.6	31.0	1.66	0.329	0.205	0.375	0.056	0.011	1.245	0.078	CL
				2	48	2.5	35.4	33.6	31.0	1.60	0.325	0.198	0.388	0.059	0.011	1.265	0.132	CL
				3	127	2.5	35.2	38.3	26.5	1.66	0.306	0.166	0.365	0.051	0.008	1.321	0.115	L
	6	Potter	3.0	1	20	22.5	37.9	35.6	26.5	1.56	0.261	0.141	0.318	0.044	0.016	1.317	0.311	GR-L
				2	132	50.0	41.6	37.4	21.0	1.68	0.133	0.062	0.141	0.015	0.042	1.402	0.416	CB-L
	23	**Potter**	**3.4**	**1**	**25**	**22.5**	**37.9**	**35.6**	**26.5**	**1.56**	**0.261**	**0.141**	**0.318**	**0.044**	**0.016**	**1.317**	**0.311**	**GR-L**
				2	**127**	**50.0**	**41.6**	**37.4**	**21.0**	**1.68**	**0.133**	**0.062**	**0.141**	**0.015**	**0.042**	**1.402**	**0.416**	**CB-L**
	30	Potter	1.6	1	25	22.5	37.9	35.6	26.5	1.56	0.261	0.141	0.318	0.044	0.016	1.317	0.311	GR-L
				2	127	50.0	41.6	37.4	21.0	1.68	0.133	0.062	0.141	0.015	0.042	1.402	0.416	CB-L
	6	Berda	4.2	1	25	9.0	38.5	36.5	25.0	1.50	0.279	0.141	0.369	0.048	0.011	1.353	0.375	L
				2	127	9.0	55.8	17.7	26.5	1.55	0.236	0.160	0.371	0.070	0.040	1.313	1.236	L
	26	Olton	1.0	1	18	2.5	34.2	37.3	28.5	1.54	0.313	0.177	0.395	0.058	0.010	1.311	0.228	CL
				2	104	5.0	29.0	31.0	40.0	1.60	0.333	0.216	0.391	0.063	0.014	1.232	0.160	CL
				3	81	7.5	34.7	32.8	32.5	1.72	0.320	0.199	0.348	0.051	0.010	1.238	0.058	CL
	10	Darrousett	1.8	1	18	1.0	20.0	49.0	31.0	1.58	0.328	0.200	0.401	0.064	0.012	1.262	0.170	SICL
				2	114	1.0	7.1	52.9	40.0	1.72	0.338	0.217	0.385	0.061	0.011	1.211	0.046	SICL
				3	71	5.0	29.0	31.0	40.0	1.64	0.332	0.215	0.381	0.060	0.013	1.228	0.122	SICL
	31	Potter	2.1	1	23	7.5	37.9	35.6	26.5	1.52	0.292	0.156	0.376	0.052	0.011	1.334	0.306	L
				2	129	50.0	41.6	37.4	21.0	1.68	0.133	0.062	0.141	0.015	0.042	1.402	0.416	CB-L
	29	Paloduro	1.0	1	30	5.0	39.8	37.7	22.5	1.55	0.296	0.156	0.375	0.051	0.010	1.341	0.275	L
				2	173	5.0	55.8	17.7	26.5	1.60	0.245	0.169	0.369	0.070	0.038	1.289	0.826	L
	28	Paloduro	0.9	1	36	5.0	39.8	37.7	22.5	1.55	0.296	0.156	0.375	0.051	0.010	1.341	0.275	L
				2	167	5.0	55.8	17.7	26.5	1.60	0.245	0.169	0.369	0.070	0.038	1.289	0.826	L

Table 5 (continued)

						SSURGO Input Parameters							Rosetta Output Parameters					
Recharge Category	*MUID*	*Component*	*% Area*	*Layer*	*Thick (cm)*	*Gravel %*	*Sand %*	*Silt %*	*Clay %*	ρ (g/cm^3)	$\theta_{0.33}$ (m^3/m^3)	θ_{15} (m^3/m^3)	θ_s (m^3/m^3)	θ_r (m^3/m^3)	α $(1/cm)$	n	K_s (cm/hr)	*Texture*
4	30	Paloduro	4.9	1	36	5.0	39.8	37.7	22.5	1.55	0.296	0.156	0.375	0.051	0.010	1.341	0.275	L
				2	167	5.0	55.8	17.7	26.5	1.60	0.245	0.169	0.369	0.070	0.038	1.289	0.826	L
	32	Pullman	3.8	1	15	0.0	18.7	47.8	33.5	1.52	0.330	0.201	0.419	0.069	0.013	1.271	0.239	SICL
				2	112	0.0	23.3	29.2	47.5	1.78	0.378	0.273	0.379	0.057	0.012	1.151	0.018	C
				3	36	0.0	30.2	32.3	37.5	1.60	0.343	0.224	0.404	0.064	0.013	1.227	0.119	CL
				4	40	5.0	27.8	29.7	42.5	1.64	0.339	0.228	0.384	0.062	0.014	1.209	0.124	CL
	sum		**80.7%**															

Table 7. Simulation results for the four basic scenarios for nonvegetated monolithic sand and texturally variable soils and for vegetated monolithic sand and texturally variable soils. Values represent average annual results for 30-yr simulations.

		Nonvegetated										*Vegetated*							
MAP		*Sand*					*Variable*					*Sand*			*Variable*				
		Recharge			*AE*	*PET/AE*	*Recharge*		*AE*	R_O	ΔS	*Recharge*		*AET*	*Recharge*		*AET*	R_O	ΔS
Total	*CV*	*Total*	*CV*	*R/P*			*Total*	*R/P*				*Total*	*R/P*		*Total*	*R/P*			
497	0.21	174	0.16	35	323	6.5	51.6	10	373	72	0.0	4.5	0.9	492	0.1	0.02	424	73	-0.4

MAP, measured 30-yr mean annual precipitation (mm); Total, simulated 30-yr mean annual value (mm); *CV*, coefficient of variation; *R*, simulated 30-yr mean annual recharge (mm); *R/P*, recharge to precipitation ratio; *AE*, simulated 30-yr mean actual evaporation (mm); *AET*, simulated 30-yr mean actual evapotranspiration (mm); ΔS, simulated 30-yr change in water storage (mm); and R_O, simulated 30-yr mean annual runoff (mm). Runoff and change in storage are 0 for both sand profiles. All ratios are expressed as percent.

Table 8. UNSAT-H simulation results. Values represent simulated 30-yr mean annual averages in mm. MUID-Component, Map Unit Identification of SSURGO soil profiles; %, normalized percent of simulated area (i.e. County, outcrop area); *E*, evaporation; *T*, transpiration; R_O, run off; ΔS, change in storage; *R*, recharge; weighted values are weighted according to percent of area represented. 30-yr mean annual precipitation is 496.6 mm

		Model Results					*Weighted values*				
MUID-Component	*%*	*E*	*T*	R_O	ΔS	*R*	*E*	*T*	R_O	ΔS	*R*
Bare Soils											
sand		323	-	0	0.0	174					
19-Lincoln	12%	366	-	0	0.0	131	45	-	0	0.0	16
22/23-Mobeetie	34%	403	-	0	0.0	93	139	-	0	0.0	32
13-Estacado	7%	400	-	84	0.0	13	29	-	6	0.0	0.9
23-Potter	46%	348	-	144	0.0	4.9	160	-	66	0.0	2.3
	100%						**373**	**-**	**72**	**0.0**	**51.6**
Sorghum											
sand		184	271	0	0.0	42					
13-Estacado	1%	202	225	73	-1.2	0.2	2	3	1	0.0	0.0
23-Potter	9%	188	179	131	-0.3	0.1	17	16	12	0.0	0.0
	10%						**19**	**18**	**12**	**0.0**	**0.0**
Shrub											
sand		198	299	0	0.0	0.4					
19-Lincoln	8%	201	296	0	-0.4	0.1	16	24	0	0.0	0.0
22/23-Mobeetie	30%	228	265	3	-0.6	0.1	68	79	1	-0.2	0.0
13-Estacado	5%	227	196	75	-0.9	0.1	11	10	4	0.0	0.0
23-Potter	41%	201	164	133	-0.2	0.1	82	67	54	-0.1	0.0
	84%						**177**	**179**	**59**	**-0.4**	**0.1**
Brush											
sand		173	324	0	-0.4	0.3					
19-Lincoln	3%	175	322	0	-0.4	0.1	6	10	0	0.0	0.0
22/23-Mobeetie	2%	201	292	4	-0.6	0.1	4	6	0	0.0	0.0
23-Potter	1%	178	187	132	-0.2	0.1	2	2	2	0.0	0.0
	6%						**12**	**18**	**2**	**0.0**	**0.0**
Total	**100.0%**						**208**	**216**	**73**	**-0.4**	**0.1**

8.0 FIGURES

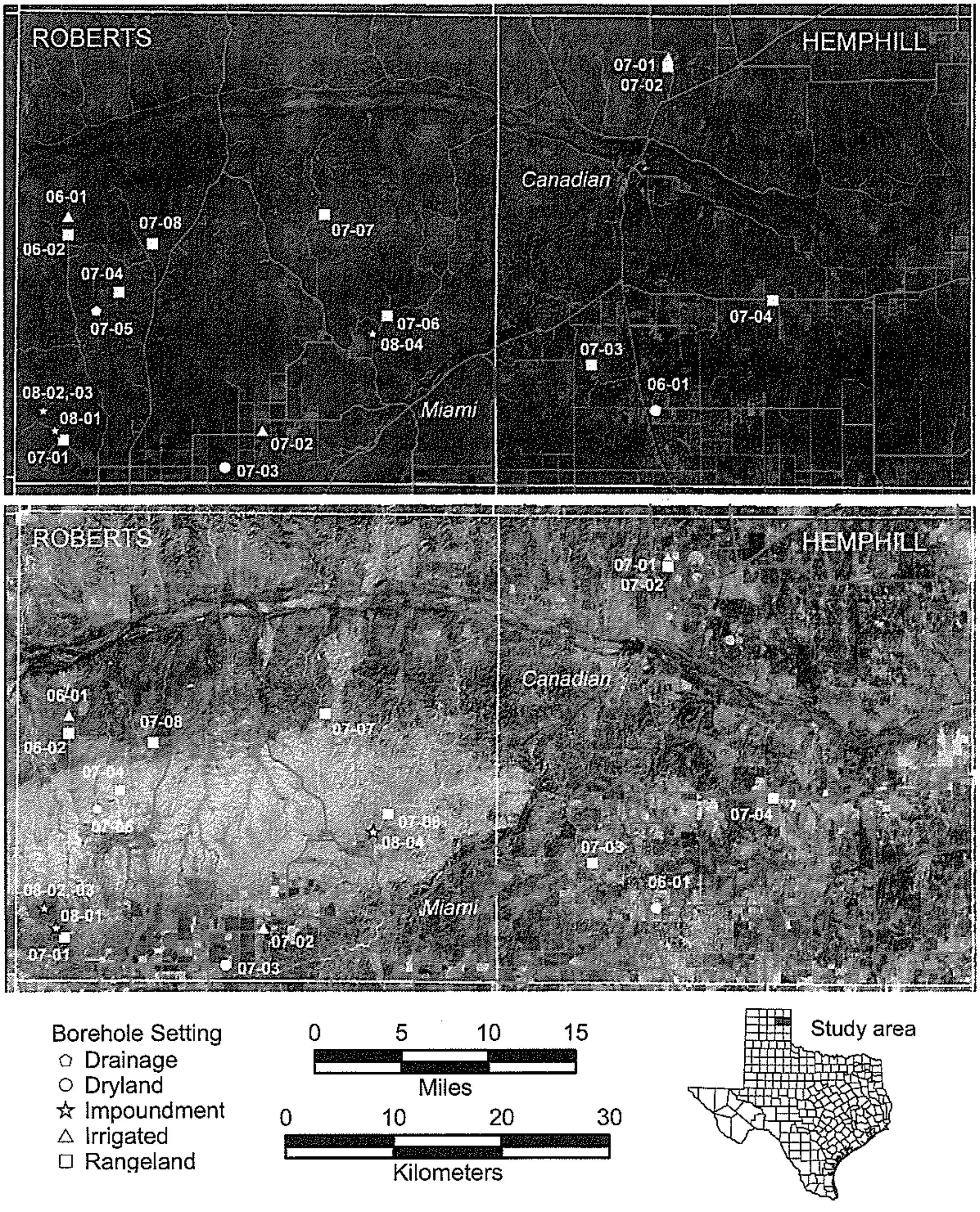

Figure 1. Borehole locations in Roberts and Hemphill counties with National Agricultural Imagery Program (NAIP) orthophoto color (2005, above) and infrared false color (2006, below) images. Road network is shown for reference. County name prefixes have been omitted from borehole designations.

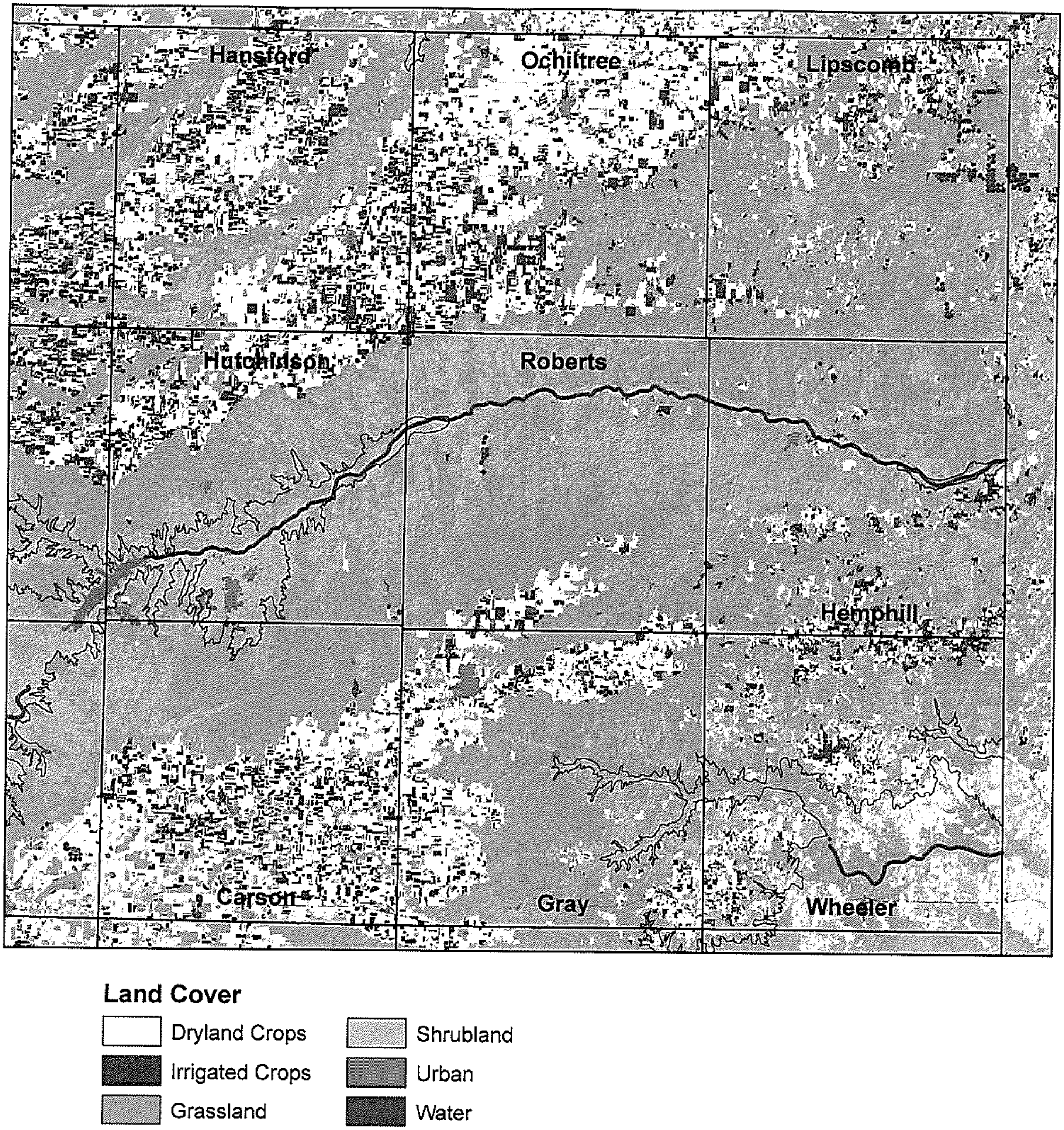

Figure 2. Generalized land cover for Roberts County, TX, and surrounding areas. Data are based on National Land Cover Data (NLCD) (Vogelmann et al. 2001).

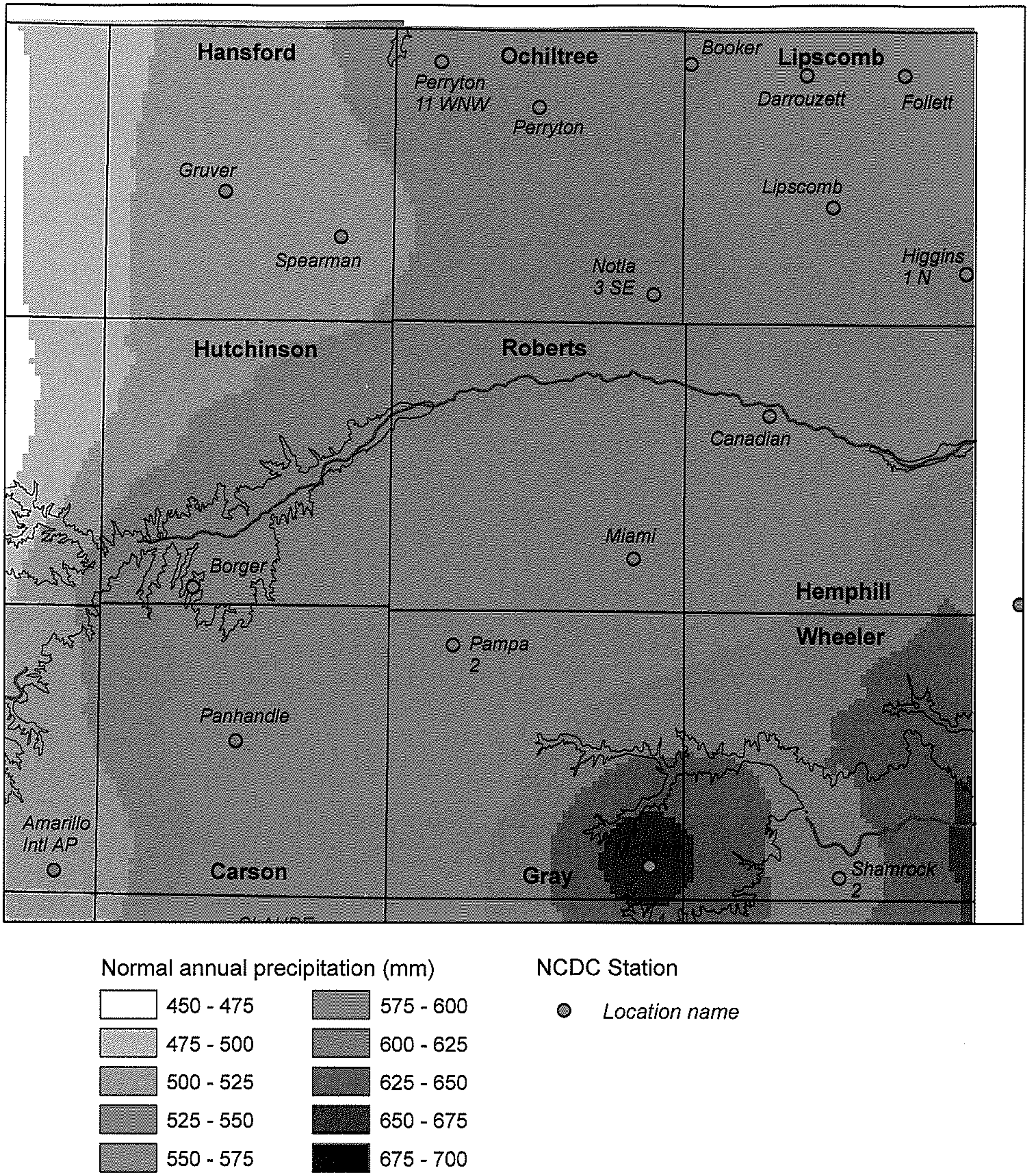

Figure 3. Mean annual precipitation for Roberts County, TX, and surrounding areas. Data are interpolated based on National Climate Data Center (NCDC) period-of-record data for the stations shown and for stations in surrounding areas.

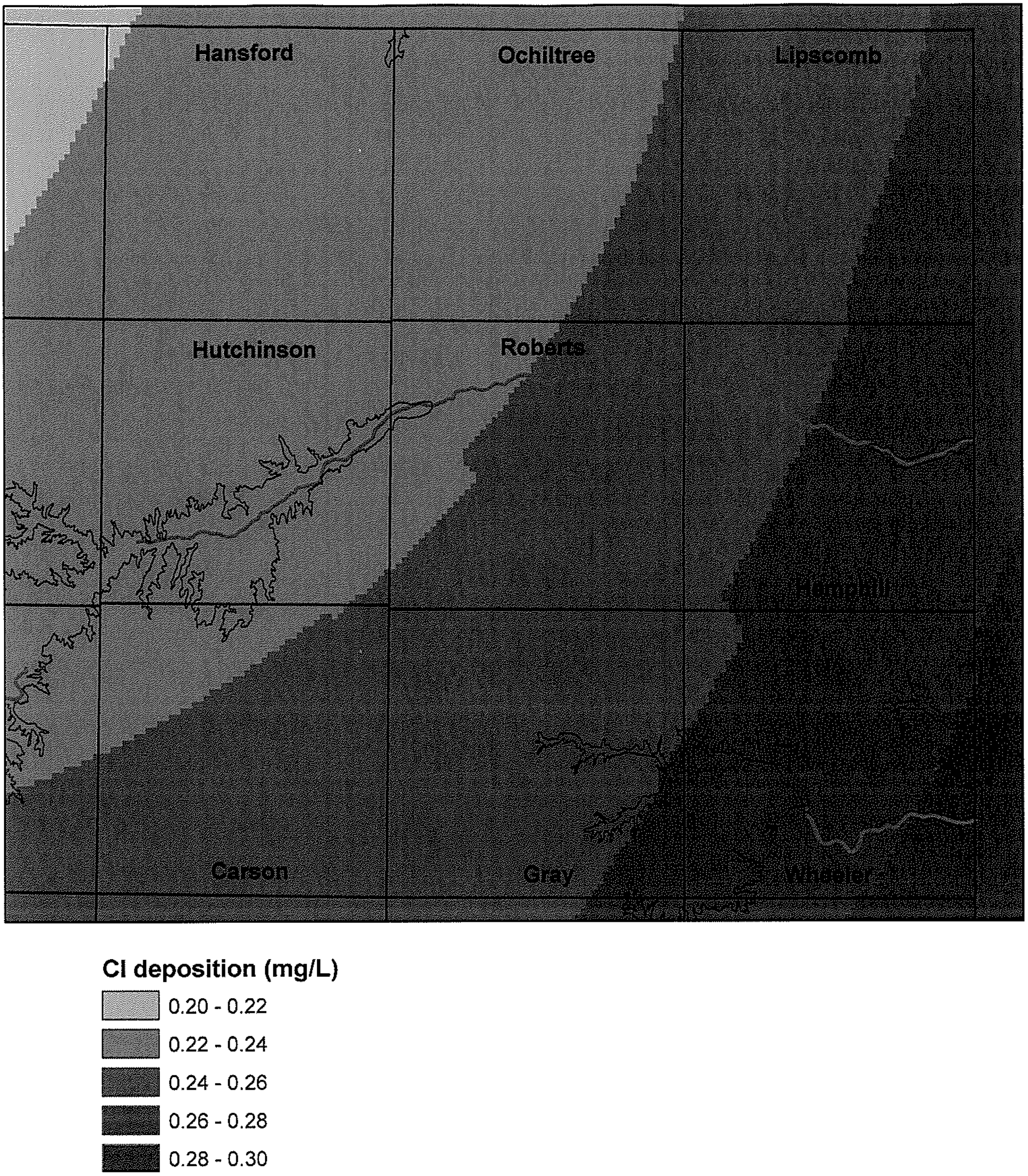

Figure 4. Mean annual chloride (Cl) deposition for Roberts County, TX, and surrounding areas. Data represent total deposition values interpolated from period-of-record wet deposition data for all Texas and neighboring-state stations (National Atmospheric Deposition Center (NADP)). No stations are located in the mapped area. Total chloride deposition was estimated as twice the wet deposition.

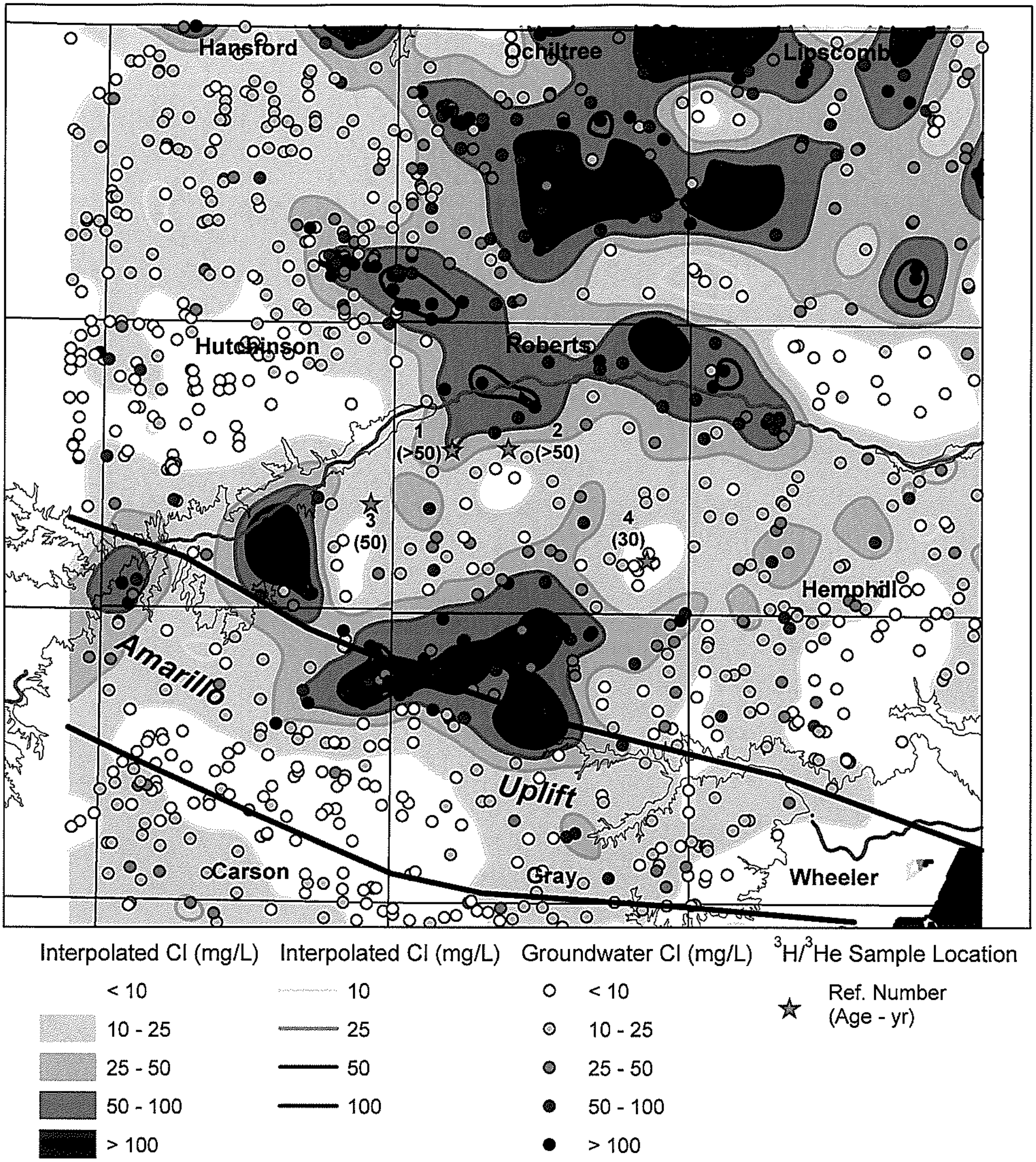

Figure 5. Groundwater chloride (*Cl*) concentrations for Roberts County, TX, and surrounding areas. Points represent 422 groundwater well samples from the TWDB database. Interpolations were generated using ArcView GIS local polynomial methods. Approximate boundary of the Amarillo Uplift structural feature is also shown (Mehta et. al, 2000). Locations of groundwater wells sampled for tritium-helium analysis are also shown with reference numbers (Table 2).

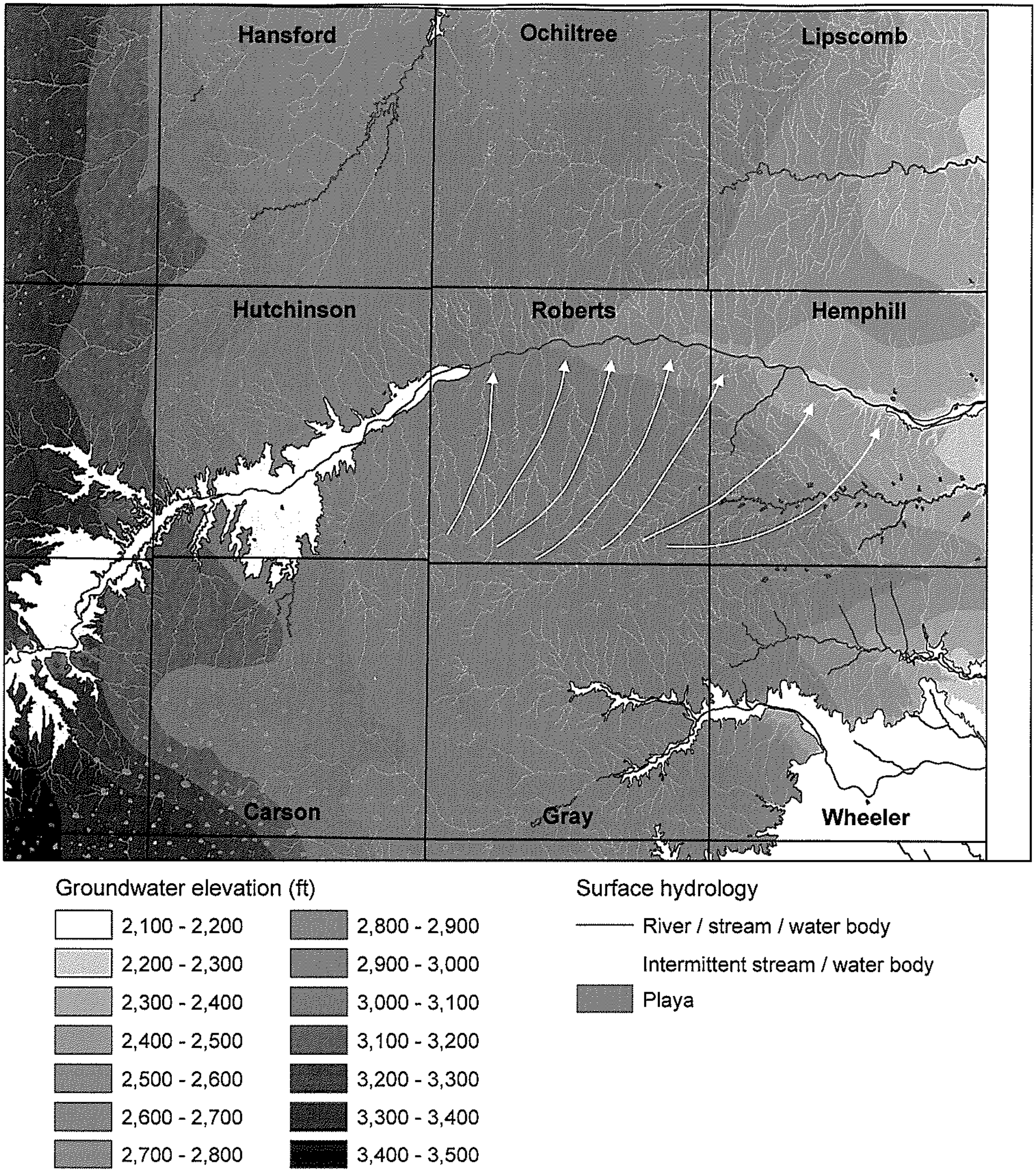

Figure 6. Water table elevations and surface hydrology for Roberts County, TX, and surrounding areas. Water table elevations are based on Texas Water Development Board (TWDB) water level database information. Arrows in Roberts County indicate general direction of groundwater flow.

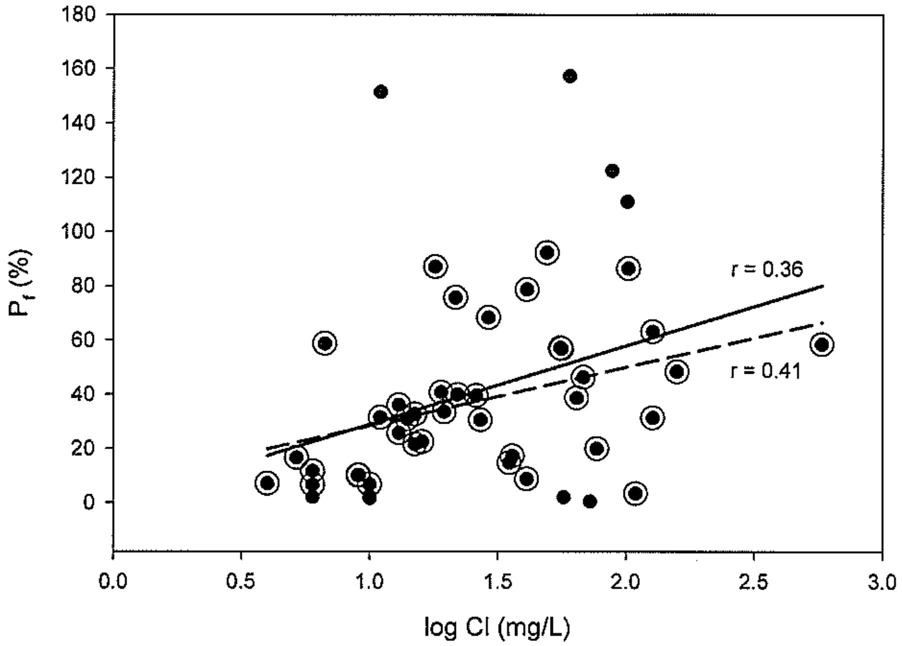

Figure 7. Relationship between chloride (log Cl) in groundwater and well penetration factor (P_f) (percentage of aquifer saturated thickness sampled by well). Solid line represents regression for all data in Roberts County (solid points). Dashed line represents regression for a data subset (open symbols) excluding 10 wells with < 10 ft (3m) of water or with $P_f > 100\%$.

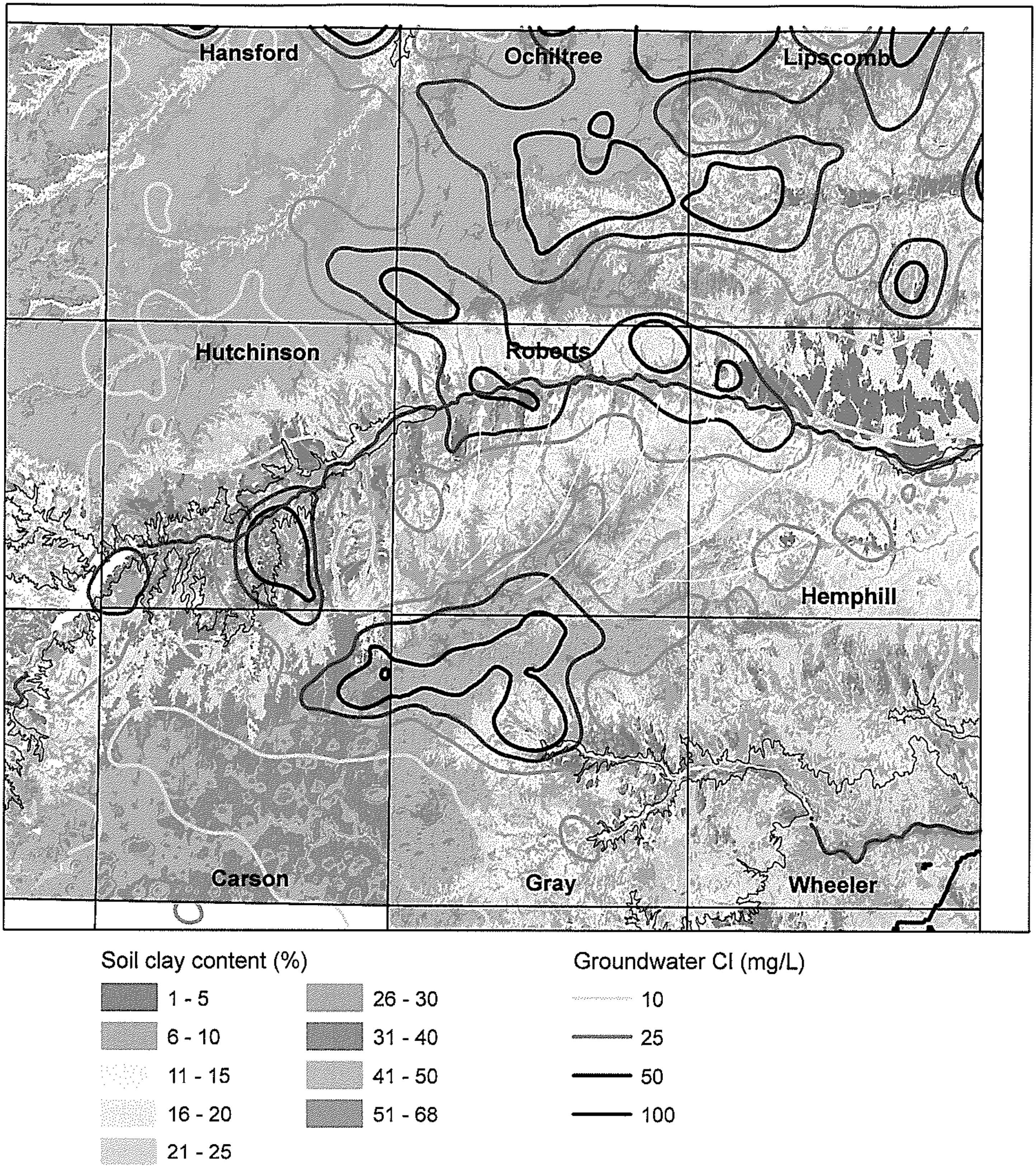

Figure 8. Soil clay content for Roberts County, TX, and surrounding areas. Data are a mosaic of county-wide surveys from the Soil Survey Geographic (SSURGO) database and generally represent weighted-average values for the 1.5 to 2 m-depth. Interpolated groundwater chloride (Cl) concentration contours from Figure 4 and groundwater flow direction arrows from Figure 5 are also shown.

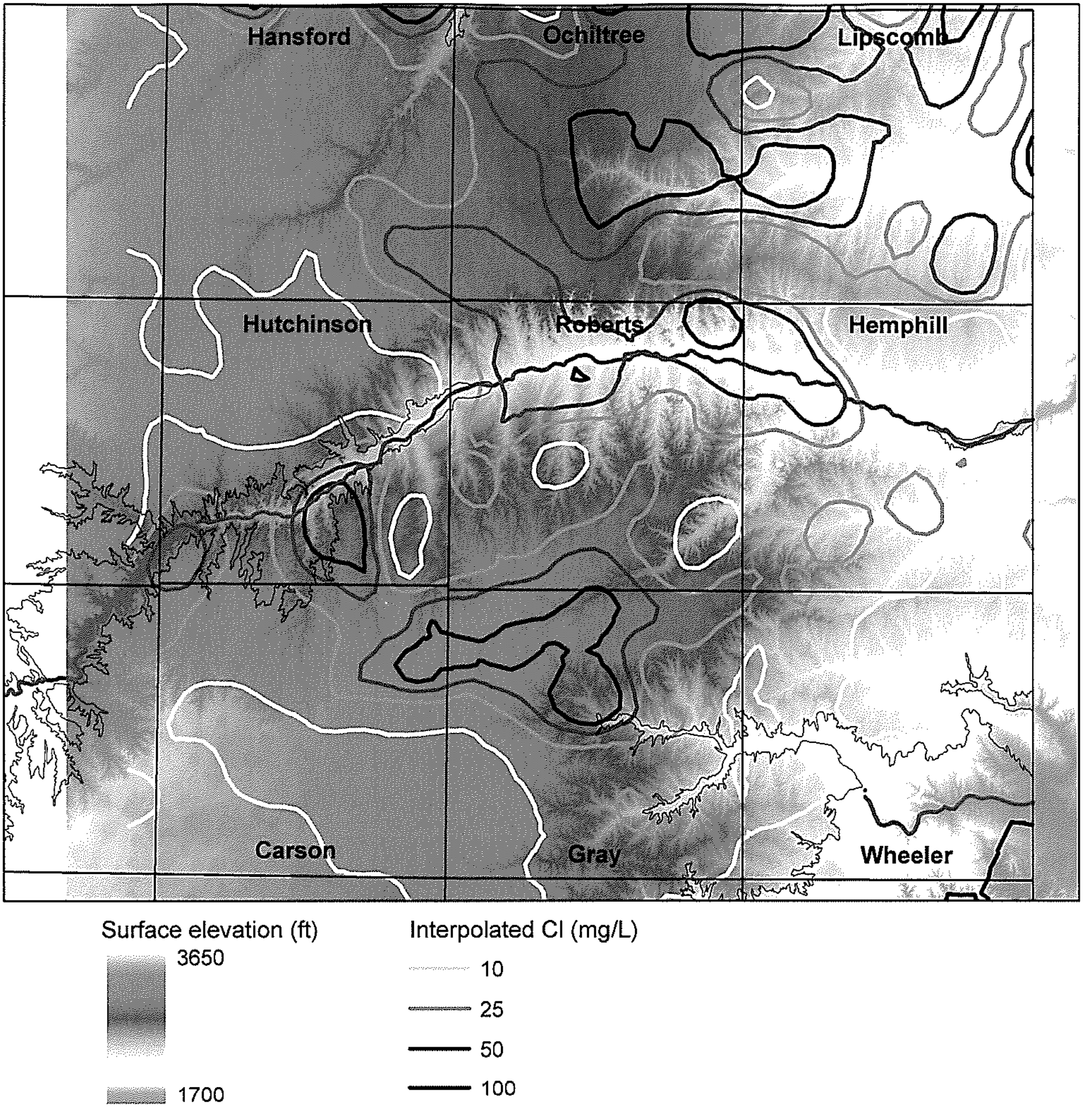

Figure 9. Surface elevation for Roberts County, TX, and surrounding areas. Interpolated groundwater chloride (Cl) concentration contours from Figure 4 are also shown.

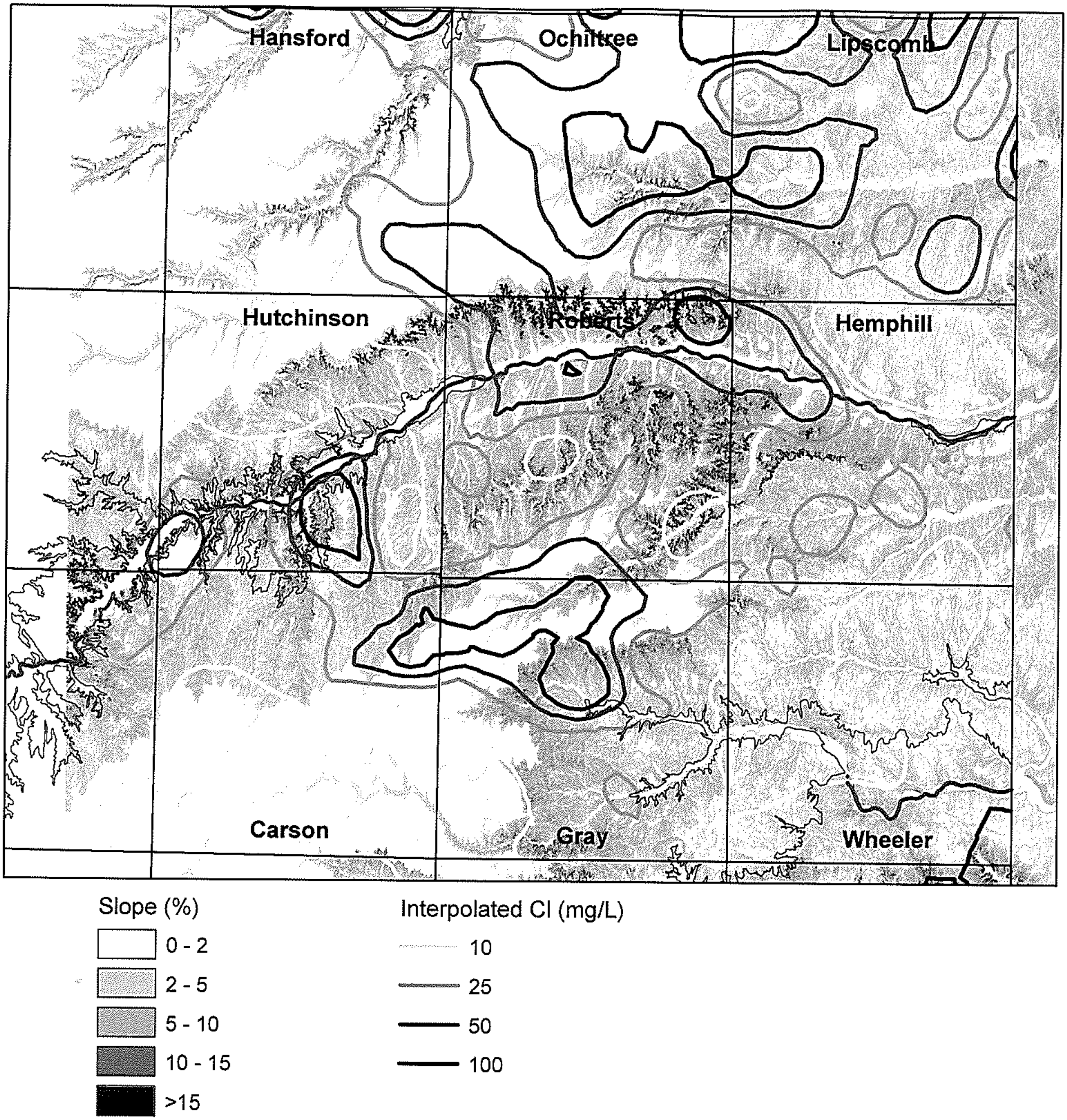

Figure 10. Surface slope for Roberts County, TX, and surrounding areas. Interpolated groundwater chloride (Cl) concentration contours from Figure 4 are also shown.

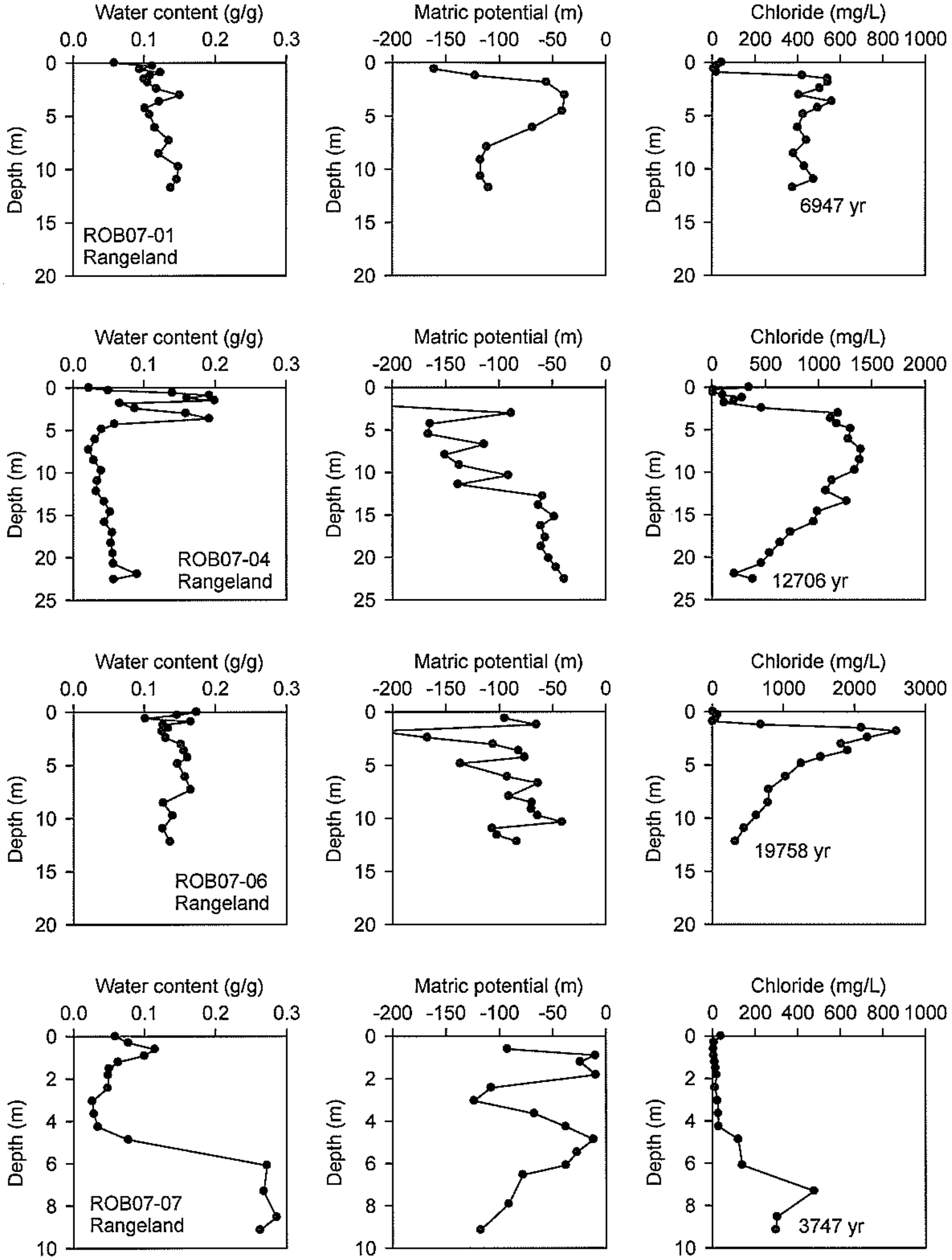

Figure 11. Water content, matric potential, and chloride profiles for rangeland setting boreholes indicating no recharge. Chloride mass balance ages are also shown.

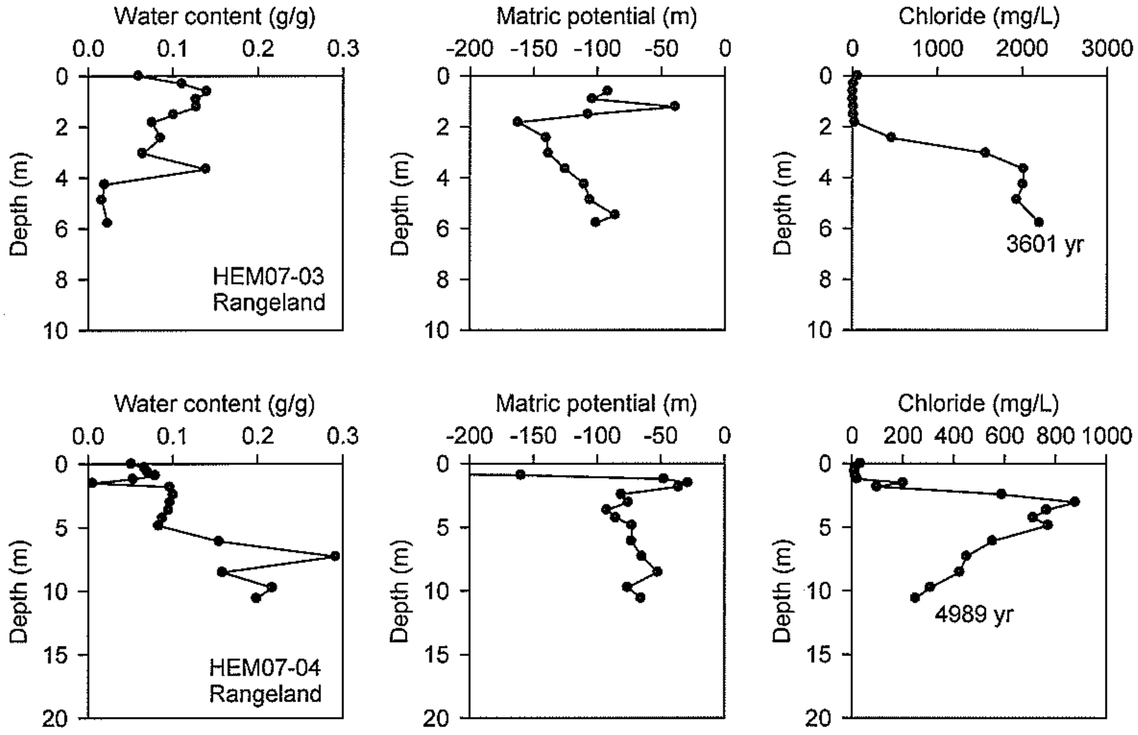

Figure 11 (cont.). Water content, matric potential, and chloride profiles for rangeland setting boreholes indicating no recharge. Chloride mass balance ages are also shown.

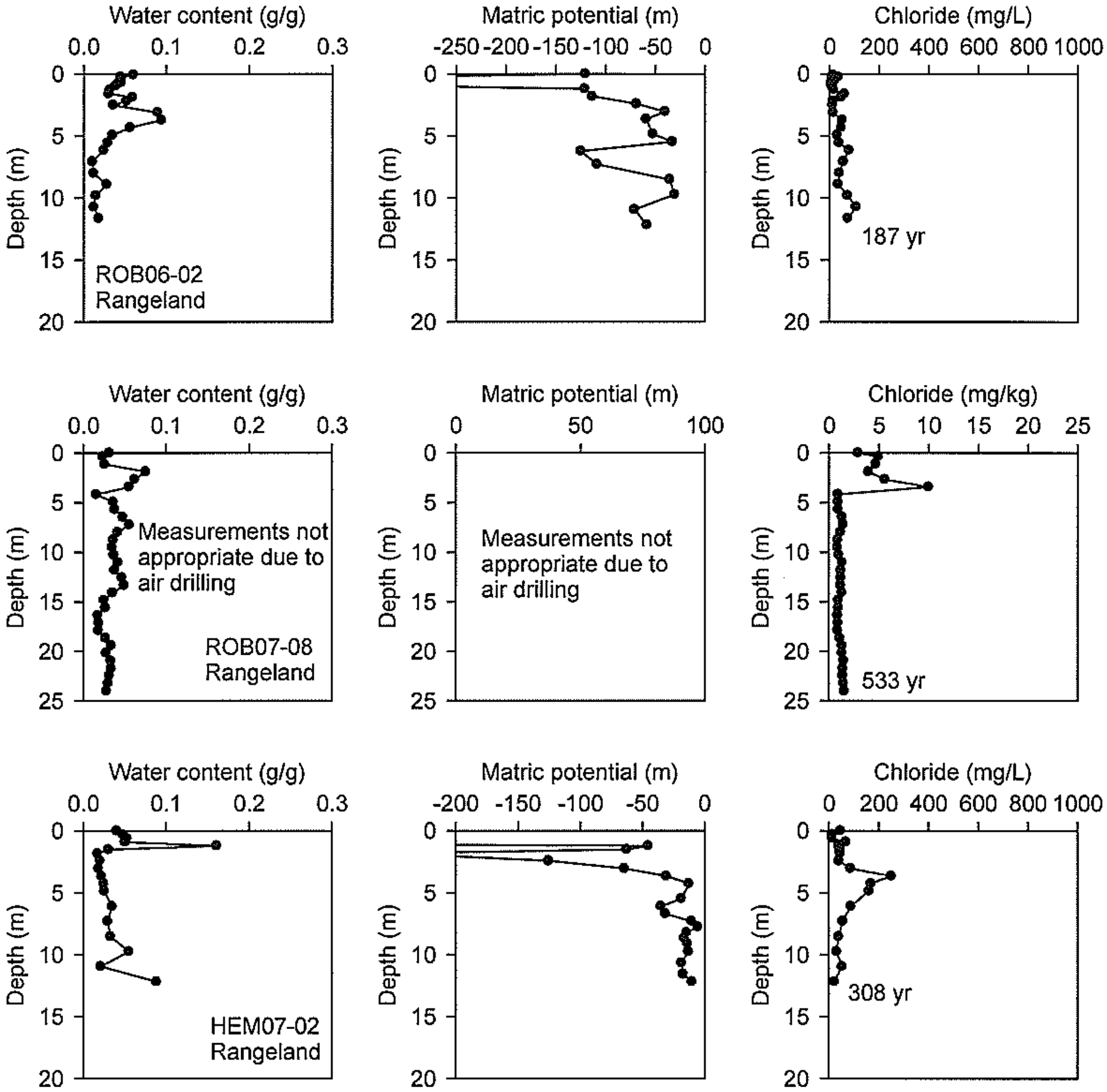

Figure 12. Water content, matric potential, and chloride profiles for rangeland setting boreholes indicating minimal recharge. Chloride mass balance ages are also shown.

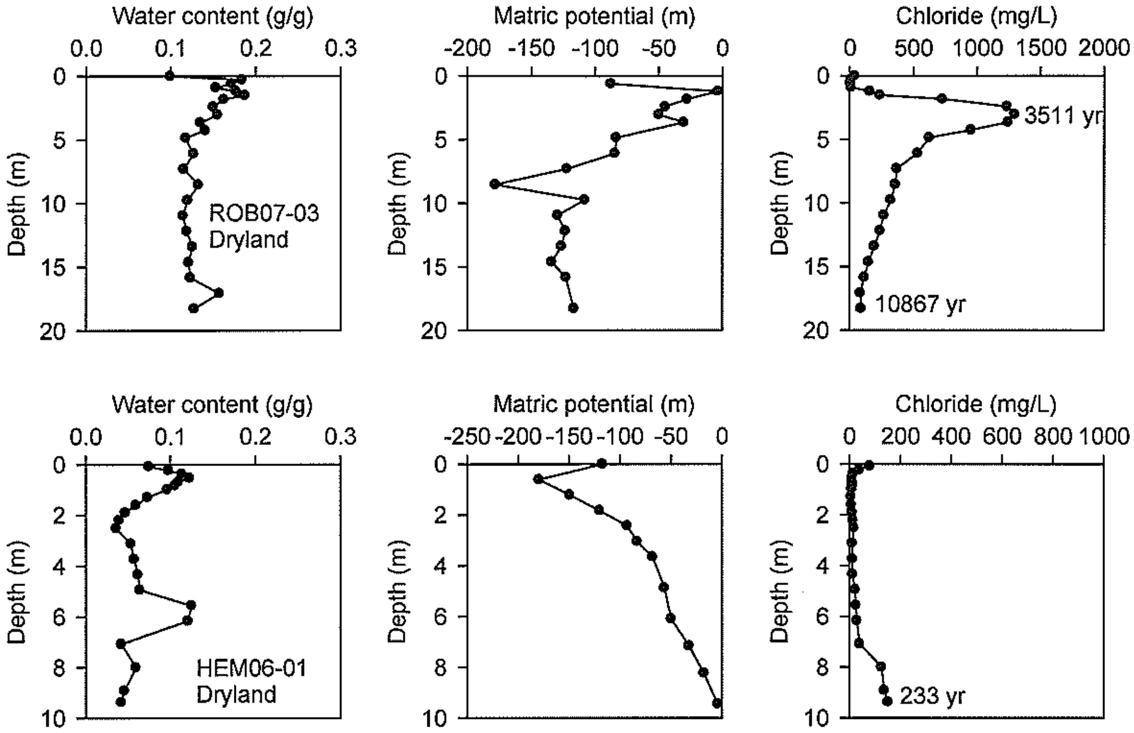

Figure 13. Water content, matric potential, and chloride profiles for dryland agricultural setting boreholes. Chloride mass balance ages are also shown.

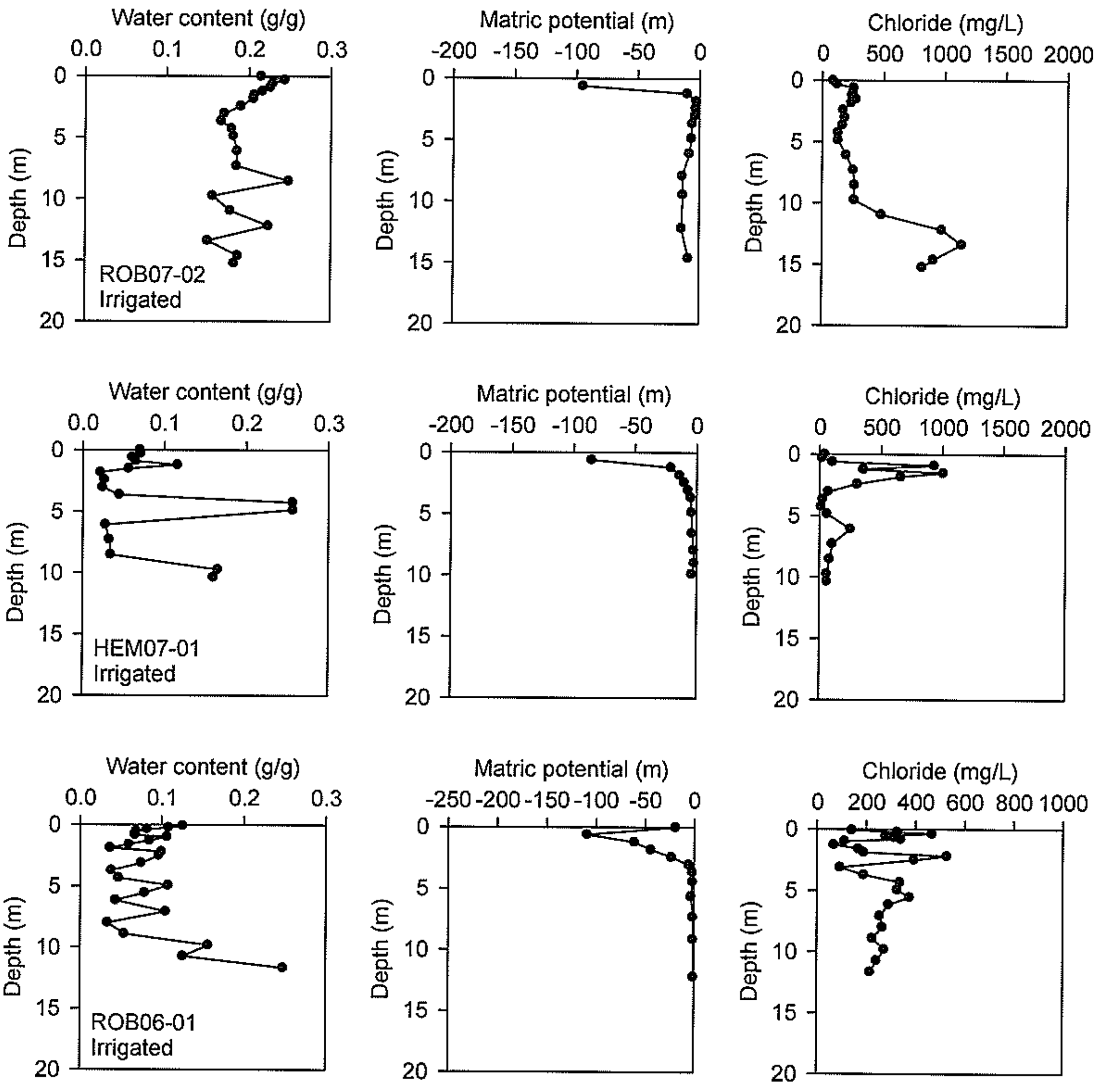

Figure 14. Water content, matric potential, and chloride profiles for irrigated agricultural setting boreholes.

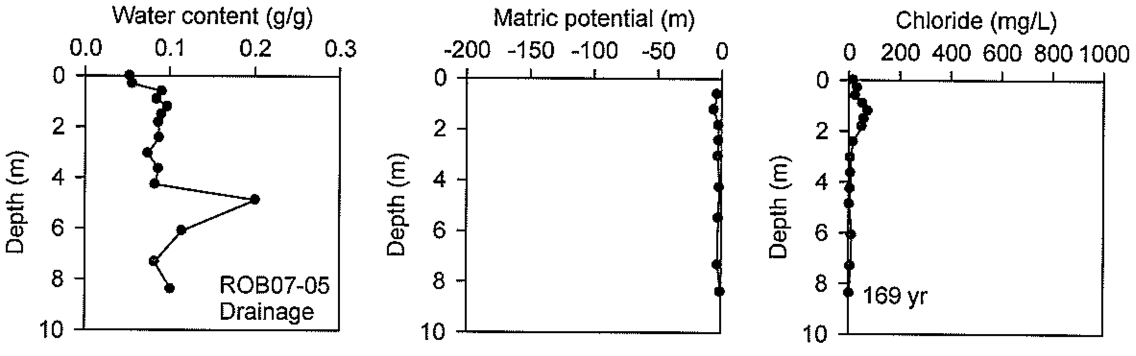

Figure 15. Water content, matric potential, and chloride profiles for a drainage setting borehole. Chloride mass balance age is also shown (assumes no runon input).

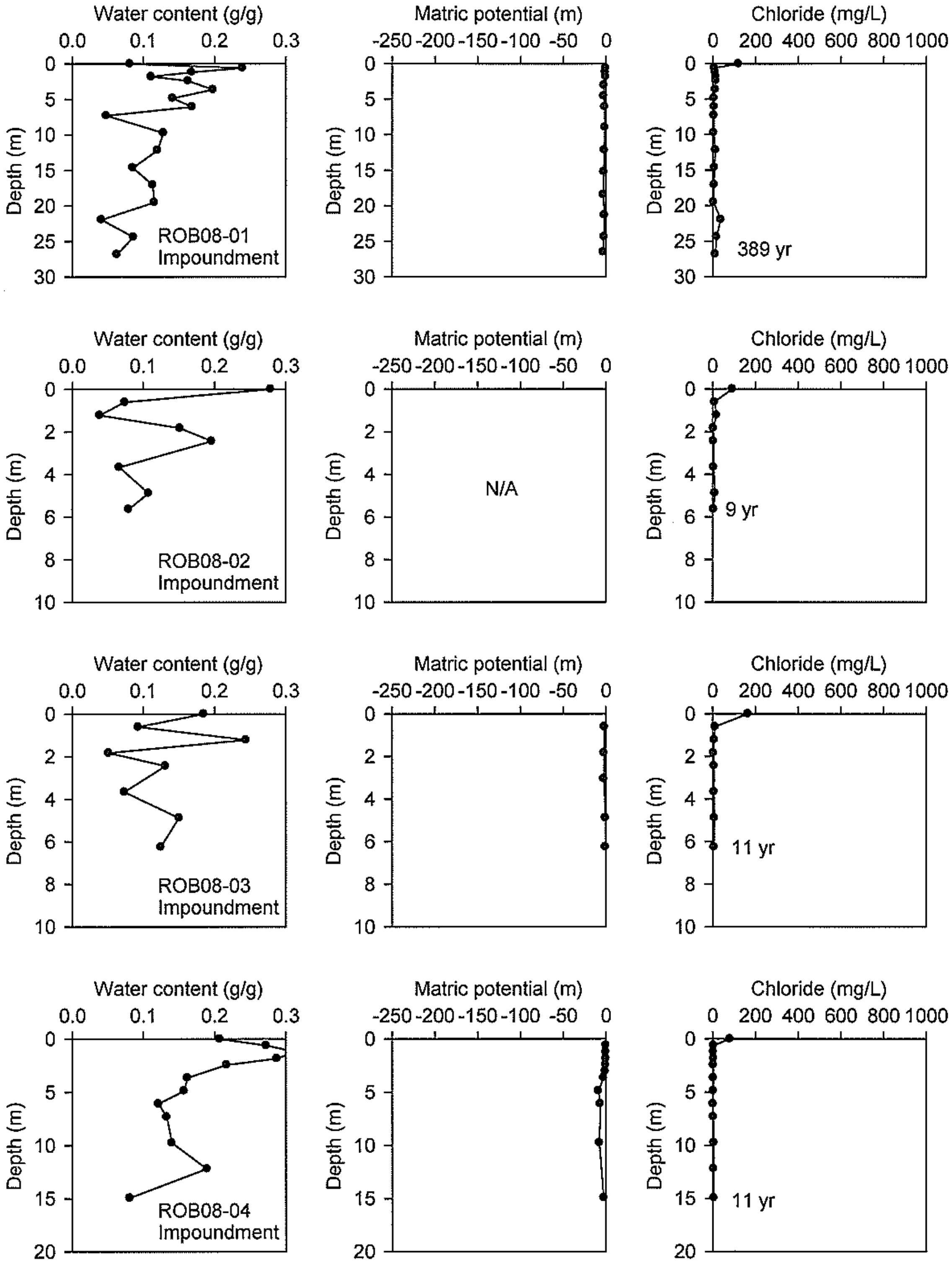

Figure 16. Water content, matric potential, and chloride profiles for stock impoundment setting boreholes. Chloride mass balance ages are also shown (assumes no runon input).

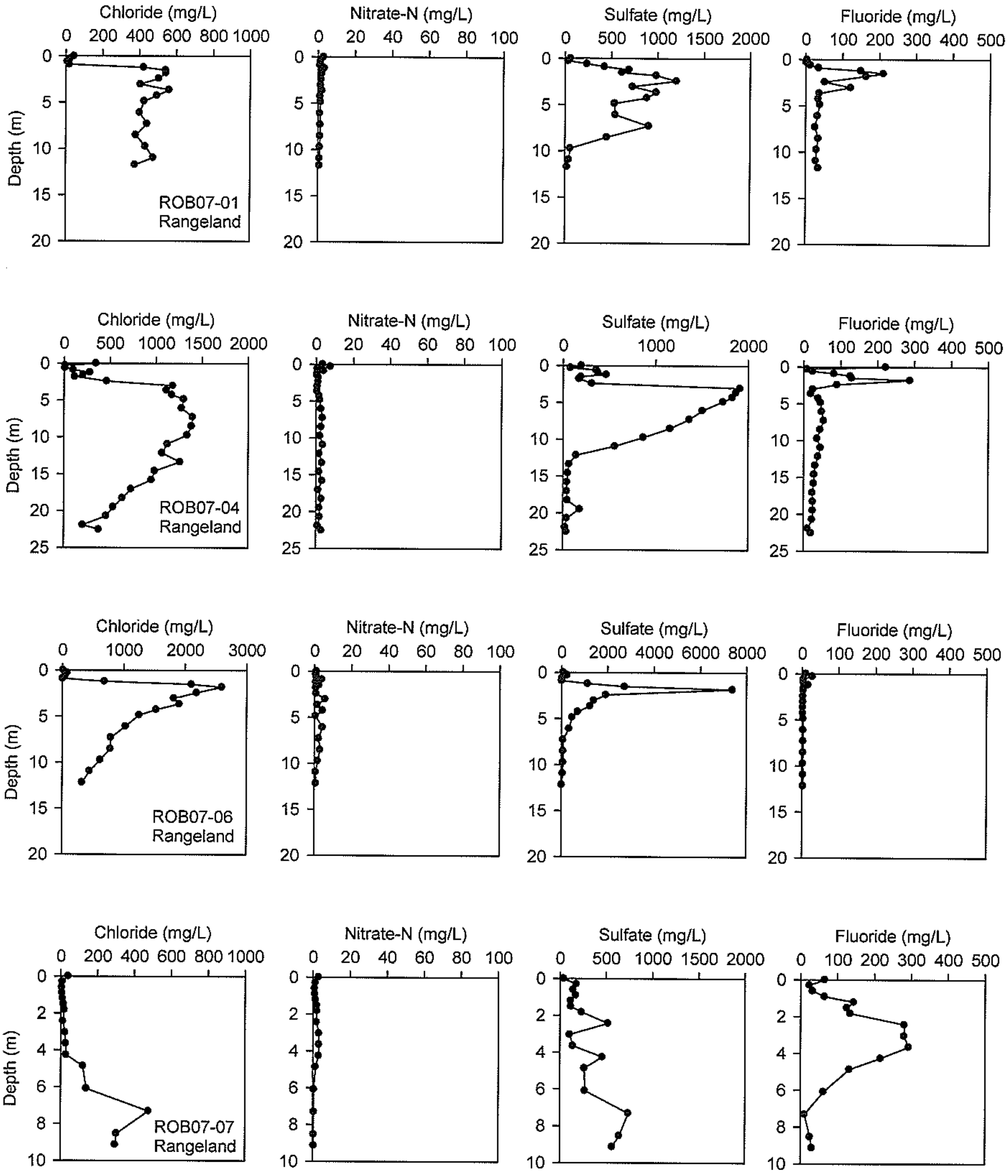

Figure 17. Chloride, nitrate-N, sulfate, and fluoride concentration profiles for rangeland setting boreholes indicating no recharge.

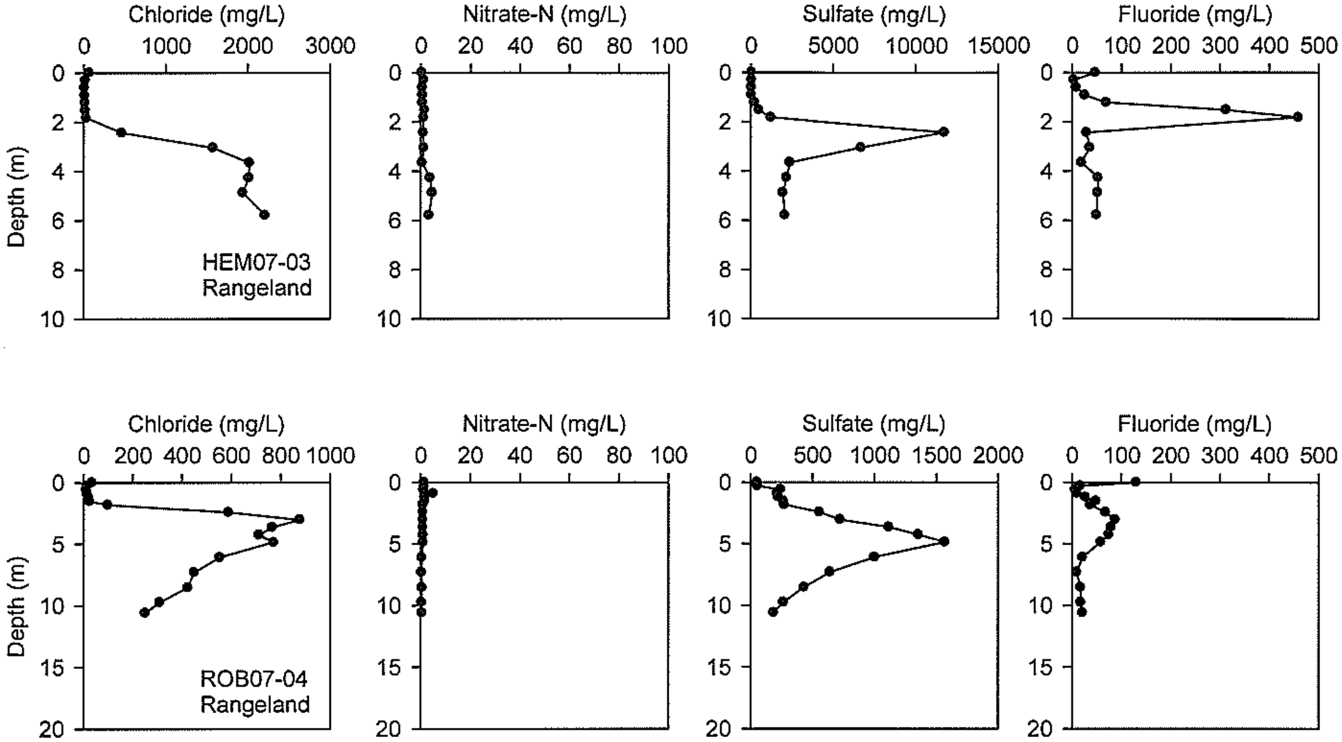

Figure 17 (cont). Chloride, nitrate-N, sulfate, and fluoride concentration profiles for rangeland setting boreholes indicating no recharge.

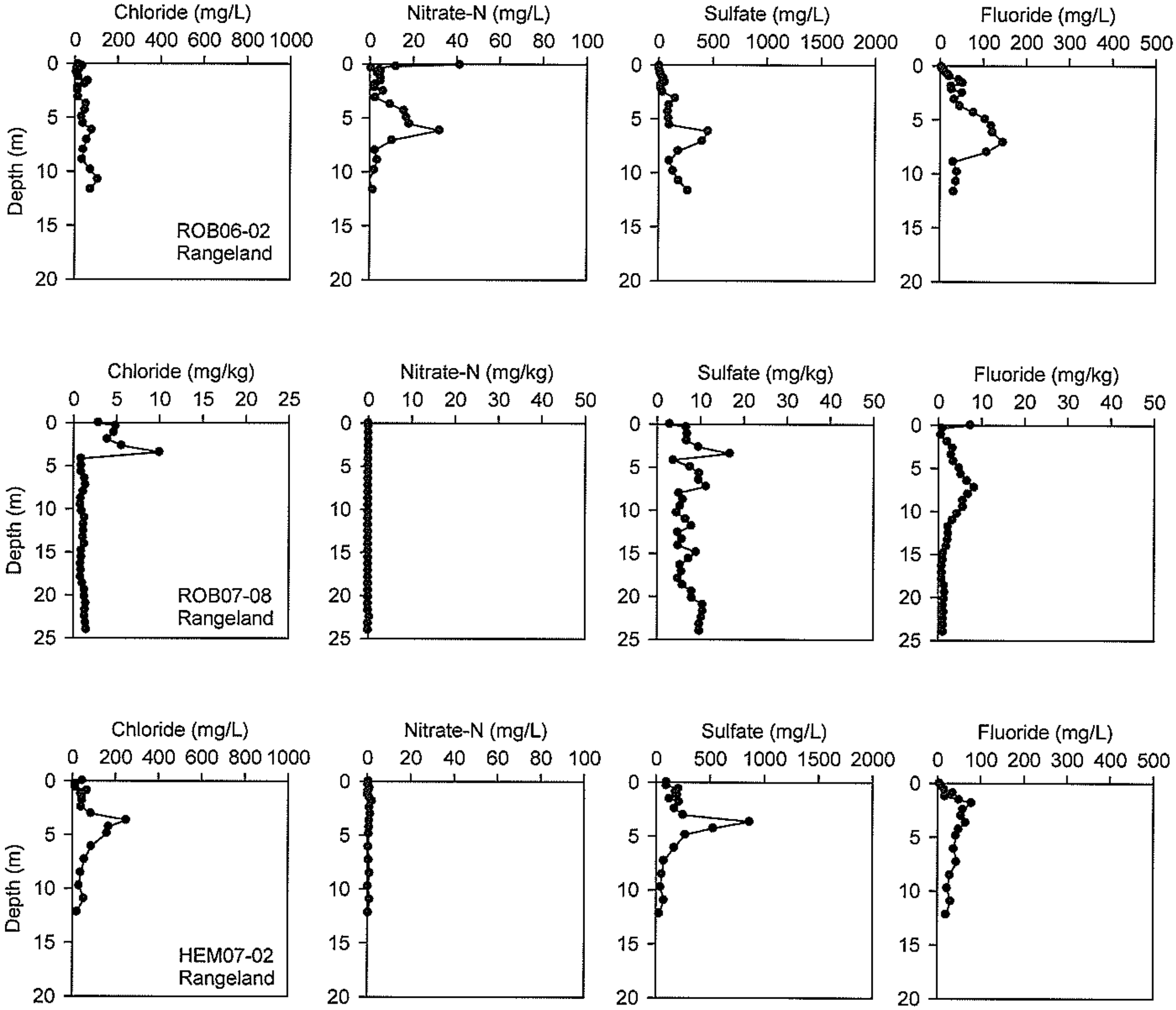

Figure 18. Chloride, nitrate-N, sulfate, and fluoride concentration profiles for rangeland setting boreholes indicating minimal recharge.

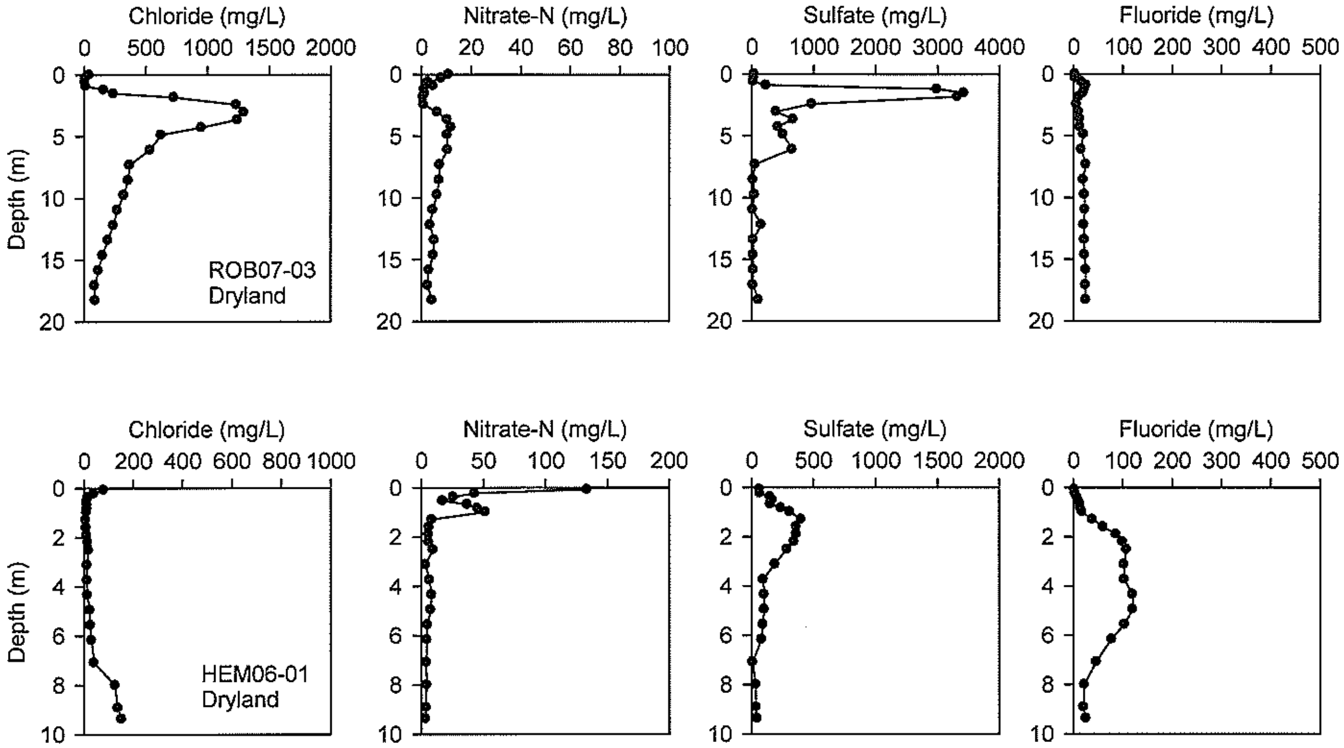

Figure 19. Chloride, nitrate-N, sulfate, and fluoride concentration profiles for dryland agricultural setting boreholes.

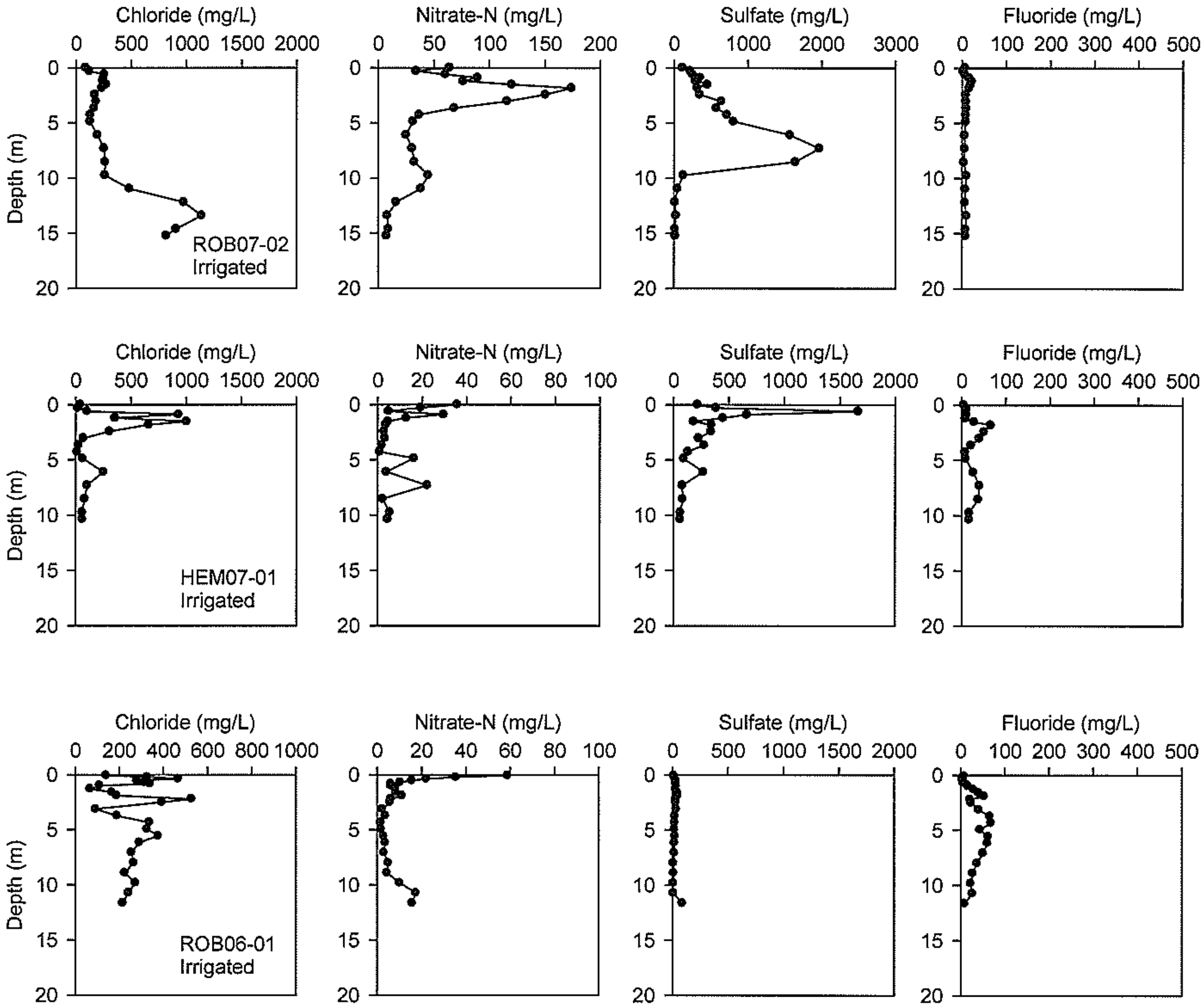

Figure 20. Chloride, nitrate-N, sulfate, and fluoride concentration profiles for irrigated agricultural setting boreholes.

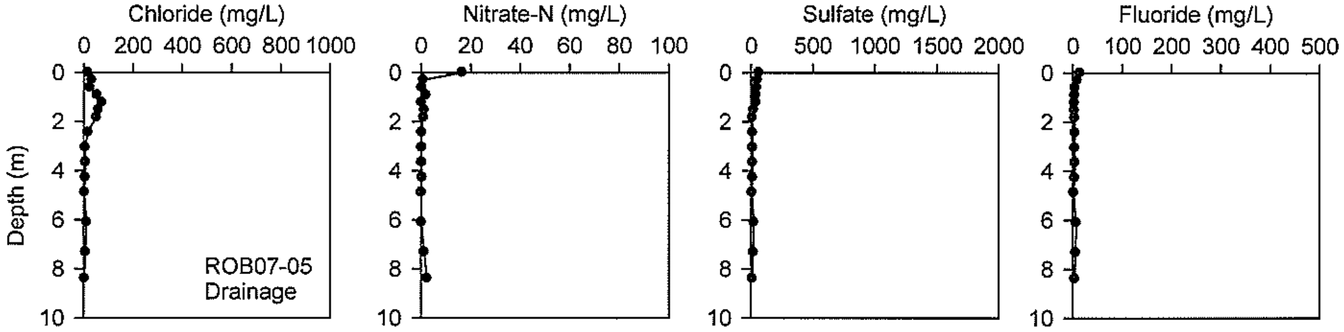

Figure 21. Chloride, nitrate-N, sulfate, and fluoride concentration profiles for the drainage setting borehole.

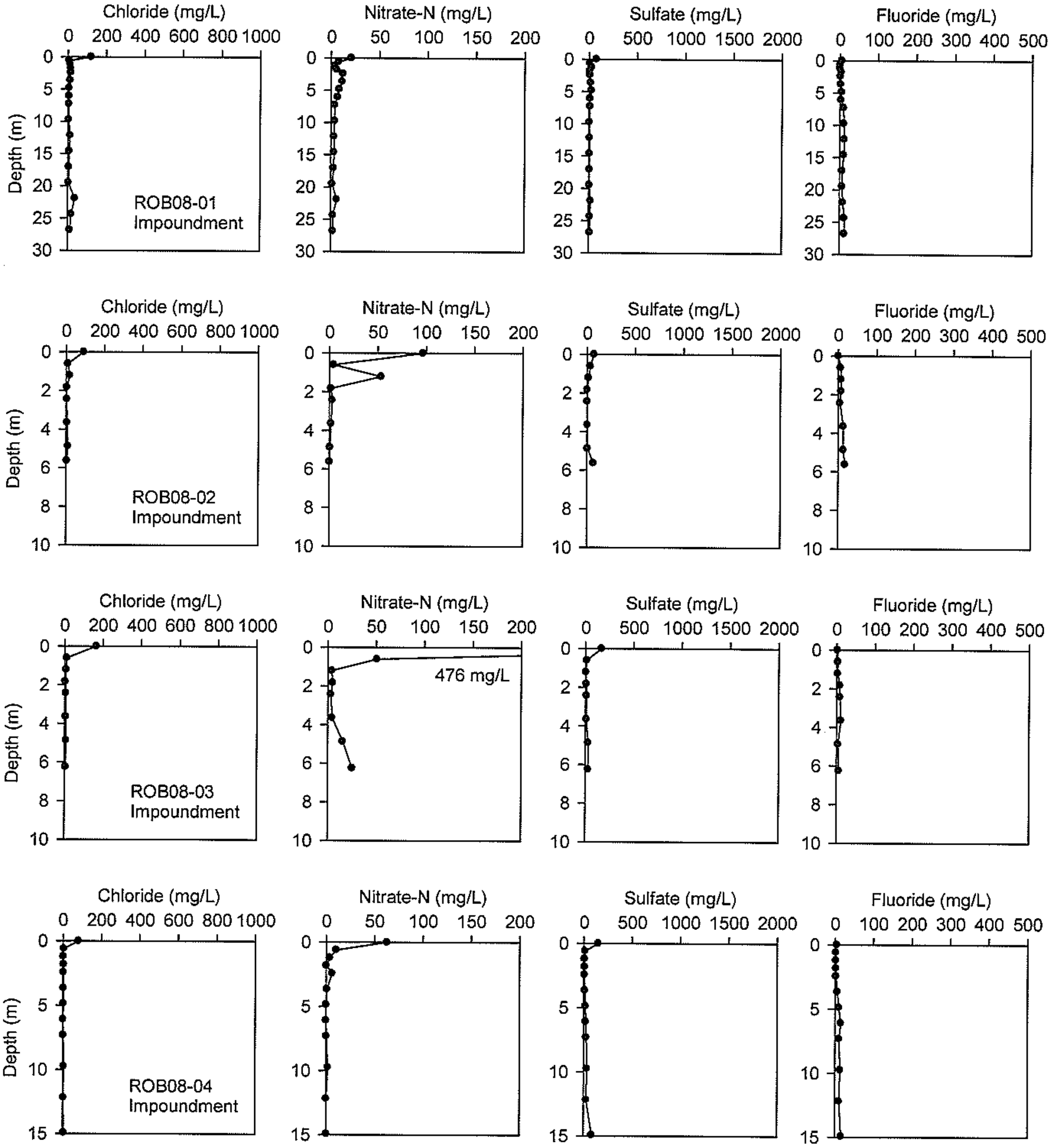

Figure 22. Chloride, nitrate-N, sulfate, and fluoride concentration profiles for stock impoundment setting boreholes.

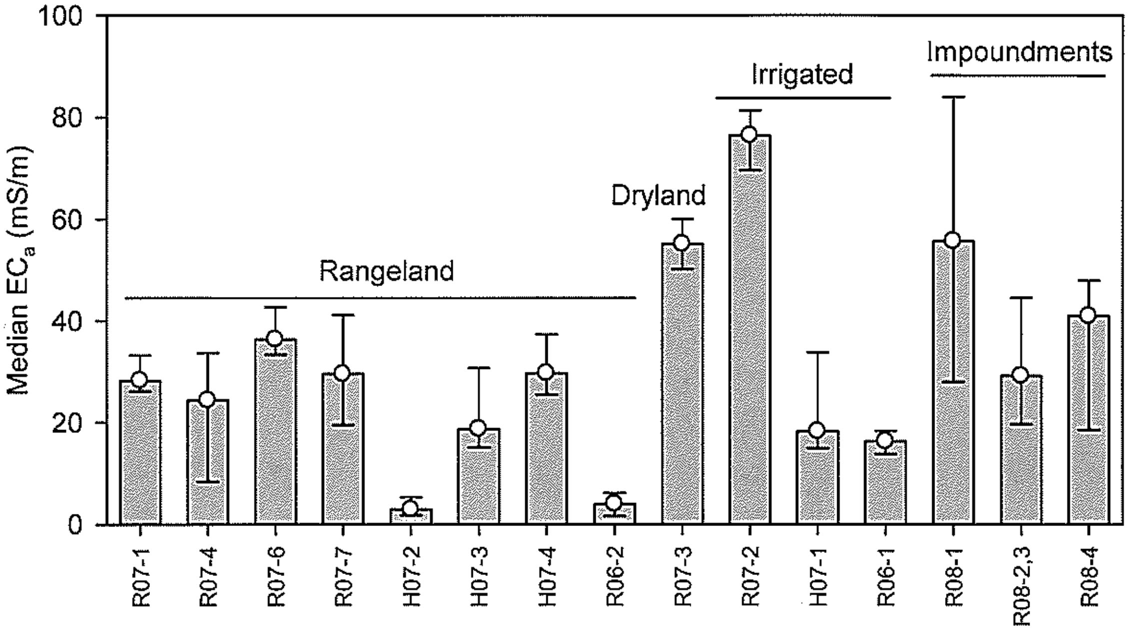

Figure 23. Median EM 31 apparent electrical conductivity (EC_a) vertical dipole measurements. Error bars represent range of measurements at each site.

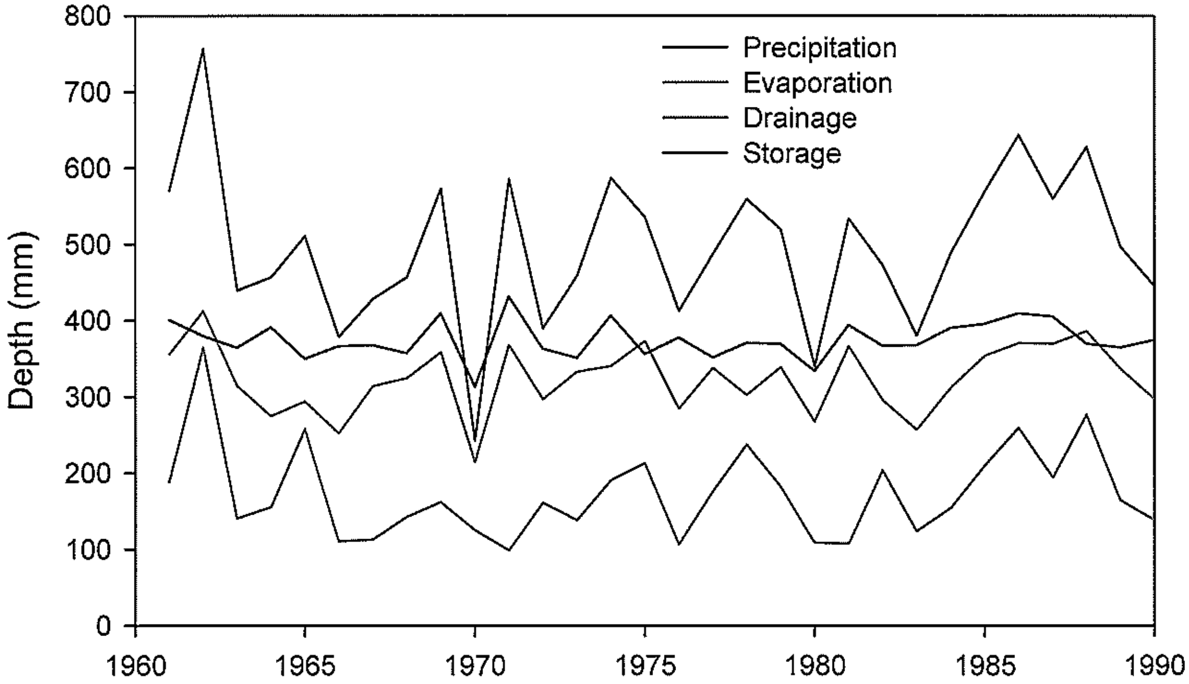

Figure 24. Simulated annual water budget parameters for nonvegetated monolithic sand.

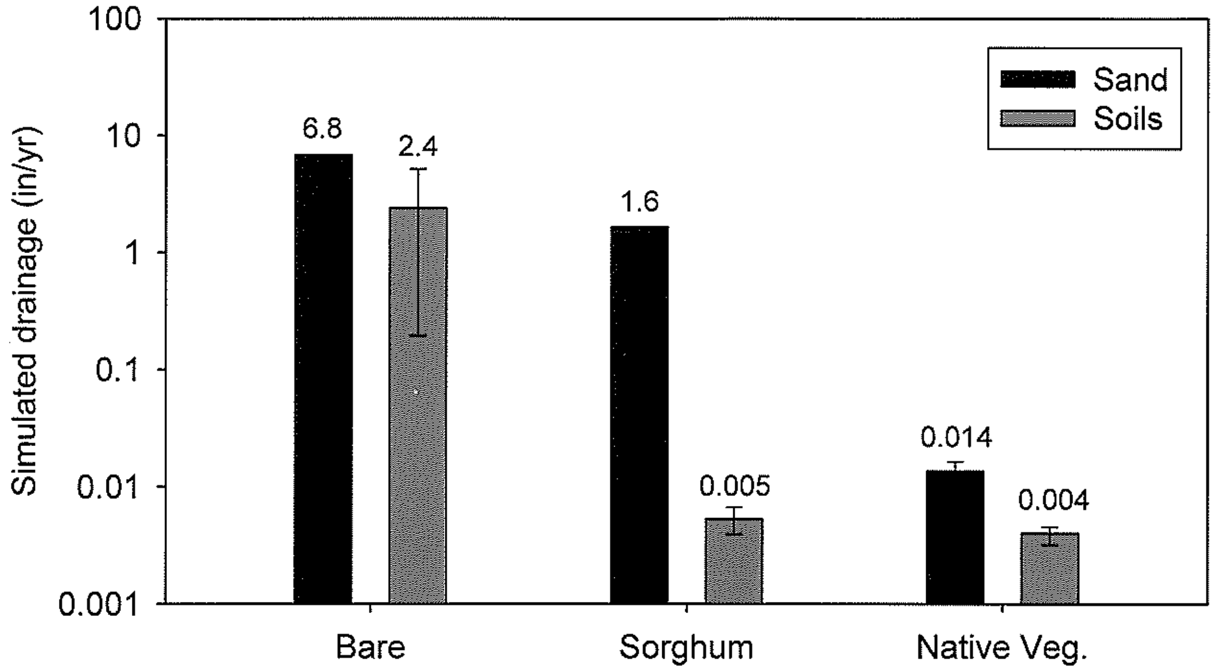

Figure 25. Drainage (recharge) results summary for the different UNSAT-H simulations. Results for soils represent the average (bar height and value) and range (error bars) of the simulated individual soil profiles within each category and do not represent the areal averages.

APPENDIX A:

Technical Memorandum

Calculation of Recharge Rates

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John Gates[1], Osama Akasheh[1], and Bridget R. Scanlon[1]
Bureau of Economic Geology, University of Texas at Austin

Executive Summary

The purpose of this study was to estimate groundwater recharge in the vicinity of Roberts County using the chloride mass balance applied to soil samples from the unsaturated zone to provide point recharge estimates in different land use settings. A total of 18 boreholes were drilled from 2006 through 2008 in different locations (13 in Roberts and 5 in Hemphill counties) to depths ranging from **19 to 74 ft** (5.8 to 22.6 m). Natural rangeland represents the dominant land use in these counties and nine boreholes were located in this setting. Two boreholes were located beneath dryland agriculture and three boreholes beneath irrigated agriculture. One borehole was drilled in a dry drainage channel and three boreholes were drilled adjacent to stock impoundments that pond water in Roberts County. Soil samples were collected in the field for laboratory measurement of soil physics (water content and matric potential head) and environmental tracers (chloride, fluoride, nitrate, and sulfate).

The chloride mass balance approach applied to the unsaturated zone resulted in a range of recharge estimates for different land use settings. Most of the profiles in rangeland settings (6 out of 9) are generally characterized by large chloride accumulations (peak chloride concentrations 477 to 2,593 mg/L) corresponding to accumulation times ranging from 3,601 to 19,758 yr. These data indicate that there is essentially no recharge in these regions and that the profiles have been drying out over these long time periods. Matric potentials are generally low in these profiles, with mean matric potentials below the root zone ranging from -68 to -108 m. These low matric potentials generally support the lack of recharge from the chloride data. Two of the remaining profiles (one in Roberts County and one in Hemphill County) have much lower chloride concentrations (mean 108 and 250 mg/L), indicating low, but measurable, recharge rates of **0.11 and 0.14 in/yr** (2.8 and 3.6 mm/yr). These boreholes are located along the breaks near the Canadian River, where soils are coarser grained. Recharge rates could not be estimated in the third profile because only cuttings, not cores, were collected. Matric potentials were measured in two of the three profiles and are slightly higher than others, with mean values of -38 and -67 m. Lack of recharge in most rangeland profiles is attributed to low permeability soils and the ability of natural grasslands/shrublands to remove all infiltrated water through evapotranspiration. Low recharge in two of the rangeland profiles is attributed to their location along the Canadian breaks and associated coarser soil textures.

Conversion of rangeland to dryland agriculture did not increase recharge below the root zone in a profile in Roberts County but did increase recharge in a profile in Hemphill County to **0.41 in/yr** (10.4 mm/yr). The lack of increased recharge in the Roberts County dryland profile is attributed to the low permeability soils (Pullman clay loam) in this region. Evidence of increased

recharge in the Hemphill County profile is provided by low chloride concentrations (mean 15 mg/L; peak 26 mg/L).

There is increased recharge under all of the irrigated sites. The chloride bulge has been displaced to 32.2 ft (9.8 m) depth in an irrigated profile in Roberts County. This site has been irrigated since the 1950s, ~55 yr, resulting in a water velocity of 0.52 ft/yr (0.16 m/yr, assuming a root zone of ~3 ft, (1 m) and a recharge rate of **1.9 in/yr** (48 mm/yr) based on an average water content of 0.30 m^3/m^3. Recharge in the other irrigated profile in Roberts County is **2.2 in/yr** (56 mm/yr), which is based on the chloride mass balance approach because a chloride front could not be identified. The recharge rate is based on an irrigation application rate of 1.5 ft/yr (0.5 m/yr) and chloride concentration in irrigation water (26 mg/L; well 616651, 1992–2005). The irrigated profile in Hemphill County is characterized by high chloride concentrations (mean 176 mg/L, peak 1005 mg/L) and high matric potentials (mean -6 m). There is also no recognizable chloride front in this profile and an irrigation application rate of 1.5 ft/yr (0.5 m/yr) and measured chloride concentration in a sample of the irrigation water (14.5 mg/L) results in an estimated recharge rate of **4.5 in/yr** (115 mm/yr) for this site.

Chloride Mass Balance Method

Chloride concentrations in groundwater or in unsaturated zone pore water have been widely used to estimate recharge. Precipitation contains low concentrations of chloride. Chloride in precipitation and dry fallout is transported into the unsaturated zone with infiltrating water. Chloride concentrations increase through the root zone as a result of evapotranspiration because chloride is nonvolatile and is not removed by evaporation or by plant transpiration. Below the root zone, chloride concentrations should remain constant if recharge rates have not varied over time. Qualitative estimates of relative recharge rates can be determined using chloride concentrations in groundwater or unsaturated zone pore water if precipitation and dry fallout are the only sources of chloride to the subsurface. In this case, chloride concentrations are inversely related to recharge rates: low chloride concentrations indicate high recharge rates because chloride is flushed out of the system, whereas high chloride concentrations indicate low recharge rates because chloride accumulates as a result of evapotranspiration. For example, low chloride concentrations beneath playas in the central and southern High Plains indicate high recharge, whereas high chloride concentrations in natural interplaya settings indicate low recharge. The chloride mass balance (CMB) approach can be applied to chloride concentrations in groundwater:

$$PCl_p = RCl_{gw}, \qquad R = \frac{PCl_p}{Cl_{gw}} \tag{1}$$

which balances chloride input (precipitation, P, times the chloride concentration in precipitation and dry fallout, Cl_P) with chloride output (recharge rate, R, times chloride concentration in groundwater Cl_{gw}). The CMB approach can similarly be applied to unsaturated zone pore water:

$$PCl_p + ICl_I = RCl_{uz}, \quad R = \frac{PCl_p + ICl_I}{Cl_{uz}} \tag{2}$$

where chloride concentration in unsaturated zone pore water (Cl_{uz}) replaces Cl_{gw} and includes an additional term to account for irrigation (I) and chloride concentration in irrigation water (Cl_I) where applicable. The age of pore water at any depth in the unsaturated zone can also be estimated by dividing cumulative total mass of chloride from the surface to that depth by the chloride input rate.

Recharge rates can also be estimated using the chloride front displacement (CFD) method at sites with insufficient data to apply the CMB approach. Large chloride bulges that accumulated under rangeland conditions are displaced downward by increased recharge rates following land use conversion to cultivation (Scanlon et al., 2005). The transition from low chloride concentrations at shallower depths (typical of cultivated areas) to higher chloride concentrations at greater depths (typical of rangeland areas) forms a chloride front at sites where rangeland was converted to cultivated land. Recharge is estimated from the velocity (v) of the (downward) chloride front displacement:

$$R = \theta v = \theta \frac{z_2 - z_1}{t_2 - t_1} \qquad (3)$$

where θ is average volumetric water content over the displacement depth interval and z_1 and z_2 are depths of the chloride front corresponding to times t_1 and t_2 related to new (dryland or irrigated) and old (rangeland) land uses.

Field Methods

Soil Cores

Core samples were obtained at 20 locations in the central High Plains (Roberts and Hemphill counties) using a track-mounted, direct push drilling rig (Model 6620DT, Geoprobe, Salina, KS) without any drilling fluid. Boreholes are designated on the basis of abbreviated county name, year sampled, and sequence number. For example, ROB07-02 is Roberts County, 2007, borehole no. 2. Cores were obtained in different land use settings: nine in rangeland (grassland/shrubland), two in nonirrigated (dryland) agriculture (cropland), three in irrigated agriculture, one beneath a dry drainage channel, and four beneath stock impoundments. Rangeland sites are vegetated with grasses and sparse shrubs. Irrigation began in the 1950s at both sites in Roberts County and in the 1970s at the Hemphill irrigated site.

Continuous cores were obtained using core tubes (4.0 ft. [1.22 m] long, 1.1 inch [29 mm] inside diameter) from the ground surface to depths ranging from 18.5 to 88 ft (5.6 to 26.8 m). Core sample tubes were cut into various lengths, capped and sealed to prevent evaporative loss, and kept in cold storage. Two boreholes were drilled in Roberts County using a commercial drilling rig with air-rotary technology. Samples consisting of cuttings circulated to the ground surface using forced air pressure were collected from these two boreholes. One of the air-rotary boreholes was drilled at the same location as borehole ROB06-02 in an attempt to obtain samples from greater depth. This air-rotary drilling approach could not drill deeper than the Geoprobe; therefore, the air-rotary samples for this borehole were not analyzed.

Laboratory Methods

Chemical parameters included anions in water leached from 351 core samples (70 from 2006, 236 from 2007, and 45 from 2008) from the unsaturated zone. The primary anion of interest in this study was chloride, which is used to estimate rate of water movement through the unsaturated zone using the chloride mass balance approach. The pore water was also analyzed for nitrate, sulfate, and fluoride. Approximately 40 mL of double deionized water (≥18.2 MOhm) was added to about 25 g of moist soil. The mixture was placed in a reciprocal shaker for 4 hr and then centrifuged at 7,000 rpm for 20 minutes. The resulting supernatant was filtered to 0.2 µm and was analyzed for anion concentrations using ion chromatography at the Bureau of Economic Geology. Soil samples were then oven dried at 105°C for 48 hr to determine gravimetric water content.

Anion concentrations in the supernatant were converted to pore water concentrations by dividing by gravimetric water content and multiplying by density of pore water, assumed to be 1.00 Mg/m^3. Concentrations are expressed as milligrams of ion per liter of pore water.

Soil samples were also analyzed in the laboratory for pressure head to determine direction of water flow in the soil. The term *pressure head* is generally equivalent to the term *matric potential*, which refers to potential energy associated with the soil matrix. Matric potentials ≥-26.2 ft (-8 m) were measured using tensiometers (Model T5, UMH, Munich), whereas matric potentials ≤-26.2 ft (-8 m) were measured using a dew-point potentiometer (Model WP4-T, Decagon Devices Inc., Pullman, WA).

Results and Discussion

RESULTS

Recharge Estimates Based on Unsaturated Zone Field Studies

Rangeland Setting

General soil texture information for different profiles was estimated from SSURGO data (USDA-NRCS, 2007). Most of the profile soils at the rangeland sites have moderate clay contents (mean clay content in the upper 2 m of 25 to 33%) with the exception of HEM07-02, located on the breaks near the Canadian River in Hemphill County which contains only 18% clay. Rangeland profiles have variable water contents. Three of the 5 rangeland profiles in Roberts County for which measurements are available have high mean water contents (0.20 to 0.24 m^3/m^3) whereas the other two profiles have low mean water contents (0.06 to 0.09 m^3/m^3). One of the profiles in Roberts County was drilled with air rotary and only cuttings were available; therefore, water content or recharge rates could not be calculated for this profile. Rangeland profiles in Hemphill County also have variable water contents, ranging from 0.06 to 0.22 m^3/m^3. Mean water content below the root zone in rangeland profiles is moderately correlated with SSURGO soil texture (r=0.58), indicating that average surface soil clay content is a controlling factor in deeper profile water content.

Apparent electrical conductivity (EC_a) values measured using the EM 31 meter near rangeland profiles are generally correlated with mean water contents (r=0.89). EC_a varies with water content, soil texture, salinity, and temperature. Relationships between EC_a and water content also reflect soil textural effect on water content and EC_a. Generally low EC_a values are found in drier sediments that are coarser grained whereas higher EC_a values are found in wetter sediments that are associated with more clay-rich sediments.

Matric potentials are low in rangeland sites (mean -38 to -117 m). Variations in matric potential do not seem to be related directly to water content variability.

Chloride concentrations in rangeland profiles are generally high. Mean chloride concentrations in rangeland profiles range from 161 to 1,115 mg/L in profiles with high water content (0.14 to 0.24 m^3/m^3). These profiles generally have low chloride concentrations in the upper 3 ft (1 m), with the exception of profile ROB07-07 which has low chloride concentrations to a depth of 14.1 ft (4.3 m). Depth of chloride flushing in this profile may reflect local runon, although this was not obvious from the local topography. Peak chloride concentrations in profiles with high mean chloride concentrations range from 477 to 2593 mg/L (6 to 24 ft; 1.8 to 7.3 m depth). These large chloride accumulations require 3,747 to 19,758 yr to accumulate, indicating that soils in these settings have been drying out over these time periods. There has been no recharge in these settings over these time periods. Profiles with lower mean chloride concentrations (49 and 78 mg/L) correspond to lower mean water contents (0.06 m^3/m^3) and coarser textured soils near the Canadian breaks. Estimated mean water fluxes below the root zone in these profiles range from **0.11 to 0.14 in/yr** (2.8 to 3.6 mm/yr). Higher water fluxes are attributed to generally coarser textured soils.

Concentrations of other ions, including nitrate, sulfate, and fluoride are variable. Concentrations of nitrate-N are generally low (median 1.5 mg NO_3-*N*/L; range 0.8 to 9.5). The only profile with moderately high nitrate-N concentrations is ROB06-02 with a mean nitrate-N concentration of 9.5 mg/L and peak concentration of 32 mg NO_3-*N*/L at 20.3 ft (6.2 m) depth. Higher nitrate concentrations in this profile are attributed to low water contents and coarse textured soils, because nitrate concentrations on a mass basis are low in this profile, similar to those in other rangeland profiles.

Sulfate profiles are quite variable, with mean concentrations ranging from 174 to 3,647 mg/L and peak concentrations of 459 to 11,738 mg/L. Peak sulfate concentrations are so high in some profiles that they suggest a lithogenic source, such as gypsum and/or anhydrite. Lower concentrations (peaks <1,000 mg/L) may be derived from precipitation and dry fallout, similar to chloride. Correlations between sulfate and chloride are variable (r=0.48 to 0.90). High correlations may reflect similar processes affecting the two ions, such as evapotranspirative enrichment, regardless of the source. Peak chloride and sulfate peaks are also coincident in some profiles (ROB07-06 and HEM07-04).

Fluoride profiles are variable, with mean concentrations from 3 to 129 mg/L and peak concentrations that range from 16 to 459 mg/L at depths of 1.2 to 7.1 m. Fluoride peaks in most profiles are found in the shallow subsurface (5 profiles ≤ 1.8 m; 3 profiles 3.0, 3.7, and 7.1 m). Fluoride may be derived partly from precipitation and dry fallout. Although information on fluoride concentrations in precipitation is limited, existing data indicate that concentrations are generally low. Fluoride may also be derived from dissolution of fluorite and/or apatite. Regardless of source, peak fluoride concentrations may be related to evapotranspirative enrichment near the root zone. Profiles with deeper peaks may be related primarily to a lithogenic source.

Dryland Setting

Only two boreholes were drilled in dryland agricultural settings, one in Roberts County and one in Hemphill County. The Roberts County profile is in fine-grained sediments (mean clay content 43%) whereas the profile in Hemphill County is in coarser textured soils (mean clay content 29%). The difference in mean water content below the root zone at the two sites (Roberts County: 0.21 m^3/m^3, Hemphill County: 0.10 m^3/m^3) reflects the difference in soil texture. Apparent electrical conductivity (EC_a) measured using the EM31 meter at the Roberts site is moderately high (median 55 mS/m).

Matric potential profiles are generally low (-213 and -338 ft; -65 and -103 m). These values are similar to those found in rangeland profiles.

Chloride profiles at the two dryland sites are quite different. High chloride concentrations in the Roberts County site (mean 417 mg/L, peak 1,295 mg/L at 9.8 ft [3.0 m] depth) are similar to the rangeland profiles and represent 10,867 yr of accumulation. This large chloride accumulation represents long-term drying over this time period and indicates that there has been no recharge in this region. The lack of impact of cultivation on recharge at this site may reflect high clay content of the soils in this region. The profile in Hemphill County has low chloride concentrations between the root zone and a depth of 18 ft (5.5 m) (mean 15 mg/L, range 7 to 26 mg/L). Calculated mean water flux for this zone is **0.41 in/yr** (10.4 mm/yr). The time represented by chloride in this section of the profile is 87 yr, which generally corresponds to the time since cultivation began at this site (early 1900s). At depths ≥18 ft (5.5 m) chloride concentrations increase to 152 mg/L, which may reflect buildup of chloride under rangeland settings that is mobilized by higher water fluxes under dryland agriculture. The profile is not sufficiently deep (31 ft, 9.4 m) to show much of the rangeland chloride.

Concentrations of nitrate, sulfate, and fluoride are variable. Concentrations of nitrate-N are generally low in both profiles below the root zone (mean 5.5 and 5.7 mg NO_3-N/L). Highest nitrate-N concentrations in the Hemphill County profile are restricted to the root zone (peak 133 mg NO_3-N/L, depth 0.08 m), which is accessible to crop roots.

Sulfate concentrations are high in the Roberts County dryland profile (peak 3,427 mg/L at 1.5 m depth) and much lower in the Hemphill County profile (peak 399 mg/L at 1.3 m depth). These variations in sulfate concentrations are consistent with chloride concentrations, which are also much higher in the Roberts County profile than in the Hemphill County profile. High sulfate concentrations in the Hemphill County profile are found in the chloride flushed zone, indicating that sulfate is much less readily mobilized by increased drainage beneath dryland agriculture relative to chloride.

Fluoride concentrations are higher in the Hemphill County profile (mean 78 mg/L, peak 120 mg/L at 5.0 m depth) than in the Roberts County profile (mean 20 mg/L, peak 26 mg/L at 7.3 m). Fluoride concentrations within the chloride flushed zone in Hemphill County indicate that fluoride, like sulfate, has not been mobilized as effectively as chloride by the change in land use.

Irrigated Setting

A total of three boreholes were drilled in irrigated sites (two in Roberts County and one in Hemphill County). Soil textures at the Roberts County profiles are 25 and 43% clay and the Hemphill profile is much lower, with only 13% clay. Mean water contents are low at one of the irrigated sites in Roberts County (0.14 m^3/m^3) and at the Hemphill County irrigated site (0.14 m^3/m^3), but are much higher at the other irrigated site in Roberts County (0.30 m^3/m^3). Median EC_a values measured using the EM31 meter vary with water content and are much higher (76 mS/m) for the Roberts County profile, which has high water content than for the other two irrigated profiles with lower water content (16 and 18 mS/m).

Matric potentials are uniformly high below the root zone in all irrigated profiles, with mean values ranging from -6 to -10 m, indicating wet conditions. Matric potential is a much more accurate indicator of wet conditions than water content because soil water content varies with soil texture.

Chloride profiles are variable in irrigated settings. Chloride concentrations in the ROB06-01 profile are moderately high and variable with depth (mean 263 mg/L, range 69 to 527 mg/L). Estimated drainage for this site is **2.2 in/yr** (56 mm/yr) using the chloride mass balance approach (equation 2), with an irrigation application rate of 1.5 ft/yr (0.5 m/yr) (meter no. 01-08-2010N; 2002–2004), and chloride concentration in irrigation water of 26 mg/L (well 616651, 9 yr, 1992–2005). The chloride profile beneath the other irrigated site in Roberts County (ROB07-02) has low concentrations in the upper 32 ft (9.8 m) (86 to 264 mg/L), underlain by a zone of high chloride with a peak concentration of 1,140 mg/L at 44 ft (13.4 m) depth. The upper 32 ft (9.8 m) zone corresponds to the depth interval impacted by irrigation return flow. High chloride concentrations below this zone are attributed to chloride accumulation under previous rangeland conditions; this chloride bulge represents ~8,750 yr of accumulation. The profile is not deep enough to sample the entire chloride profile that developed under rangeland conditions. Water flux can be calculated using the chloride front displacement method (equation 2), which is based on downward displacement of the chloride front from 3 ft (1 m, base of root zone in typical rangeland profiles) to 32 ft (9.8 m) (distance 29 ft, 8.8 m) over ~55 yr irrigation time. This calculation results in a velocity of 0.53 ft/yr (0.16 m/yr) and a recharge rate of **1.9 in/yr** (48 mm/yr) when multiplied by the average water content of 0.30 m^3/m^3. The irrigated profile in Hemphill County has high chloride concentrations in the upper 12 ft (3.7 m) with peak chloride concentration of 1005 mg/L at a depth of 5 ft (1.5 m). High chloride concentrations in this zone are also associated with high sulfate concentrations (peak 449 mg/L at 1.2 m depth) and high fluoride concentrations (peak 66 mg/L at 1.8 m depth). Concentration of salts in this zone is attributed to evapotranspirative enrichment of irrigation water. Estimated recharge for this site is **4.5 in/yr** (115 mm/yr) using the chloride mass balance approach (equation 2) and an irrigation application rate of 1.5 ft/yr (0.5 m/yr) and chloride concentration of 14.5 mg/L measured in a sample of the irrigation water.

Concentrations of nitrate, sulfate, and fluoride are variable. Concentrations of nitrate-N are generally low in two profiles below the root zone (means 5.9 and 7.3 mg/L). Much higher nitrate concentrations in ROB07-02 profile extend below the root zone (peak 174 mg /L, depth 1.8 m). A secondary bulge of nitrate near the base of the profile and associated with the displaced chloride bulge may represent organic matter originally in the soil profile that was mineralized and displaced downward following conversion from rangeland.

Sulfate concentrations are high in 2 of the 3 irrigated profiles (peak 449 mg/L at 1.2 m depth; 1,969 mg/L at 7.3 m depth) and low in the third profile, ROB06-01 (46 mg/L at 1.9 m depth. Variations in peak sulfate concentrations generally follow variations in chloride concentrations. However, the peak sulfate concentration in ROB07-02 is much shallower (7.3 m depth) than that of the chloride peak (13.4 m depth), indicating that sulfate is not as readily mobilized by increased drainage beneath irrigated sites as chloride. The difference in peak depths of chloride and sulfate is not as great in the Hemphill County irrigated profile (0.6 m for sulfate and 0.9 m for chloride).

Fluoride concentrations are moderately low in all profiles with peak concentrations ranging from 22 mg/L (1.2 m depth) to 69 mg/L (4.3 m depth). Fluoride profiles do not seem to bear any relation to chloride profiles as the highest peak fluoride concentration is found in the profile with the lowest peak chloride concentration (ROB06-01). Fluoride does not seem to be mobilized under increased drainage resulting from irrigation return flow.

SUMMARY

Unsaturated zone chloride profiles indicate that there is essentially no recharge beneath most rangeland sites in Roberts and Hemphill Counties. Many rangeland profiles (6 out of 9) are characterized by large chloride accumulations that required 3,601 to 19,758 yr to accumulate and indicate that soils have been drying out over these time periods. The remaining rangeland profiles (one in Roberts and one in Hemphill counties) have much lower chloride concentrations (mean 49 to 78 mg/L) indicating low recharge rates of **0.11 and 0.14 in/yr** (2.8 and 3.6 mm/yr) attributed to coarser textured soils and location on the breaks near the Canadian River. Recharge could not be estimated for one rangeland profile in Roberts County because only cuttings could be collected with the air rotary drilling technique. Conversion from rangeland to dryland agriculture did not increase recharge in the Roberts County profile because of fine textured soils but did result in low recharge in the Hemphill County profile **0.41 in/yr** (10.4 mm/yr). Irrigation increased recharge in all 3 irrigated profiles to values of **1.9, 2.2, and 4.5 in/yr** (48, 56, and 115 mm/yr), which is attributed to excess irrigation water leaching below the root zone. Salts are accumulating near the root zone in the Hemphill irrigated profile, which can be attributed to deficit irrigation and evapotranspirative enrichment. A profile beneath a dry stream drainage in Roberts County also showed significant recharge as evidenced by low chloride concentrations; a minimum recharge of rate of **0.68 in/yr** (17 mm/yr) was calculated for this site. The actual recharge rate could not be estimated accurately because the runon amount and chloride concentration in runon were not quantified. Similarly, 4 profiles beneath 3 stock impoundments also showed significant (minimum) recharge rates ranging from **0.64 to 1.4 in/yr** (16 to 35 mm/yr), although actual recharge rates could not be estimated for the same lack of chloride input data.

APPENDIX B

Technical Memorandum

Evaluation of Existing Ponds as Analogs for Enhanced Recharge Structures

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Executive Summary

Four boreholes were drilled beneath or adjacent to three stock impoundments that pond water frequently. All profiles are characterized by low chloride concentrations and high matric potentials throughout, indicating high recharge rates. Minimum recharge rates based on precipitation and chloride in precipitation only ranged from **0.64 to 1.4 in/yr** (16 to 36 mm/yr). Assuming ponded depths of 2 ft/yr (0.6 m/yr) and chloride concentrations in ponded water of 1 mg/L results in recharge rates of 3.4 to 7.3 in/yr (86 to 185 mm/yr). Although recharge rates are locally high, the areal extent of such ponds is < 1%; therefore, volumetric recharge rates are low.

Chloride Mass Balance Method

Chloride concentrations in groundwater or in unsaturated zone pore water have been widely used to estimate recharge. Precipitation contains low concentrations of chloride. Chloride in precipitation and dry fallout is transported into the unsaturated zone with infiltrating water. Chloride concentrations increase through the root zone as a result of evapotranspiration because chloride is nonvolatile and is not removed by evaporation or by plant transpiration. Below the root zone, chloride concentrations should remain constant if recharge rates have not varied over time. Qualitative estimates of relative recharge rates can be determined using chloride concentrations in groundwater or unsaturated zone pore water if precipitation and dry fallout are the only sources of chloride to the subsurface. In this case, chloride concentrations are inversely related to recharge rates: low chloride concentrations indicate high recharge rates because chloride is flushed out of the system, whereas high chloride concentrations indicate low recharge rates because chloride accumulates as a result of evapotranspiration. For example, low chloride concentrations beneath playas in the central and southern High Plains indicate high recharge, whereas high chloride concentrations in natural interplaya settings indicate low recharge. The chloride mass balance (CMB) approach can be applied to chloride concentrations in groundwater:

$$PCl_p = RCl_{gw}, \qquad R = \frac{PCl_p}{Cl_{gw}} \tag{1}$$

which balances chloride input (precipitation, *P*, times the chloride concentration in precipitation and dry fallout, Cl_P) with chloride output (recharge rate, *R*, times chloride concentration in groundwater Cl_{gw}). The CMB approach can similarly be applied to unsaturated zone pore water:

$$PCl_p + ICl_I = RCl_{uz}, \quad R = \frac{PCl_p + ICl_I}{Cl_{uz}} \tag{2}$$

where chloride concentration in unsaturated zone pore water (Cl_{uz}) replaces Cl_{gw} and includes an additional term to account for irrigation (I) and chloride concentration in irrigation water (Cl_I) where applicable. The age of pore water at any depth in the unsaturated zone can also be estimated by dividing cumulative total mass of chloride from the surface to that depth by the chloride input rate.

Recharge rates can also be estimated using the chloride front displacement (CFD) method at sites with insufficient data to apply the CMB approach. Large chloride bulges that accumulated under rangeland conditions are displaced downward by increased recharge rates following land use conversion to cultivation (Scanlon et al., 2005). The transition from low chloride concentrations at shallower depths (typical of cultivated areas) to higher chloride concentrations at greater depths (typical of rangeland areas) forms a chloride front at sites where rangeland was converted to cultivated land. Recharge is estimated from the velocity (v) of the (downward) chloride front displacement:

$$R = \theta v = \theta \frac{z_2 - z_1}{t_2 - t_1} \qquad (3)$$

where θ is average volumetric water content over the displacement depth interval and z_1 and z_2 are depths of the chloride front corresponding to times t_1 and t_2 related to new (dryland or irrigated) and old (rangeland) land uses.

Field Methods

Soil Cores

Core samples were obtained at four locations beneath stock impoundments. Continuous cores were obtained using core tubes (4.0 ft. [1.22 m] long, 1.1 inch [29 mm] inside diameter) from the ground surface to depths ranging from 18.5 to 88 ft (5.6 to 26.8 m). Core sample tubes were cut into various lengths, capped and sealed to prevent evaporative loss, and kept in cold storage. Two boreholes were drilled in Roberts County using a commercial drilling rig with air-rotary technology. Samples consisting of cuttings circulated to the ground surface using forced air pressure were collected from these two boreholes. One of the air-rotary boreholes was drilled at the same location as borehole ROB06-02 in an attempt to obtain samples from greater depth. This air-rotary drilling approach could not drill deeper than the Geoprobe; therefore, the air-rotary samples for this borehole were not analyzed.

Laboratory Methods

Chemical parameters included anions in water leached from core samples from the unsaturated zone. The primary anion of interest in this study was chloride, which is used to estimate rate of water movement through the unsaturated zone using the chloride mass balance approach. The pore water was also analyzed for nitrate, sulfate, and fluoride. Approximately 40 mL of double deionized water (≥18.2 MOhm) was added to about 25 g of moist soil. The mixture was placed in a reciprocal shaker for 4 hr and then centrifuged at 7,000 rpm for 20 minutes. The resulting supernatant was filtered to 0.2 µm and was analyzed for anion concentrations using ion chromatography at the Bureau of Economic Geology. Soil samples were then oven dried at 105°C for 48 hr to determine gravimetric water content.

Anion concentrations in the supernatant were converted to pore water concentrations by dividing by gravimetric water content and multiplying by density of pore water, assumed to be 1.00 Mg/m^3. Concentrations are expressed as milligrams of ion per liter of pore water.

Soil samples were also analyzed in the laboratory for pressure head to determine direction of water flow in the soil. The term *pressure head* is generally equivalent to the term *matric* *potential*, which refers to potential energy associated with the soil matrix. Matric potentials ≥-26.2 ft (-8 m) were measured using tensiometers (Model T5, UMH, Munich), whereas matric potentials ≤-26.2 ft (-8 m) were measured using a dew-point potentiometer (Model WP4-T, Decagon Devices Inc., Pullman, WA).

RESULTS

Recharge Estimates Beneath and Adjacent to Stock Impoundments

Four boreholes were cored beneath or adjacent to stock impoundments in Roberts County. Two boreholes were located in the same impoundment and offset by about 30 ft (9m), with the second borehole being an attempt to obtain greater depth than the first. Both were analyzed for all parameters except matric potential, for which measurements were made for only one profile. Soil texture at the sites is representative of rangeland areas and ranges from 23 to 27%. Mean water contents are moderate to high (0.17 to 0.26 m^3/m^3) and matric potentials are very high (mean -4.3 to -15.7 ft; -1.3 to -4.8 m) (Table 2, Fig. 16). Median EC_a measured using the EM31 was high (39 to 56 mS/m) reflecting combined clay and water contents. As with the drainage setting location, it is difficult to estimate recharge rates beneath the impoundments because we do not know the chloride input (ponding rate and chloride concentration). Lower bounds on recharge rates can be estimated by assuming no ponding and a range from **0.64 to 1.4 in/yr** (16 to 35 mm/yr). Assuming a ponding rate of 2 ft/yr (600 mm/yr) and chloride concentrations in the ponded water of 1 mg/L, recharge rates range from 4.3 to 7.3 in/yr (87 to 186 mm/yr). Increasing ponding depth and chloride concentration in pond water would linearly increase calculated recharge rates.

Mean nitrate-N concentrations below the root zone are generally high compared with most rangeland sites and are comparable to cultivated sites (mean 1.3 to 9.8 mg/L). Peak nitrate-N concentrations below the root zone (12 to 53 mg/L, 1.2 to 6.3 m depth) also follow this pattern, higher than rangeland and comparable to cultivated sites. The highest nitrate-N concentrations in all impoundment profiles occur at the surface or within the root zone, and range from 21 to 480 mg/L, reflecting the high deposition rate of cow manure at these locations.

As with the drainage site profile, mean concentrations of sulfate and fluoride in the impoundment profiles are generally low to very low and concentrations are generally uniform with depth. These measurements, along with the chloride profiles, are similar to stream drainage profile concentrations and indicate that recharge at these sites is also occurring fast enough to prevent solutes from building up through evapotranspiration.

ATTACHMENT C

TWDB Contract No. 0704830686

1. Ogallala Recharge Study (Studies 1, 2, and 3 from the Scope of Work)
2. Plan Consistency and Interregional Coordination – Study 4 from the Scope of Work

TWDB Comments on Draft Region-Specific Study Reports

1. Ogallala Recharge Study – Studies 1, 2, and 3 from the Scope of Work

a. Please submit all data, maps, GIS files and functioning analytic models in an electronic format along with the final report as required by the contract between TWDB and Region A.

Response: Data, maps, GIS files are being submitted in an electronic format.

b. The Scope of Work for Studies 1, 2, and 3 requires that the report contain the purpose of the study including how the study supports regional water planning (see "Work Products" in the scope). Please include this information in the final report.

Response: Pages 4 and 5 now address each task as identified in the Scope of Work and identifies where each task is directly addressed in the Report. Additionally, how each task relates to the ongoing regional planning effort is also addressed.

c. The Scope of Work for Study 1, Task D2 and Study 2, Task D require that technical memoranda be prepared for these studies. Please include these technical memoranda in an appendix in the final report.

Response: Data from these technical memoranda were used to write the final report. The technical memoranda are being submitted as Appendix A and Appendix B respectively.

d. The Scope of Work for Study 2 notes that local ecologists and agronomists will be consulted to obtain vegetation parameters. Please mention the experts contacted and summarize the results of these discussions in the final report.

Response: Information for sorghum was obtained from Louis Baumhardt (USDA, ARS) and Thomas Marek (Texas A&M AgriLife Research and Extension Service) and is now included in the text (p. 16).

Vegetation parameters required for UNSAT-H include percent bare area, planting and harvesting dates for crops, time series of leaf area index (LAI) and rooting depth (RD), and root-length density (RLD). **These parameters for shrubs and brush were obtained from Keese et al. (2005) and were primarily determined from the literature. Information on sorghum, including sowing and harvesting dates, rooting depth, and leaf area index were obtained from Louis Baumhardt (USDA, Agricultural Research Service, Bushland, Texas, pers. comm., 2008) and Thomas Marek (Texas A&M AgriLife Research and Extension Center, Amarillo, Texas, pers. comm.., 2008).** Time series for LAI and root growth were specified on particular days of the year and linearly interpolated. Root growth was simulated for crops only; other plant types were modeled as perennial, with a constant rooting depth. The RLD function is based on the assumption that normalized total root biomass is related directly to RLD (ρ_{rL}) and can be related to depth below the surface (z) by:

$$\rho_{rL} = ae^{(-bz)} + c \tag{7}$$

where *a*, *b*, and *c* are coefficients that optimize fit to normalized biomass data. Dominant vegetation types that represented ~70–80% of the area of each region were simulated.

e. The draft report does not address the work required by Scope of Work Study 3 – Geochemical Studies. Please include the results of this work in the final report.

The sections titled
Section 3.1 "Recharge Estimates Based on Groundwater Chloride Data"
and
Section 3.2 Groundwater Tritium-Helium Age-Dating Results
essentially constitute the Geochemical Studies.

f. Please consider organizing or clarifying the report in such a manner to clearly delineate the three studies in the scope of work.

Response: Pages 4 and 5 now address each task as identified in the Scope of Work and identifies where each task is directly addressed in the Report. Additionally, how each task relates to the ongoing regional planning effort is also addressed.

2. Plan Consistency and Interregional Coordination – Study 4 from the Scope of Work

a. The Executive Summary on page 1 and Section 3.4 page 8 discusses using conference rooms at Texas A&M Agrilife facilities for interactive video conferences. Both pages state that "additional research will be needed to confirm the size of the facility and specific costs". However, this has been determined by the study performed for Region O and it concludes that this is the recommended alternative to purchasing equipment. It would appear that no additional research is necessary and Regions A and O can hold joint video conferences at minimal expense.

Response: The entirety of the Plan Consistency and Interregional Coordination portion, Study 4, of the final report has been modified to include the more appropriate language inclusive of Region O's findings.

Panhandle Area
Water Planning Group

Freese and Nichols, Inc.

PLAN CONSISTENCY AND INTERREGIONAL COORDINATION

December 16, 2008

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PLAN CONSISTENCY AND INTERREGIONAL COORDINATION

1 EXECUTIVE SUMMARY

This study was authorized to document and facilitate coordination between the Panhandle Area Water Planning Group and adjoining regions. Specifically, the inter-regional coordination effort focused on coordination activities with the Llano Estacado Region (Region O) and reviewing the timing, quantity, location, and impact of water management strategies in other regions utilizing source water from within Panhandle Area (Region A).

Inter-regional coordination activities included:

- Identifying changed conditions for suppliers of water to users outside of Region A
- Communicating the results of the Ogallala Aquifer Recharge Study, which is a special study conducted for Region A, to the consultants for Region O
- Communicating the findings of potential joint video conferencing meetings with Regions A and O. This was a special study for Region O.
- Reviewing potential water managements strategies recommended for other regions that use water from Region A.

Each of these activities is documented in this study report. In summary:

- There are changed conditions for the timing and quantities of developing groundwater supplies by the Canadian River Municipal Water Authority (CRMWA). Due to continued drought, groundwater development has been expedited and expanded with initial expansions of 20,000 acre-feet per year by 2010. CRMWA will ultimately add 60 million gallons per day of transmission capacity from the new well fields.
- The Ogallala Recharge study found generally low recharge rates in Roberts and Hemphill Counties. The median recharge rate is 0.26 inches per year, which is similar to values reported in previous studies. The results of this study were provided to Region O and will be presented at a Region O meeting in early 2009.
- The Region O consultants identified several options to hold joint video conference meetings. It was suggested that Regions A and O schedule an Interactive Video Conferencing demonstration using the AgriLife Research facilities at Lubbock and Amarillo to test the functionality of Interactive Video Conferencing for interregional coordination. In the interim, it is recommended to continue to communicate through telephone, email and written correspondence.
- There is only one recommended water management strategy in other regions that use water from Region A. This is a recommended strategy for customers of CRMWA. At this time these customers intend to continue purchasing water from CRMWA. Any

changes to CRMWA's strategies will be evaluated for the 2011 Panhandle Area Water Plan.

2 INTRODUCTION

Water from the Panhandle Area currently supplies users in the Panhandle Area (Region A), the Llano Estacada Region (Region O) and Region B. Groundwater from the Ogallala Aquifer in the Panhandle Area has been identified as a potential water source for other areas in the state, including Region C. The major water providers to other regions include the Canadian River Municipal Water Authority (CRMWA), which supplies water to Region O, and Greenbelt Municipal and Industrial Water Authority (GMIWA), which supplies water to Region B.

Since the completion of the *2006 Regional Water Plan for the Panhandle Water Planning Area*, the current drought has had a significant impact to regional water supplies including potential transfers to users outside of the region. Lake Meredith recently reached a historic low and the reliable supply from this source has decreased from over 70,000 acre-feet per year to about 30,000 acre-feet in 2008. There has been renewed interest in developing other sources of water, with specific interest in expanding development of the Ogallala Aquifer. As part of the special studies conducted for the Panhandle Area, the Panhandle Area Water Planning Group (PWPG) authorized additional study of the Ogallala Aquifer. The Ogallala Recharge Study was conducted by the Bureau of Economic Geology and is published separately.

As part of an inter-regional coordination effort, the PWPA authorized Freese and Nichols, Inc. to review and coordinate the results from the Ogallala recharge study with Region O, and evaluate the timing, quantity, location, and impact of water management strategies in other regions utilizing source water from within Region A. This inter-regional coordination is funded through a Research and Planning Grant sponsored by the Texas Water Development Board.

3 RESULTS

3.1 Changed Conditions

Drought has greatly impacted the surface water supplies in the Panhandle region. As previous discussed, the reliable supply from Lake Meredith has decreased substantially over the last five years. Other regional surface water sources, Lake Palo Duro and Lake Greenbelt, are also in drought conditions. The impact of the reduced supplies to the Panhandle region may have significant impacts to users in Region A as well as those in Regions B and O. Without renewable surface water, the region must rely on groundwater.

Canadian River Municipal Water Authority

The Canadian River Municipal Water Authority (CRMWA) uses surface water from Lake Meredith and groundwater from the Ogallala Aquifer. About half of its total water use is transported to users in Region O. The remaining allocation supplies water users in the Panhandle Area.

The 2009 allocation for the entire CRMWA System is 75,000 acre-feet per year (AFY). That includes 45,000 AFY of groundwater and 30,000 AFY from Lake Meredith. The 2007 and 2008 system allocations were 85,000 AFY and 80,000 AFY, respectively. The reduced allocation is due primarily to the reduced yield of Lake Meredith in recent drought conditions. The CRMWA allocations for 1990 to 2009 are shown in Table 1.

Currently, the CRMWA groundwater system includes well fields in Roberts County and an existing 54-inch pipeline from the existing Roberts County Well Field to CRMWA's main aqueduct. This system has an ultimate transmission capacity of 71,659 AFY. For *2006 Regional Water Plan for the Panhandle Water Planning Area* (2006 Region A Water Plan) the existing well field capacity was estimated at 40,000 AFY. One of CRMWA's water management strategies in the 2006 Region A Water Plan included securing 31,659 AFY of additional water rights in Roberts County to maximize the existing transmission capacity. The well field expansions were scheduled to be in operation by 2008. While CRMWA has continued to secure additional water rights, with continued declining lake levels in Lake Meredith CRMWA has decided to move forward with additional well field expansions and additional transmission capacity. The Phase III well field expansion is expected to add 20,000 to 21,000 AFY yield to their system by 2010. It will also include approximately 43 million gallons per day (MGD) of initial transmission system capacity. The ultimate peak capacity of the new pipeline will be approximately 60 MGD (Phase IV). The timing of the Phase IV expansion has not been determined as yet.

Table 1

Total CRMWA Allocation to Member Cities 1990 to 2009

	CRMWA Allocation (AF)		
Year	**Lake Meredith**	**Groundwater**	**Total**
1990	82,400		82,400
1991	82,400		82,400
1992	82,400		82,400
1993	82,400		82,400
1994	82,400		82,400
1995	82,400		82,400
1996	82,400		82,400
1997	82,400		82,400
1998	92,700		92,700
1999	92,700		92,700
2000	103,000		103,000
2001	105,000		105,000
2002	76,000	40,000	116,000
2003	76,000	40,000	116,000
2004	35,612	46,500	82,112
2005	50,000	40,000	90,000
2006	50,000	40,000	90,000
2007	35,000	50,000	85,000
2008	30,000	50,000	80,000
2009	30,000	45,000	75,000

Greenbelt Municipal and Industrial Water Authority

Greenbelt Municipal and Industrial Water Authority (GMIWA) obtains its water from Lake Greenbelt in Donley County. It supplies water to customers in Region A and Region B. While the recent drought has impacted the lake levels, there is sufficient supply to meet the current and projected demands of GMIWA's customers.

3.2 Ogallala Recharge Study

The Bureau of Economic Geology (BEG) conducted several studies to determine recharge rates for the Ogallala aquifer in Roberts and Hemphill counties. The draft report titled

"Recharge Estimate for Roberts County based on Groundwater Chloride Data" focuses primarily on the Roberts County area. Another report, "Groundwater Recharge in the Central High Plains of Texas: Roberts and Hemphill Counties", was written in conjunction with the Panhandle Groundwater Conservation District and focuses on both Roberts and Hemphill Counties.

Recharge Estimate for Roberts County

The Roberts County study found a median recharge rate for the central portion of the county of 0.26 inches per year. The study found that little to no recharge occurs beneath rangeland vegetation. The highest recharge rates, which represent only about 2% of the study area, range from 0.7 to 0.9 inches per year. The higher recharge rates were found in drainage areas, which appear to function in a similar way to playa lakes in other regions. The density of playa lakes in Roberts County is very low, with all playa lakes located in the southeastern portion of the county.

This study confirmed previous estimates that there is little to no recharge beneath rangeland vegetation. The regional median recharge rate in the recent study, 0.26 inches per year, is similar to previous regional estimates for the central High Plains based on chloride data analyses.

Recharge in the Central High Plains: Roberts and Hemphill Counties

The Roberts and Hemphill Counties study also found that little to no recharge occurs beneath vegetated rangeland. Six of nine test locations in a rangeland setting indicated essentially no recharge to the aquifer. Two of the nine test locations indicated recharge rates of 0.11 and 0.14 inches per year. Recharge rates were not estimated for the ninth location. The absence of recharge in most rangeland areas can be attributed to low permeability soils and evapotranspiration of the natural grasses and shrubs.

Where rangeland was converted to dryland agriculture, recharge did not increase in a test location in Roberts County but did increase in a Hemphill County test location to 0.41 inches per year. The test location in Roberts County has a low permeability clay loam soil.

The study found increased recharge under all irrigated locations. Two test locations in Robert County were found to have recharge rates of 1.9 and 2.2 inches per year, and a test location in Hemphill County had an estimated recharge rate of 1.3 inches per year.

Evaluation of one test location in a dry drainage channel in Roberts County indicated high recharge rates. It is estimated that a lower bound on the recharge rate may be 0.7 inches per year. The study also evaluated recharge beneath impoundments in Robert County and found the recharge rate to be between 0.6 and 1.4 inches per year.

General Observations from the Ogallala Aquifer Recharge Studies

The studies indicate that the regional recharge rates in Roberts and Hemphill counties are relatively low and similar to values estimated in previous studies. It is noted in both reports that different site conditions result in different recharge rates. The Roberts and Hemphill Counties study evaluated the following site conditions, in order of increasing recharge rates: vegetated rangeland, dryland agricultural areas, irrigated agricultural areas, drainage channels, and impoundments. The results from the studies are summarized in Table 2. This information will be used to refine estimates of groundwater availability in the Ogallala Aquifer for the 2011 Panhandle Area Water Plan.

Table 2

Recharge Rates in Inches per Year in Roberts and Hemphill Counties

Description of Area	Roberts County	Hemphill County
Regional Recharge	0.26	N/A
Rangeland	0.0 – 0.2	0.0 – 0.2
Dryland Agriculture	0.0	0.4
Irrigated Agriculture	0.8 – 1.9	0.6
Drainage Channel	>0.7	N/A
Impoundment	0.6 – 1.4	N/A

3.3 Water Management Strategies in Other Regions Utilizing Source Water from within Region A

Table 3 lists the recommended water management strategies in the 2006 regional water plans for water user groups in other regions utilizing water sources within Region A. The sections following the table discuss the changes to recommended strategies in Region O and the alternative strategy for Ogallala aquifer water in Region C.

Table 3

Recommended Strategies in the 2006 Regional Water Plans for Other Regions Utilizing Region A Water Sources

Water User Groups	Recommended Water Management Strategy	Sources Allocated to Other Regions in 2006 Plan (AFY)					
		2010	2020	2030	2040	2050	2060
Region O							
Lubbock	CRMWA Expand Groundwater Supply	14,911	14,911	14,911	14,911	14,911	14,911
Brownfield	CRMWA Expand Groundwater Supply	494	494	494	494	494	494
Total Supply Region A to Other Regions		**15,405**	**15,405**	**15,405**	**15,405**	**15,405**	**15,405**

Water Management Strategies in Region O

As shown in Table 1, the 2006 Region O Water Plan includes additional CRMWA groundwater supplies as recommended water management strategies for the City of Lubbock and the City of Brownfield. Lubbock is a current customer of CRMWA and plans to continue being a customer of CRMWA. The additional CRMWA groundwater supply remains a strategy for the City of Lubbock, but the quantity and timing may change. This will be evaluated in the next round of regional water planning.

When the scope for this study was prepared, the City of Lubbock was considering purchasing additional groundwater from Region A, specifically Amarillo's Hartley groundwater rights. However, since the 2006 regional water plans and the scope for this study were prepared, Lubbock has been working on a project to transport raw water from Lake Alan Henry to the City of Lubbock. The quantities and timing of Lubbock's water management strategies will be reevaluated in the next round of planning.

Water Management Strategies in Region C

Ogallala groundwater in Roberts County (Mesa Water) is not a recommended water management strategy for Region C but is listed as an alternative strategy in the *2006 Region C Water Plan* for Dallas and North Texas Municipal Water District. The Region A consultant will continue to monitor this project and notify the Panhandle Area Water Planning Group of any changes.

3.4 Coordination with Region O

In past regional water planning cycles, Region A and Region O water planning groups have held joint meetings on topics of interest to both regions. Because several Region O water management strategies include significant water supplies from Region A, it is important to coordinate and communicate regional water planning activities. Considering time, traveling distance, and fuel prices, the Region O consultants have researched facilities available for Region A and Region O to hold joint meetings via interactive video conferencing. This information was provided to the regions for consideration.

If Region A wants to pursue the option to hold joint meetings with Region O using video conferencing, Region A will need to purchase video conferencing equipment or use a meeting facility that already has the required equipment. According to information from the Region O consultant, estimated costs to establish interactive video conferencing capabilities range from $12,000 to $25,000 per site. However, existing interactive video conferencing facilities are available at a low price to both Regions A and O at Offices of the AgriLife Research Facilities of the Texas A&M University System in Amarillo and Lubbock. Region O suggested that Regions A and O schedule an Interactive Video Conferencing demonstration using the AgriLife Research facilities at Lubbock and Amarillo to test the functionality of Interactive Video Conferencing for interregional coordination. In the interim, it is recommended to continue to communicate through telephone, email and written correspondence.

A copy of the Ogallala Recharge Study report was provided to Region O consultants and chairman. A brief presentation of the results will be given to the Region O water planning group in early 2009.

4 CONCLUSIONS AND RECOMMENDATIONS

The Ogallala recharge studies confirmed that the regional recharge rate in Roberts and Hemphill Counties is relatively low as indicated in previous studies. Recharge rates beneath irrigated agriculture and impoundments are higher than rangeland and dryland agriculture; however, these areas are limited in Roberts and Hemphill Counties.

The water supply yield from existing sources in the CRMWA system has decreased over recent years, and CRMWA's allocations have decreased in response. CRMWA expects to add an additional 20,000 to 21,000 AFY yield from groundwater to their system by 2010. In addition, CRMWA is increasing its transmission capacity from the well fields in Roberts County.

Since the 2006 Region A Water Plan was prepared, there have been no known additional requests from other regions to utilize water sources within Region A. The Mesa Water supply project continues to be of interest to water providers in other regions, but at this time no agreements have been announced. The quantity and timing of sources from Region A to meet demands for CRMWA's customers in Region O will be reevaluated in the next round of regional water planning.

It is recommended that Region A and Region O continue to coordinate via telephone and written correspondence. The planning groups can pursue joint meetings if they so choose or if planning efforts require further coordination in the future.