Kansas Geological Survey

HOLOCENE AND LATE PLEISTOCENE GROUND-WATER RECHARGE AND RECHARGE TEMPERATURES IN THE CENTRAL GREAT PLAINS DEDUCED FROM NOBLE GAS, STABLE ISOTOPE, CL$^-$, AND ^{36}CL IN SHALLOW GROUND WATER

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P.A. Macfarlane, J.F. Clark, M.L. Davisson, G.B. Hudson,
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Kansas Geological Survey Open-File-Report #97-77

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KANSAS GEOLOGICAL SURVEY

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ABSTRACT

Recently acquired data on the climate-sensitive geochemical tracers (noble gasses, stable isotopes, Cl and ^{36}Cl) from shallow ground-water systems further quantify the changes toward a more arid climate on the High Plains of southeastern Colorado and western Kansas during the late Pleistocene and Holocene noted in the literature. Samples were collected from the unconfined to poorly confined Dakota and Morrison-Dockum and the unconfined High Plains aquifers. The samples from the shallower wells (Group 1) were recharged during the last few thousand years (radiocarbon age), whereas the samples from the deeper wells (Group 2) recharged earlier in the Holocene and late Pleistocene. Recharge temperatures were generally about 5°C cooler in the earlier Holocene and late Pleistocene than during the later Holocene. Using the Cl$^-$ in ground water and in modern wet and dry atmospheric input, the calculated average recharge rates were conservatively estimated to be 200% higher during the Altithermal climatic event than during the last few thousand years. Recharge rates calculated for the last few thousand years are consistent with other published estimates of modern recharge (<2.54 mm/yr) and computer modeling. Paradoxically, average annual precipitation is believed to have been at least 25% less than present day values during the Altithermal. One possible interpretation of these results is that temporal changes in annual precipitation and intensity may have played an important role in determining recharge rates through the middle and late Holocene. Intense storms (extreme hydrologic events) are believed to have been more frequent during the Altithermal and played an important part in providing recharge to aquifer systems. In spite of higher average annual precipitation, recharge rates have diminished due to a decrease in the incidence of extreme hydrologic events in the last 2,000 yrs.

Regionalized estimates of natural recharge form the basis for many ground-water management plans in the Great Plains region of the United States (Sophocleous, 1993). Our understanding of natural recharge and the dynamics under which it occurs typically develops from computer models of the ground-water flow system. These models are infrequently supported by sets of *in situ* point recharge measurements collected over relatively short time periods or derived by other means using hydrometeorologic data. More often than not these models are poorly constrained due to longer term fluctuations in recharge in time and space, such as the change in rates associated with the late Pleistocene-Holocene climate transition.

Very little is known of the effects of the late Pleistocene-Holocene climatic transition on ground-water systems in the central Great Plains of North America. Records of late Pleistocene and Holocene climate change in the central Great Plains of North America have been elucidated primarily from studies of Quaternary deposits and the paleosols and proxies of climate indicators preserved within them (Johnson and Park, in press). The $\delta\ ^{13}C$ signature of soil carbonates, fossil pollen, and residual rock magnetism are used as proxies to qualitatively determine the record of Quaternary climates. These proxies are related to a complex of climate indicators or a single indicator, such as temperature, rainfall, or evaporation, through transfer functions, often with considerable uncertainty. In spite of these uncertainties, it is clear that significant changes in moisture conditions in the Great Plains region occurred during the late Pleistocene-Holocene climatic transition associated with ice-sheet retreat and changes in the dominant wind patterns (Johnson and Park, in press).

Recent work in ground-water systems (Andrews et al., 1994; Stute et al., 1992; Stute et al., 1993, and Clark et al., 1997) in Europe and the Gulf Coast and southwestern regions of the United States has focused on using naturally occurring geochemical tracers to capture the paleoclimate signals preserved in shallow ground waters. These tracers include the noble gases (He, Ne, Ar, Kr, and Xe), the stable isotopes (^{2}H and ^{18}O), Cl, ^{36}Cl, and ^{14}C. These climate indicators can be used in a relatively straightforward manner by sampling along a flow path. Because of the natural tendency for ground water to flow away from where it is recharged toward points of discharge, the flow system becomes a relatively continuous natural archive of climate change over geologic time. However, we are unable to fully "read" this archive because of the limited number of existing wells and the dispersion or mixing that occurs due to flow through porous media. Consequently, the paleoclimate records as sampled from ground water are discontinuous and preserve only long term trends of climate change in the flow system. In spite of these limitations, the paleotemperature and paleorecharge rates calculated using these geochemical tracers clearly demonstrate the impact of the late Pleistocene-Holocene climatic transition on shallow ground-water systems.

From a more local point of view, these longer term fluctuations in paleorecharge rates are not particularly germane to present-day ground-water management. However, an understanding of recharge mechanisms and these longer term fluctuations resulting from past climate change may provide a glimpse into the effects of future climate change associated with global warming.

The objectives of this investigation were to use these naturally occurring geochemical and isotopic tracers to (1) discern the overall pattern of recharge fluctuations and (2) develop an understanding of the conditions influencing these fluctuations through the Holocene in western Kansas and southeastern Colorado (the central Great Plains region). First, we present the analytical data pertinent to this investigation. From the limited data set, we estimate recharge temperatures using the noble gas concentrations and average annual recharge rates using the Cl^{-} concentrations in the aquifer and average annual atmospheric deposition rates. Finally, we argue that the fluctuations in the calculated recharge temperature and recharge rates are due to systematic changes in climate during the Holocene.

Regional Climate and Hydrogeology

The study area includes the regional recharge area of the Dakota aquifer which is located in the Raton, Colorado Piedmont, and High Plains sections of the Great Plains physiographic province. Within the study area the land surface slopes eastward from approximately 1,509 m above mean sea level (a.s.l.) at sample site 57 in southeastern Colorado to approximately 1,007 m a.s.l. at sample site 69 in western Kansas over a distance of approximately 189 km (Figure 1). The major drainage crossing the study area is the Arkansas River and its tributaries. The valleys cut by this drainage impose only moderate topographic relief on the eastward sloping land surface. The region is in a warm, semiarid continental environment. Mean annual temperature and rainfall range from 12.2 °C and 37.3 cm near sample site 55 to 11.4 °C and 43.4 cm at sample site 69, respectively. Annual evapotranspiration is much higher than annual rainfall. Annual lake evaporation ranges from 157 cm near sample site 55 to 165 cm near sample site 69 (Farnesworth et al., 1982).

The major aquifer units in the study area are the High Plains, Dakota, and Morrison-Dockum aquifers (Macfarlane, 1993; Figure 1). The High Plains aquifer consists of the Pliocene Ogallala Formation and associated unconsolidated Quaternary sediments, whereas the Dakota and Morrison-Dockum bedrock aquifers are in Cretaceous and Jurassic sandstones, respectively. These aquifers are unconfined and hydraulically connected over much of southeastern Colorado and southwestern Kansas south of the Arkansas River. Elsewhere, the bedrock aquifers are semi-confined where they are overlain by thin, leaky remnants of the Upper Cretaceous aquitard. The low total dissolved solids (TDS), mixed cation-HCO_3 to mixed cation-HCO_3, SO_4 type ground waters in the Dakota and Morrison-Dockum reflects freshwater recharge. Regional ground-water flow in all three aquifer units is to the east or northeast following the regional topographic gradient (Macfarlane, 1993). Flow-model results suggest that shallow local flow systems are superimposed on the regional system due to the moderate local topographic relief and low to moderate eastward regional slope of the land surface (Macfarlane, 1993; 1995).

Sampling and Analysis of the Water Samples

Water sampling and analysis were conducted jointly by the Kansas Geological Survey and the Lawrence Livermore National Laboratory. The samples were collected from thirteen wells in southeastern Colorado and adjacent western Kansas during the summers of 1992 and 1993. Eleven of the wells are open to either the Dakota, the Dakota and High Plains, or the Dakota and Morrison-Dockum aquifers. One well is open only to the Morrison-Dockum and one

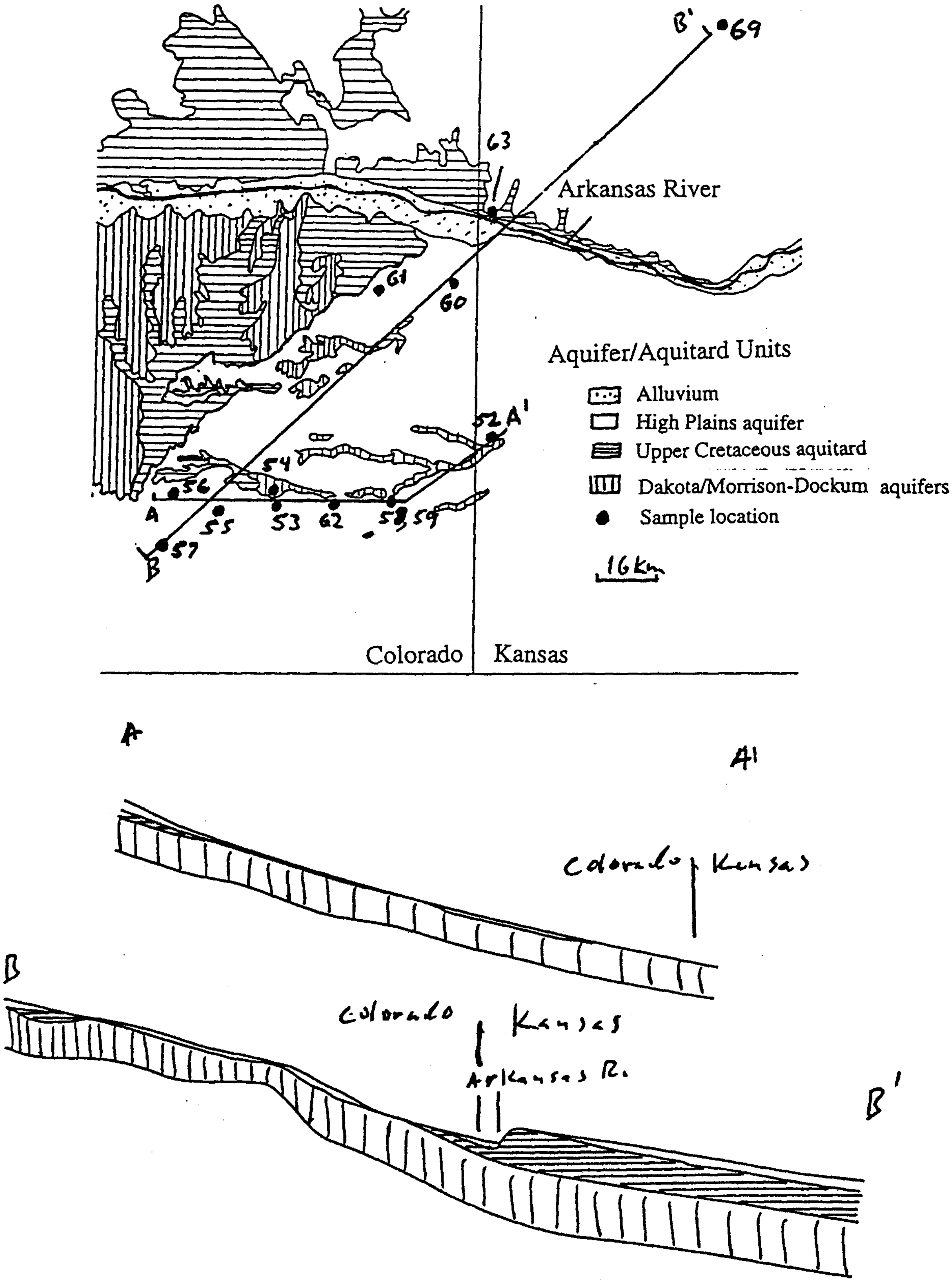


Figure 1. Hydrogeologic setting and location of sampling points in the study area.

only to the High Plains aquifer. The major constituents and selected minor and trace constituents were determined by the Analytical Services Section, Kansas Geological Survey, using standard techniques of inductively coupled plasma and atomic absorption, spectrometry, and automated colorimetry. The stable isotopes (^{2}H and ^{18}O), ^{3}H, ^{14}C, the noble gases (He, Ne, Ar, Kr, Xe), and ^{36}Cl in the water samples were determined by Lawrence Livermore National Laboratory. The stable isotopes were determined using standard mass spectrometric techniques and reported using the standard δ notation. ^{3}H was determined by the ^{3}He accumulation method (Surano et al., 1992) and reported as tritium units (TU). ^{14}C was determined by accelerator mass spectrometry and reported as percent modern carbon (pmc). ^{36}Cl was determined on a tandem accelerator mass spectrometer and reported as $^{36}Cl/Cl^{-}$. ^{36}Cl is reported here in concentration units as atoms/L.

Samples were collected from eleven of the thirteen wells to determine noble gas content. Noble gas concentrations were determined on a Nuclide 6-60 noble gas spectrometer using an isotope dilution method and reported as cm^{3}/gm. Recharge temperatures were calculated from concentrations of Ne, Ar, Kr, and Xe after correcting for excess air (Stute and Schlosser, 1993; Stute et al., 1995a) using solubility equilibrium data (Weiss, 1970, 1971; Clever, 1979) and the inferred elevation of the recharge area. This method can easily resolve the temperature change between Holocene and late Pleistocene climates and has become an important tool in reconstructing continental temperatures of past climates (e.g. Stute et al., 1992; Stute et al., 1993, and Clark et al., 1997). These studies have also shown that noble-gas temperatures of young ground water (<10,000 yrs) are identical to modern mean annual soil temperatures, which in the United States are typically 0-2° C more than mean annual temperature (Smith et al., 1964).

Results

On the basis of the tracer and well construction data and the location of the sampling points in the flow systems, each sample was placed into one of two groups. Group 1 samples were collected only from wells in unconfined aquifers. The wells that produced these samples are shallower than the ones that produced the Group 2 samples. Some of the Group 2 samples were collected from wells in the semi-confined bedrock aquifers. Group 1 samples have a mean ^{14}C content of 74 pmc and contain appreciable ^{3}H (Table 1). These samples are believed to be evidence of relatively recent recharge. The measurable ^{3}H in these samples indicates that some of this recent recharge has entered the flow system since the 1950s and 1960s. The Group 2 samples have a mean ^{14}C content of 32 pmc and with the exception of sample 52, none of them contain appreciable ^{3}H. Sample 52 comes from a recently installed monitoring well in the lowermost aquifer unit, the Morrison-Dockum. The ^{3}H in the sample from this well suggests that a small fraction of the water used in monitoring-well installation remains in the aquifer. All

Table 1. Geochemical tracer data in ground-water samples from southeastern Colorado and western Kansas.

Sample No.	Aquifer Units[1]	Elevation (m a.s.l.)	$\delta^{13}C$ (‰)	^{14}C (PMC)	App. ^{14}C Age kyr	^{14}C Age kyr (Vogel, 1970)	^{2}H (‰)	^{18}O (‰)	^{3}H (TU)	Cl^- (mg/L)	^{36}Cl x 10^{-7} (atoms/L)
Group 1 53	H,D	1,344	-3.0	81.1	1.7	0.4	-85	-11.4	5.0	25.0	52.3
54	D	1,325	-5.4	74.4	2.4	1.1	-75	-10.7	5.8	20.4	52.2
57	D	1,509	-5.2	75.0	2.4	1.1	-67	-9.8	0.9	7.7	12.8
58	D	1,208	-7.4	72.4	2.7	1.3	-68	-9.4	1.1	49.1	92.6
59	D	1,206	-6.2	68.2	3.1	1.8	-66	-9.7	4.0	22.2	41.5
69	H	1,007	-8.1	70.9	2.8	1.5	-61	-8.9	4.1	30.8	41.5
Average				73.7	2.5	1.2					
Group 2 52	M	1,087	-6.6	17.9	14.2	12.9	-79	-10.9	2.0	20.3	34.6
55	D	1,422	-4.9	27.8	10.6	9.2	-104	-14.1	0.7	23.6	47.7
56	D	1,455	-5.7	40.6	7.5	6.1	-80	-11.5	0.1	2.6	4.9
60	D	1,104	-7.7	37.5	8.1	6.8	-60	-9.2	0.4	7.5	13.7
61	D	1,184	-8.6	44.6	6.7	5.4	-69	-10.0	0.1	9.2	18.1
62	D,M	1,268	-6.3	21.6	12.7	11.3	-88	-12.2	-	5.4	9.9
63	D	1,031	-4.5	35.7	8.5	7.2	-93	-13.0	0.0	11.9	26.1
Average				32.2	9.8	8.4					

[1] Aquifer units: H, High Plains; D, Dakota; and M, Morrison-Dockum.

of the samples plot along the meteoric water line (Figure 2). The Group 1 samples appear to be less depleted in ^{2}H and ^{18}O than the more variable Group 2 samples. The apparent elevation effect on ^{18}O is -0.5‰ per 100 m of elevation gain for all samples, but the relationship between the variables is very weak and not statistically significant.

Absolute ^{14}C ages were difficult to calculate for the sampled wells using standard correction methods because of the $\delta^{13}C$ range found in young ground water ($^{14}C > 68$pmc). For instance in Table 1, the isotopic composition of dissolved inorganic carbon from sample 53 ($\delta^{13}C = -3.0$‰ and $^{14}C = 81$ pmc) is not a simple mixture of biogenic CO_2 soil gas and aquifer carbonate material. Rather, it indicates that the dissolved inorganic carbon has equilibrated to some extent with the soil atmosphere. The extent of equilibration varies significantly and cannot be predicted from other well data. For the purposes of this work ^{14}C ages were calculated using the simple model of Vogel (1970) which assumes that the initial ^{14}C content of the water was 85 pmc. Because the range of dissolved inorganic carbon concentrations of the Group 1 and 2 samples are similar, the adjusted ^{14}C ages should reflect relative age differences among the samples at the very least. The adjusted ages of the Group 1 and 2 samples are believed to be less than 2,000 yrs and 6,000 to 13,000 yrs, respectively (Table 1). As a crosscheck, the travel times

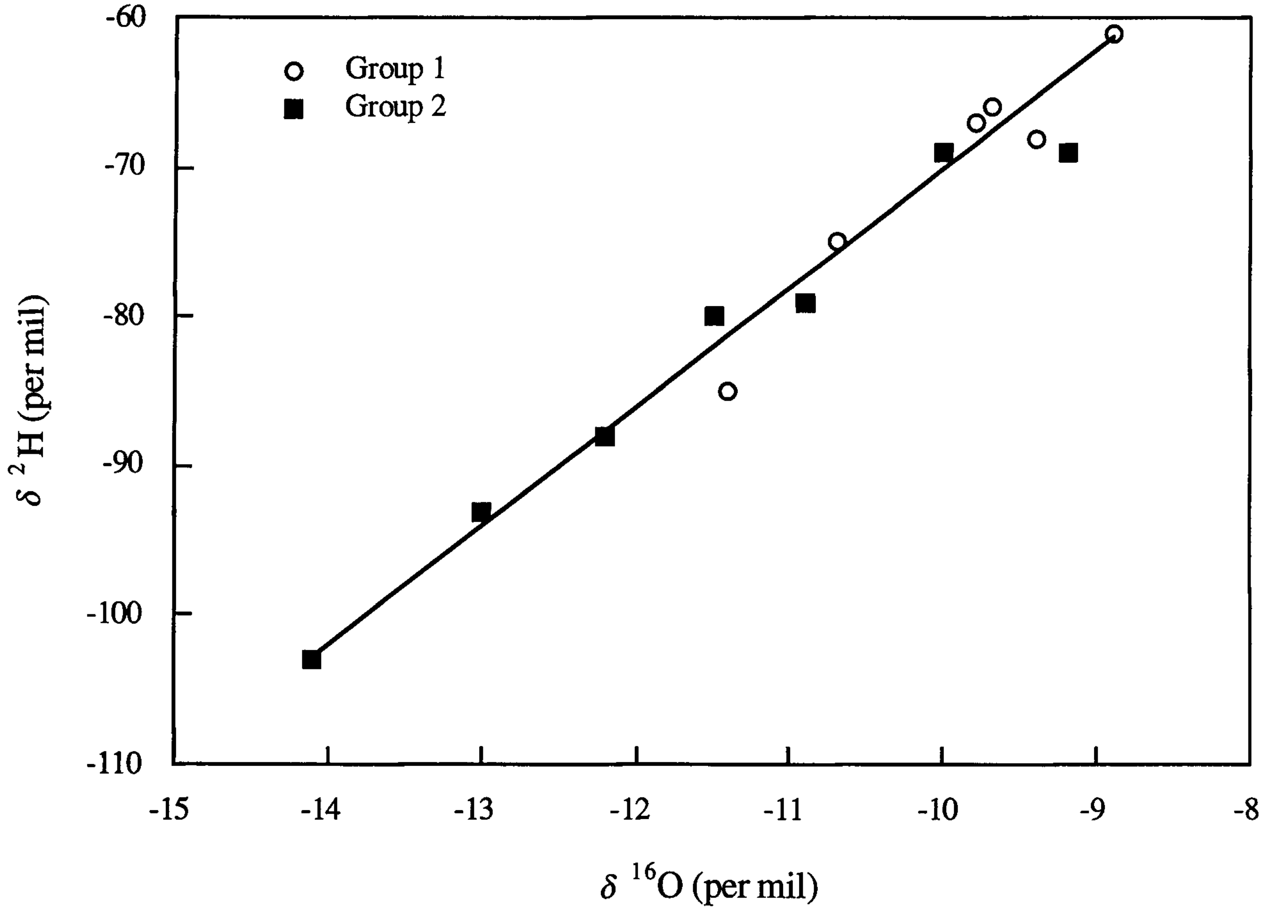


Figure 2. Stable isotope content of the water samples collected from the High Plains, Dakota and Morrison aquifers in southeastern Colorado and western Kansas. All of the samples plot along the meteoric water line (Fontes, 1980) indicating that none of samples have been affected by evaporation.

between local recharge areas and the sampling points were estimated from flow-path analysis using potentiometric surface maps and reasonable estimates of hydraulic conductivity and effective porosity.

The present-day deposition of ^{36}Cl is estimated to be 6.07 x 10^{12} atoms/ha (an assumed atmospheric ^{36}Cl/Cl$^-$ = 700 x 10^{-15} in precipitation) from data in Bentley et al. (1986). Additional contributions of ^{36}Cl from subsurface production and nuclear testing in the 1950s and early 1960s are assumed to be relatively insignificant in the shallow part of the flow system. This assumption is supported by the narrow range of ^{36}Cl/Cl ratios and their low correlation with ^{3}H. ^{36}Cl is radiogenic but with a half life of 301 kyr. In Table 1, the ^{14}C age of the oldest sample is estimated to be less than 13,000 yrs. Thus the maximum estimated loss due to radioactive decay is less than 3% of the input concentration.

The Cl$^-$ and the ^{36}Cl concentrations in the ground-water samples are listed in Table 4. The concentrations of these constituents in the samples and their estimated concentrations in present-day precipitation plot generally along a line that shows the conservative nature of these constituents in shallow ground water (Figure 3). In general, Cl$^-$ and ^{36}Cl are more concentrated in the Group 1 samples than in the Group 2 samples.

The Recharge Rate Calculation

Recharge rates to shallow, unconfined aquifers can be calculated using a conservative tracer, such as Cl$^-$ following the methods outlined in Allison (1988) and Stute et al. (1993). A simple model of Cl$^-$ input to the shallow ground-water system is illustrated in Figure 4. Recharge is assumed to be the net difference between precipitation and evapotranspiration (effective moisture). Within the study area, the topographic relief is low to moderate and the surface soils are predominately sandy to silty in texture which would favor water infiltration over runoff. Therefore, runoff is assumed to be negligible and none of the deposited Cl$^-$ is lost due to runoff. Long term flushing by freshwater recharge from infiltrating precipitation acting over millions of years has removed most of the formation water Cl$^-$ from the more permeable portions of the deeper bedrock aquifer units (Whittemore and Fabryka-Martin, 1992). As a result, the only significant source of Cl$^-$ in the shallow, more active part of the regional flow system is from infiltrated precipitation (Figure 4). It is also assumed that the accumulated Cl$^-$ in the unsaturated zone is approximately at steady state over long periods of time. Cl$^-$ transport through the unsaturated zone to the water table is assumed to be vertically downward primarily by advection. Recharge is assumed to move down under potential gradients to the water table as later infiltrated water moves below the root zone, i.e., the mechanism of "piston flow." With these assumptions

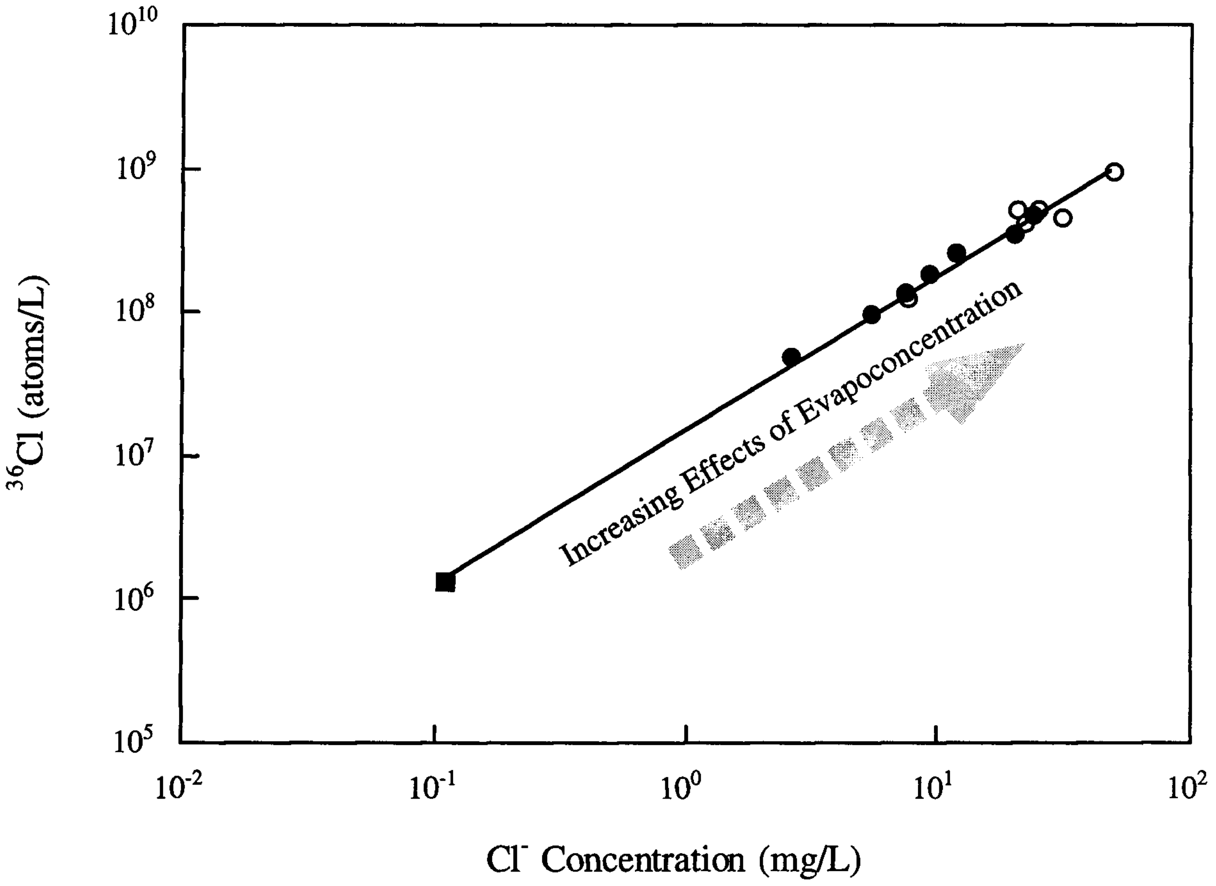
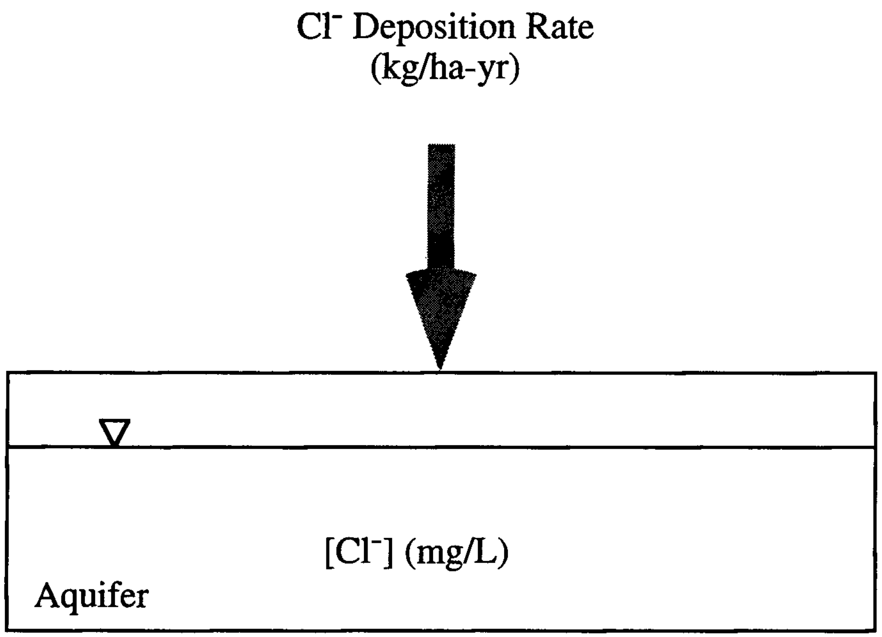


Figure 3. Cl$^-$ and ^{36}Cl concentrations measured in the Group 1 (white circles), Group 2 (black circles), and the average concentrations of these constituents in rainfall assuming an estimated ^{36}Cl/Cl ratio of 700. x 10^{-15}. Measurement errors are less than or equal to the half-width of the symbols used in the plot. The line through the data represents the concentration of these constituents by evaporation to dryness.



$$\text{Ave. Annual Recharge Rate } (L/T) = \frac{\text{Cl}^- \text{ Deposition Rate } (M/L^2T)}{\text{Cl}^- \text{ Concentration } (M/L^3)}$$

Figure 4. Calculation of recharge from the using the Cl^- deposition rate from precipitation and the concentration of Cl^- in the aquifer.

the Cl^- concentration in the aquifer depends only on the deposition rate at the surface and the recharge rate. The recharge rate can then be calculated as:

$$\text{Recharge Rate (L/T)} = \frac{\text{Cl}^- \text{ Deposition Rate (M/L}^2\text{T)}}{\text{Cl}^- \text{ Concentration (M/L}^3\text{) in Ground Water}} \qquad (1)$$

Estimates average annual paleorecharge can be made if the relationship between average annual rainfall and Cl^- deposition is known for the time period of interest. In this paper it is assumed that the modern relationship between the variables has not changed significantly during the late Pleistocene and Holocene.

Modern Annual Cl^- Deposition

Modern annual Cl^- deposition was estimated using data collected from four monitoring sites in the National Atmospheric Deposition Program that surround the study area (Figure 5). All of these sites are located within 160 km of the center of the sampling traverses (Tables 2 and 3). Because of the shortness of the monitoring period, the data were pooled to develop regional relationships between the variables.

It is readily apparent in Figure 6 that both the pooled Cl^- deposition rate and the pooled concentration data are log-normally distributed variables. However, the pooled annual precipitation data appear to fit a normal distribution. The mean annual precipitation for these four stations is approximately 10% higher than the average annual precipitation along the sampling traverse. A plot of annual precipitation *vs.* annual Cl^- deposition demonstrates that the variables are positively correlated but with considerable scatter in the data cloud (Figure 7). A best-fit line through the data is described by the following log-linear equation:

$$\log D_{Cl^-} = -0.624245 + 0.00713902P \text{ ; } R^2 = 0.39 \qquad (2)$$

where D_{Cl^-} is the annual Cl^- deposition (kg/ha) and P is the annual precipitation (cm).

Approximately 39% of the variation in annual Cl^- deposition is accounted for by variations in annual precipitation. However, this is largely an artifact of the data because the annual Cl^- deposition is calculated from measurements of annual precipitation and mean annual Cl^- concentration. Only a small fraction (11%) of the variation in average annual Cl^- concentration measured at each site is explained by variations in annual precipitation (Figure 8). The slightly negative correlation between the variables suggests rainout effects on atmospheric dust and aerosols during wetter periods.

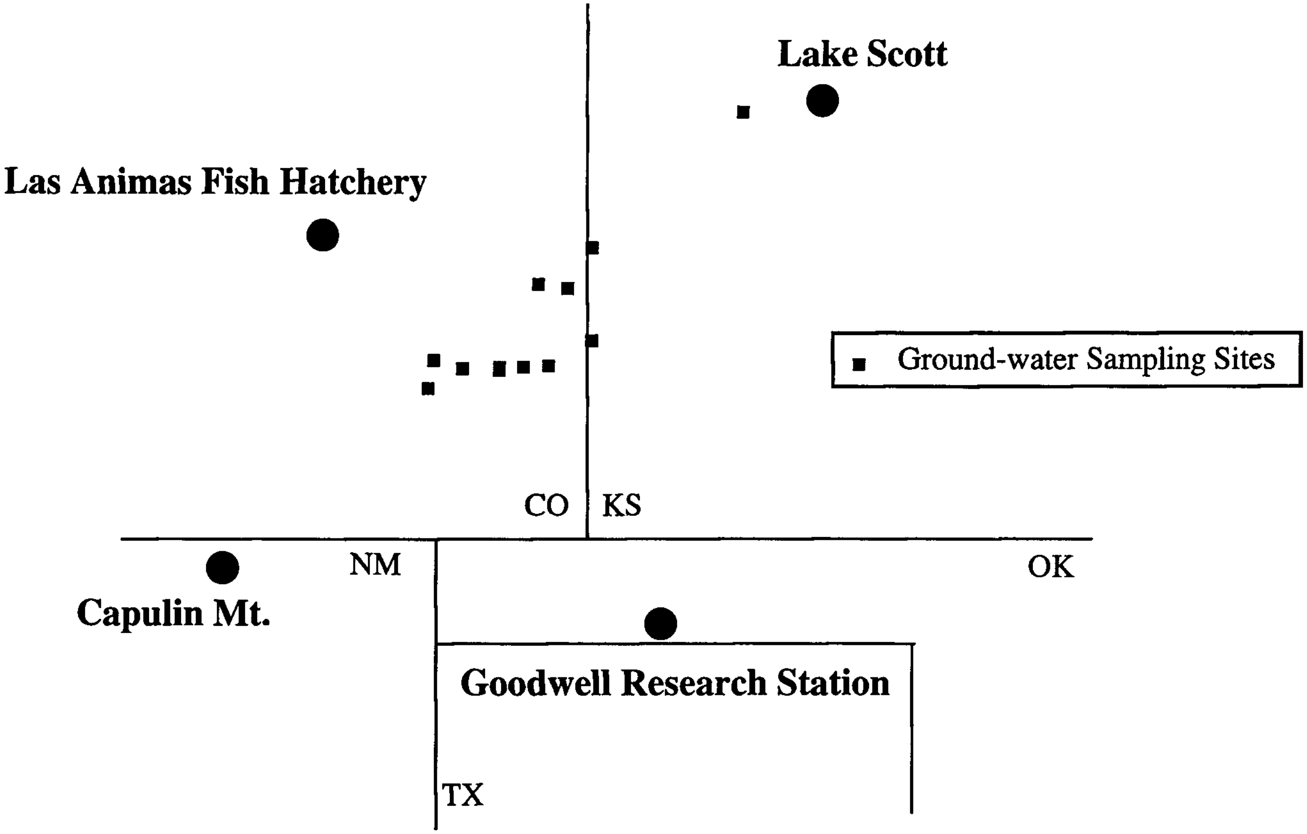


Figure 5. Location of the monitoring site in the National Atmospheric Deposition Program with respect to the location of the wells sampled in this investigation. This map is not to scale, but shows the relative position of the sampling and monitoring points.

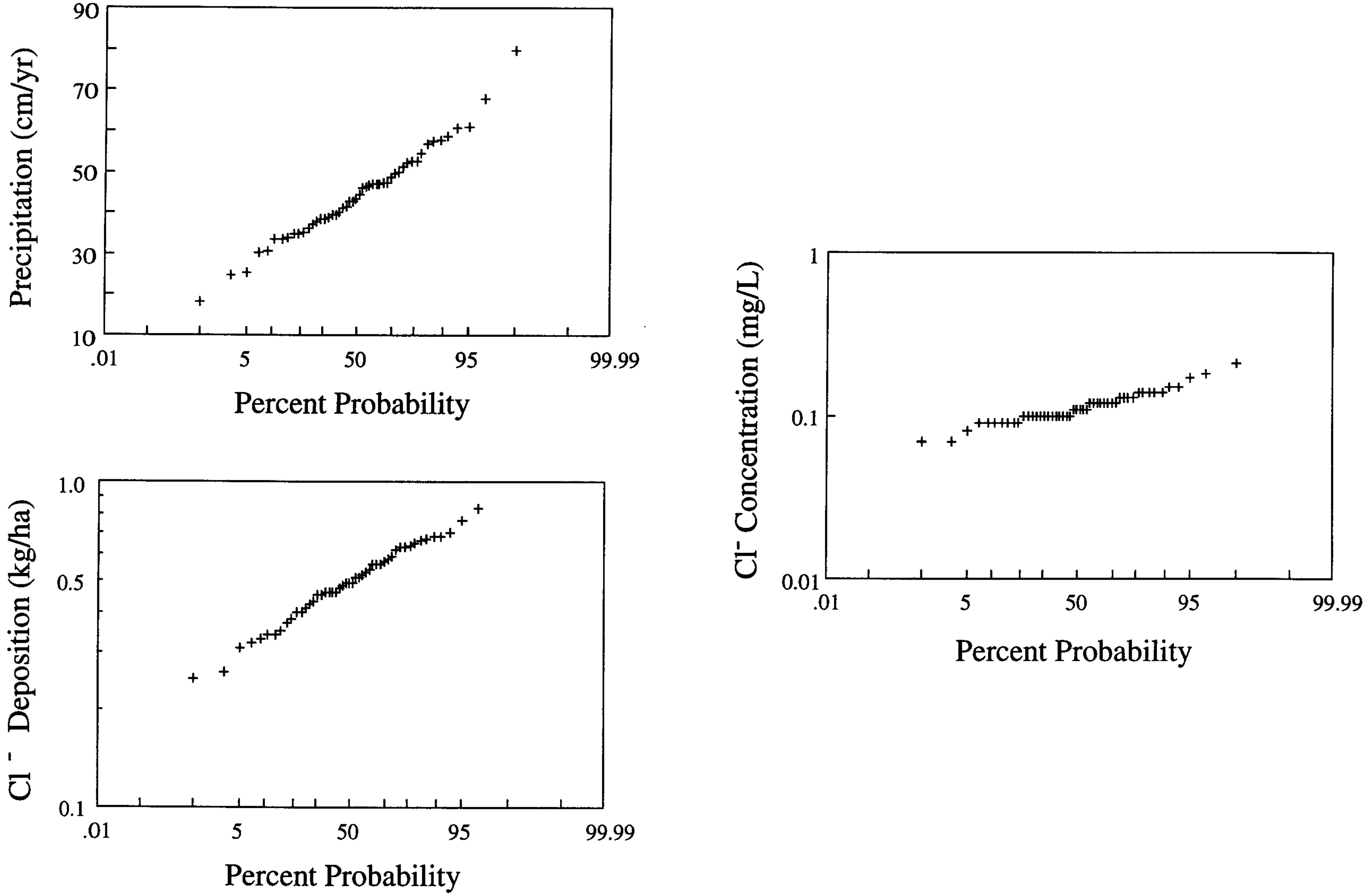


Figure 6. Pooled annual precipitation (A) and Cl^- deposition (B) and concentration (C) data for four monitoring sites in the National Atmospheric Deposition Program.

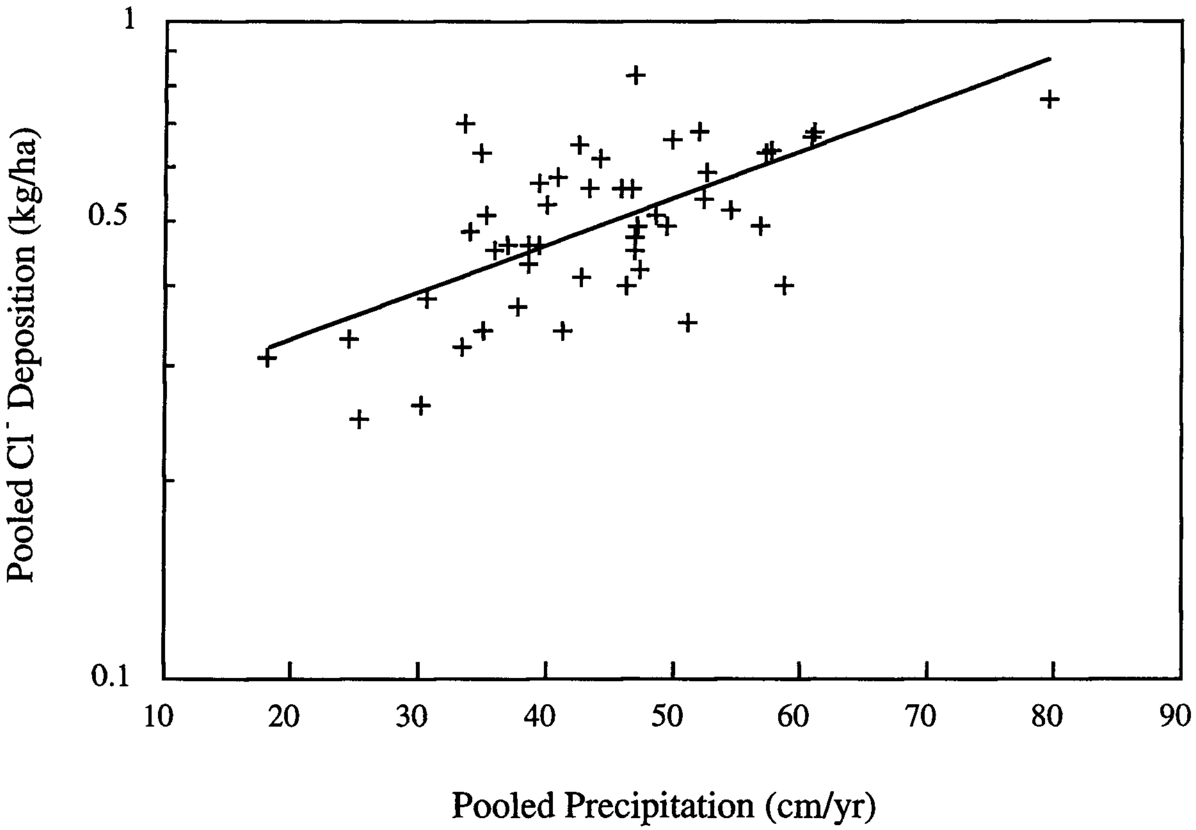


Figure 7. Log-linear plot of pooled precipatation vs. pooled Cl^- deposition for four stations in the National Atmospheric Deposition Program for the years 1984-1996. 39% of the variation in Cl^- deposition is explained by variations in annual precipitation. The equation of the best-fit line from regression is: $\log D_{Cl^-} = -0.624245 + 0.00713902P$.

Table 2. Summary statistics on Cl^- deposition at monitoring sites maintained by the National Atmospheric Deposition Program.

Monitoring Site	Years of Record	Cl^- Deposition (kg/ha)		
		Geometric Mean	Standard Deviation	Standard Error
Las Animas Fish Hatchery, CO	1984 - 1996	0.43	0.13	0.04
Lake Scott, KS	1984 - 1996	0.52	0.14	0.04
Capulin Mt., NM	1985 - 1996	0.52	0.14	0.04
Goodwell Research Research Station, OK	1985 - 1996	0.58	0.17	0.04
Pooled Data		0.51	0.15	0.02

Table 3. Summary statistics on annual precipitation at the monitoring sites maintained by the National Atmospheric Deposition Program.

Monitoring Site	Years of Record	Annual Precipitation (cm)		
		Mean	Standard Deviation	Standard Error
Las Animas Fish Hatchery, CO	1984 - 1996	34.6	7.2	2.0
Lake Scott, KS	1984 - 1996	50.0	12.2	3.4
Capulin Mt., NM	1985 - 1996	48.4	8.8	2.6
Goodwell Research Research Station, OK	1985 - 1996	44.9	10.2	2.9
Pooled Data		44.4	11.3	1.6

Estimates of Past Average Annual Precipitation

Quantitative estimates of long term annual precipitation for the late Pleistocene and Holocene are unavailable from studies of Quaternary deposits. Based on their review of climate proxy data in the literature, Johnson and Park (in press) conclude that the Great Plains was wetter than the present during the late Pleistocene and Holocene until approximately 8,000 yrs ago. From the pollen record preserved in sediments, Fredlund (1995) concluded that a positive water balance existed at Cheyenne Bottoms in central Kansas due to higher rates of infiltration at about 11,000 yrs ago. After 8,000 yrs, the data indicate increasingly warmer and drier conditions, especially during the Altithermal climatic event from 8,000 to 5,000 yrs ago. The paleoclimate

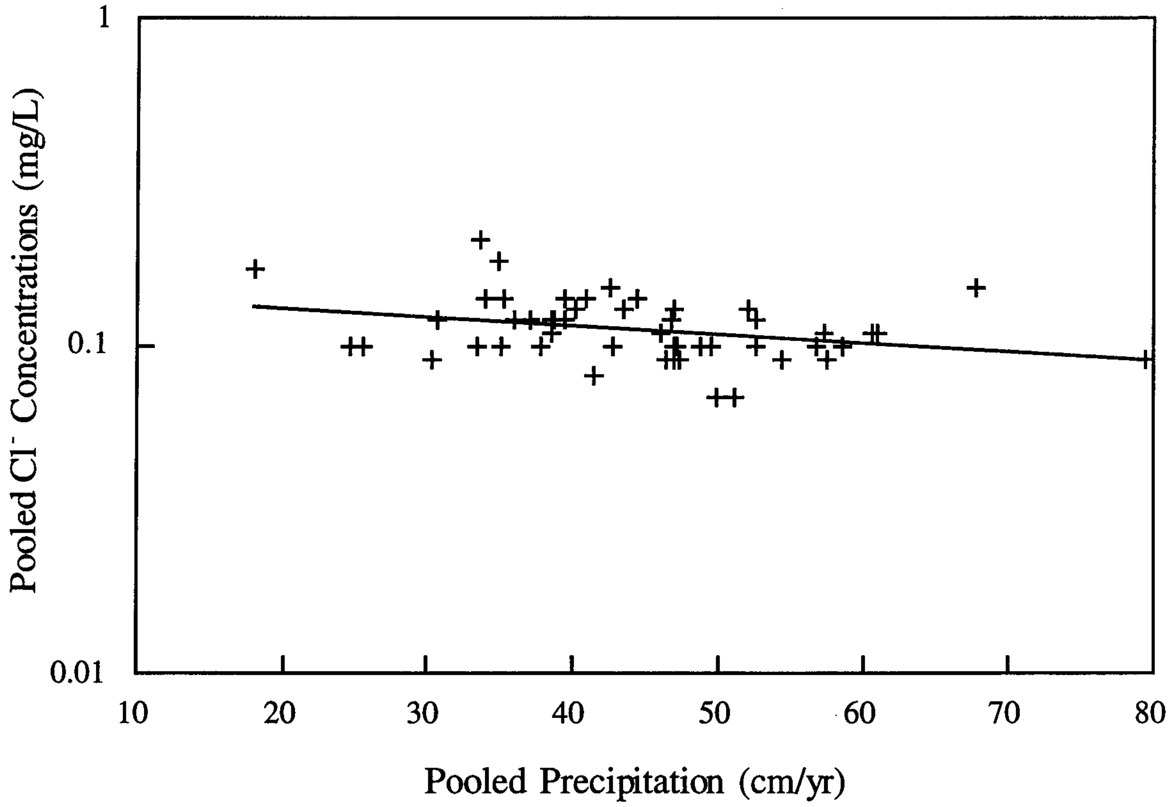


Figure 8. Log-linear plot of pooled precipatation vs. Cl^- concentration for four stations in the National Atmospheric Deposition Program for the years 1984-1996. 11% of the variation in Cl^- concentration is explained by variations in annual precipitation. The equation of the best-fit line from regression is: $Log\ [Cl^-] = -0.0831778 - 0.002681P$

models suggest that annual precipitation during the Altithermal may have been as much as 25% less than present-day values in the region (Kutzbach, 1987). On the basis of preserved fossil pollen suites from Minnesota, Bartlein et al. (1984) suggested a 20% decrease in precipitation during this period. However, these estimated decreases in annual precipitation are for the Great Plains region as a whole and do not take into account subregional effects on annual precipitation, such as the rain shadow effect of the Rocky Mountains on the western Great Plains. It is believed that this overall warming trend continued from 5,000 yrs to the present along with a gradual increase in annual precipitation up to present levels (Holliday, 1985; Fredlund, 1995). Madole (1994) documented frequent periods of severe drought and sand-dune activity to the along the Platte River in northeastern Colorado during this period.

Past average annual Cl^- deposition rates were estimated using Eqn. 2 and the qualitative estimates of annual precipitation for the late Pleistocene and Holocene from the climate proxies (Table 4). It is assumed that the mean annual precipitation (44.4 cm) recorded by the four monitoring network stations (Table 3) is representative of the overall annual precipitation distribution for (1) the last 2,000 yrs and (2) the early Holocene transition from the Younger Dryas to the Altithermal climatic event about 9,000 yrs. ago. Wetter than present-day conditions of the late Pleistocene are assumed to be equivalent to an average annual precipitation that is 1.5 standard deviation units higher than the present mean value (61.4 cm). Drier than present-day conditions of the middle Holocene were assumed to be equivalent to an average annual precipitation that is 1.5 standard deviation units less than the present mean value (27.4 cm).

Table 4. Estimates of average annual precipitation based on qualitative estimates from the literature.

		Estimated Annual Precipitation in the Past	
Event/ Time Period (kyrs, b.p.)	Qualitative Estimates of Average Annual Precipitation	Relative to the Modern Distribution	Estimated Value (cm/yr)
Modern 0 – 2	Present day	mean	44.4
Altithermal climatic event (5 – 8)	Drier than present day	mean - 1.5 stdrd. dev.	27.4
Younger Dryas-Altithermal transition (9.5 – 8)	Present day	mean	44.4
Late Pleistocene (> 10)	Wetter than present day	mean + 1.5 stdrd. dev.	61.4

The assumed annual precipitation that represents the drier conditions of the middle Holocene is 38% less than present day annual precipitation for the region and is lower than the estimated decrease of 25% for the region as whole. This lower estimate may be more consistent with the additional drying associated with the rain shadow cast by the Rocky Mountains on the study area.

Calculation of Soil Temperatures

In order to estimate recharge temperatures, noble gas concentrations need to be corrected for excess air. Previous studies have shown that the noble gas concentration of excess air is frequently the same as the atmosphere (Andrews and Lee, 1979; Stute and Deàk, 1989; Stute et al., 1992, 1995a). When this is the case, recharge temperatures can be calculated using an iterative method described by Stute and Schlosser (1993). Fractionated excess air has been found in other aquifer systems (Stute et al, 1995b; Clark et al., 1997). Of the eleven wells sampled during this study, noble gas recharge temperatures could be calculated for only a few of them assuming that the composition of the excess air component was similar to that of the atmosphere. Poor agreement was found between the calculated soil temperature for each noble gas in the remaining samples indicating that the excess air component was fractionated. In these cases, it was assumed that a portion of the excess air was lost due gas transfer across the water table after formation and recharge temperatures were calculated using the method outlined by Stute et al. (1995b). Noble gas partial pressures were corrected for the differences in elevation of recharge prior to calculating noble gas temperature. The recharge elevations were estimated by examining detailed potentiometric surface maps and likely flow paths from areas of recharge to the sampled wells. A recharge temperature could not be calculated for sample 55 because most of the excess air was lost from the sample due to gas transfer. Samples for noble gas analysis were not collected for from the wells at sites 57 and 61.

Recharge Temperatures and Recharge Rates During the Late Pleistocene and Holocene

It is widely believed that air temperatures generally increased from the late Pleistocene through the Holocene in the Great Plains region (Johnson and Park, in press). This has been deduced from the trend in δ ^{13}C signature of soil carbonates preserved in late Pleistocene and Holocene deposits. The carbon isotopic composition (δ ^{13}C) of soil carbonates depends on the mode of carbon fixation used by plants during photosynthesis (Dienes, 1980). Plants using the C_4 photosynthetic pathway are enriched in ^{13}C compared to plants using the C_3 photosynthetic pathway. C_4 biomass is a function of minimum July temperature (Teeri and Stowe, 1976) and/or moisture conditions (Boutton et al., 1980; Goodfriend and Magaritz, 1988). The more depleted isotopic values of ^{13}C correspond to cooler and/or wetter climate preferred by the C_3 grasses whereas the more enriched isotopic values correspond to warmer climatic conditions preferred by the C4 grasses.

Figure 9A shows the generalized change in the composition of the grasses in the prairie ecosystem through the Holocene according to the carbon isotopic composition of paleosol carbonates preserved at the Sargent site in western Nebraska (Dort, personal communication, 1997) and the Lubbock Lake archaeological site in Texas (Haas et al., 1986). The Sargent and Lubbock Lake sites are located on the High Plains approximately 320 km north and 490 km south of the study area, respectively, and are approximately at the same altitude as the study area. Both data sets contain a shift towards less depleted values of ^{13}C during the period from 5,000 to 8,000 yrs ago. This indicates that C4 grasses increasingly dominated the prairie ecosystem due to the increasingly warmer environment of the Altithermal climatic event.

The calculated recharge temperatures and their corresponding ^{14}C ages are listed in Table 5 and also plotted in Figure 9A. An interpretation of the results sample by sample is probably unwarranted given that recharge temperatures could be calculated for only ten of the

Table 5. Chemical tracer data indicative of recharge and paleoclimate in ground-water samples from southeastern Colorado and western Kansas.

Sample No.	Aquifer Units[1]	^{14}C Age kyr (Vogel, 1970)	Recharge Temperature (°C)	Cl^- Recharge[3] (mm/yr)
Group 1				
53	H,D	0.4	14.5 ± 0.6	2.05 ± 0.27
54	D	1.1	13.3 ± 0.6	2.51 ± 0.32
57	D	1.1	-	6.63 ± 0.67
58	D	1.3	13.1 ± 0.6	1.04 ± 0.13
59	D	1.8	13.1 ± 0.6	2.30 ± 0.30
69	H	1.5	13.1 ± 0.6	1.66 ± 0.21
Average[2]		1.2	13.4 ± 0.6	2.70 ± 2.09
Group 2				
52	M	12.9	10.6 ± 0.6	3.21 ± 0.34
55	D	9.2	-	2.17 ± 0.28
56	D	6.1	8.5 ± 0.6	14.3 ± 2.5
60	D	6.8	11.7 ± 0.6	4.95 ± 0.80
61	D	5.4	-	4.04 ± 0.68
62	D,M	11.3	7.8 ± 0.6	12.1 ± 1.40
63	D	7.2	4.8 ± 0.6	3.16 ± 0.49
Average[2]		8.4	8.7 ± 0.6	6.28 ± 4.48

[1] Aquifer units: H, High Plains; D, Dakota; and M, Morrison-Dockum.

[2] Average of all calculated values - Indicates no data

[3] Calculated values with their associated 95% confidence limits

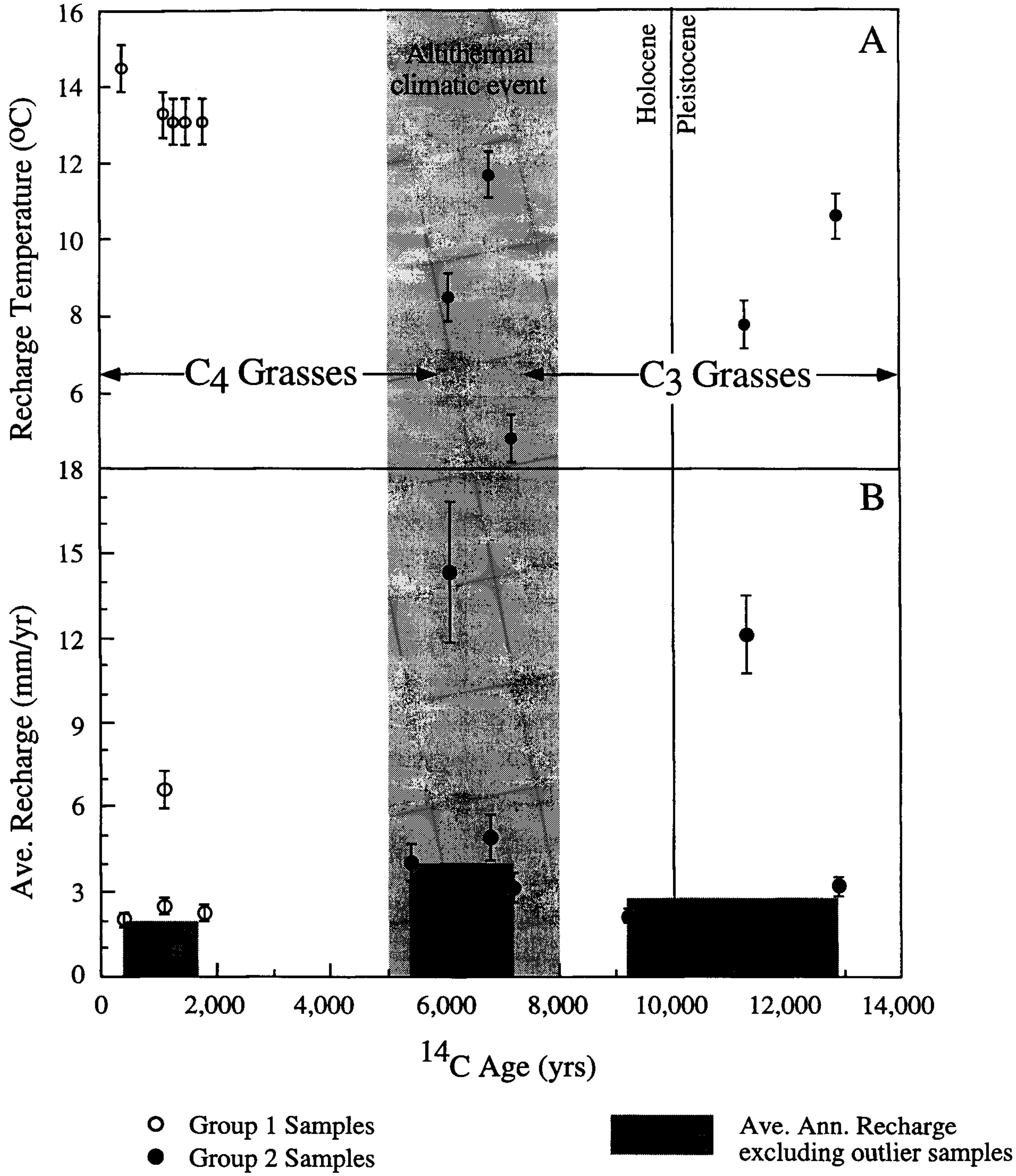


Figure 9. Calculated values of recharge temperature (A) and average annual recharge rates (B) for the thirteen samples in this investigation.

thirteen samples. The recharge temperatures generally reflect the overall trend of increasing air temperature for the late Pleistocene-Holocene climatic transition, including the Altithermal climatic episode. The recharge temperatures of the Group 1 samples are in good agreement with the local present-day mean annual temperature (12.5 °C ± 0.6 °C). Recharge temperatures during the late Pleistocene and the early to mid Holocene (Group 2 samples) were generally 5 °C less than present-day average values for the study area (Table 5).

The calculated average recharge rates show considerable variability through the late Pleistocene and Holocene (Table 5, Figure 9B). As with the recharge temperature results, a detailed discussion of the results is unwarranted given the small number of recharge values and clumped nature of their distribution through time. Disregarding the three highest recharge values calculated from samples 56, 57, and 62, the results indicate an overall trend towards decreasing recharge beginning sometime between 5,400 and 2,000 yrs ago (Figure 9B). The average annual recharge rates are 6.28 mm ± 4.48 mm and 2.70 mm ± 2.09 mm calculated from the samples >5,400 and <2,000 yrs old, respectively. The average annual recharge for the Group 1 samples is very close to the estimated regional maximum potential recharge rate (< 2.54 mm) of Dugan and Peckanpaugh (1985). From steady-state, ground-water flow model results, Macfarlane (1993; 1995) reported average recharge rates of 1.8 mm/yr to the Dakota aquifer from infiltrated precipitation in southeastern Colorado south of the Arkansas River.

A closer examination of the results reveals a paradox involving long term changes in mean annual precipitation and recharge through the middle and late Holocene (<8,000 yrs ago). Disregarding the highest calculated values for each time period, the average annual recharge rates are 1.91 mm ± 0.72 mm and 4.05 mm ± 2.22 mm for the samples that entered the flow system during the last 2,000 yrs and the Altithermal climatic event (8,000-5,000 yrs ago), respectively. Thus, recharge rates for the Altithermal climatic event are approximately twice the average annual rate calculated for the late Holocene (Figure 9B). Curiously, these higher rates of recharge are based conservatively on a mean annual precipitation that is 38% less than the present-day value (Table 4).

This overall reduction in recharge from the end of the Altithermal climatic event to the present seems to follow the 5 °C increase in recharge temperature between 5,400 and the present (Figure 9A). However, the decrease in recharge does not follow the slight lowering of mean summer temperature that is believed to have occurred during this time period. The paleoclimate models suggest the mean summertime temperatures during the Altithermal were as much as 2 °C higher than present day mean values (COHMAP members, 1988). Prolonged periods of drought are believed to have occurred in the southern Great Plains 6,500 yrs and 4,500 yrs ago (Holliday, 1989) and at more frequent intervals in the few thousand yrs (Madole, 1994; Arbogast, 1996).

Presumably, the higher than present day average temperature and the lower average annual precipitation of the Altithermal would have increased evaporation at the expense of recharge producing water-level declines in shallow aquifers (Fredlund, 1995; Mandel, 1994; Holliday, 1989). This would have resulted in an increase in the volume of the unsaturated zone available for storage of accumulated salts and a greater likelihood that the infiltrating water would evaporate before reaching the water table. Consequently, the dissolved solids concentration, including Cl^-, should be as high or higher for recharge that entered the flow system during the Altithermal than for recharge that entered the flow system in the last 2,000 yrs. However, the higher Cl^- and ^{36}Cl concentrations in the Group 1 than in the Group 2 samples suggest otherwise (Figure 3). The concentrations of these constituents are three times higher in the Group 1 samples (<2,000 yrs) than in the samples that entered the flow system during the Altithermal (Table 1). Furthermore, the stable isotope data show that all of the samples have a close affinity to the meteoric water line which indicates that they have not been significantly affected by evaporation (Figure 2).

The Effects of Climate Change on Recharge: A Possible Solution to the Paradox

One possible solution to this paradox is the influence of long term changes in annual precipitation and precipitation intensity on recharge through the mid to late Holocene in the Great Plains. At the beginning of the Altithermal climatic event, Knox (1983) hypothesized a change in seasonal precipitation patterns from frequent, widespread, gentle rains under moist conditions to less frequent, periods of intense storm activity (extreme hydrologic events) under dryer, less vegetated conditions in the Great Plains region. As a result of these high intensity events and lower ground-water levels beneath the dry streambeds (Mandel, 1994), large volumes of water would have move moved periodically through the drainage networks and into the shallow ground-water system as recharge. Mandel (1994) concluded from the distribution of ^{14}C dated deposits that very large volumes of sediment were transported out of the upstream reaches of the drainages in south–central Kansas and deposited downstream as a result of these high intensity storms. During these periods of intense storm activity, the infiltrating water would not have undergone significant evaporation before reaching the water table because of the high volume of precipitation. Thus, the average concentration of Cl^- and ^{36}Cl in the recharge slug would be low, approaching the concentrations of these constituents in rainfall (Table 1 and Figure 6). In between these periods of more intense storms during the Altithermal, infiltration below the root zone would have been very low due to lower annual precipitation and higher than present summer temperatures (COHMAP members, 1988; Holliday, 1989). The Cl^- accumulation rates in the unsaturated zone also would have been low because of low deposition rates associated with lower annual precipitation.

A similar scenario has been reported during the recent warming trend of the last century using recent climate and hydrologic data. Karl (1997) examined the precipitation records from many parts of the globe and found a trend increase in the frequency and intensity of precipitation concomitant with decreases in precipitation from low to moderate intensity events. During the spring and summer of 1993, a wetter than normal period with intense storm activity produced widespread flooding over large areas of the midwest. Sophocleous et al. (1996) documented the effects of this recent extreme hydrologic event on shallow aquifers in the south–central Kansas region. They estimated that the recharge from this extreme event was three to four times the average annual recharge for the region.

Following the Altithermal climatic event, annual precipitation and Cl^- deposition rates increased up to present levels but periods of drought remained frequent (Holliday, 1985; Madole, 1994). In the last few thousand years, extreme hydrologic events have become infrequent with changes in atmospheric circulation and a decrease in the mean summertime temperature (Mandel, 1994). As a result, water levels in the shallow aquifer rebounded but were more unstable due to periodic drought (Fredlund, 1995). Cl^- and ^{36}Cl may have accumulated at higher rates in the unsaturated zone than during the Altithermal due to higher deposition rates. Individual recharge events were volumetrically smaller due to an increase in the frequency of low to moderate intensity events and a decrease in the frequency of extreme events than during the Altithermal. Consequently, the pulses of infiltrating water would be less effective in flushing the salts accumulated in the unsaturated zone during the drier periods, resulting in higher concentrations of Cl^- in the recharge water (Prill, 1977).

Summary

From studies of Quaternary deposits, it is widely known that the late Pleistocene and Holocene in the Great Plains is characterized by an overall climatic transition from cool and moist to warm and dry conditions. However, the effect of this transition on shallow ground-water systems is poorly understood using only the evidence from these studies. Additional quantitative information on temperature and recharge (precipitation - evaporation) is provided using the climate-sensitive chemical tracers found in ground water. To obtain this information, a suite of thirteen water samples were collected from wells in southeastern Colorado and western Kansas. The samples were analyzed for selected major, minor, and trace constituents, the noble gases, and selected stable and radiogenic isotopes.

Recharge temperatures were calculated from the concentrations of noble gases in the samples. These temperatures were generally 5 °C lower in the older Group 2 samples (> 5,400 yrs) than the Group 1 samples (<2,000 yrs). The overall pattern of increasing temperature is consistent with the patterns deduced from $\delta\ ^{13}C$ profiles in late Pleistocene and Holocene deposits.

Recharge rates in the late Quaternary were determined using (1) the Cl^- concentrations in the samples and (2) the data from four monitoring sites in the National Atmospheric Deposition Program to develop a log-linear regression equation between annual precipitation and Cl^- deposition. Estimates of average annual Cl^- deposition were made using the qualitative estimates of annual precipitation deduced from detailed investigations of late Pleistocene and Holocene deposits and paleoclimate models. Paradoxically, average annual recharge rates during the Altithermal climatic event were a factor of two greater than present day, even though average annual precipitation was lower during the last 2,000 yrs. One possible interpretation of the tracer data, and the calculated recharge temperatures and average annual recharge rates is that temporal changes in annual precipitation and intensity coupled with changes in the temperature regime may have played an important role in determining recharge rates. This suggests that intense storms (extreme hydrologic events) were more frequent and played an important part in providing recharge to aquifer systems during the Altithermal. In spite of higher annual precipitation, recharge rates have diminished due to a decrease in the incidence of extreme hydrologic events in the last 2,000 yrs.

Further sampling may provide additional detail on the recharge temperature and recharge record of the last 13,000 yrs.

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