HYDROGEOLOGY AND HYDROCHEMISTRY OF THE OGALLALA AQUIFER, SOUTHERN HIGH PLAINS

by

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Prepared for the
U.S. Department of Energy
Office of Nuclear Waste Isolation
under Contract No. DE-AC97-83WM46651

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1987

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ABSTRACT

The Ogallala aquifer which underlies the Southern High Plains consists of the saturated sediments of the Ogallala Formation (Neogene). The Ogallala aquifer, the main source of water for the High Plains of Texas and New Mexico, has been severely depleted by extensive pumpage. The hydrology and hydrochemistry of the aquifer are controlled by the surface topography of the underlying formations and by the thickness and permeability of formation deposits.

Two different hydrogeologic provinces were observed. Increased formation thickness and saturated section, as well as higher porosities and hydraulic conductivities characterize the first province, which is located along paleo valleys filled with coarse fluvial sediments. These paleo valleys trend from northwest to southeast and ground-water flow lines follow their orientation. Within this province the hydrochemical composition is relatively constant (Ca-HCO_3 to mixed-HCO_3 water, depleted in $\delta^{18}O$, δD and tritium). The formation is thinner and less permeable in the other hydrogeologic province, where sediments are mostly fine-grained eolian clastics. In this province ground-water discharge from aquifers in the Cretaceous. Cross-formational movement of water and low permeability in the Ogallala Formation in these areas result in varying hydrochemical facies and in isotopic composition which differ from this of the first hydrogeologic province. Areas where upward cross formational flow occurs are evident by presence of permeable contacts between the Ogallala and the underlying formations, water level-head differences and chemical and isotopic similarities.

Secondary factors that affect the chemical composition of Ogallala Formation ground water locally include contamination from evaporating saline lakes, agricultural chemicals and fertilizers, and oil field brines. Impact of chemicals and brines may increase in the future, because many of these contaminants may be still moving through the unsaturated zone toward the water table.

INTRODUCTION

The Ogallala aquifer (Tertiary) underlies the Southern High Plains (fig. 1). The Southern High Plains are the southern extension of the Great Plains which extends northward through Oklahoma, Colorado, Kansas, Wyoming, Nebraska, and South Dakota. However, this study is limited to the aquifer area south of the Canadian River (fig. 1). The Ogallala aquifer, which is the main water supply in the Southern High Plains, is being severely depleted by extensive pumpage for irrigation. The aquifer overlies the Permian evaporites that are being considered as a potential repository for the isolation of high-level nuclear wastes in Deaf Smith County, Texas (fig. 1). Potential contamination of the aquifer by these wastes and further depletion of the limited water resources are major concerns in the area.

In the event of accidental spills on the surface or in the subsurface, several problems need to be addressed:

(1) What are the transport rates of a surface spill from land surface to the water table; how long will it take before the contaminants reach the Ogallala water table?

(2) What are the flow directions of the contaminant in the aquifer?

(3) What is the residence time of water (and spills) in the aquifer?

(4) What are the discharge locations where contamination can emerge into the biosphere or leak into another aquifer?

(5) In case of a subsurface spill within the Permian host rocks, what are the possibilities that vertical flow will carry the contaminated fluid from the Permian host rocks into the Ogallala and how long would it take?

To answer these questions one must first characterize the hydrogeology of the Ogallala. In this study we address major hydrogeologic issues, including:

(1) The nature of the geologic contacts between the Ogallala aquifer and the underlying formations,

(2) porosity and permeability distribution in the Ogallala aquifer and in the underlying formations,

(3) relations between the potentiometric surfaces of the Ogallala aquifer and the underlying formations,

(4) recharge methods and rates into the Ogallala aquifer and the overlying formations,

(5) discharge points and rates from the Ogallala aquifer, and

(6) geochemical similarities between ground water in the Ogallala aquifer and in the underlying aquifers and corresponding implications for cross-formational flow.

DATA AND METHODS

Data from available publications or data bases were combined with original data, especially produced or collected for this study. The nature of the contact between the Ogallala aquifer and the underlying formations was mapped in this study to help predict areas where aquifers are hydrologically continuous or where cross-formational flow is likely. Data were taken from well logs (McGowen and others, 1977; Presley, 1981) and type-section descriptions (Brand, 1953).

Water-level data for the Ogallala and the underlying aquifers were obtained from the computerized data base and open-file records of the Texas Natural Resources Information System and Hudson (1976, 1978, 1983). Water-level maps were produced by the author for the aquifers in the Permian and Cretaceous rocks (the Ogallala water-level map is from Gutentag and Weeks [1980] and the water-level map for the aquifer in the Triassic Dockum Group is from Dutton and Simpkins [1985]). Water-level head difference maps were constructed for in the Ogallala and for water in each of the underlying aquifers in the Permian, Triassic and Cretaceous rocks.

Permeability and porosity data for the Ogallala and the underlying aquifers were obtained from Myers (1969) and from Knowles and others (1984).

A total of 3,698 chemical analyses of water in the Ogallala aquifer, plus 187 analyses of water from the aquifer in the Triassic Dockum Group, 84 analyses of water from the aquifers in the Cretaceous Trinity and Edwards formations and 157 analyses of water from the aquifer in the Permian rocks were carefully studied (all data from the computerized data bases of the Texas Natural Resources Information System and U.S. Geological Survey in New Mexico, and Cooper, 1960) (app. 1). Detailed hydrochemical study was conducted wherever cross-formational flow was suggested, based on geologic and hydrologic considerations.

Because isotope data of ground water were available for only the aquifer in the Triassic rocks (Dutton and Simpkins, 1985), 53 ground-water samples from the Ogallala aquifer were collected across the Southern High Plains, in addition to 9 water samples from the aquifers in the Cretaceous Trinity and Edwards rocks and 7 water samples from the Permian formations (fig. 1). Areas where cross-formational flow seemed possible were included in this sampling program. Eleven ground-water samples were also taken from the Quaternary deposits at the Rolling Plains, the potential discharge zone of the Ogallala aquifer. All samples were analyzed for general chemical constituents and for $\delta^{18}O$, δD, tritium, $\delta^{34}S$, and $\delta^{13}C$ (app. 2).

Contamination by oil field brines that may affect Ogallala hydrochemistry was studied using 530 chemical analyses of water samples taken from all major oil-producing formations across the Southern High Plains (app. 3). Data were obtained from Burnitt and others (1963), Reed (1963), Burnitt (1964), McAdoo (1964), and Crouch (1965). A well in Hockley County that injects brine produced from the Permian Clear Fork Formation and three Ogallala wells in its vicinity were also sampled (app. 2).

The study of recharge mechanisms was based on comparison of rainfall and playa-lake water analyses with ground-water analyses. Precipitation was collected on a daily basis at four stations in the Southern High Plains (Amarillo, Clovis, Lubbock, and Midland) and at one station in the Rolling Plains (Paducah), during one year (November 1984 through October 1985). Samples were analyzed for $\delta^{18}O$, δD, and occasionally for tritium (app. 4). Two playa lakes and six wells in their vicinity were sampled in Lubbock County.

The well numbering method used in this study (app. 2) follows the system adopted by the Texas Department of Water Resources (TDWR) (Knowles and others, 1984). When sampling a well with an unknown TDWR number, a temporary name was assigned to it; the name includes the first four digits of the area (according to TDWR), the initials "RN," and another number and letter.

HYDROLOGIC SETTING

Physiography and Climate

The Southern High Plains form a well-defined, topographically isolated plateau that slopes toward the southeast. Soil cover in the northern part of the study area consists mainly of clays and clay loams, whereas in the southern part the soils are sandy loams (fig. 2). The difference in the grain-size distribution of the soil cover may affect the annual recharge rates and will be discussed later in the report. Large parts of the Southern High Plains have scattered depressions called playa-basins. These depressions range from a few feet to 50 ft (1 to 15 m) or more in depth, and from a few hundred feet to a mile (up to 1.5 km) or more in diameter. Runoff following large rains accumulates in these depressions and forms lakes. As a result, large areas of the Southern High Plains have poorly developed drainage systems and all the streams that head on the Rolling Plains are intermittent or have very small perennial flow.

The Southern High Plains have a semiarid to subhumid climate. Annual mean precipitation, (Geohydrology Associates, Inc., 1978, Bomar, 1983), ranges from 13 inches in the southwest to 19 inches in the north (330 to 480 mm). Most precipitation falls between May and October. An isohyet map (fig. 3) shows a greater amount of rainfall in the northeastern part of the Southern High Plains. Annual pan evaporation in the study area ranges from 60 inches to 91 inches (1.5 m to 2.3 m) (Bomar, 1983); New Mexico Engineering Office, 1956). Other estimates (U.S. Geological Survey in Nelson and others, 1983) indicate a range from 80 to 96 inches (2 to 2.5 m). During the summer, potential evaporation may reach 100 inches (2.5 m). Evaporation increases from the northeast to the southwest.

Mean annual low temperature ranges between 44°F in the north to 50°F in the south (6.6 to 9.9°C, respectively). Mean annual high temperature ranges between 71°F (21.5°C) and 77°F (25°C), respectively (Bomar, 1983; Kunkel, 1984). The average difference between summer and winter temperatures is about 29°F (16°C). The prevailing winds are from the southwest and south (summer) in the northern and central parts of the Southern High Plains and from the south or south-southeast (spring and summer) in the southern part (Bomar, 1983).

General Hydrology of the Ogallala Aquifer

The Tertiary Ogallala Formation is composed of terrigenous deposits, such as sands, gravels, and finer materials (Seni, 1980). The aquifer is covered by Quaternary deposits and it unconformably overlies Cretaceous, Triassic, and Permian rocks. Some of these formations may be hydraulically connected to the Ogallala aquifer. Water-table conditions prevail throughout the aquifer. Flow directions approximately follow the regional topographic slope from the northwest to the southeast. Local ground-water depressions, which have been formed by intensive pumpage, can lead to local changes in flow direction. A typical rate of water movement is approximately 7 inches (18 cm) per day (Knowles and others, 1984). The aquifer is recharged by direct precipitation and by resulting runoff that mainly accumulates in playa lakes as well as in riverbeds. Flow from the underlying formations can be another source for recharge in certain areas. Pumpage of water from the aquifer far exceeds annual recharge. As a result, there is a substantial decrease in ground-water levels in the heavily pumped areas. However, in other locations a rise in water table was observed and can perhaps be related to percolation of surplus water from irrigation into the shallow ground water in these areas (Kier and others, 1984). Because of the water-level decline, many springs along the eastern escarpment have ceased flowing (Brune, 1981). Most of the current discharge from the aquifer is by water pumpage.

GEOLOGIC FRAMEWORK

The base of the Tertiary Ogallala Formation rests unconformably on Permian, Triassic, and Cretaceous strata (fig. 4). Quaternary sediments cover the Ogallala rocks in most parts of the Panhandle. In this section the geologic features of the Tertiary Ogallala Formation, the overlying Quaternary deposits, and of the underlying formations that are related to the hydrology of the Ogallala aquifer are described.

Quaternary Strata

Quaternary eolian, fluvial, and lacustrine sediments cover large areas of the Tertiary Ogallala Formation. The Blackwater Draw Formation, the most widespread unit, ranges in age from at least 1,400,000 yr to late Holocene (Machenberg and others, 1985). It covers the Ogallala with loess deposits to a depth of 80 ft (25 m). Alluvium, which consists of sands, silts, and occasionally gravels, occurs along riverbeds, and silt and clay materials line the bottom of most playa lakes. Quaternary deposits control the amount of recharge into the Ogallala aquifer. Their diverse lithology is the factor that affects their distribution of vertical permeabilities, and thereby the downward water flux into the Ogallala.

The Tertiary Ogallala Formation

The Tertiary Ogallala Formation contains both coarse fluvial conglomerate and sandstone, and fine-grained eolian siltstone and clay. Seni (1980) suggested that the depositional environment of the Ogallala Formation and the overlying Quaternary deposits produced a series of overlapping humid-type alluvial fans. Seni (1980) identified three lobes whose grain size vary as a function of the distance from the major channel system. Along the major channel axes, grain size expected to be coarser than in the interfan areas. However, Gustavson and Winkler (in preparation) suggest that grain size of the Ogallala Formation clastics is controlled by the topography of the underlying mid-Tertiary erosional surface. They indicate that coarse fluvial clastics were deposited in paleo-valleys, whereas finer eolian sediments covered upland areas. Eolian clastics also overlie the fluvial sediments in the paleo valleys as sand sheets and loess. The change from fluvial to eolian sedimentation probably resulted from diversion of Ogallala streams to form the Pecos and Canadian Rivers (Gustavson and Winkler, in preparation).

Figure 5 presents the thickness of the Ogallala Formation, including the overlying Quaternary deposits. Their combined thickness reaches 800 ft (250 m) and reflects the underlying paleo topography. This paleo surface is controlled by collapses of Permian rocks induced by evaporite dissolution, and by pre Ogallala erosion.

Wind and stream erosion have cut into the Ogallala Formation and eroded its deposits. Consequently, Cretaceous rocks are exposed in some saline lakes in the southern part of the Southern High Plains, and Triassic and Permian rocks crop out along the Canadian and Red Rivers. Generally, the Ogallala and the overlying Quaternary deposits are thicker in the northern part of the Southern High Plains (0 to 800 ft or 250 m) compared to the southern part (0 to 500 ft or 150 m).

As a result of this depositional pattern, fluvial sediments along the major paleo valleys are coarser, whereas materials in between these areas are finer (fig. 6). In addition, a general upward-fining texture trend occurs in the Ogallala Formation. These textural trends may have a significant effect on the spatial distribution of porosity and permeability in the Ogallala aquifer.

A resistant calcrete layer called the caprock caliche lies at or near the surface of the Ogallala Formation. Caliche develops as an authigenic accumulation of calcium carbonate that results from soil-forming processes, precipitation from ground water, or some combination of both (Stone, 1985). In the northern part of the Southern High Plains several layers of caliche are encountered, whereas in the southern part their number and thickness decrease. Caliche is commonly regarded as a barrier to recharge because its permeability is considered very low (Knowles and others, 1984). However, Wood and Osterkamp (1984) and Weeks (1978) suggest that caliche can be dissolved and consequently become permeable. Calcium carbonate and silica-cemented sandstone was also observed at the base of the Ogallala in places (Gustavson and Holliday, 1985).

Cretaceous Strata

Three separate subcrops of southeast-dipping Cretaceous strata underlie the southern part of the Ogallala Formation (fig. 4). These isolated remnants represent a larger area that was formerly covered by Cretaceous rocks, the original extent of which is not known (Brand, 1953). The rocks were deposited in an epineritic and littoral environment of stable shelf seas whose subsidence was slow (Brand, 1953). The rocks were classified into three groups (for detailed description refer to Brand, 1953) from base to top:

(1) The Trinity Group consists of the sandy, permeable Paluxy/Antlers Formation.

(2) The Fredericksburg Group includes several limy to shaly formations, of which only the Edwards Limestone is considered an aquifer.

(3) The Washita Group consists of the shaly Duck Creek Formation, which has relatively low permeability.

Following the Laramide Revolution and the withdrawal of the Cretaceous sea, parts of the deposited material were removed by early and middle Tertiary erosion. Because erosion truncated various formations at different locations, there are places where the top of the permeable Edwards Limestone or the Paluxy Sandstone form the contact with the

Ogallala aquifer. In these locations, a continuous permeable sequence may exist from the Ogallala into the cretaceous beds (fig. 4). In other places only a thin, shaly layer separates these permeable Cretaceous formations from the Ogallala.

Triassic Strata

The Triassic Dockum Group underlies large areas of the Ogallala aquifer in the study area (fig. 4). The sediments accumulated in a variety of depositional systems, including braided and meandering streams, alluvial fan deltas, lacustrine deltas, lacustrine systems, and mud flats, which are all of continental origin (McGowen and others, 1977). The terrigenous clastics were mainly derived from older sedimentary rocks that accumulated in Texas, Oklahoma, and New Mexico. The maximum preserved thickness of Triassic rocks (2,000 ft or 610 m) occurs in the Midland Basin. The lower lithologic cycle of the Triassic, often referred to as the Santa Rosa Formation or Lower Dockum, is characterized by a sandy lower segment that becomes increasingly muddy upward. The upper lithologic cycle exhibits similar overall upward fining in the northwestern part of the study area. However, upward fining is not typical of this cycle farther south in the northwestern Midland Basin. In this area, sand from an eastern source was deposited throughout the preserved part of the upper Triassic cycle (McGowen and others, 1977).

The Permian-Triassic contact has been studied using well logs (McGowen and others, 1977; Presley, 1981). In some locations within the study area, such as Deaf Smith and Carson Counties, Texas, and Roosevelt County, New Mexico (figs. 7 and 8), the lithologies on both sides of the contact are permeable (sandstone packages in ????? Triassic and limestone at ??? Permian) and could permit flow from one to another.

The Triassic Dockum Group is overlain in some areas of the Southern High Plains by Cretaceous sediments, the original extent of which is not known because of partial erosion before Ogallala deposition. Study of the Triassic-Cretaceous contact using well logs (McGowen and others, 1977) and type-section descriptions (Brand, 1953) suggests that these formations are permeable on both sides of the contact (sandstone in ???? cretaceous overlying sand packages of top triassic) in Lynn, Martin, and Ector Counties, Texas (fig. 9). Observations are limited to a relatively small number of outcrops where the base of the Cretaceous is exposed. It is assumed, therefore, that permeable contact between Triassic and Cretaceous rocks can also be found elsewhere.

Study of the Ogallala-Triassic contact based on well logs (McGowen and others, 1977) indicates sand packages in upper Dockum Group overlain by basal sandstone and conglomerate of the Ogallala, forming a permeable sequences in both formations in parts of Potter, Swisher, Castro, Crosby, Dickens, Martin, Andrews, and Garza Counties, Texas and Roosevelt County, New Mexico (fig. 4).

Permian Strata

Permian rocks underlie the entire Panhandle and are composed of a wide range of marine to terrestrial sediments. Thick, salt-bearing zones representing evaporitic phases are being considered as possible host rocks for nuclear waste isolation at Deaf Smith County, Texas. For a detailed description of the Permian formations refer to Handford (1980a, 1980b), Handford and Dutton (1980), and Presley (1981).

Within the study area, the Ogallala Formation contacts Permian rocks (mainly Whitehorse Group and Blaine Formation) in a relatively limited area along the northeastern Texas Panhandle in parts of Carson, Gray, Wheeler, Armstrong, and Donley Counties (fig. 4). The thickness of the Permian formations that overlie the San Andres/Blaine dolomites and anhydrites ranges from 350 to 500 ft (107 to 152 m) (Presley, 1979). They mainly include mudstones and siltstones that accumulated in a mud-(salt?)-flat environment (Presley, 1981).

The Ogallala-Permian contact is characterized by closed, contoured collapse basins that were formed by solution of Permian evaporites. These basins were later filled with thick Ogallala deposits (Dutton and others, 1979; Gustavson and others, 1980; Seni, 1980).

Study of the Ogallala-Permian contact based on well logs (Presley, 1981) indicates that the upper layers of the Permian consist of mudstones, anhydrites, or salt with relatively low permeabilities. Therefore, permeable pathways at that contact between the Ogallala and the Permian rocks on a regional basis are limited (fig. 4). Locally, however, breccia pipes could provide conduits to ground water leakage.

HYDROGEOLOGY

In this section the hydraulic features of the Ogallala and the underlying aquifers are discussed. Distribution of porosity and hydraulic conductivity that affect flow rates and residence time of water in the Ogallala aquifer are presented. Recharge sources into the Ogallala and points of discharge from the aquifer are outlined and their relative importance discussed. Both issues are crucial for the study of the flow paths of potential spills. Water levels in the Ogallala aquifer and the underlying aquifers are discussed for the purpose of assessing potential for vertical flow between them. The relations between the saturated and unsaturated thickness of the Ogallala in various locations are outlined as a major factor that controls the vertical movement of various contaminants from the surface to the water table.

Distribution of Porosity and Hydraulic Conductivity

Specific yield and hydraulic conductivity maps were published by Knowles and others (1984) in their regional study of the Ogallala aquifer. These maps are based on lithologic descriptions taken from drillers' logs, and the calculated specific yield and hydraulic conductivity are based on previous studies which correlated porosity and permeability with various lithologies (Johnson, 1967; Morris and Johnson, 1967). Patterns of high specific yield follow areas of high sand and gravel percentages (fig. 6) along major axes of sedimentation (fig. 10).

Cores retrieved from 41 test holes that were analyzed for their specific yield and hydraulic conductivity (Knowles and others, 1984) provide a cross-check for the hydraulic conductivity and specific yield maps. In addition, hydraulic conductivity values calculated from pumping tests (Myers, 1969) performed in 19 wells in six counties in Texas can be used for the same purpose. They range from 70 to 1,680 gal/d/ft^2 (3 to 70 m/d) with an arithmetic mean value of 420 gal/d/ft^2 (17 m/d). Core-specific yields range between 7.2 and 19.5 percent with an overall average of 16.1 percent, and core hydraulic conductivities range from 22 to 1,930 gal/d/ft^2 (1 to 80 m/d) with an overall average of 230 gal/d/ft^2 (9 m/d).

The core results, when overlaid on the specific yield map (fig. 10), confirm the suggested pattern of the map: High core-specific yield values (greater than 18 percent) fall along the main fluvial valleys and the suggested contour of 20 percent specific yield. Low core-specific yield values (7 to 10 percent) are found next to 12 percent or less contours in the finer sediments. The specific yield map, therefore, correlates well with specific yield values from cores.

The hydraulic conductivity map (fig. 11) does not correlate very well with either the isopach or the percent of sand and gravel maps (figs. 5 and 6). Although the central and southern fluvial valleys can be recognized by relatively high hydraulic conductivity (1,000 to 1,500 gal/d/ft^2 or 40 to 60 m/d), the northern coarse-grained area is not clearly differentiated by higher conductivity. Also, large discrepancies exist between the measured core or pumping test values and the map (fig. 11). Generally, the map provides higher values than the direct measurements. It is of interest to note that the higher values of these measurements are also arranged along the main fluvial valleys. However, they are much more scattered and less consistent compared to the porosity map. No clear relationship was observed between hydraulic conductivity and depth, even though sediments are coarser toward the base of the aquifer (Knowles and others, 1984).

Few hydraulic conductivity data are available for the underlying aquifers. Eight well tests in the aquifer in the Triassic rocks in Deaf Smith and Swisher Counties, Texas indicate aquifer conductivity values from 33 to 280 gal/d/ft^2 (1.3 to 11.5 m/d) (Dutton and Simpkins, 1985). Eight pumping tests are also available for the aquifers in the Cretaceous rocks; all of the tests were made in Midland County, Texas in Trinity Sandstone. Aquifer conductivity at the test sites ranges from 120 to 510 gal/d/ft^2 (4.7 to 21 m/d) and the thickness of the aquifer there is about 70 to 90 ft (21 to 27 m) (Myers, 1969). No pumping tests are available for the aquifer in the Permian rocks in the area where it underlies the Ogallala.

Potentiometric Surface

Ground water in the Ogallala aquifer occurs under water-table conditions. Potentiometric surface of the Ogallala aquifer varies from 5,000 to 2,400 ft (1,524 to 730 m) above sea level from west to east across the Southern High Plains (fig. 12) reflecting the regional gradient. The gradient of the water-level surface ranges from 5 to 50 ft/mi (1 to 9 m/km) with a mean value of 15 ft/mi (3 m/km). The average rate of water movement is approximately 7 inches/d (18 cm/d) (Knowles and others, 1984). However, considering the ranges of hydraulic gradients (5-50 ft/mile or 1 to 9 m/km), hydraulic conductivities (22 to 1934 gal/d/ft^2 or 1 to 80 m/d) reported by Knowles and others (1984), and porosities (8–49%) reported by Ashworth (1980) ground water velocity may vary between 0.4 to 60 inches/d (1.0 to 150 cm/d). Calculation followed the equation

$$v = \frac{k}{n} \frac{dh}{dl}$$

where:

v = ground water velocity

k = hydraulic conductivity

n = porosity

$\frac{dh}{dl}$ = hydraulic gradient

Water-level altitudes reflect the regional topographic gradient. A linear regression (fig. 13) based on 470 old measurements of water levels in 20 counties (taken prior to the heavy pumpage which started during 1940's show a very strong correlation (r=.99) with topography. Since the 1940's, heavy pumpage from the aquifer has caused severe water table decline in large areas (figs. 13 and 14). Declines have mainly occurred in the northern parts of the study area, whereas in the south water levels have risen in places. Possible reasons for this will be discussed later in this section.

Potentiometric surfaces of ground water in the aquifers in the Permian (fig. 15), Triassic (Dutton and Simpkins, 1985), and Cretaceous (fig. 15) rocks have a similar eastern to southeastern gradient but lie at different altitudes. To study the potential of recharge or discharge from these aquifers into the Ogallala aquifer, a water-level difference map showing head differences between the Ogallala aquifer and each of the underlying aquifers was prepared (fig. 16).

The altitude of the water table in the Ogallala Formation is higher than the potentiometric surface of the aquifer in the Triassic rocks, except in a large area in Roosevelt and Curry Counties, New Mexico, where the potentiometric surface of the Dockum Group is higher than or similar to the Ogallala water table (fig. 16). Along the escarpment areas, potentiometric surfaces of aquifers in the Dockum Group and in Permian formations also are higher than water levels in the Ogallala aquifer. On the other hand, the potentiometric surface of the aquifers in the Trinity and Edwards beds is equal to or higher than the Ogallala water table in large areas (fig. 16). As a result, ground water may flow from the Ogallala aquifer into the Dockum aquifer in the northern part of the

Southern High Plains and from the aquifers in the Dockum and Cretaceous rocks into the Ogallala aquifer in the western and southern parts, respectively, wherever permeable contacts are available (fig. 4). Chemical evidence of cross-formational flow will be discussed in the section on geochemistry.

Recharge

Recharge into the Ogallala aquifer can take place through direct infiltration into the outcrops, through the Quaternary deposits that overlie it in large areas, and through local intake areas such as playa lakes or riverbeds. Because annual precipitation is relatively small and most of the rain falls between May and October when evapotranspiration is at its peak, only a small amount of water is available for recharge.

Direct recharge into the Ogallala has been studied extensively. Barnes (1949) assumed that recharge is reduced in areas where soil cover has finer grain size in the northern Texas Panhandle (fig. 2). Caliche that forms the upper surface of the Ogallala is regarded as a severe barrier to recharge because its permeability is considered to be very low (Broadhurst, 1942; Ries, 1981; Knowles and others, 1984). Indeed, deep percolation of water in 19 of 22 sites that were studied across the Texas Panhandle using neutron log measurements did not exceed 20 to 30 ft (6 to 9 m) (Klemt, 1981). In another study, Wood and Osterkamp (1984) did not observe a moisture increase below a depth of 6 ft (2 m) over a more than 2-yr period that included significant rain events. Because caliche was observed to be currently forming in their study area, it was suggested that evaporation from the soil is greater than recharge.

Recharge probably takes place along riverbeds, because flowing rivers at the western and central section of the Southern High Plains are nearly dry by the time they reach the Rolling Plains. But the poorly developed drainage system of these rivers indicates that the annual recharge from riverbeds is insignificant.

Recharge from playa lakes is a controversial issue. The large number of playa lakes, 20,000 to 30,000 (Ward and Huddlestone, 1979), or one lake per 510 to 3,160 acres (2 to 13 km^2) (Dvoracek and Black, 1973), has attracted the attention of everyone that has studied the hydrology of the Southern High Plains. The large surface areas that are being drained into the playa lakes are estimated to total 30,000 mi^2 (78,000 km^2) (Ward and Huddlestone, 1979), or up to 89 percent of the entire Southern High Plains (Dvoracek and Black, 1973). The annual amount of water that is accumulated in the playa lakes is estimated to be 2 to 3 million acre-ft (2.5 to 3.7 x 10^9 m^3) (Templer, 1978 in U.S. Bureau of Reclamation, 1982). It was noted (Lotspeich and others, 1971; Dvoracek and Black, 1973) that areas with finer soil cover in the northern part of the Southern High Plains (fig. 2) have larger but fewer lakes compared with the southern part, which has soils with coarser grain-size distribution.

The two major mechanisms that control water loss from playa lakes are evaporation and infiltration. Clay-rich soils in the bottom of the playa lakes may be impervious, at least shortly after they are filled with water (Harris and others, 1972; Knowles and others, 1984). The caliche below the lake beds is considered to be a second impermeable barrier (Knowles and others, 1984). If the soils and caliche have low permeability, significant recharge is prevented and most of the water must eventually evaporate. Various estimates for evaporation from the lakes in the Southern High Plains range from 55 percent to 60 percent of the available water (Reddell, 1965; Ward and Huddlestone, 1979; U.S. Bureau of Reclamation, 1982).

Other studies have suggested that the playa lakes are actually a major source of recharge into the Ogallala aquifer (Texas Department of Water Resources, 1980; Kier and others, 1984; Stone, 1984; Wood and Osterkamp, 1984). In 1937 and 1938 several hundred test holes were drilled in the beds of many playa lakes (White and others, 1946). Under almost every playa some caliche was encountered, but in many cases the caliche included sand and was relatively permeable. Shrinkage cracks in the playa-floor clays, in conjunction with solution channels that were commonly observed in the underlying caliche, seem to provide passageways for downward movement of water. Lotspeich and others (1971) also suggested that the caliche under playa lakes was partially dissolved, permitting leakage. Wood and Osterkamp (1984) pointed to the area of more permeable soil that immediately surrounds the basin floor as the main recharge zone in the playa. Lack of evaporites among the playa-floor materials (Harris and others, 1972) and lack of hallophytic flora also suggest that these basins are being well flushed, rather than accumulating salts as a result of evaporation. Low water salinities in playa lakes (Wells and others, 1970; Felthy and others, 1972; Lehman, 1972) also support this assumption. Stone (1984) and Wood and Osterkamp (1984) observed significantly lower dissolved solutes in soil samples below the playas compared with other areas. Presence of tritium in some ground-water samples in Lea County, New Mexico at the end of the 1950's also suggests rapid recharge mechanisms, such as can take place by focused recharge below playa lakes, rather than by regional, slow, diffuse percolation (Wood and Osterkamp, 1984).

Owing to these conflicting hypothesis concerning the role of the playas, a wide range of recharge rates have been estimated (0.01–1 inch/yr):

Table 1. Estimates of annual recharge into the Ogallala aquifer, Southern High Plains

	Recharge from playa lakes	Recharge from diffused percolation	Recharge from sand dunes
Stone, 1984	0.11 inches (0.28 cm)	0.01 inches (0.025 cm)	0.05 inches (0.13 cm)
Wood and Osterkamp, 1984	1.60 inches (4.1 cm)	~0.00 inches	
U.S. Bureau of Reclamation, 1982	1.00 inches (2.54 cm)		
Klemt, 1981		0.2 inches (0.51 cm)	
Knowles and others, 1984		0.058–0.571 inches (0.15–1.45 cm)	0.833 inches
Barnes, 1949	0.10 inches (0.25 cm)		

The working hypothesis in this study was that if a diffuse percolation over the region dominates recharge, and water in playa lakes evaporates rather than infiltrates, then playa-lake water should become enriched in δD and $\delta^{18}O$ with regard to precipitation (Craig and Gordon, 1965; Zimmermann, 1979) Groundwater, recharged mainly by diffuse percolation, would be enriched with regard to precipitation, because precipitation becomes enriched in heavy isotopes in the vadose zone as a result of evaporation (Zimmermann and others, 1967). On the other hand, if rapid recharge from playa lakes occurs, the isotope composition of playa-lake water should remain constant and similar to precipitation and ground-water values. In order to determine recharge methods and thereby recharge rates, playa-lake and ground waters were collected (fig. 1, app. 2) and rainfall was sampled on a daily basis in five stations across the Southern High Plains during one year (fig. 1).

Of 251 precipitation samples that were collected at the fice stations during the study period, 216 daily samples were analyzed for $\delta^{18}O$ and δD, and 33 daily samples were measured for tritium. Isotopic data of daily samples are presented in appendix 4. Analyses of daily samples were weighted by the amount of precipitation which they represent to determine a weighted mean value for each event, month, and year, respectively, at each station. The calculation of weighted mean isotopic value for an event followed the equation

(1) $$\delta^{o}/oo \text{ weighted by event precipitation} = \frac{\sum_{i=1}^{n} \delta^{o}/oo_i \times P_i}{P}$$

where

δ^{o}/oo_i = δ^{o}/oo or δD value ($^{o}/oo$) of the precipitation sample for the i-day.

P_i = Precipitation amount during the i-day.

P = Precipitation amount recorded during the event.

n = No. of days in the precipitation event.

Monthly measured weighted mean values were calculated based on equation (1) but

$\delta ^{o}/oo_{i}$ = The weighted $\delta^{18}O$ or δD value ($^{o}/oo$) of precipitation for the i-event.

P_i = Precipitation amount during the i-event.

P Total amount of sampled and analyzed precipitation during the month.

Thirty five samples (mainly from Summer 1985) were not analyzed for δD and δD and $\delta^{18}O$ because of budgetary reasons. Instead, one or two precipitation events were analyzed for each month during the Summer of 1985. A few of the monitored precipitation events were not sampled because of human failure. In order to adjust the mean annual values and compensate for the Summer events which were not fully analyzed, we calculated monthly mean isotopic values for each station by weighting the isotopic composition measured in analyzed samples (representing only part of the monthly precipitation) by the actual monthly precipitation amount. These reconstructed monthly data were then used to estimate annual weighted mean values for $\delta^{18}O$ and δD for each station. Calculation followed equation (1) but

$\delta ^{o}/oo_{i}$ = Measured weighted mean of $\delta^{18}O$ or δD ($^{o}/oo$) for the i-month.

P_i = Amount of precipitation recorded (but not always fully analyzed) during the i-month at the station.

P = Total annual precipitation recorded at the station.

Values of $\delta^{18}O$ and δD form the local meteoric water line (fig. 17a) and range from −22.7 to +4.7$^{o}/oo$ for $\delta^{18}O$ and from −162 to +14$^{o}/oo$ for δD. Figure 17b indicates that both playa-lake water and ground water in the Southern High Plains scatter along this line and become concentrated on the heavy side. However, it was found (Nativ and Riggio, in preparation) that precipitation samples that fall within the range of playa-lake and ground-water samples form 60% of the total precipitation sampled. Only 21% of the sampled precipitation has lighter isotopic composition than playa-lake and ground water. This observation and the absence of any shift of playa-lake and ground water from the meteoric line indicate that evaporation of rainwater in playa lakes prior to infiltration is limited.

Tritium activity of rainwater ranged from 1.1 to 14.7 TU, having a weighted mean of 8.04 TU (app. 4; Nativ and Riggio, in preparation). Tritium activity in Ogallala ground water ranged from 0.0 to 73 TU (app. 2). High activities in ground water were observed in the southern part of the Southern High Plains in Hockley, Lamb, Lubbock and Terry Counties, Texas (fig. 20), where the unsaturated zone of the aquifer is relatively thin, indicating that the aquifer may be rapidly recharged by focused sources such as water that accumulates in playa lakes. Tritium activities in ground water in the rest of the area were essentially zero, apparently because of the thicker unsaturated zone.

Ground water with maximum tritium activity--73 TU--is most likely derived from 1966/67 rainfall, based on the tritium decay curve for tritium activities measured in Waco, Texas, and Albuquerque, New Mexico. Using the time period of 19 to 20 yr (1966/67 to 1986), and taking into account a short vertical path of 25 ft (7 m) in the unsaturated section that can represent a large area in the high-tritium zone, the annual flux can be calculated (app. 5). The recharge rate into the vadose zone ranges from 0.5 inches to 3.24 inches/yr (1.3 to 8 cm/yr), depending on the moisture content of the soil profile. It should be noted that this is a simplified model that assumes a piston flow and complete displacement of water present in the vadose and saturated zones by the recharging water, and therefore provides a minimum estimate for the water age and maximum estimate for annual recharge rate.

Calculated diffusive recharge rates for this area were slower than this rate (0.058 to 0.571 inches/yr; Barnes, 1949; Klemt, 1981; Knowles and others, 1984) whereas calculated recharge rates from playa lakes coincide with the lower values within this range (0.11 to 1.6 inches/yr; U.S. Bureau of Reclamation, 1982; Stone, 1984; Wood and Osterkamp, 1984).

Based on the high calculated recharge rates using tritium as a tracer and the slightly enriched values of $\delta^{18}O$ and δD in ground water, we assume the most likely method for ground water recharge is focused percolation of partly evaporated playa lake water. Quantitative determination of focused versus diffusive recharge and the evaluation of potential isotopic enrichment of ground water in the vadose zone instead of in playa lakes requires more information about surface water and water in the unsaturated zone.

An additional source of recharge into the Ogallala is upward discharge of water from the underlying formations. This concept has never been recognized on a general basis. The Cretaceous aquifer has generally been regarded hydraulically as part of the Ogallala aquifer because of its small outcrop areas and thus its lack of independent recharge sources (Knowles and others, 1984; W. Wood, written communication, 1986). However, in the western parts of the Southern High Plains (Roosevelt and Lea Counties, New Mexico, fig. 18) the potentiometric surface of the Dockum aquifer is higher than or similar to the potentiometric surface of the Cretaceous aquifer and may recharge the Cretaceous aquifer. Also in Roosevelt and Lea Counties, New Mexico, Quaternary dunes and thick alluvial sediments in the Portales Valley directly overlie the Cretaceous rocks, providing them with independent recharge sources that are not associated with the Ogallala aquifer (Nativ and Gutierrez, in preparation). Based on these observations, we assume that wherever hydraulic connection between the Cretaceous and the Ogallala is lithologically possible (fig. 4) and potentiometric surface of the Cretaceous aquifer is higher than water levels in the Ogallala aquifer (fig. 18), recharge from the Cretaceous aquifer is possible.

Fink (1963) and Dutton and Simpkins (1985) state that in the Southern High Plains area, the Dockum Group does not have any independent recharge sources except the Ogallala aquifer. According to these studies, precipitation falling on the outcrop areas of the Triassic west of the Southern High Plains moves toward the Pecos River or toward the Canadian River but does not percolate into the subsurface below the Southern High Plains. However, the western part of the Southern High Plains is also the area where water in the Dockum aquifer has higher potentiometric surface than water levels in both the Ogallala and Cretaceous aquifers (Roosevelt and Curry Counties, New Mexico, and parts of Parmer and Deaf Smith Counties, Texas, fig. 18). In this area, wherever hydraulic connection is lithologically possible (fig. 4), we assume that the Dockum aquifer may recharge both aquifers.

Discharge

Discharge from the Ogallala aquifer occurs through natural outlets such as seeps and springs or leakage to the underlying formations; pumpage, however, is by far the most significant discharge component. Springs once flowed in many locations across the Southern High Plains and along its escarpments. Many of them ceased flowing during the last 40 yr because of increasing pumpage for irrigation. Brune (1981) and Knowles and others (1984) assumed that recharge and spring flow in the Ogallala Formation were in equilibrium before pumpage began. However, the Southern High Plains has been uplifted and tilted and has undergone climatic changes during the Holocene that could still affect the rate of ground-water flow in the Ogallala aquifer. Therefore the assumption that annual recharge controlled the amount of spring flow before the aquifer was extensively developed may be incorrect.

Today, springs are mainly located along the escarpments (fig. 21) and their annual discharge ranges from 1.6 to 730 acre-ft/yr (0.002 to 0.9 million m^3/yr) (calculated from reported measurements taken from 1977 through 1979 by Brune, 1981). Calculated total discharge volume of the springs does not exceed 3250 acre-ft/yr (4 million m^3/yr).

Discharge of Ogallala ground water along the Caprock Escarpment into the adjacent formations at lower elevations in the Rolling Plains is still possible, even though most of the springs ceased flowing or have decreased yields. In order to evaluate the potential of subsurface lateral discharge from the Ogallala aquifer into the Rolling Plains, we sampled ground water in the Rolling Plains from wells that were completed in Quaternary alluvium deposits (fig. 1, app. 2). Some of these deposits are adjacent to the Caprock Escarpment and therefore may be recharged by the Ogallala aquifer, and others are farther away and have other recharge sources, but all of them overlie Permian rocks. Ground water in the isolated deposits typically has Ca-SO_4 hydrochemical facies and $\delta^{34}S$ values that range from +9.7 to +10.3^{o}/oo, indicating recharge from water in the underlying Permian rocks. Varying amounts of tritium indicate modern recharge from rainfall and runoff in addition to the contribution from ground water in the Permian beds (samples 83-89, app. 2). Ground water in alluvial deposits where recharge from the Ogallala seems possible has water facies similar to water in the Ogallala; lower $\delta^{34}S$ values than typically observed in ground water in Permian beds, but higher tritium values than usually found in water in the Ogallala in the area (samples 90-93, app. 2). We assume that because of the thin unsaturated section of these deposits, high-tritium rain and runoff water can reach the water table faster than in the adjacent Ogallala Formation and thus provide a source of recharge in addition to the contribution from the Ogallala aquifer.

Pumpage from the Ogallala aquifer started in 1911 and increased drastically after World War II. Water volumes currently being withdrawn from the aquifer are far beyond the annual recharge from precipitation. Rough calculations comparing annual pumpage in 1974 (Wyatt and others, 1976a-g, 1977; Bell and Morrison, 1977a,b, 1978a-f, 1979a,b, 1980a-d, 1981, 1982a-c) with annual recharge (based on Knowles and others, 1984) indicate (fig. 22) that while recharge estimates range from 0.058 to 0.833 inches/yr (0.15 to 2.1 cm/yr), annual pumpage ranged at 1974 from 0.5 to 6.55 inches/yr (1.3 to 16.6 cm/yr) (when dividing the annual pumpage by the area in each county). In 14 out of 26 counties where these calculations were made, annual pumpage volume is at least 10 times that of annual recharge.

Ogallala ground water may also discharge into underlying formations. A hydraulic connection appears to exist locally between the Ogallala Formation and the Dockum Group. Except in the western parts of the Southern High Plains, water levels in the Ogallala are generally higher than they are in the Dockum aquifer (fig. 18). Leakage from the Ogallala into the Dockum aquifer may occur where there are sandstones in the upper Dockum

Group. Discharge from the Ogallala into the Cretaceous aquifer is possible where permeable beds occur at the top of the Cretaceous (fig. 4) and water level in the Ogallala aquifer is higher than the potentiometric surface of the Cretaceous aquifer (fig. 18).

Unsaturated and Saturated Zones

Thickness of the unsaturated zone above the Ogallala water level ranges from 460 ft (140 m) to 0 ft (fig. 23). Large areas, mainly in the southern part of the study area have water levels that are closer than 100 ft (30 m) to the land surface. These counties include Bailey, Borden, Dawson, Gaines, Lynn, Ector, Midland, Andrews, Martin, Howard, Texas and Lea, New Mexico, and some parts of Hockley, Lamb, Lubbock, and Yoakum, Texas in the south. Donley, Hemphill, Randall, and Wheeler, Texas are the northern counties that also have shallow depth to water. In some of these counties, the thin unsaturated zone may permit contamination of ground water by agricultural chemicals (reflected in high nitrate and arsenic concentrations in ground water) and will be discussed later in the report. Where water levels are extremely shallow, direct evaporation may take place and ground water consequently becomes saline.

The above-mentioned observations may explain why water levels have declined in the north, whereas they have risen or have not changed in the south. The southern part has a higher rate of annual recharge and a smaller ratio of annual pumpage to annual recharge (0.93 to 3.15) than in the north (0.35 to 6.55) (fig. 22). Also, a much thinner unsaturated zone in the southern part of the study area enables faster recharge from irrigation-water surpluses to the water table. Possible upward discharge of water from the Cretaceous in the south also could contribute to the difference in water-level fluctuation patterns in the two areas.

Saturated thickness (fig. 24) of the Ogallala aquifer ranges between 0 and 300 ft (90 m) and is highly controlled by the topography of the pre-Ogallala surface. Along the major troughs and flow channels that carried the Ogallala clastics, the saturated thickness ranges from 100 to 300 ft (30 to 90 m), whereas in the interchannel areas it ranges from less than 20 to 100 ft (<6 to 30 m). Saturated thickness of the aquifer decreased considerably as a result of increasing pumpage. Comparison of water-level data from 1980 and 1960 (by 1960, water levels were already depleted) shows that areas that once had a thick saturated section (200 to 300 ft [60 to 90 m]) decreased from 11% to only 2% of the total area of the Ogallala (fig. 25). On the other hand, areas that had a very thin saturated thickness (0 to 20 ft [6 m]) increased from 11% to 15% during the same time. Fifty percent of the area had less than 80 ft (25 m) of saturated thickness in 1960, whereas in 1980, 50% of the area had only a saturated thickness of less than 60 ft (18 m). These changes in saturated thickness could affect the water quality of the Ogallala aquifer. Because it is possible that the aquifer is connected to the underlying Cretaceous or Triassic aquifers, which have inferior water quality compared to the Ogallala, decrease in the saturated thickness may enable a faster upward flow of low-quality water into the Ogallala in areas where the potentiometric surface of the underlying aquifers is higher than that of the Ogallala aquifer. This issue will be discussed further in the following section.

HYDROCHEMISTRY

The study of the chemistry of the water in the Ogallala aquifer is important for the purpose of tracing cross-formational flow into or out of the Ogallala aquifer. In this section the chemistry of water in the Ogallala is outlined and major factors that may affect it are discussed. Based on this information, the possibility of vertical flow into the Ogallala aquifer from the underlying aquifers is considered.

The chemical and isotopic composition of ground water in the Ogallala aquifer is controlled by the composition of its recharge components (rainfall and leakage from the underlying formations or from various waste disposal pits or wells), as well as by geologic and hydrologic variations within the aquifer (lithology, porosity, and thickness of the saturated and unsaturated zones). The effects of variations in aquifer parameters on the water chemistry are discussed. Isotopic composition of rainfall was compared with that of ground water in the Ogallala. The chemical and isotopic composition of the water in the underlying aquifers, as well as of oil field brines, were examined, and possible contributions to Ogallala water chemistry are discussed.

Chemical and Isotopic Composition of Ground Water in the Ogallala Aquifer

Spatial distribution of total dissolved solids (TDS) in water of the Ogallala is presented in figure 26 (from Knowles and others, 1984). A major feature of Ogallala water composition is the sharp increase of TDS from below 400 mg/l in the northern part of the Southern High Plains to 3,000 mg/l in the southern part.

A chemical facies map of water in the Ogallala aquifer was produced (fig. 27) based on 3,698 complete chemical analyses taken from the computerized data bases of the Texas Department of Water Resources and U.S. Geological Survey in New Mexico and Cooper (1960). Hydrochemical facies are named after the ions that make up more than 50% of the total concentration (meq/L) (Piper, 1944; Back, 1966). A mixed-cation and mixed-anion facies refers to water that does not have any prevailing cation or anion.

Based on the chemical facies map it can be concluded that in the northern part of the southern High Plains, where water is fresher (TDS <400 mg/l), water is of Ca-HCO_3 type in the northeast (zones 4 and 6, fig. 27), and of mixed cations-HCO_3 type in the rest of the area (zone 7, fig. 27). The Piper diagram (fig. 29) demonstrates that the mixed-HCO_3 facies is derived from the increasing amount of Mg and a relative decrease in Ca in the ground water, thus forming a Ca-Mg-HCO_3 type of water.

The southern part of the Southern High Plains (underlain mainly by Cretaceous rocks and where TDS >400 mg/l) has a greater variety of water types, most commonly a mixed-cation - mixed-anion facies (zone 14, fig. 27). Based on a Piper diagram for this area (fig. 28) it appears that this facies is a Ca-Mg-Na-HCO_3-Cl type, because the amount of

Na and Cl is higher. Locally, areas of Na-mixed-anion or Mg-mixed-anion hydrochemical facies (zones 17 and 19, fig. 27) are also present.

Along the escarpment various hydrochemical facies are encountered. They include Na-HCO_3 facies in Deaf Smith, Parmer, and Dickens Counties, Texas and Curry and Quay Counties, New Mexico (zones 8 and 15); Ca-SO_4 or mixed-cation-SO_4 facies in Donley and Wheeler Counties, Texas (zone 3), and Na-Cl and mixed-cation-Cl facies in Garza and Howard Counties, Texas (zones 16 and 18). Na-SO_4 and mixed-cation-SO_4 facies also found away from the escarpment (zones 10, 12, and 13) in some places in the southern part of the Southern High Plains.

The major hydrochemical facies (zones 4, 7, 14, and 19) are aligned from northwest to southeast following depositional systems and inferred ground water flow lines. In the area adjacent to the Canadian River the trend of hydrochemical facies seems to follow the local flow pattern from southwest to northeast (zones 1 and 4).

Mean values were calculated for various ions in ground water in the northern and southern parts of the study area (app. 1). In the northern part Ca > Mg > Na and HCO_3 > SO_4 > Cl (in meq/L). In the south Mg > Na > Ca and HCO_3 = Cl > SO_4. Salinity diagrams based on these mean values for both parts of the study area (fig. 29) reflect this pattern. The Na/Cl ratio (app. 1) in the northern part of the Southern High Plains is higher than in the south (1.62 and 1.04, respectively) and may reflect a Na source other than halite (ion exchange?). Other differences in ion ratios between the northern and southern parts of the study area (app. 1) are derived from the relative increase of Mg and Cl in the south compared to the north.

$\delta^{18}O$, δD, tritium, $\delta^{13}C$ and $\delta^{34}S$ were measured in 53 ground water samples from the Ogallala across the Southern High Plains during 1985 (figs. 20, 30, 31, app. 2). Mean $\delta^{18}O$ (−6.96 ‰) and δD (−51 ‰) values in the northern part of the Southern High Plains are more depleted than $\delta^{18}O$ and δD in the south (−5.9‰ and −40‰, respectively) (figs. 19b, 27, and 30). "Heavier" values are encountered along the eastern escarpment, although no consistent enrichment from west to east can be observed (fig. 30). Tritium values range from 0 to 73 tritium units (TU). Generally, tritium activity is very low, except for a specific area in the Southern High Plains (figs. 20 and 27 [zone 14]). $\delta^{34}S$ ranges from −12.7 to +9.5 $^{o}/oo$ with relatively high values observed in the northeastern and the southernmost parts of the study area (fig. 31). Negative or near zero values are observed in the area that stretches northwest to southeast from Oldham County to Floyd County, Texas.

Lithologic and Structural Effects

Three major alluvial fan systems in the Panhandle have higher percentages of sand and gravel (fig. 7). In these areas the aquifer is thickest, most permeable and most porous (figs. 5, 12, 13, and 24). Ground-water flow lines controlled by southeastward dipping and land surface topography coincidently follow the trend of major deposition axes (fig. 14). Water chemistry and isotope values also are constant within these major flow elements. Ground water in the alluvial fans has mainly mixed-cation-HCO_3 and Ca-HCO_3 facies and relatively depleted $\delta^{18}O$ and δD values. The water in the southern (zone 19) and northern (zones 1 and 4) alluvial fans also has higher $\delta^{34}S$ values than the central fan (zone 7) (fig. 27).

Between these major flow areas (zone 14), the percentage of sand and gravel is smaller, permeabilities are lower, and the aquifer is thinner. Hydrochemical facies vary and consist of mixed-cation − mixed-anion, Na-mixed-anion, Mg-mixed-anion, and even mixed-cation-SO_4, mixed-cation-Cl, Na-SO_4, Na-Cl, and Ca-SO_4 facies. $\delta^{18}O$ and δD values are enriched relative to water in major fan axes.

Correlation of hydrochemical facies with saturated thickness in 412 Ogallala wells (fig. 32) supports the assumption that wherever the Ogallala is relatively thick, hydrochemical facies are mainly Ca-HCO_3 and mixed-cation-HCO_3 types. Other hydrochemical facies are limited to areas where saturated thickness is less than 90 ft (0 to 30 m).

Constant chemical facies and isotopic composition within the major alluvial fans result from ground-water flow along preferential pathways, which is controlled by the larger grain size of the fans and thus their higher permeabilities. The thick saturated section within the fan area helps mask other recharge sources that may affect the chemical and isotopic composition of ground water flowing there. Consequently, chemical and isotopic composition of ground water flowing along these areas does not vary. On the other hand, in the interfan areas, sediments have smaller grain size, resulting in lower permeabilities. Residence time of ground water in these areas is probably longer, and rock/cement - ground-water interactions are more intensive, resulting in higher salinities. Ground water in the thin saturated zone cannot mask salt contribution from the adjacent formation or from surface and subsurface contamination. Therefore, chemical and isotopic composition of ground water in the interfan areas is more heterogeneous, representing local flow conditions that are highly variable.

Effects of Water-Level Altitudes

Aquifers with shallow water table are more susceptible to surface contamination or salinization because the unsaturated section is thin. Agricultural chemicals such as nitrate and arsenic can quickly travel the short distance to the water table. To determine if there is a link between contamination and depth to ground water, the thickness of the unsaturated zone was checked in wells where water analyses indicate very high concentrations of nitrate (>90 ppm) and potassium (>40 ppm). Of 3,698 chemical analyses of Ogallala ground water, 11 samples had high concentrations of contamination. Of the 11 samples, 10 are from wells that have a very shallow water table (<60 ft [<20 m] from ground surface) and 5 are from wells that have a water table less than 30 ft (<7 m) from ground surface. Leakage from the surface may cause the unusually high concentrations.

Arsenic is another potential hazard. In many areas in the Southern High Plains, calcium-arsenate and arsenic acid have been used since 1925 as a cotton defoliator and insecticide. Locally in the southern part of the Southern High Plains, arsenic concentrations approach or are higher than the limits permitted for potable water (0.05 mg/L) (fig. 33). In Howard and Martin Counties, Texas, cattle are reported to have died as a result of this hazardous contamination (C. Rogers, Texas Department of Agriculture, Austin, Texas, personal communication, 1985). High concentrations of arsenic in Ogallala ground water are found where water levels are generally less than 40 ft (<12 m) below land surface. Arsenic can be adsorbed by clay in the unsaturated zones, but large arsenic applications in areas with shallow water tables apparently exceed the adsorption capacity and contaminate ground water.

Extremely shallow water levels (< 5 ft [<1.5 m]) allow direct evaporation from ground water through capillary fringes in the thin vadose zone. Saline lakes in the southern part of the Southern High Plains are possible products of ground-water evaporation in the Ogallala aquifer. Of 22 saline lakes studied by Reeves (1970), 18 are located where water levels range from 5 to 50 ft (1.5 to 15 m) below land surface. Lake waters and ground water near the lakes are characterized by an unusual Na-SO_4 and Na-Cl hydrochemical facies (calculated from Reeves' [1970] data). This is true in Mound Lake (wells 23-42-601, 24-56-403, 24-64-101), Bull Lake (well 24-06-201), Cedar Lake (wells 27-20-801, 24-16-401, 27-22-602, 24-16-701), Shaffer Lake (wells 27-38-201, 27-52, 201, 27-53-402), and Gooch Lake (wells 28-01-801, 28-01-902). For case studies where Ogallala ground water was affected by these lakes, see figure 34a. A few isotope analyses from springs in Gooch Lake in Lynn County, Texas, and from springs and wells at Rich and Mound Lakes in Terry County, Texas (W. Wood, U.S. Geological Survey, Reston, VA, unpublished data) show enriched values and for some, a shift from the meteoric line, which may indicate evaporation (fig. 19b).

Effects of Natural Recharge from Precipitation

Rainwater sampled in the northern and western parts of the study area (Amarillo and Clovis Stations, figs. 1, 19a) had generally lighter isotopic composition than rainwater in other parts of the study area (Lubbock, Midland and Paducah Stations, figs. 1, 19a). Annual mean values (weighted by precipitation amount) calculated for these stations were -8.9, -7.3, -6.3, -8.8 and -6.2‰ for $\delta^{18}O$ and -54, -48, -39, -62 and -37‰ for δD, in Amarillo, Lubbock, Midland, Clovis and Paducah, respectively (Nativ and Riggio, in preparation). The higher altitude of the northern and western stations, the lower mean temperature and evaporation in their area and their greater distance of the contributing air masses from the main source of moisture--the Gulf of Mexico--may account for the difference in isotopic composition.

Ground water in the northwestern part of the study area also has lighter isotope composition (-9.1 to -7.1‰ for $\delta^{18}O$, fig. 30) than ground water in the rest of the area (-6.7 to -4.2‰). Ground-water samples in the areas that are heavier than the annual means of local rainfall may represent some degree of evaporation of rainwater in playa lakes or the vadose zone prior to recharge or may result from other recharge sources, such as partly evaporated water from irrigation surpluses.

Effects of Underlying Aquifers

A brief chemical characterization of waters in the aquifers below the Ogallala aquifer is needed to detect possible interaction effects. Previous sections have indicated cross flows of ground water between the Ogallala aquifer and the Triassic and Cretaceous aquifers. These relationships have been based on prescreening of permeable contacts between these aquifers as well as on comparisons of their potentiometric surfaces. A third approach to identify leakage between formations is through water chemistry.

The Cretaceous Aquifer

Mean values (calculated from 87 water analyses from the Cretaceous aquifers) for major ions are given in appendix 1 and show that Na > Ca > Mg and Cl > HCO_3 > SO_4. Piper diagrams (fig. 28) reflect these patterns. Water salinity is not much higher than in Ogallala water in the southern High Plains. $\delta^{18}O$ and δD values range from −7.2 to −4.9°/oo for $\delta^{18}O$ and from −45 to −30°/oo for δD (based on seven Cretaceous wells sampled during 1985, app. 2). Heavier values exist along the eastern escarpment and more depleted values are found to the west (fig. 19b, app. 2). Tritium values are surprisingly high and range from 14.7 to 68.2 TU (app. 2), which indicates a recent recharge (post-1954). $\delta^{34}S$ ranges from +2.7 to −7.6 with no observed spatial pattern.

In the southern part of the study area some chemical and isotopic similarities exist between ground water in the Ogallala and underlying Cretaceous aquifers. It was previously suggested that ground water in the Cretaceous moves upward into the Ogallala aquifer (based on permeable contacts between the aquifers and on comparisons of their potentiometric surfaces). This hypothesis will also be studied geochemically.

As previously mentioned, Na and Cl increase in Ogallala water in the southern part of the Southern High Plains. Na and Cl are also the major dissolved ions in the aquifers in the Cretaceous rocks and could account for the high concentrations of Na and Cl in Ogallala ground water in this area. Because Na and Cl concentrations are generally less than 50% of total cation and anion concentrations, both aquifers have mixed-cation – mixed-anion hydrochemical facies (app. 1). Piper diagrams of both aquifers (fig. 28) reflect this chemical similarity. Ion composition in Ogallala ground water in this area more closely resembles composition of water in aquifers in the Cretaceous rocks than any other aquifer unit (fig. 29).

Isotopically, waters in the Cretaceous and Ogallala aquifers in the Southern High Plains are very similar (app. 2). Both are heavy with regard to $\delta^{18}O$ and δD when compared to ground water in the Ogallala in the northern part of the Southern High Plains (figs. 19b, 30). Both have high tritium activities, whereas ground water in the Ogallala in the north has essentially zero tritium activity (fig. 20, app. 2). The $\delta^{34}S$ and $\delta^{13}C$ values in both aquifers fall within the same range (fig. 31, app. 2). The possibility of upward discharge of ground water from the aquifers in the Cretaceous was suggested previously (figs. 4 and 18). In Lubbock and Gaines Counties, Texas, hydrochemical facies coincide particularly well (fig. 35a, b) and demonstrate that mixing due to upward movement of water from the aquifers in the Cretaceous probably does take place. It is important to note that the suggested movement of water from the aquifers in the Cretaceous into the Ogallala is restricted to specific areas within the southern part of the Southern High Plains (most parts of zones 14 and 20, fig. 27).

In other areas in the southern part of the Southern High Plains, where water levels of the Ogallala aquifer are higher than those of the aquifers in the Cretaceous (fig. 18), isotope values are less enriched and tritium activity is low (zone 19, fig. 28). These areas follow the central and southern major alluvial fans, where saturated zones are thick, sand and gravel abundant and permeabilities high. In these areas, Ogallala water has mixed-cation-HCO_3 facies, water isotope values are less enriched and tritium values drop to nearly zero. Their chemical characteristics are similar to those of Ogallala water in the northern part of the Southern High Plains (zone 7). Upward movement of water from the aquifers in the Cretaceous is focused within interfan areas, where saturated thickness of the Ogallala aquifer is small, fine-grained materials prevalent and permeabilities low.

The Triassic Aquifer

Salinities of ground water of the Triassic are higher than those of Ogallala water in the northern High Plains. The water becomes more saline in the south and its chemical facies changes (Dutton and Simpkins, 1985). Therefore, the chemical features of ground water in the northern and the southern parts of the Southern High Plains will be described separately. Mean values for the major ions in ground water in the Triassic in the north and in the south were calculated from 187 chemical analyses and are provided in appendix 1. Sodium is the prevailing cation in Triassic water, whereas Ca and Mg concentrations are very low (less than 10 ppm) in the north and relatively low in the south. HCO_3 is the major anion in the north; however, concentrations of other anions are also high when compared to Ogallala water. In the south, SO_4 and Cl concentrations increase considerably, changing chemical facies from Na-HCO_3 and Na-mixed-anion in the north to either Na-Cl or Na-SO_4 type in the south (Dutton and Simpkins, 1985).

Hydraulic head in the Ogallala aquifer is higher than hydraulic head in the Dockum aquifer by 300 ft (91 m) in the northern part of the Southern High Plains and by 700 ft (213 m) in the southern part (fig. 18). In most places, direction of cross-formational flow should be downward. However, comparisons of water chemistry and isotopic composition of both aquifers do not readily locate areas of similar water composition. In the northern part of the Southern High Plains, Ogallala water generally has high Ca and Mg concentrations, but Dockum Group water is typically Na-dominated. Isotopic composition of Dockum Group water is more depleted than Ogallala water with regard to $\delta^{18}O$ and δD (figs. 19b, 27, 30, app. 2). In the southern part of the Southern High Plains, Ogallala water has higher concentrations of Na and Cl than in the northern part, but not as high as water in the Dockum Group. In the same area, hydrodynamic head of ground water in Cretaceous rocks is higher than the Ogallala water table, and downward flow from the Ogallala aquifer through the Cretaceous aquifers into the lower Dockum Group aquifer is unlikely.

However, lithologic contact between sandstone in the upper Dockum Group and conglomerate in basal deposits of the Ogallala Formation indicates that there are few locations where high permeability favors upward cross-formational flow (fig. 4). In some locations in the western part of the study area and along the escarpment, hydraulic heads in the Dockum Group aquifer are higher than those in the Ogallala aquifer (fig. 18), and upward flow from the Dockum aquifer to the Ogallala is possible. Chemical similarities in these places support this possibility. In Deaf Smith and northwestern Parmer Counties, Texas, and in Curry County, New Mexico (fig. 35c), Ogallala water changes from the typical mixed-cation-HCO_3 facies into Na-HCO_3 water, similar to the water facies of the Dockum Group. A similar change takes place in Dickens County, Texas (zones 8 and 15, fig. 27; fig. 36d). In Howard and Garza Counties, Texas, the Ogallala facies is Na-Cl type, similar to the underlying Dockum Group water (zones 16 and 18, fig. 27). In other parts of the escarpment, where the potentiometric surface of the water in the Dockum aquifer is poorly known, upward movement of Dockum water into the Ogallala is also possible. It appears that even in areas beyond the escarpment, where saturated thickness of the Ogallala is small and hydraulic head in the Dockum Group is sufficiently high, ground water discharges from the Dockum Group aquifer into the Ogallala aquifer. One example of this movement occurs in Tierra Blanca Creek in southeastern Deaf Smith County, Texas. Owing to erosion of the Ogallala aquifer and a local structural high of top Triassic, the saturated zone of the Ogallala aquifer is less than 20 ft (7 m). The water-level difference between the Ogallala aquifer and the Dockum Group aquifer, which in this area typically ranges from 350 to 410 ft (107 to 125 m), drops to 25 ft (8 m). fig. 35c shows the chemical similarity between the waters in the Ogallala and Dockum aquifers in the area. Because Na-HCO_3 facies is unusual for water in the Ogallala but typical for water in the Dockum Group, upward flow from the Dockum Group aquifer into the Ogallala aquifer appears possible.

The Permian Aquifer

The upper section of the Permian aquifer is considered to have low permeability because of the presence of mudstone, shale and evaporite beds (fig. 4). The head difference map indicates only one small area where upward movement of water from the Permian into the Ogallala aquifer is possible (fig. 18). However, a brief description of its water chemistry is provided.

Three uppermost formations--the Quartermaster, Whitehorse, and Blaine--are considered here. Water in the Permian is more mineralized than water in the Ogallala. The Blaine has the most saline water of the three formations. Mean values for major ions of waters in the Quartermaster, Whitehorse, and Blaine Formations were calculated (based on 22, 109, and 26 chemical analyses, respectively), and are provided in appendix 1.

Water in all three aquifers is of $Ca-SO_4$ to mixed-cation-SO_4 facies. These waters have exceptionally low HCO_3/Cl ratios compared to the overlying Ogallala water. High Na/Cl and SO_4/Cl ratios relative to the Ogallala are also typical of ground water in the Permian. Five Permian wells that were sampled for this study are all depleted with respect to $\delta^{18}O$ (-6.3 to -9.1°/oo) and δD (-33 to -63°/oo) (figs. 1, 19b, app. 2). $\delta^{34}S$ values are relatively high (-1.4 to +10.1°/oo). Water in the Ogallala aquifer, wherever underlain by Permian strata, is usually of $Ca-HCO_3$ or mixed-cation-HCO_3 facies. In only three places typically Permian mixed-SO_4 or $Ca-SO_4$ facies were encountered in the Ogallala (along the escarpment at Donley and Wheeler Counties, Texas). However, water in the Ogallala from some wells within this area is relatively enriched in $\delta^{34}S$ (+8.6 to +9.5°/oo). These are the highest $\delta^{34}S$ values identified in the Ogallala water (fig. 31). Permian rocks usually have $\delta^{34}S$ values of +11°/oo (Hoefs, 1973) and in this area they range from 10.4 to 14.2 °/oo (Posey, 1985). Water sampled from wells completed in the Permian in this area (samples 49, 60, and 61, app. 2; Dutton and others, 1985) ranges from +9.0 to +11.92°/oo. These few examples of chemical and isotopic similarities between water in the Ogallala and water in the Permian may indicate some local upward diffusion from the Permian aquifer along the escarpment. Because values for $\delta^{18}O$ and δD are in the range typical of the Ogallala (figs. 19b, 31, app. 2), they can neither support nor eliminate this assumption. Heavy $\delta^{34}S$ values in ground water in the southern part of the Southern High Plains (zone 19, fig. 9), which resemble values in ground water in the Permian, are still an enigma, because cross-formational flow into the Ogallala is not indicated in this area.

Effects of Oil Field Brine Contamination

Contamination of ground water by disposal of oil field brines is presumed to take place chiefly by infiltration from unlined disposal pits used in the past and by leakage along broken or poorly cemented casing of oil, gas and injection wells. Oil exploration and production are concentrated in the southern part of the Southern High Plains and along the Amarillo Uplift, Anadarko and Midland Basins. Ground-water contamination from oil field activities is most likely limited to these areas.

To identify brine contamination, approximately 530 chemical analyses of oil field brines from 16 formations in the Southern High Plains were studied. Data were taken from Burnitt and others (1963), Reed (1963), Burnitt (1964), McAdoo (1964), and Crouch (1965). Mean values were calculated for the major ions in each of the formations and are presented in appendix 3. Brine waters are very saline and TDI range from 1,891 to 5,726 meq/l. The chemical characteristics of all brines are similar: Na > Ca > Mg and Cl >> SO_4 > HCO_3, and water has Na-Cl facies. These patterns are reflected in the Piper diagram for these brines (fig. 36). All brines show an increase in Na and Cl with TDI and close correlation between Na and Cl (fig. 37). In the Permian brines, strong correlation also exists between Ca and Cl. Brines always seem to have very low ratios (in meq/L) of HCO_3/Cl (0.001 to 0.020) and SO_4/Cl (0.006 to 0.06). High ratios of Ca/(HCO_3+SO_4) (4.87 to 48.1) are encountered for all brines. The Na/Cl ratio generally ranges from 0.698 to 0.938, but extremely low values (0.15 to 0.22) are encountered in the Permian brines, which may suggest that halite precipitation took place in these brines. It seems, therefore, that several criteria could serve for the identification of brine contamination of water in the Ogallala: high salinities, low ratios of HCO_3/Cl, and SO_4/Cl, and high ratios of Ca/(HCO_3+SO_4).

Occurrences of high salinity were screened from 3,698 Ogallala chemical analyses examined for this study. These exceptional salinities were compared with adjacent oil field brines in order to detect the salinity source. In several places in Andrews, Howard, Gaines, and Hockley Counties, Texas, high salinities in the water of the Ogallala Formation appear to be related to nearby oil fields (for examples, see fig. 34b). The Na-SO_4 facies that generally accompany high salinities in the Ogallala water is typical of saline lakes and does not resemble oil field brines. Some oil field brine may still be in the unsaturated zone below empty and abandoned brine disposal pits. The rate of future ground water contamination is controlled by the distribution of vertical permeabilities in the unsaturated zone and recharge rates. It is anticipated, therefore, that past activities of brine disposal will have an increasing effect on Ogallala water chemistry in the future.

CONCEPTUAL MODEL OF THE OGALLALA AQUIFER

The Ogallala aquifer in Texas and New Mexico is the southern end of an extensive aquifer system that underlies the High Plains from South Dakota to Texas. Its varying hydrological and hydrochemical features are basically controlled by the surface topography of the underlying formations and its own lithologic facies. Thickness of the Ogallala aquifer is governed by the topography of the eroded surface of underlying formations and by the location of major axes of Ogallala fan deposition. Three major areas of alluvial-fan deposits trend from northwest to southeast and are characterized by relatively high thickness and permeability. The saturated section in these areas is thick and the chemical composition relatively constant (Ca-HCO_3 to mixed-cation-HCO_3-type hydrochemical facies, depleted in $\delta^{18}O$, δD and tritium). External effects on the chemical composition are less pronounced. In areas between these major channels and along the Southern High Plains escarpment, the thickness of the Ogallala Formation decreases and the aquifer is thinner and less permeable. As a result, upward discharge of water from underlying formations is regionally and locally possible. Combined effects of water from other sources and reduced permeabilities result in heterogeneity in hydrochemical facies and in isotopic compositions different from those in areas with thick alluvial-fan deposits.

Permeable contacts between aquifers in the Cretaceous and the Ogallala aquifer, higher potentiometric surface of the Cretaceous aquifers and chemical similarities of water in both aquifers suggest there is an upward cross-formational flow from the Cretaceous formations to the Ogallala Formation in the southern part of the Southern High Plains (in parts of Bailey, Lamb, Hale, Cochran, Hockley, Lubbock, Yoakum, Terry, Lynn, Gaines, Dawson, Ector, Martin and Glasscock Counties, Texas, and Lea County, New Mexico). Discharge of water from the Triassic Dockum Group into the Ogallala Formation probably takes place in Roosevelt and Curry Counties, New Mexico, along the Caprock Escarpments (Deaf Smith, Floyd, Motley, Dickens and Garza Counties, Texas) and along a major river valley incised in the Southern High Plains in Deaf Smith County. Possible upward movement of water from Permian rocks into the Ogallala Formation may also occur along the escarpment in the northeastern Texas Panhandle (Donley County). Changes in water chemistry as a result of vertical flow from the underlying aquifers can be traced.

Secondary factors that locally affect the chemistry of the Ogallala water are evaporation where the water table is very shallow and contamination by oil field brines and agricultural chemicals and fertilizers.

The main source of recharge to the aquifer is precipitation. Playa lakes probably provide the principal pathways for infiltration but more research is needed to test their role in recharge.

PRELIMINARY OBSERVATIONS RELATED TO A POSSIBLE NUCLEAR WASTE REPOSITORY AND THE OGALLALA AQUIFER

Several issues have been addressed in this study concerning a hypothetical accidental nuclear waste spill in the surface or in the subsurface of the Southern High Plains and its effect on the Ogallala aquifer. The issues include transport rates into water table, ground-water flow directions, residence time of water in the aquifer, points of discharge from the aquifer, and possibilities of cross-formational flows between the Ogallala and underlying aquifers.

Although this study is ongoing, some preliminary conclusions can be drawn:

(1) It appears that recharge rates in the northern part of the Southern High Plains are smaller than in the south, caused by different grain-size distribution in the soil cover. Based on several cases where high concentrations of nitrates and arsenic were observed, it seems that in areas where water levels are high and the unsaturated zone is thin, chances for faster contamination of ground water are greater. Areas of high water table in the vicinity of Deaf Smith County exist in Randall County, Texas. Recharge rates based on tritium values were calculated for areas south of Deaf Smith County and range from 0.5 to 3.24 inches/yr (1.3 to 8.6 cm/yr), assuming all tritium contribution is derived from precipitation.

(2) Flow directions within the aquifer are mainly from northwest to southeast and follow preferential zones of increased permeability with similar directions. The maximum rate of water movement in the aquifer is up to 3.9 inches (10 cm) per day.

(3) Residence time of water in the aquifer is still being studied. It is likely that ground water flows faster along high permeability zones, such as the southeastern part of Deaf Smith County.

(4) Discharge locations were indicated on a springs location map (fig. 21). However, it is thought that owing to heavy pumpage in Castro, Swisher, Randall, Texas and other adjacent counties, most of the discharge water flowing down gradient from Deaf Smith County is in wells in the vicinity of the proposed site and not along the eastern escarpment.

(5) Cross-formational flow from underlying formations appears possible at various areas across the Southern High Plains. Although the Permian-Ogallala contact is of low permeability, examples of chemical facies typical for water from the Permian were

encountered in Ogallala water in Donley and Wheeler Counties, Texas. Also, $\delta^{34}S$ values of Ogallala water underlain by Permian rocks are relatively heavy and approach Permian water values, suggesting a possibility of local solute migration from the Permian into the Ogallala.

Water in the Triassic flows into the Ogallala along the eastern and western escarpment and Roosevelt and Curry Counties, New Mexico. In Deaf Smith County, upward flow was suggested along the escarpment, but also near Tierra Blanca Creek away from the escarpment. Because the Permian-Triassic contact in this area was indicated to be permeable, a detailed study of the vertical flow direction across this contact is required to estimate the possibility of water moving upward from the Permian into the Triassic and then into the Ogallala. Other locations where permeable contact is suggested for the Triassic and the Ogallala, and where downward flow is indicated by head differences, did not show chemical or isotopic similarities between waters.

Based on geologic, hydrologic, and geochemical considerations, flow from Cretaceous aquifers into the Ogallala aquifer seems to be possible in large areas in the southern part of the Southern High Plains. Information about water heads in the Triassic aquifer in the area overlain by the Cretaceous is scarce, but indicates that water levels are lower than those of the Cretaceous. Therefore, it is unlikely that contamination of water in the Ogallala by water in the Triassic or Permian will occur in the south, because water heads of the Cretaceous aquifer are higher than those of the Ogallala or Triassic aquifers.

ACKNOWLEDGMENTS

We thank Gerald Baum, Doug Cocker and Philip Nordstrom of the Texas Department of Water Resources and Don McReynolds of the High Plains Underground Conservation District No. 1 for their cooperation and help. Rainwater was collected during 1984/85 by Charles Megee, Lawrence Smith, Jim Yates (National Weather Service stations in Lubbock, Amarillo and Midland, respectively), Jerry Antine (KWKA-KTKM radio station in Clovis, New Mexico) and Ora Lee Frazier (Paducah, Texas). Charles Megee assisted also at the Paducah and Clovis substations. At the Bureau of Economic Geology, The University of Texas at Austin, Alan R. Dutton, Bernd Richter, Charles W. Kreitler and Jules R. DuBar reviewed and improved the manuscript significantly. Warren Wood of the U.S. Geological Survey made helpful suggestions, and his critical review is warmly appreciated. Scott Hamlin helped with ground-water sampling. Gay Nell Gutierrez and Arten Avakian provided invaluable assistance with data processing and mapping. Jack W. Lund helped with chemical data processing. Annie Kubert-Kearns did the drafting under the supervision of Richard L. Dillon. Word processing was by Rosanne M. Wilson, under the supervision of Lucille C. Harrell, and editing was by Mary Ellen Johansen. Funding for this study was provided by the U.S. Department of Energy under contract no. DE-AC97-83WM46651.

REFERENCES

Back, W., 1966, Hydrochemical facies and ground water flow patterns in northern part of Atlantic Coastal Plain. U.S. Geological Survey Professional Paper 498-A, 42 p.

Barnes, J. R., 1949, Geology and ground water in the irrigated region of the Southern High Plains in Texas, progress report no. 7: Texas Department of Water Resources, Miscellaneous Publication M125.

Bell, E. A., and Morrison, S., 1977a, Analytical study of the Ogallala aquifer in Briscoe County: Texas Department of Water Resources Report 212.

__________ 1977b, Analytical study of the Ogallala aquifer in Hockley County: Texas Department of Water Resources Report 214, 63 p.

__________ 1978a, Analytical study of the Ogallala aquifer in Cochran County: Texas Department of Water Resources Report 217.

__________ 1978b, Analytical study of the Ogallala aquifer in Dawson and Borden Counties: Texas Department of Water Resources Report 225, 63 p.

__________ 1978c, Analytical study of the Ogallala aquifer in Lubbock County: Texas Department of Water Resources Report 216, 63 p.

__________ 1978d, Analytical study of the Ogallala aquifer in Yoakum County, Texas: Texas Department of Water Resources Report 221, 63 p.

__________ 1978e, Analytical study of the Ogallala aquifer in Lynn and Garza Counties: Texas Department of Water Resources Report 233, 63 p.

__________ 1978f, Analytical study of the Ogallala aquifer in Terry County: Texas Department of Water Resources Report 222.

__________ 1979a, Analytical study of the Ogallala aquifer in Carson County: Texas Department of Water Resources Report 242, 64 p.

__________ 1979b, Analytical study of the Ogallala aquifer in Gaines County: Texas Department of Water Resources Report 227, 63 p.

__________ 1980a, Analytical study of the Ogallala aquifer in Armstrong County: Texas Department of Water Resources Report 125, 64 p.

__________ 1980b, Analytical study of the Ogallala aquifer in Gray County: Texas Department of Water Resources Report 243, 64 p.

__________ 1980c, Analytical study of the Ogallala aquifer in Randall County: Texas Department of Water Resources Report 250, 64 p.

__________ 1980d, Analytical study of the Ogallala aquifer in Swisher County: Texas Department of Water Resources Report 241, 64 p.

__________ 1981, Analytical study of the Ogallala aquifer in Donley County: Texas Department of Water Resources Report 260, 64 p.

__________ 1982a, Analytical study of the Ogallala aquifer in Hemphill County: Texas Department of Water Resources Report 267.

__________ 1982b, Analytical study of the Ogallala aquifer in Oldham County: Texas Department of Water Resources , Report 265, 71 p.

__________ 1982c, Analytical study of the Ogallala aquifer in Wheeler County: Texas Department of Water Resources Report 266, 64 p.

Bomar, G. W., 1983, Texas weather: Austin, University of Texas Press, 265 p.

Brand, J. P., 1953, Cretaceous of Llano Estacado of Texas: University of Texas, Austin, Bureau of Economic Geology Report of Investigations No. 20, 59 p.

Broadhurst, W. L., 1942, Recharge and discharge of the ground water resources on the High Plains in Texas: American Geophysical Union Transactions, pt. 1, p. 9-15.

Brune, G., 1981, The springs of Texas: Fort Worth, Branch-Smith, 566 p.

Burnitt, S. C., 1964, Investigation of ground water contamination, P. H. D., Hackberry and Storie oil fields, Garza County, Texas: Texas Water Commission Report LD 764.

Burnitt, S. C., Adams, J. B., Rucker, O. C., and Porterfield, H. C., 1963, Effects of surface disposal of oil field brines on the quality and development of ground water in the Ogallala formation, High Plains of Texas: prepared for Texas Water Commission public hearing held by Water Pollution Control Board, September 25, 1963, Austin, Texas.

Caran, S. C., and Baumgardner, R. W., Jr., in preparation, Quaternary stratigraphy, Western Rolling Plains of Texas: The University of Texas at Austin, Bureau of Economic Geology.

Cooper, J. B., 1960, Ground water in the Causey-Lingo area, Roosevelt County, New Mexico. New Mexico State Engineer. Technical Report 14.

Crouch, R. L., 1965, Investigation of ground water contamination in the Vealmoor oil field, Howard and Borden Counties, Texas: Texas Water Commission Report LD 265.

Dansgaard, W., 1964, Stable isotopes in precipitation, Tellus, v. 16, pp. 436-469.

Dutton, S. P., Finley, R. J., Galloway, W. E., Gustavson, T. C., Handford, C. R., and Presley, M. W., 1979, Geology and geohydrology of the Palo Duro Basin, Texas Panhandle, a report on the progress of nuclear waste isolation feasibility studies (1978): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 79-1, 99 p.

Dutton, A. R., Fisher, R. S., Richter, B. C., and Smith, D. A., 1985, Hydrologic testing in the salt-dissolution zone of the Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Open-File Report OF-WTWI-1985-3.

Dutton, A., and Simpkins, W., 1985, Hydrogeology and water resources of the Lower Dockum Group (Triassic) in the Texas Panhandle and eastern New Mexico: The University of Texas at Austin, Bureau of Economic Geology, topical report prepared for the U.S. Department of Energy under contract no. DE-AC-97-83WM46651, 26 p.

Dvoracek, M. J., and Black, W. H., 1973, Assessment of water availability in Texas High Plains playa lakes: Texas Tech University, Agricultural Engineering Department.

Felthy, J. R., Modler, R. L., Reckers, R. G., and Huddlestone, E. W., 1972, Potential pollution of the Ogallala by recharging playa lake water: Proceedings, Playa lake symposium, Arlington, Texas, Fish and Wildlife Service, U.S. Department of the Interior.

Geohydrology Associates, Inc., 1978, Collection of hydrological data, east side Roswell Range Eis Area, New Mexico. Prepared for the Bureau of Land Management, Denver, Colorado, New Mexico Bureau of Mines and Mineral Resources. OF Report No. 95.

Gustavson, T. C., Finley, R. J., and McGillis, K. A., 1980, Regional dissolution of Permian salt in the Anadarko, Dalhart, and Palo Duro Basins of the Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 106, 40 p.

Gustavson, T. C., and Holliday, V. T., 1985, Depositional Architecture of the Quaternary Blackwater Draw and Tertiary Ogallala Formations, Texas Panhandle and Eastern New Mexico: The University of Texas at Austin, Bureau of Economic Geology, OF-WTWI-1985-23, 60 p.

Gutentag, E. D., and Weeks, J. B., 1980, Watertable in the High Plains Aquifer in 1978 in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming, USGS, Hydrological Investigations Atlas HAG42.

Handford, C. R., 1980a, Lower Permian facies of the Palo Duro Basin, Texas: depositional systems, shelf-margin evolution, paleogeography, and petroleum potential: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 102, 31 p.

__________ 1980b, Facies patterns and depositional history of a Permian sabkha complex: Red Cave Formation, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 80-9, 38 p.

Handford, C. R., and Dutton, S. P., 1980, Pennsylvanian - Early Permian depositional systems and shelf-margin evolution, Palo Duro Basin, Texas: American Association of Petroleum Geologists Bulletin, v. 64, no. 1, p. 88-106.

Harris, B. L., Davis, K. R., Miller, G. B., and Allen, B. L., 1972, Mineralogical and selected chemical properties of High Plains playa soils and sediments: Proceedings, Playa lake symposium, Arlington, Texas, Fish and Wildlife Service, U.S. Department of the Interior.

Hoefs, J., 1973, Stable isotopes geochemistry: New York, Springer-Verlag, 112 p.

Hudson, J. D., 1976, Ground water levels in New Mexico, 1975. New Mexico State Engineer Basic Data Report.

__________ 1978, Ground water levels in New Mexico, 1976. New Mexico State Engineer Basic Data Report.

Hudson, J. D., and Borton, R. L., 1983, Ground water levels in New Mexico, 1978-1980. New Mexico State Engineer Basic Data Report.

Johnson, A. I., 1967, Specific yield--compilation of specific yields for various materials: U.S. Geological Survey Water-Supply Paper 1662-D, 74 p.

Jordan, L., and Vosburg, D. L., 1963, Permian salt in the Anadarko Basin, Oklahoma and Texas: Oklahoma Geological Survey Bulletin 102.

Kier, R. S., Stecher, S., and Brandes, R. J., 1984, Rising ground water levels: Proceedings, Ogallala aquifer symposium II, Texas Tech University, Water Resources Center, Lubbock, Texas.

Klemt, W. B., 1981, Neutron probe measurement of deep soil moisture as an indicator of aquifer recharge rates: Texas Department of Water Resources LP 142.

Knowles, T., Nordstrom, P., and Klemt, W. B., 1984, Evaluation of the ground water resources of the High Plains of Texas: Texas Department of Water Resources Report 288.

Kunkel, K. E., 1985, Temperatures and precipitation summaries for selected New Mexico locations. New Mexico Department of Agriculture.

Lehman, O., 1972, Playa water quality for ground water recharge and use of playas for impoundment of feedyard runoff: Proceedings, Playa lake symposium, Arlington, Texas, Fish and Wildlife Service, U.S. Department of the Interior.

Lotspeich, F. B., Lehman, O., Hauser, V. L., and Stewart, B. A., 1971, Hydrogeology of a Playa near Amarillo, Texas: Agricultural Resources Service, U.S. Department of Agriculture, Technical Report No. 10.

Machenberg, M. D., DuBar, J. R., and Gustavson, T. C., 1985, A depositional model for post-Ogallala sediments on the Southern High Plains (abs.): Geological Society of America, Abstracts with Programs, v. 17, no. 3.

McAdoo, G. D., 1964, Geology and ground water resources of Carson County and part of Gray County, Texas, progress report no. 2: Texas Water Commission Bulletin 64-2.

McGowen, J. H., Granata, G. E., and Seni, S. J., 1977, Depositional systems, uranium occurrence and postulated ground water history of the Triassic Dockum Group, Texas Panhandle - Eastern New Mexico: The University of Texas at Austin, Bureau of Economic Geology, prepared for the U.S. Geological Survey.

Morris, D. A., and Johnson, A. I., 1967, Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the hydrologic laboratory of the U.S. Geological Survey, 1948-1960: U.S. Geological Survey Water-Supply Paper 1839-D, 42 p.

Myers, B. N., 1969, Compilation of results of aquifer tests in Texas: Texas Water Development Board Report 98, 532 p.

Nativ., R., and Gutierrez, G. N., in preparation, Characterization study of the Cretaceous aquifer, Southern High Plains, The University of Texas at Austin, Bureau of Economic Geology.

Nativ, R., and Riggio, R., in preparation, Rain events in the Southern High Plains--their distribution and isotope composition patterns, The University of Texas at Austin, Bureau of Economic Geology.

Nelson, R. W., Logan, W. J., and Weller, E. C., 1983, Playa wetlands and wildlife on the southern Great Plains: a characterization of habitat: Fish and Wildlife Service, U.S. Department of the Interior.

Piper, A., 1944, A graphic procedure in the geochemical interpretation of water analyses. American Geophysical Union Trans., 25, p. 914-923.

Posey, H. H., 1985, Completion of analysis, Wolfcamp geochemistry: The University of Texas at Austin, Bureau of Economic Geology Open-File Report.

Presley, M. W., 1979, Upper Permian evaporites and red beds, in Dutton, S. P., and others, Geology and geohydrology of the Palo Duro Basin, Texas Panhandle, a report on the progress of nuclear waste isolation feasibility studies (1978): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 79-1, p. 39-49.

__________ 1981, Middle and Upper Permian salt-bearing strata of the Texas Panhandle, lithologic and facies cross sections: The University of Texas at Austin, Bureau of Economic Geology Cross Sections.

Reddell, D. L., 1965, Water resources of playa lake: The Cross-Section, v. 12, no. 3.

Reed, E. L., 1963, Study of salt water pollution in Gaines County, Texas.

Reeves, C. C., 1970, Location, flow and water quality of some Texas playa lake springs: Texas Tech University, Water Resources Center, WRC 70-5, 25 p.

Ries, G. V., 1981, Preliminary work on calcrete horizon maps with infiltration rates: Texas Tech University, Master's thesis.

Seni, S. J., 1980, Sand-body geometry and depositional systems, Ogallala Formation, Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 105, 36 p.

Stone, W. J., 1984, Preliminary estimates of Ogallala aquifer recharge using chloride in the unsaturated zone, Curry County, New Mexico: Proceedings, Ogallala aquifer symposium II, Texas Tech University, Water Resources Center, Lubbock, Texas, p. 376-391.

__________ 1985, Recharge through calcite, in Memoires, International Symposium on the Hydrogeology of Rocks of Low Permeability, Tucson, Arizona.

Texas Department of Water Resources, 1980, Playa lake monitoring for the Llano Estacado total aquifer management study, Texas, Oklahoma, New Mexico, Colorado, and Kansas: Texas Department of Water Resources LP114.

U.S. Bureau of Reclamation, 1982, Llano Estacado playa water resources study, a special investigation: Southwest Regional Office, Amarillo, Texas.

Ward, C. R., and Huddlestone, E. W., 1979, Multipurpose modification of Playa lakes: Proceedings, Playa lake symposium, Arlington, Texas, Fish and Wildlife Service, U.S. Department of the Interior.

Weeks, J. B., and Gutentag, E. D., 1981, Bedrock geology, altitude of base, and 1980 saturated thickness of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming: U.S. Geological Survey Hydrol. Inc. Atlas HA-648.

Wells, D. M., Rekers, R. G., and Huddlestone, E. W., 1970, Potential pollution of the Ogallala by recharging playa lake water: Texas Tech University, Water Resources Center, WRC 70-4.

White, W. N., Broadhurst, W. L., and Lang, J. W., 1946, Ground water in the High Plains of Texas: U.S. Geological Survey Water Supply Paper 889-F.

Wood, W. W., and Osterkamp, W. R., 1984, Recharge to the Ogallala aquifer from playa lake basins on the Llano Estacado (An outrageous proposal?): Proceedings, Ogallala aquifer symposium II, Texas Tech University, Water Resources Center, Lubbock, Texas.

Wood, W. W., and Petraitis, M. J., 1984, Origin and distribution of carbon dioxide in the unsaturated zone of the Southern High Plains of Texas: Water Resources Research, v. 20, no. 9, p. 1193.

Wyatt, W., Bell, A. E., and Morrison, S., 1976a, Analytical study of the Ogallala aquifer in Bailey County, Texas: Texas Water Development Board Report 207, 63 p.

__________ 1976b, Analytical study of the Ogallala aquifer in Castro County, Texas: Texas Water Development Board Report 206, 63 p.

__________ 1976c, Analytical study of the Ogallala aquifer in Crosby County, Texas: Texas Water Development Board Report 209, 63 p.

__________ 1976d, Analytical study of the Ogallala aquifer in Floyd County, Texas: Texas Water Development Board Report 211, 63 p.

__________ 1976e, Analytical study of the Ogallala aquifer in Hale County, Texas: Texas Water Development Board Report 200, 63 p.

__________ 1976f, Analytical study of the Ogallala aquifer in Lamb County, Texas: Texas Water Development Board Report 203, 63 p.

__________ 1976g, Analytical study of the Ogallala aquifer in Parmer County, Texas: Texas Water Development Board Report 205, 63 p.

__________ 1977, Analytical study of the Ogallala aquifer in Deaf Smith County, Texas: Texas Water Development Board Report 213, 63 p.

Tritium values in precipitation and calculated residual tritium in ground water.

Year	Weighted annual mean at Waco, TX	Weighted annual mean at Albuquerque, NM	Mean calculated from both stations for the High Plains	No. of years elapsed till 1985	Percent of residual tritium	Calculated residual tritium (TU)
1961	400	/	400	24	26	100
1962	421	/	421	23	28	118
1963	1129	1529	1329	22	29	385
1964	372	1688	844	21	31	262
1965	205	481	343	20	33	113
1966	152	282	217	19	35	76
1967	78	240	159	18	36	57
1968	73	188	131	17	39	51
1969	72	196	134	16	40	53.6
1970	61	200	130	15	42	55
1971	44	203	123	14	45	55

Appendix 5. Calculation of recharge rate based on tritium activities in ground water of the Ogallala aquifer in the Southern High Plains.

Comparison of tritium values in rainwater and ground water may indicate the rate of recharge. However, in the unsaturated zone and in ground water, tritium decays and its concentration decreases to a half after 12.3 yr, to a quarter after another 12.3 yr, and so on. As a result, comparison of tritium values in a ground-water sample that has been recently collected with tritium values in current precipitation is not valid. A decay curve of the tritium should be used to reconstruct from past tritium values in rainwater the tritium values of current ground water. The sets of reconstructed "ground-water" values (each set can be attributed to a different year of precipitation) are the ones to be compared and matched with tritium values in current ground-water samples. As a result, based on current tritium values in ground water, the year when the water was recharged from precipitation may be traced back.

It is possible to attribute the high values of tritium in the water of the Ogallala in the Southern High Plains to the thinness of the unsaturated zone, which results in a shorter recharge path into the aquifer. The feasibility of the assumption can be checked by comparing current tritium in ground water of the Ogallala to tritium values in precipitation during the last 30 years. However, back records of tritium need to be corrected for radioactive decay. Records from Waco, Texas, and Albuquerque, New Mexico, were used for this purpose. According to the table below, which corrects tritium in precipitation for their radioactive decay, it seems that rainfall of 1966 or 1967, when corrected, provides similar tritium values as those currently observed in ground water of the Ogallala in the Southern High Plains.

Based on a time period of 18 to 19 years (1966-1967 to 1985), and assuming a thin unsaturated section of 25 ft (7 m) that can represent a large area in the high tritium zone, and soil moisture content of 10 percent in this zone, the calculated annual recharge flux is 1.62 inches/yr (4.1 cm/yr):

$$\frac{25' \times 0.1}{18.5y} = 0.13'/y = 1.62''/y$$

If dry or wet conditions are assumed for the unsaturated zone (3 percent of moisture content or 20 percent, respectively), the annual recharge ranges from 0.5 inches to 3.24 inches/yr (1.3 to 8 cm/yr). These values are in the range of annual recharge mentioned in this study. It appears, therefore, that shorter recharge paths at the Southern High Plains permit fast recharge flux, which is reflected by high tritium values.

The suggested model of recharge estimates based on the tritium activities in ground water is a simplified model that assumes a piston flow and a complete displacement of water present in both the vadose and saturated zones by the recharging water. The reality is that the final "mixture" of ground water is formed by an old water component derived by lateral flow (with low or no tritium at all) and a young water component derived by vertical rain/playa lake water percolation (that has higher tritium activities than the final mixture, and therefore could be derived from rains earlier than 1966/67). If the young water component with higher tritium activity could be separated from the mixture, the annual calculated recharge rates would be smaller. Therefore, the model provides a minimum estimate for the water age and maximum value for annual recharge rate.

FIGURE CAPTIONS

Figure 1. Location map of study area, rain sampling stations and sampled wells. Ground water samples were analyzed for general chemistry, $\delta^{18}O$, δD, tritium, $\delta^{34}S$ and $\delta^{13}C$ (app. 2). Precipitation was collected daily at five stations across the Southern High Plains and Rolling Plains during one year, and samples were analyzed for $\delta^{18}O$, δD and occasionally for tritium (app. 4).

Figure 2. Mean annual precipitation increases from east to west (data from Bomar, 1983 and Geohydrology Associates, Inc., 1978).

Figure 3. Soil cover in the northern part of the study area consists mainly of clays and clay loams, whereas in the southern part the soils are sandy loams (modified from Klemt, 1981, p. 7).

Figure 4. The basal gravels of the Ogallala unconformably overlie Permian, Triassic and Cretaceous strata (Seni, 1980). Owing to preferential erosion in places, the Ogallala permeable base overlies the top of the permeable Cretaceous Edwards limestone or the Cretaceous Trinity sandstone, thus forming one hydrologic continuum. In other parts of the Southern High Plains, sandstone of the Triassic Dockum Group also appear to be hydrologically continuous with the Ogallala aquifer. Lithologic data were taken from well logs (McGowen and others, 1979; Presley, 1981) and type locality descriptions (Brand, 1953).

Figure 5. (a) The Neogene Ogallala Formation was deposited in an environment that produced humid-type alluvial fans composed of sand, gravel and finer materials derived from the Southern Rocky Mountains. Axes of three major alluvial fans trend from

northwest to southeast. (b) Deposition of Ogallala alluvial fans shifted toward the south, successively overlying higher land elevations and unconformably overlying Permian, Triassic and Cretaceous strata (from Seni, 1980).

Figure 6. Formation thickness reaches 800 ft (244 m) along the major axes of deposition but thins in the interfan areas and toward the escarpment of the Southern High Plains. Thickness is controlled mainly by the relief of pre-Ogallala drainage valleys and collapse basins formed by solution of evaporites (from Seni, 1980).

Figure 7. Relative abundance of sand and gravel decreases away from the major axes of fan deposition (from Seni, 1980).

Figure 8. Sandstone at base Triassic forms a permeable contact with the Permian rocks at Armstrong, Deaf Smith, Lamb, Cochran, Hockley, Yoakum, Lynn, Gaines and Ector Counties, Texas, and at Roosevelt and Lea Counties, New Mexico (data from McGowen and others, 1979).

Figure 9. Limestone at the top Permian may form a permeable contact with the Triassic rocks in Oldham, Randall, Deaf Smith, Armstrong and Lamb Counties, Texas, and in Roosevelt County, New Mexico (data from Presley, 1981).

Figure 10. Permeable sandstone at base Cretaceous form a permeable contact with the Triassic rocks at Garza, Borden, Andrews, Martin, Howard and Ector Counties, Texas (data from Brand, 1953).

Figure 11. Sandstone at top Triassic forms a permeable contact with base Cretaceous rocks at Hale, Cochran, Hockley, Yoakum, Terry, Lynn, Gaines, Martin, Ector and Midland Counties, Texas (data from McGowen and others, 1979).

Figure 12. Specific yield of the Ogallala Formation is highest (up to 22%) in the thick deposits of sand and gravel along the major axes of alluvial fan deposition. In interfan areas, specific yield of the Ogallala is as low as 4% (modified from Knowles and others, 1984).

Figure 13. Relatively high permeabilities (1,000 to 1,500 gal/d/ft^2) were calculated for the central and southern alluvial fans areas, whereas the northern fan area is not clearly differentiated by higher permeabilities. Core analyses (Knowles and others, 1984) and pumping tests (Myers, 1969) usually provided lower values than the mapped calculated permeabilities (modified from Knowles and others, 1984).

Figure 14. Ground water in the Ogallala aquifer occur under water-table conditions. Flow lines follow the regional topography gradient and orientation of the alluvial fans, from northwest to southeast (from Gutentag and Weeks, 1980).

Figure 15. Water level altitude reflect the regional topography gradient. A linear regression based on 470 old measurements of water levels (taken prior to the 1940's and therefore unaffected by pumpage) shows a very close correlation (r=0.99) with topography. Since then, water levels in the northern part of the study area have been greatly affected by heavy pumpage from the aquifer, which has caused severe declines in many areas.

Figure 16. Extensive pumpage from the Ogallala aquifer caused severe declines of water table in many areas. Declines have mainly occurred in the northern parts of the study area (modified from Weeks and Gutentag, 1984).

Figure 17. The potentiometric surfaces of ground water in the Cretaceous and the Permian formations, where they underlie the Ogallala Formation, trend from northwest to southeast, similarly to the potentiometric surfaces of ground water in the Ogallala and Dockum aquifers.

Figure 18. Potentiometric head differences between the Ogallala and the underlying aquifers suggest that there is an upward cross formational flow from the Cretaceous and Dockum aquifers to the Ogallala aquifer in the New Mexico area of the Southern High Plains and toward the escarpment of the Southern High Plains. Possible upward movement of water from Permian formations into the Ogallala also may occur along the escarpment in the northeastern Texas Panhandle.

Figure 19. $\delta^{18}O$ and δD values of precipitation in the Southern High Plains plot across a wide range on a line parallel to but slightly above the meteoric line. Isotope composition values of ground water in the Ogallala and underlying aquifers scatter along the meteoric water line and are concentrated in its heavier part. However, rainwater samples that fall within the range of ground water samples form more than 60% of the total rain sampled (app. 2 and app. 4).

Figure 20. Tritium activity in ground water in the Ogallala ranges from 0 to 73 tritium units (TU) (app. 2). Generally, values are very low, except for a specific area in the Southern High Plains where the unsaturated zone above water table is relatively thin and recharge path is shorter.

Figure 21. Springs once flowed in many locations across the Southern High Plains and along its escarpments. Many of them ceased flowing during the last 40 years because of increased pumpage for irrigation. Today, springs are mainly located along the escarpments and their annual discharge ranges from 0.002 to 0.9 million m^3/yr (calculated from reported measurements taken from 1977 through 1979 by Brune, 1981). Their total calculated discharge volume does not exceed 4 million m^3/yr.

Figure 22. Rough calculations comparing annual pumpage (Wyatt and others, 1976a-g, 1977; Bell and Morrison, 1977a,b, 1978a-f, 1979a,b, 1980a-d, 1981, 1982a-c) with estimated annual recharge (Knowles and others, 1984) indicate that while recharge estimates range from 0.058 to 0.833 inches/yr (0.15 to 2.1 cm/yr), annual pumpage ranges from 0.5 to 6.55 inches/yr (1.3 to 16.6 cm/yr) (when dividing the annual pumpage by the area in each county). In 14 of 26 counties where these calculations were made, annual pumpage volume is at least 10 times that of annual recharge (modified from Knowles and others, 1984).

Figure 23. The thickness of the unsaturated zone above the Ogallala water table ranges form 0 to 460 ft. Large area has water table closer to land surface than 50 ft (15 m) along the Caprock escarpments but also away from it in Roberts, Randall, Lamb, Terry, Lynn, Dawson, Gaines, Andrews, Martin, Howard and Midland Counties, Texas, and in Lea County, New Mexico. The thin unsaturated zone may permit fast recharge from irrigation surplus water but also contamination of ground water by agricultural chemicals and surface-disposed oil-field brines. Extremely shallow water table can lead to direct evaporation from ground water and resulting salinization, as observed around saline lakes at the southern part of the study area.

Figure 24. Saturated thickness of the Ogallala Formation is highly controlled by the topography of the pre-Ogallala surface. Along the major troughs and flow channels that

carried the Ogallala clastics saturated thickness ranges from 100 to 300 ft, whereas in the interchannel areas it ranges from less than 20 ft to 100 ft (from Knowles and others, 1984, p. 67).

Figure 25. As a result of increasing pumpage, the saturated thickness of the aquifer has decreased considerably. Comparison between water level data from 1980 and 1960 (and by 1960, water levels were already depleted) shows that areas that used to have a thick saturated section (200 to 300 ft) decreased from 11% to only 2% of the total area of the Ogallala. However, areas that once had a very thin saturated thickness (0 to 20 ft) increased from 11% to 15% during the same time period. 50% of the area had 0 to 80 ft of saturated thickness in 1960, whereas in 1980 50% of the area had only 0 to 60 ft thickness.

Figure 26. A major feature of Ogallala water composition is the sharp increase in total dissolved solids (TDS) from below 400 ppm in the northern part of the study area to 3,000 ppm in the southern part (from Knowles and others, 1984, p. 149).

Figure 27. Along the major axes of fan deposition, the aquifer has a higher percentage of coarse sediments, is thickest, most porous and the chemical composition of its water is relatively constant. Water has mainly mixed-cation - HCO_3 and Ca - HCO_3 facies, very low tritium activity and is relatively depleted in $\delta^{18}O$ and δD (zones 1, 4, 7, and 19). Between these fan areas (i.e., zone 14) the percentage of coarser sediments is smaller, porosities are lower and the aquifer is thinner. Hydrochemical facies vary and consist of mixed-cation -mixed-anion, Na - mixed-anion, Mg - mixed-anion and even mixed-cation - SO_4, mixed-cation - Cl, Na - So4, Na - Cl and Ca - SO_4. Tritium activity is higher, and $\delta^{18}O$ and δD values are enriched relatively to water in major fan axes.

Figure 28. The southern part of the Southern High Plains has a larger variety of water types, most commonly a mixed-cation - mixed-anion facies. Based on the Piper diagram for this area, it appears that this facies is a Ca-Mg-Na -HCO_3-Cl type, resulting from increasing amounts of of Na and Cl in the south. Na and Cl are also the major ions of the Cretaceous aquifer and could contribute to this increase. Similarity between ground water in the Cretaceous and ground water in the Ogallala aquifer in the southern part of the Southern High Plains supports our assumption concerning their hydraulic connection.

Figure 29. Salinity diagrams of mean ion concentration for various aquifers in the Southern High Plains.

Figure 30. $\delta^{18}O$ values in the northern part of the study area are more depleted compared to the south, following a similar pattern of local precipitation (Nativ and Riggio, in preparation). Enriched values are encountered along the eastern escarpment, although no consistent enrichment from west to east can be observed. Similar patterns were observed for δD values (not shown, see app. 2).

Figure 31. $\delta^{34}S$ ranges from -12.7 to +9.5 o/oo with relatively high values observed in the northeastern (underlain by Permian rocks) and the southernmost parts of the Southern High Plains. Negative or near zero values are observed in the area northwest to southeast from Oldham County to Floyd County.

Figure 32. Correlation of hydrochemical facies with the saturated thickness in 412 wells supports the assumption that wherever the aquifer is relatively thick, hydrochemical facies are mainly Ca - HCO_3 and mixed-cation - HCO_3 types. Other hydrochemical facies are limited to saturated thickness less than 90 ft.

Figure 33. In many areas in the High Plains, calcium-arsenate and arsenic acid have been used since 1925 as a cotton defoliator and insecticide. Locally, in the southern part of the Southern High Plains, arsenic concentrations approach or are higher than the limits permitted for potable water (50 micrograms/L). High concentrations of arsenic are found where water table is generally less than 40 ft (12 m) below land surface. Arsenic can be adsorbed by clay in the unsaturated zones, but large arsenic applications in areas with shallow water table apparently exceed the adsorption capacity and contaminate ground water.

Figure 34. Salinity diagrams that demonstrate the chemical similarity of contaminated water in the Ogallala aquifer to (a) saline lakes and (b) oil field brines. Lake water and ground water near the lakes are characterized by an unusual Na $-SO_4$ and Na -Cl hydrochemical facies. In other cases, high salinities in the water of the Ogallala aquifer, in addition to Na -Cl facies, very low ratios (meq/L) of HCO_3/Cl, and SO_4/Cl and a high ratio of $Ca/(HCO_3 + SO_4)$ appear to be related to nearby oil fields.

Figure 35. (a) In Lubbock and Gaines Counties, Texas, where Ogallala and Cretaceous aquifers have similar potentiometric heads, hydrochemical facies of ground water in the Ogallala aquifer coincided particularly well with ground-water facies of the Cretaceous (but differ from the mean facies of water in the Ogallala in the southern part of the Southern High Plains) and demonstrated that mixing due to upward movement of water from the Cretaceous aquifer probably does take place. (b) In Deaf Smith and Dickens Counties, Texas, where the potentiometric surface of the Dockum aquifer is higher than that of the Ogallala aquifer, water in the Ogallala changes form the typical mixed-cation - HCO_3 water into Na - HCO_3 facies, similar to the water facies of the Dockum Group in this area.

Figure 36. Approximately 530 chemical analyses of oil field brines from 16 formations in the Southern High Plains were studied (data taken from Burnitt and others, 1963; Reed, 1963, Burnitt, 1964; McAdoo, 1964 and Crouch, 1965). Brine waters are very saline and TDS range from 1,891 to 5,726 meq/L. The chemical characteristics of all brines are Na > Ca > Mg and Cl >> SO_4 > HCO_3, and water has Na-Cl facies.

Figure 37. All oil field brines show an increase in Na and Cl with TDS and good correlation between Na and Cl. In the Permian Brines, close correlation also exists between Ca and Cl.

Appendix 4: Isotopic analyses of rain samples collected in the Southern High Plains and Rolling Plains, Texas and New Mexico.

BEG #	Station[(a)]	Date	Rain amount (inches)	$\delta^{18}O$(°/oo)	δD (°/oo)	Tritium (TU)
R001	A	10/24/84	.15	-13.4	-89	
R002	A	10/24/84	.24	-10.5	-66	
R003	A	10/31/84	.05	-2.3	-5	
R004	A	11/17/84	.12	-6.6	-39	
R005	A	11/18/84	.54	-15.2	-104	14.3
R006	A	11/24/84	.28	-15.4	-107	8.4
R007	A	11/24/84	.04	-14.9	-101	
R008	A	11/26/84	.02	-17.6	-121	
R009	A	12/04/84	.03	-7.0	-23	
R010	L	10/26/84	.04	-5.1	-28	
R011	L	11/16/84	.04	-4.7	-20	7.8
R012	L	11/24/84	1.00	-18.2	-126	6.8
R013	L	11/25/84	.01	-14.8	-101	8.6
R014	L	12/13/84	.02	-11.4	-72	
R015	L	12/14/84	.08	-6.8	-40	4.0
R016	L	12/15/84	.72	-8.5	-58	
R017	M	11/17/84	1.23	-4.6	-19	9.1
R018	M	11/24/84	.50	-6.5	-32	8.0
R019	M	12/15/84	.45	-7.2	-46	6.2
R020	M	12/31/84	.39	-9.7	-61	8.6
R021	C	11/17/84	.01	-5.4	-28	
R022	C	11/18/84	.29	-15.4	-107	12.0
R023	C	11/24/84	.35	-10.4	-64	11.4
R024	C	11/25/84	.72	-21.8	-155	6.1
R025	C	12/13/84	.03	-6.5	-59	
R026	C	12/14/84	.92	-8.4	-58	5.2
R027	C	12/15/84	.05	-7.8	-47	6.0
R028	C	12/16/84	.24	-6.5	-52	2.4
R029	C	12/20/84	.22	-13.2	-88	
R030	C	12/29/84	.05	-7.4	-57	5.0
R031	M	1/1-2/85	.03	-14.6	-102	

Appendix 4 (cont.)

BEG #	Station[a]	Date	Rain amount (inches)	$\delta^{18}O$(°/oo)	δD(°/oo)	Tritium (TU)
R032	M	01/12/85	.41	-22.7	-162	9.6
R033	M	01/30-2/1/85	.37	-9.7	-65	14.7
R034	L	12/28/84	.03	-3.6	-17	
R035	L	12/29/84	.04	-8.0	-48	
R036	L	12/30/84	1.18	-6.6	-38	
R037	L	01/27/85	.02	-7.1	-45	
R038	M	02/19-20/85		-1.8		
R039	M	02/23/85		-9.1		
R040	M	02/28/85	.42	-11.7	-74	12.5
R041	A	12/13/84	.15	-13.0	-85	1.1
R042	A	12/14-15/84	.16	-7.5	-40	7.6
R043	A	12/20/84	.20	-12.6	-87	6.7
R044	A	12/28-29/84	.09	-6.1	-38	
R045	A	01/31/85		-12.7	-87	
R046	A	12/19/84	.01	-4.8	-29	
R047	P	10/25/84	.05	-8.3	-46	
R048	P	10/27/84	.31	-5.7	-28	
R049	P	11/17/84	.45	-5.1	-19	9.8
R050	P	11/18/84	.90	-9.4	-48	8.7
R051	P	11/25/84	.63	-12.0	-74	10.8
R052	P	12/05/84	.16	-8.3	-34	
R053	P	12/13/84	.23	-10.6	-63	10.0
R054	P	12/14/84	.05	-9.5	-53	
R055	P	12/15/84	.61	-6.9	-36	7.3
R056	P	12/16/84	1.19	-5.5	-27	4.0
R057	P	12/18/84	.05	-5.4	-29	
R058	P	12/31/84	1.12	-10.0	-65	4.7
R059	P	01/01/85	.16	-13.6	-95	
R060	P	01/27/85	.08	-7.5	-39	
R061	P	01/31/85	.14	-11.1	-69	
R062	P	02/01/85		-12.5		
R063	P	02/01/85	.08	-6.1	-29	10.3

Appendix 4 (cont.)

BEG #	Station[a]	Date	Rain amount (inches)	$\delta^{18}O$(°/oo)	δD(°/oo)	Tritium (TU)
R064	P	02/21/85	.11	-4.4	-20	5.2
R066	L	02/20/85	.16	-7.2	-40	
R067	L	02/22/85	.03	-3.4	-16	
R068	L	02/23/85	.04	-5.1	-23	
R069	L	03/19/85	1.25	-10.4	-68	9.3
R070	A	02/22/85	.05	-6.7	-40	
R071	A	02/21-22/85	.60	-6.5	-40	
R072	A	02/23/85	.09	-10.8	-79	
R073	A	03/06/85	.03	-11.3	-82	
R074	A	03/19/85	.46	-17.9	-134	
R075	A	03/19-20/85	.98	-18.2	-133	
R076	A	03/29/85	.02	-5.6	-46	
R078	C	01/09/85	.10	-16.7	-119	
R079	C	01/12/85	.11	-10.9	-76	
R080	C	03/20/85	1.96	-17.4	-135	
R081	C	03/21/85	.50	-19.9	-138	
R082	M	03/16/85	.14	-8.1	-56	
R083	M	03/19/85	.49	-9.5	-64	
R084	M	04/12/85	.05	-0.6	-10	
R085	M	04/16/85	.14	+2.7	+14	
R086	L	03/29/85	.17	-10.3	-67	
R087	L	04/26/85	.17	-8.4	-65	
R088	L	04/27/85	.23	-7.1	-45	
R089	L	04/28/85	.07	-5.9	-30	
R091	M	05/17/85	.22	-6.6	-54	
R092	M	05/20/85	.04	-3.2	-26	
R093	M	05/21/85	.01	-6.2	-38	
R094	M	05/24/85	.53	-4.7	-30	
R095	M	05/25/85	.15	-4.3	-32	
R096	M	05/31-06/1/85	.04	-1.4	+1	
R097	M	06/01/85	.23	-3.4	-19	
R098	L	05/05/85	.18	-2.7	-23	

Appendix 4 (cont.)

BEG #	Station[(a)]	Date	Rain amount (inches)	$\delta^{18}O$(°/oo)	δD(°/oo)	Tritium (TU)
R099	L	05/22/85	1.47	-7.7	-56	
R100	L	05/16/85	.47	-4.8	-31	
R101	L	05/17/85	.32	-6.1	-43	
R102	L	05/20/85	.13	-6.5	-39	
R103	L	05/31/85	.20	-5.3	-39	
R104	L	06/01/85	.02	-5.2	-36	
R105	L	06/04/85	.59	-2.9	-11	
R107	L	06/05/85	2.20	-8.9	-60	
R108	L	06/11/85	.35	-4.6	-36	
R109	L	06/17/85	.29	-4.7	-37	
R110	L	06/18/85	.14	-4.8	-36	
R111	L	06/20/85	.14	-6.3	-39	
R112	L	06/25/85	.50	-6.1	-46	
R113	L	7/1-2/85	.55	-3.5	-12	
R114	M	06/05/85	.36	-8.6	-53	
R115	M	06/11/85	.05	-4.0	-23	
R116	M	06/12/85	.11	-8.6	-58	
R117	M	06/25/85	.04	-0.9	-4	
R118	P	03/15-16/85	0.06	-3.2	-15	
R119	P	03/19-20/85	1.25	-8.8	-57	
R120	P	03/20/85	.63	-16.1	-110	
R121	P	03/26/85	.35	-7.3	-51	
R122	P	03/29/85	.39	-11.7	-96	
R123	P	04/21/85	.45	-4.5	-33	
R124	P	04/27/85	.49	-5.5	-34	
R125	P	04/28/85	.28	-5.1	-38	
R126	P	04/29/85	.05	-2.4	-16	
R127	P	05/13/85	.16	-4.6	-28	
R128	P	05/17/85	.09	-1.9	-27	
R129	P	5/19-20/85	1.08	-9.3	-62	
R130	P	05/20/85	.04	-8.4	-56	
R131	P	05/25-26/85	.41	-2.5	-25	

Appendix 4 (cont.)

BEG #	Station(a)	Date	Rain amount (inches)	$\delta^{18}O$(°/oo)	δD(°/oo)	Tritium (TU)
R132	P	06/01/85	.37	-1.9	-14	
R133	P	06/05/85	3.15	-4.7	-26	
R134	P	06/5-6/85	.90	-8.4	-56	
R135	C	03/30/85	.08	-11.7	-79	
R136	C	04/14/85	.21	-13.8	-101	
R137	C	04/16/85	.05	-0.8	-36	
R138	C	04/29/85	1.05	-5.7	-34	
R139	C	05/17/85	.42	-4.8	-24	
R140	C	05/18/85	.75	-9.8	-72	
R141	C	05/19/85	.43	-14.2	-99	
R142	C	05/22/85	1.16	-11.1	-75	
R143	C	05/23/85	.18	-9.9	-67	
R145	C	06/05/85	2.02	-5.9	-35	
R146	C	06/06/85	.04	-6.3	-44	
R147	C	06/12/85	.22	-8.3	-60	
R148	C	06/14/85	.35	-4.7	-31	
R149	C	06/17/85	.03			
R150	A	04/12/85	.65	-9.8	-73	
R151	A	04/28/85	1.99	-6.7	-45	
R152	A	05/17/85	.15	-7.6	-60	
R153	A	05/20/85	.20	-9.1	-68	
R154	A	05/22/85	.48	-10.2	-75	
R155	A	06/03/85	2.12	-5.5	-39	
R156	A	06/09-11/85	.28	-6.3	-47	
R157	A	06/14/85	.20	-5.4	-49	
R158	A	07/10/85	.03	+4.9	+14	
R159	L	07/25/85	2.65	-6.1	-37	
R160	L	07/24/85	.60	-6.1	-34	
R161	M	07/02/85	.02	+2.6	+35	
R162	M	07/03/85	.33	-2.6	-15	
R163	M	07/20/85	.09	-2.8	-15	
R164	M	07/20/85	.04	-1.7	+1	

Appendix 4 (cont.)

BEG #	Station[a]	Date	Rain amount (inches)	$\delta^{18}O$(‰)	δD(‰)	Tritium (TU)
R165	M	07/22-23/85	.11	-5.6	-37	
R166	M	07/25/85	.14	-4.9	-33	
R167	L	08/10/85	.11	+3.4	+22	
R168	L	08/14/85	.27	-3.1	-11	
R169	L	08/23/85	.10	-3.1	-14	
R170	M	08/13/85	.44	-2.8	-11	
R171	M	08/14/85	.21	-4.5	-32	
R172	L	08/27/85	.04			
R173	L	09/14/85	.21	-5.1	-28	
R174	L	09/19/85	1.53	-6.7	-40	
R175	L	09/20/85	1.20	-6.8	-37	
R176	L	09/20/85	.65	-5.2	-29	
R177	L	09/21/85	.10	-7.8	-52	
R178	L	09/28/85	.72	-7.5	-48	
R179	C	07/02/85	.71	-5.2	-33	
R182	C	07/25/85	.06	-5.1	-36	
R183	C	07/27/85	.31	-8.4	-68	
R184	C	07/28/85	.12	-3.2	-25	
R187	C	08/08/85	.03	+1.6	-7	
R188	C	08/11/85	.76	-4.4	-32	
R189	C	08/15/85	.63	-2.7	-21	
R191	C	08/21/85	.47	-5.1	-39	
R192	C	08/24/85	1.20	-3.4	-26	
R193	C	08/27/85	0.15	-3.2	-24	
R194	C	09/04/85	1.12	-5.4	-42	
R195	C	09/12/85	.70	-4.7	-30	
R196	C	09/16/85	.08	-5.4	-33	
R197	C	09/19/85	.45	-6.5	-49	
R198	C	09/20/85	.50	-6.3	-46	
R199	C	09/21/85	.17	-6.0	-37	
R201	M	09/05/85	.18	-5.0	-45	
R202	M	09/12/85	1.13	-6.0	-36	

Appendix 4 (cont.)

BEG #	Station[a]	Date	Rain amount (inches)	$\delta^{18}O$(o/oo)	δD(o/oo)	Tritium (TU)
[illegible]			[illegible]	-3.0	-12	
R204	M	09/19-20/85	.50	-3.4	-26	
R206	A	07/24-26/85	1.65	-6.6	-48	
R207	A	07/25/85	.05	-6.6	-49	
R208	A	07/26-27/85	.12	-5.3	-41	
R209	A	07/28-29/85	.20	-3.2	-47	
R213	A	08/23/85	.13	-1.6	-21	
R214	A	09/10/85	.13	+0.8	-9	
R215	A	09/12/85	.53	-7.3	-52	
R216	A	09/18/85	.48	-6.3	-51	
R217	A	09/18-19/85	.42	-6.1	-53	
R218	A	09/20/85	.64	-8.4	-66	
R221	L	10/9-10/85	2.60	-7.6	-51	
R224	M	10/01/85	.07	-7.0	-48	
R225	M	10/09/85	2.04	-5.4	-33	
R228	P	06/11/85	.18	-4.4	-39	
R232	P	07/25/85	1.28	-3.7	-35	
R234	P	08/21/85	.45	-6.2	-44	
R235	P	08/24/85	.35	+1.2	-1	
R236	P	09/13/85	.62	-3.9	-22	
R237	P	09/20/85	.87	-5.5	-32	
R239	P	10/09/85	.11	-2.8	-13	
R240	P	10/10/85	1.15	-4.2	-22	
R241	P	10/11/85	.06	-4.9	-24	
R244	C	10/09/85	1.12	-9.1	-62	
R245	C	10/10/85	.42	-14.6	-107	
R246	C	10/11/85	.70	-10.7	-71	

(a) Station abbreviations: A - Amarillo, Texas; L - Lubbock, Texas; M - Midland, Texas; C - Clovis, New Mexico; P - Paducah, Texas. For rain station location see figure 1.

Appendix 1. Mean values ($\frac{mg/l}{meq}$) for chemical parameters of water in the major aquifers in the Southern High Plains.

	Ogallala North	Ogallala South	Cretaceous	Triassic North	Triassic South	Permian (Quartermaster)	Permian (Whitehorse)	Permian (Blaine)
Ca^{+2}	57/2.84	76/3.79	91/4.54	30/1.49	86/4.29	295/14.7	427/21.11	531/25.49
Mg^{+2}	30/2.47	60/4.94	33.5/2.76	16/1.31	44/3.55	145/11.95	101/8.26	140/11.06
Na^{+}	45/1.96	108/4.70	151/6.58	245/10.64	1174/51.1	423/18.38	210/9.07	292/12.69
K^{+}	8/0.2	13/0.33	8/0.19	2.3/0.06	0.8/0.02	10/0.25	4/0.09	4/0.10
HCO_3^{-}	278/4.56	275/4.51	292/4.78	387/6.34	443/6.97	279/4.57	142/2.33	225/3.69
SO_4^{-2}	66/1.37	196/4.08	185/3.87	161/3.05	1145/23.81	1509/31.41	1347/28.04	1716/35.73
Cl^{-}	43/1.21	160/4.51	170/5.07	128/3.61	988/27.86	310/8.76	300/8.45	392/11.05
TDI	429/14.74	800/27.04	830/27.88	961/26.98	3881/117.9	2857/90.16	2493/77.65	3197/100.08
Ion ratios								
HCO_3^{-}/Cl^{-}	3.77	1.00	0.95	1.76	0.25	0.52	0.28	0.33
Na^{+}/Cl^{-}	1.62	1.04	1.30	2.95	1.83	2.10	1.07	1.15
SO_4^{-2}/Cl^{-}	1.13	0.9	0.76	0.84	0.85	3.59	3.32	3.23
Water type	Mixed-Cations-HCO_3	Mixed-Cations-Mixed-Anions	Mixed-Cations-Mixed-Anions	Na-Mixed-Anions	Na-Mixed-Anions	Mixed-Cations-SO_4	Ca-SO_4	Ca-SO_4
No. of analyses	2179	1383	87	73	81	22	109	26