Recharge into Southern High Plains Aquifer—Possible Mechanisms, Unresolved Questions

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ABSTRACT / The High Plains aquifer in the Southern High Plains (Texas and New Mexico), consisting of Tertiary, Cretaceous, and Triassic formations, has traditionally been considered to be recharged by its uppermost water-bearing unit, the Tertiary Ogallala aquifer. This article provides hydrologic, chemical, and isotopic evidence that in the Southern High Plains: (1) Cretaceous rocks actually contain independent recharge sources; (2) Triassic rocks cannot currently be recharged by the Ogallala aquifer in significant quantities; and (3) in places, both Cretaceous and Triassic aquifers recharge the overlying Ogallala aquifer. On the basis of chemical and isotopic data, playa lakes seem to act as the predominant recharge source of the Ogallala aquifer, suggesting recharge rates greater than 30 mm/yr, as opposed to the much lower rates reported by others. The Cretaceous aquifers are being recharged by cross-formational flow from the Ogallala aquifer but also from overlying Quaternary sands and the underlying Triassic aquifer in eastern New Mexico. Current recharge into the Triassic aquifer may be insignificant.

Introduction

The High Plains aquifer underlies the High Plains of the United States, which extend from Texas and New Mexico northward through Oklahoma, Colorado, Kansas, Wyoming, Nebraska, and South Dakota (Fig. 1). About 20 percent of the irrigated land in the United States is in the High Plains, and about 30 percent of the groundwater used for irrigation is pumped from the High Plains aquifer system (Weeks and Gutentag 1989). The Southern High Plains (80,000 km^2), which comprise the study area discussed here, are located south of the Canadian River in northwestern Texas and eastern New Mexico (Fig. 1).

About 0.5×10^{12} m^3 of drainable water is stored in the High Plains aquifer in the Southern High Plains (Weeks and Gutentag 1984). The aquifer is the main water supply in this area, and it is being severely depleted by extensive pumpage for irrigation (Weeks and Gutentag 1989). Pumpage of groundwater for irrigation from more than 70,000 wells in the Southern High Plains was estimated to be 7.6×10^9 m^3 from 1975 through 1979 (Luckey and others 1986). Declining water levels and decreasing water supplies threaten the future of irrigation using groundwater in this area.

The Pecos River, which incised the Southern High Plains during the late Tertiary and Pleistocene (Gustavson 1986), cut off the Southern High Plains aquifer from its western (and more humid) recharge sources in eastern New Mexico. Potential recharge of the aquifer in the Southern High Plains is currently restricted to local precipitation and precipitation-derived surface runoff. The exact portion of annual precipitation that is currently being recharged into the aquifer has been debated for the last 40 years; estimates vary by more than two orders of magnitude (Table 1).

Clearly, a more precise understanding of annual recharge into the Southern High Plains aquifer is needed for better aquifer management and for forecasting future water-level declines. This article discusses recharge mechanisms into the southern part of the High Plains aquifer, the significance of the various recharge estimates, and the information required to reach a conclusive estimate. A detailed description concerning the data base and practiced methods can be found in Nativ (1988).

Hydrogeologic Setting

The Southern High Plains form a well-defined, topographically flat, isolated plateau that gently slopes toward the southeast. The only surface reliefs are shallow depressions of varying size that fill with water during the rainy season to form temporary "playa" lakes. A number of large but ephemeral rivers, including the Red, Brazos, and Colorado, cross the Southern High Plains; however, about 90 percent of local runoff drains into the playa depressions.

The Southern High Plains have a semiarid to subhumid climate. Annual mean precipitation ranges from 350 mm in the southwest to 500 mm in the northeast.

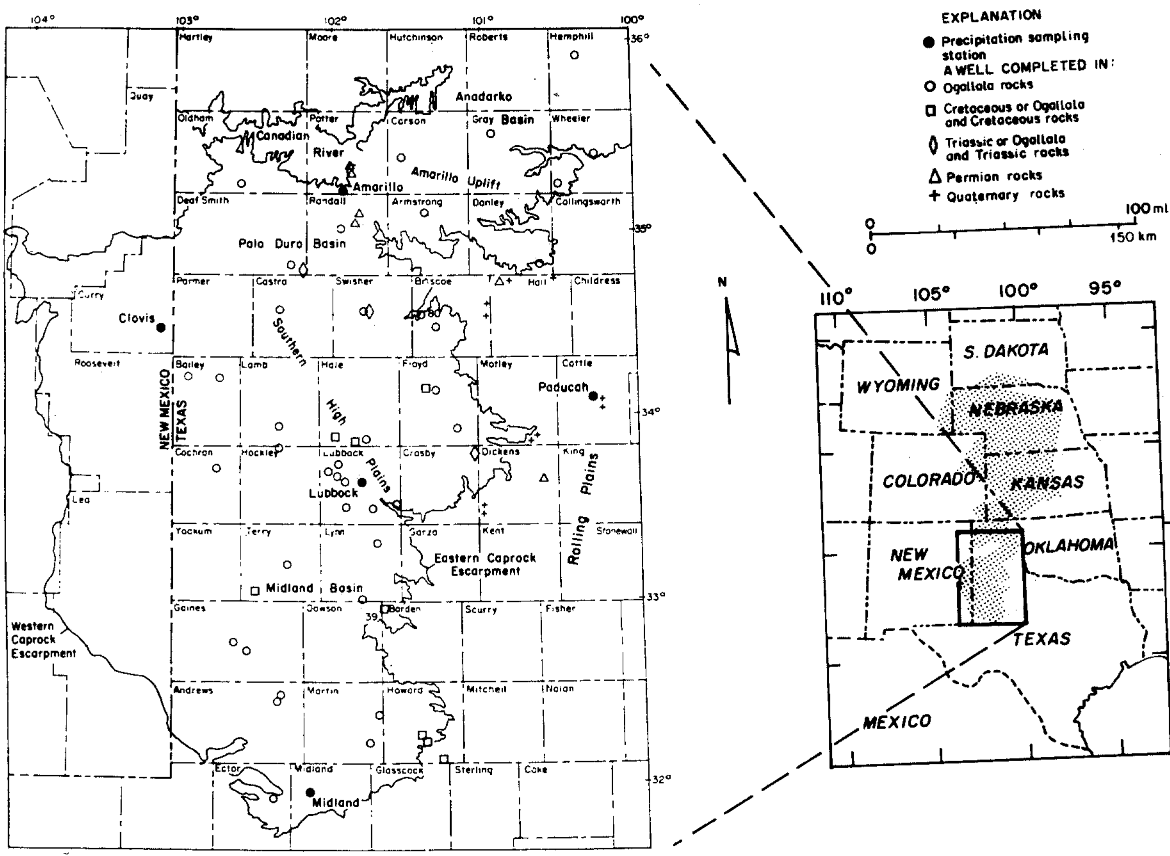

Figure 1. Distribution map of the High Plains aquifer (insert), High Plains (stippled), and location map of the study area, precipitation stations, and wells sampled for ground water.

Table 1. Estimates of annual recharge (mm) into High Plains aquifer, Southern High Plains[a]

	Recharge from		
	Playa lakes	Diffuse percolation	Sand dunes
Stone and McGurk (1985)	12.2	0.25	1.3
Wood and Osterkamp (1984)	41	~0	—
U.S. Bureau of Reclamation (1982)	25.4	—	—
Klemt (1981)	—	5.1	—
Knowles and others (1984)	—	1.5–14.5	21.2
Barnes and others (1949)	—	2.5	—

[a]Estimates are based on both regional and local studies.

Most precipitation falls between May and October. Annual pan evaporation ranges from 1,500 to 2,300 mm.

Quaternary sands and silts of the Blackwater Draw Formation form the uppermost sediments of the Southern High Plains. They overlie the Tertiary Ogallala Formation, which is composed of continental deposits such as sands, gravels, and finer sediments. The Ogallala unconformably overlies Cretaceous, Triassic, and Permian rocks (Fig. 2). In parts of Lea and Roosevelt counties, New Mexico, the Ogallala Formation is absent and the Quaternary deposits overlie Cretaceous rocks. Gutentag and others (1984) and Knowles and others (1984) defined the High Plains aquifer in the Southern High Plains as being composed of the saturated sediments both of the Ogallala Formation and of the geologic units in the Cretaceous and Triassic formations that contain potable water and are in hydraulic continuity with the Ogallala.

Interrelations Among Aquifers Forming the High Plains Aquifer

Gutentag and others (1984) and Knowles and others (1984) suggested that the Ogallala aquifer, being the major water-bearing unit in the Southern High Plains, recharges the underlying Cretaceous and Triassic aquifers. The Triassic rocks contain a regional aquifer in

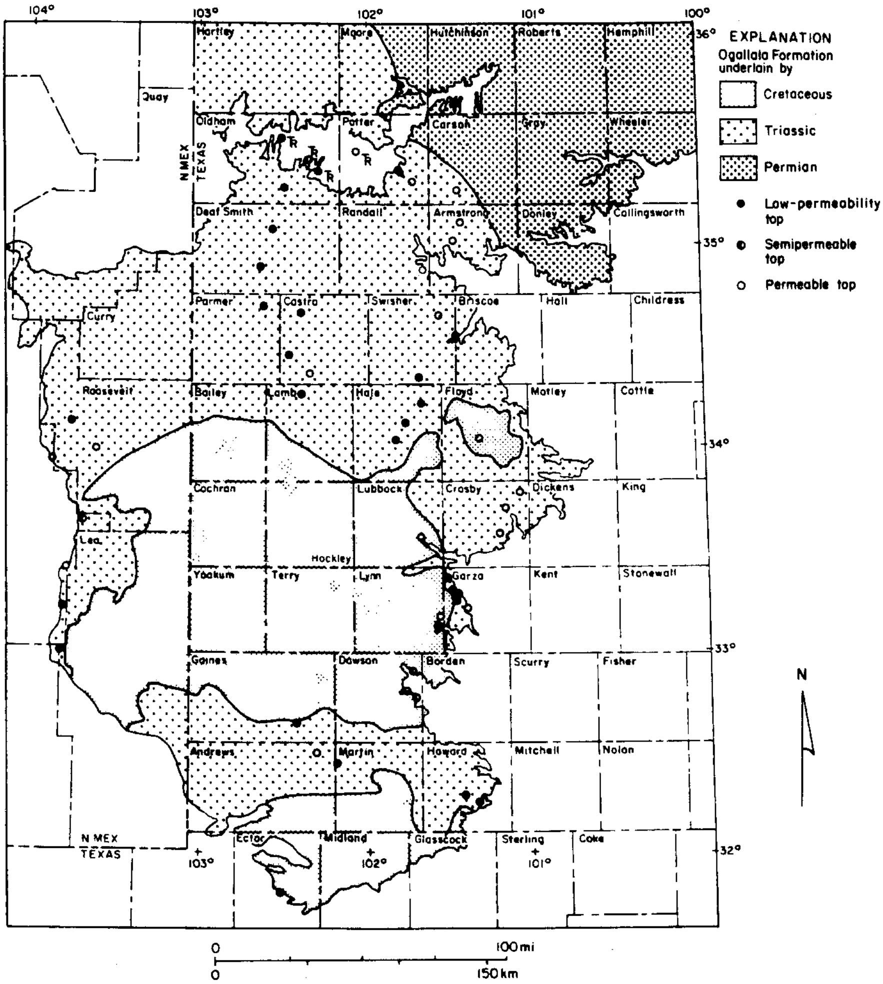

Figure 2. Subcrop map at the base of the Ogallala Formation. The basal gravels of the Ogallala unconformably overlie Cretaceous, Triassic, and Permian strata. In parts of the Southern High Plains, sandstone of the Triassic Dockum Group appears to be hydrologically continuous with the Ogallala aquifer. Lithologic data were taken from well logs (McGowen and others 1977).

sands of the Lower Dockum Group. Subcrops of Cretaceous rocks are hosts to aquifers in the Trinity sandstone and Edwards limestone. The Cretaceous Duck Creek and Kiamichi Formations also contain a local aquifer, where they change facies from shales to sandstone and limestone. The potential for cross-formational flow between the Ogallala aquifer and the underlying aquifers can be assessed from a map of the hydraulic-head differences between the Ogallala aquifer and each of the underlying aquifers (Fig. 3).

Ogallala and Triassic Dockum Aquifers

The altitude of the potentiometric surface of the Ogallala aquifer is higher than the potentiometric surface of the Dockum aquifer, except in western Texas and in a large area in eastern New Mexico (Fig. 3), where the potentiometric surface of the Dockum aquifer is higher than the Ogallala water table. This observation is true even when predeveloped water levels of the Ogallala aquifer are considered (data base and open-file records of the Texas Natural Resources Information System). Therefore, in the eastern margins of the study area, groundwater may flow from the Dockum aquifer into the Ogallala aquifer wherever lithologic contacts are permeable (Fig. 2) (criteria used for permeability classification are listed in Nativ 1988, p. 3). A similar water chemistry in these areas supports this possibility. For example, in the western area, Ogallala water changes from the typical mixed-cation–HCO_3 facies to Na–HCO_3 water (Fig. 4a). Because Na–HCO_3 facies is unusual for water in the Ogallala aquifer but typical for water in the Dockum aquifer, upward flow from the Dockum into the Ogallala appears possible locally. A similar change from mixed-cation–HCO_3 to Na–HCO_3 water takes place along the eastern margin of the Southern High Plains (Fig. 4b). Farther south along this boundary, the Ogallala water facies is Na–Cl type, similar to that of the underlying Dockum water.

Where the Ogallala water table is higher than the potentiometric surface of the Dockum aquifer, downward cross-formational flow is suggested wherever lithologic contacts are permeable. However, on the basis

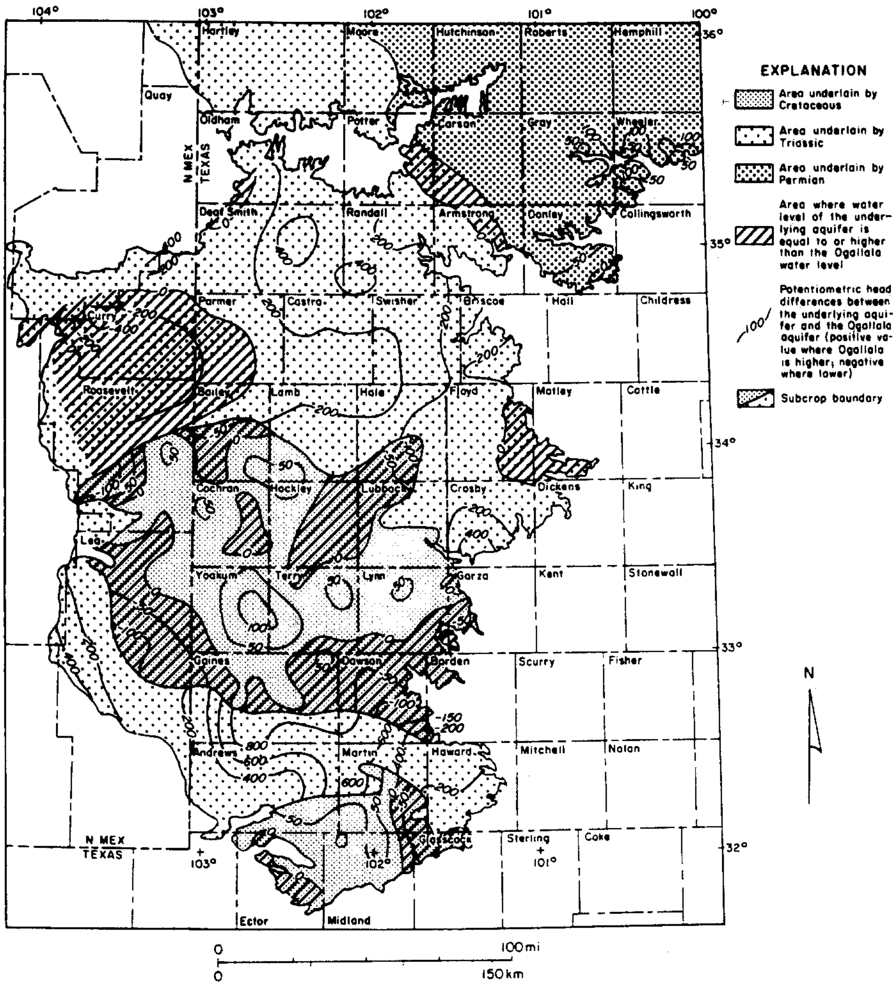

Figure 3. Potentiometric-head-difference map between the Ogallala aquifer and each of the underlying aquifers. Hydraulic-head differences suggest an upward cross-formational flow from the Cretaceous and Triassic Dockum aquifers into the Ogallala aquifer in the Southern High Plains of New Mexico and toward the escarpment of the Southern High Plains.

of the distinctively light isotopic composition of the water in the Dockum aquifer (Fig. 5b), Nativ and Smith (1987) and Dutton and Simpkins (1989) suggested that cross-formational flow from the Ogallala aquifer into the Dockum aquifer is probably insignificant.

Ogallala and Cretaceous Aquifers

In large areas the potentiometric surfaces of the Cretaceous aquifers in Trinity sandstone, Edwards limestone, and Duck Creek–Kiamichi sandstone and limestone are equal to or higher than the present Ogallala water table (Fig. 3). However, because the Ogallala water levels have declined as a result of extensive pumpage, predeveloped water levels (Weeks and Gutentag 1984) were compared with the potentiometric surface of the Cretaceous aquifers. This comparison shows that the potentiometric surface of the Cretaceous aquifers has historically been higher than the Ogallala water table, even before the development of the Ogallala in most of the areas indicated in Figure 3. These observations suggest upward cross-formational flow wherever lithologic contacts are permeable (Fig. 6). Chemical similarity in groundwaters from these aquifers also supports this suggestion. Water salinity in the Ogallala aquifer is generally higher where underlain by the northern Cretaceous subcrop than in areas farther north (Knowles and others 1984, their Fig. 38). Ogallala water salinity resembles that in the subjacent Cretaceous aquifers. Hydrochemical facies of the Ogallala aquifer above the northern Cretaceous subcrop area are similar to facies identified in groundwater in underlying Cretaceous aquifers. The $\delta^{18}O$ values of groundwater from the Ogallala aquifer in the area underlain by Cretaceous rocks were the least depleted of those measured in the aquifer (-6.2 to -4.2 per mil) and were similar to those encountered in the underlying Cretaceous aquifers. Groundwater found in the Ogallala aquifer that is underlain by Triassic or Permian rocks is more depleted in $\delta^{18}O$ (as much as -9.1 per mil) (Nativ and Smith 1987). Tritium values in Ogallala groundwater

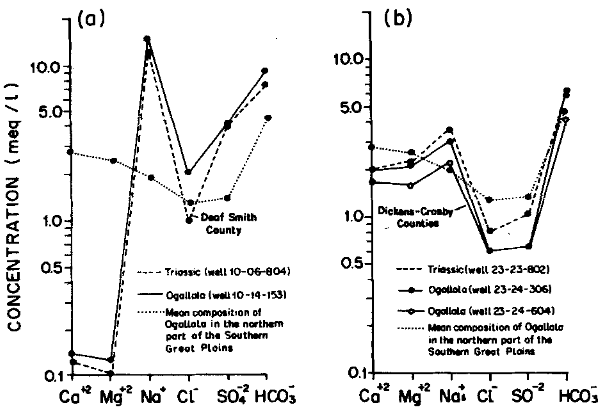

Figure 4. Salinity diagrams of groundwater in Ogallala and Triassic rocks in Deaf Smith County (a) and Dickens and Crosby counties (b), Texas. For county locations see Figure 1. The well numbering method used here was adopted from the Texas Department of Water Resources (Knowles and others 1984). In parts of these counties, the potentiometric surface of the Dockum aquifer is higher than that of the Ogallala aquifer, and Ogallala water exhibits Na–HCO_3 facies, similar to the water facies of the Dockum Group. Mixing due to upward movement of water from the Dockum aquifer into the Ogallala aquifer is suggested in these areas.

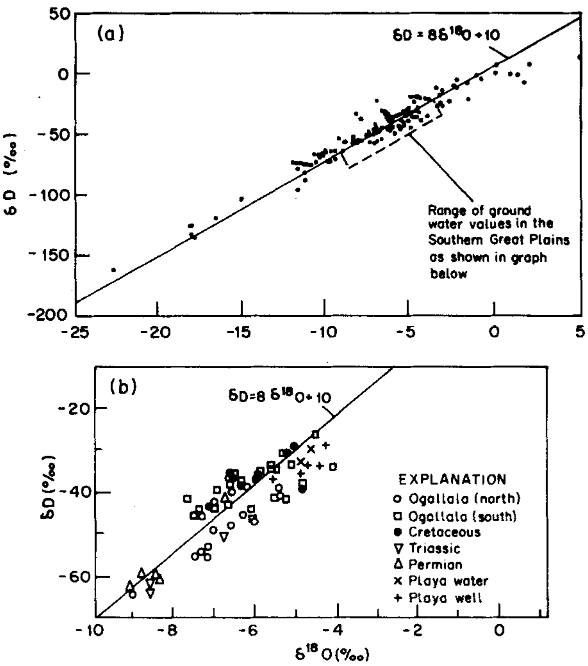

Figure 5. $\delta^{18}O$ versus δD for weighted precipitation samples (by event precipitation) (a) and for groundwater from various aquifers in the Southern High Plains (b). Precipitation values fall near the world meteoric line. Isotopic composition values of groundwater in the Ogallala and underlying aquifers plot along the meteoric line and become concentrated on the heavy side. However, precipitation samples that fall within the range of playa-lake and groundwater samples form 60 percent of the total precipitation sampled. Only 21 percent of the sampled precipitation had lighter isotopic composition than playa-lake and groundwater. No shift of playa-lake and groundwater away from the meteoric line is observed, suggesting that evaporation of precipitation in playa lakes prior to infiltration is small.

are commonly close to zero in the northern part of the Southern High Plains, which is not underlain by Cretaceous rocks. In the southern part of the Southern High Plains, tritium concentrations in the Ogallala aquifer are high (as much as 73 tritium units [TU]) in most of the area underlain by Cretaceous rocks, similar to those concentrations observed in groundwater of the Cretaceous aquifers (Nativ 1988). Figure 7a,b presents examples that demonstrate hydrochemical facies change in Ogallala groundwater, possibly resulting from upward cross-formational flow of groundwater from the Cretaceous aquifers.

In areas where the water table of the Ogallala aquifer is higher than the potentiometric surfaces of the Cretaceous aquifers (Fig. 6), the Ogallala aquifer is probably recharging the Cretaceous aquifers.

Cretaceous and Dockum Aquifers

Generally, the potentiometric surface of the Dockum aquifer is lower than those of the Cretaceous aquifers by 20–230 m, suggesting downward flow from the Cretaceous aquifers into the Dockum aquifer wherever lithologic contacts are permeable (Fig. 8). However, the isotopic composition of groundwater in the Cretaceous aquifers ranges from -7.1 to -4.9 per mil for $\delta^{18}O$ and from -44 to -38 per mil for δD; these values are significantly less depleted than those measured in the Dockum aquifer (mean values of -8.3 and -59 per mil, respectively) (Fig. 5b). Consequently, Dutton and Simpkins (1989) ruled out the possibility of significant cross-formational flow from the Cretaceous aquifer into the Dockum aquifer.

Hydraulic-head difference between the Dockum and Cretaceous aquifers is least in areas of eastern New Mexico, where it varies from 38 m to zero. In this area, similar Na–mixed-anion water facies typifies water in both aquifers, suggesting upward leakage from the Dockum aquifer. Along the eastern boundary of the study area, the potentiometric surface of the Dockum aquifer is higher than that of the Cretaceous aquifer by 76 m. In this area, upward cross-formational flow can-

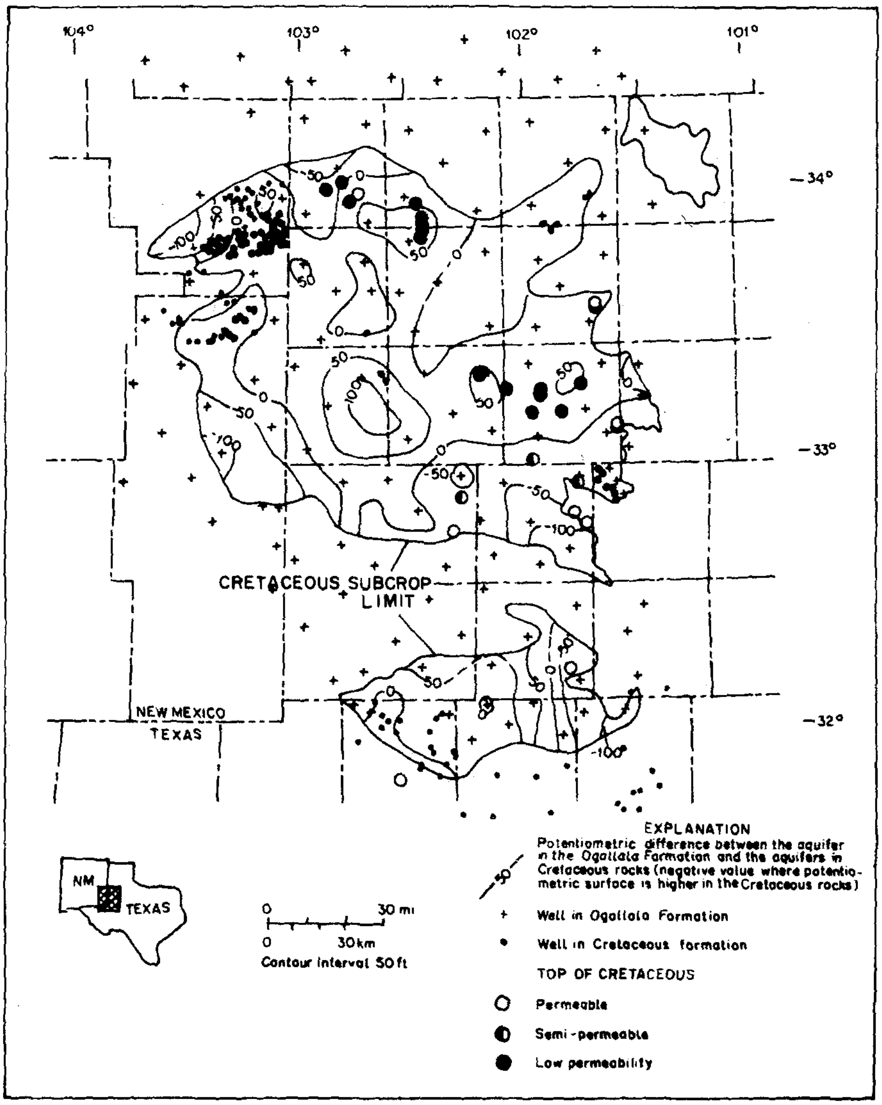

Figure 6. Permeability of the contact between Ogallala and Cretaceous rocks and hydraulic-head differences between these aquifers. Lithology is based on Brand (1953) and Seni (1980). Hydraulic-head data are from Texas Natural Resources Information System, Hudson (1976, 1978), and Hudson and Borton (1983). Criteria for permeability classification are listed in Nativ (1988).

not be tested chemically or isotopically because of scarcity of data (Nativ 1988).

Possible Recharge Mechanisms

Ogallala Aquifer

Upward discharge of water from the underlying formations into the Ogallala aquifer in certain areas has been discussed above. Recharge from above into the Ogallala aquifer can take place through diffuse infiltration directly into Ogallala outcrops and through Quaternary deposits that overlie the Ogallala in large areas. Recharge may also occur through local intake areas such as playa lakes or riverbeds. Such focused recharge can be much faster than diffuse recharge. Because annual precipitation is relatively small and most of the rains fall during the summer, when evapotranspiration is at its peak, only a small amount of water is available for recharge.

Precipitation. Direct recharge into the Ogallala has been studied extensively. Barnes and others (1949) suggested that recharge is reduced in areas in the northern Texas Panhandle where soil cover contains finer grain size. Caliche that formed in the upper surface of the Ogallala Formation has been regarded as a recharge barrier because it has very low permeability (Broadhurst 1942; Ries 1981; Knowles and others 1984). Indeed, transient water pulses did not exceed 10 m in 19 of 22 sites that were studied across the Texas Panhandle using neutron log measurements (Klemt 1981). In another study, Wood and Osterkamp (1984) observed that soil moisture did not vary below a depth of 2 m

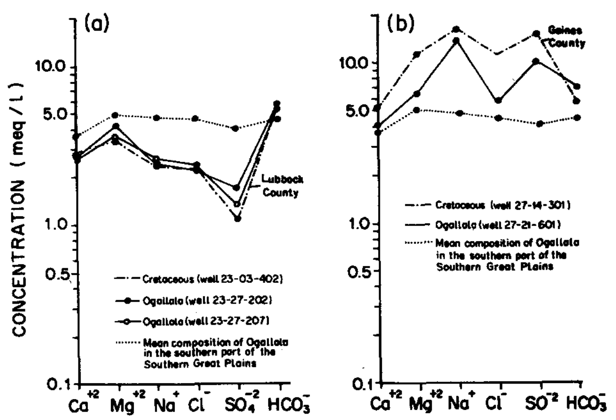

Figure 7. Salinity diagrams of groundwater in Ogallala and Cretaceous rocks in Lubbock County (a) and Gaines County (b), Texas. For county locations see Figure 1. The well numbering method used here was adopted from the Texas Department of Water Resources (Knowles and others 1984). The Ogallala and Cretaceous aquifers exhibit similar hydraulic heads. Ionic composition of groundwater in the Ogallala aquifer is similar to that of ground water in the Cretaceous rocks (but differs from the mean composition of water in the Ogallala in this part of the study area) and demonstrates that mixing due to upward movement of water from the Cretaceous aquifers probably does take place.

during a more than 2-yr period that included significant rain events. Because caliche was observed to be currently forming in their study area, they suggested that evaporation from the soil in their study sites is greater than recharge.

Surface runoff. Recharge probably also takes place along riverbeds because flowing rivers in the western and central sections of the Southern High Plains are nearly dry as they reach the Rolling Plains to the east. However, only a very small portion of the rainfall drains into the rivers, which traverse the High Plains (Knowles and others 1984), resulting in a poorly developed drainage system of these rivers. Consequently, the annual recharge from riverbeds into the Ogallala aquifer cannot be significant.

Playa lakes. The role of playa lakes in recharging the Ogallala aquifer is controversial. The large number of playa lakes, 20,000–30,000 (Ward and Huddlestone 1979), or one lake per 2–13 km^2, has attracted the attention of many who have studied the hydrology of the Southern High Plains. The surface area that drains into playa lakes is estimated to total 78,000 km^2 (Ward and Huddlestone 1979), or up to 89 percent of the entire Southern High Plains (Dvoracek and Black 1973). The amount of water that accumulates in these lakes annually is estimated to be 2.5–3.7 $\times$ 10^9 m^3 (Templer 1978, in U.S. Bureau of Reclamation 1982). Lotspeich and others (1971) and Dvoracek and Black (1973) noted that areas with finer soil cover in the northern part of the study area have larger but fewer lakes compared with the southern area, where soils are coarser.

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 have low permeability, at least shortly after playas are filled with water (Harris and others 1972; Knowles and others 1984). Caliche, which occurs throughout the Southern High Plains, is a second possible recharge barrier beneath the lake sediments (Knowles and others 1984). If soil and caliche permeability beneath playa lakes is very low, significant infiltration is prevented and much of the water must eventually evaporate. Various estimates of evaporation from playa lakes in the Southern High Plains range from 55 to 60 percent of the available water (Reddell 1965; Ward and Huddlestone 1979; U.S. Bureau of Reclamation 1982).

Other studies suggest that the playa lakes are 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, 1987). In 1937 and 1938, several hundred test holes were drilled in the beds of many playa lakes (White and others 1946). Some caliche was found under almost every playa, but in many cases the calcified layers included sand and were relatively permeable. Similar observations were reported by Osterkamp and Wood (1987). Shrinkage cracks in the playa-floor clays, in conjunction with solution channels that were commonly observed in the underlying caliche, seem to provide passageway for downward movement of water (Lotspeich and others 1971). Wood and Osterkamp (1984, 1987) believed that a ring of more permeable soil that surrounds the playa floor acts as the main recharge zone during periods of ponding. They suggested that the organic material introduced with the percolating water is oxidized to CO_2, which dissolves in the water, forms carbonic acid, and enhances the dissolution of the underlying caliche layers, thus increasing the subsurface porosity.

Lack of evaporites within the playa-floor sediments (Harris and others 1972) and absence of hallophytic flora also suggest that these playa-lake basins drain rapidly (even through the clay-covered playa floor) rather than accumulating salts as a result of evaporation. Low salinities of playa waters (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 beneath the playas than beneath interplaya areas, suggesting increased flushing by the percolating

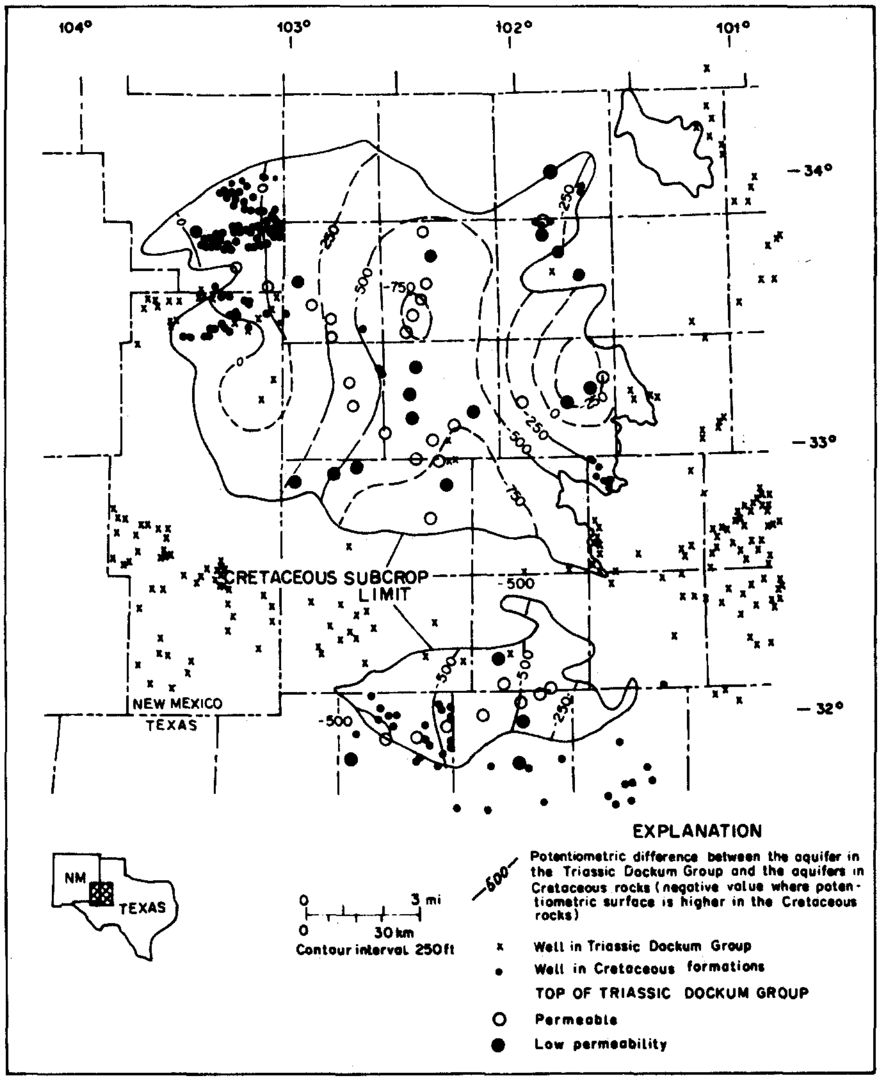

Figure 8. Permeability of the contact between Cretaceous and Triassic rocks, and hydraulic-head differences between these aquifers. Lithology is based on Brand (1953) and McGowen and others (1977). Hydraulic-head data are from Texas Natural Resources Information System, Hudson (1976, 1978), Hudson and Borton (1983), and Dutton and Simpkins (1986). Criteria for permeability classification are listed in Nativ (1988).

water. The presence of tritium in 12 of 62 groundwater samples in Lea County, New Mexico, at the end of the 1950s (Wood and Osterkamp 1984) and the recharge rates calculated by using chloride concentrations in soil profiles (Stone and McGurk 1985) suggest rapid recharge rates, indicative of focused recharge below playa lakes rather than of regional, slow, diffuse percolation.

Owing to conflicting hypotheses concerning recharge from playa lakes, a wide range of annual recharge rates into the Ogallala aquifer has been suggested (0–41 mm/yr) (Table 1). Researchers who have assumed that most of the water in playa lakes evaporates have excluded large quantities of water from potential recharge volumes, and their annual recharge estimates are small. Researchers who have assumed that playa lakes are the major source of recharge to the Ogallala aquifer have come up with higher recharge estimates.

Nativ and Smith (1987) assumed that if water in playa lakes mainly evaporates rather than infiltrates, playa-lake water should become more saline and isotopically enriched in δD and $\delta^{18}O$ relative to precipitation (Craig and Gordon 1965; Zimmermann 1979). They also assumed that if Ogallala groundwater is being recharged mainly by diffuse percolation over the region, it is expected to be isotopically enriched with regard to precipitation because precipitation becomes enriched in heavy isotopes at shallow depth in the vadose zone as a result of evaporation (Zimmermann and others 1967). The alternate hypothesis is that salinity and isotopic composition of playa-lake water should remain constant and similar to precipitation and groundwater composition if rapid and focused recharge beneath playa lakes occurs and evaporation is negligible. To determine recharge methods and, thereby, recharge rates, Nativ and Smith (1987) sampled rainfall on a daily basis during 1 yr at five stations across the Southern High Plains and collected playa-lake water and groundwater (Fig. 1).

On the basis of the similarity in the isotopic composition of precipitation and groundwater and the observed slight shift of playa-lake water and groundwater away from the local meteoric line (Fig. 5a,b), Nativ and Smith (1987) suggested that evaporation of rainwater in playa lakes prior to infiltration is small. Their estimates of recharge rates (12.7–82.3 mm/yr), using tritium in groundwater as a tracer, were higher than diffuse recharge rates (0.25–14.5 mm/yr) (Barnes and others 1949; Klemt 1981, Knowles and others 1984; Stone and McGurk 1985) and coincided better with recharge rates from playa lakes calculated by the U.S. Bureau of Reclamation (1982), Wood and Osterkamp (1984), and Stone and McGurk (1985) (12.2–41 mm/yr) (Table 1). Following these observations of the isotopic composition of precipitation, playa-lake water, and groundwater, Nativ and Smith (1987) suggested that recharge of the Ogallala aquifer is predominantly by focused percolation of playa-lake water.

A more decisive conclusion concerning the role of playa lakes in recharging the Ogallala aquifer can be reached if the problem is approached systematically, on a basin level, using hydrologic, hydrochemical, and isotopic tools. A reasonable approach would include: (1) monitoring the amount of precipitation in a playa basin, the volume of water stored in the playa lake and its variations with time, the evaporation from the lake, and the changes of soil moisture beneath the lake as well as beneath the interplaya divide area (this would have to be carried out in several basins for the purpose of preparing hydrologic balances for these basins) and (2) sampling precipitation, playa water, and soil water beneath the playa lake as well as beneath the interplaya divide area for chemical and isotopic analyses. Wood and Osterkamp (1987) observed that few data exist on dissolved solids in the unsaturated zone adjacent to playa-lake basins to support interpretations of recharge processes. The monitoring of water content as well as its chemical and isotopic composition along transects in several hydrologic settings will allow the determination of recharge distribution in the Ogallala aquifer and the role of playa lakes in focusing recharge. Testing sites to determine natural recharge from precipitation have to be selected carefully to avoid playa lakes that have received or currently receive irrigation runoff of pumped Ogallala water.

Cretaceous Aquifers

Recharge from the Ogallala and Triassic Dockum aquifers in areas where the hydraulic heads in Ogallala and Dockum aquifers are higher than the potentiometric surface of the Cretaceous aquifers has been discussed above. Potential recharge areas are marked in Figure 9.

Outcrops of Cretaceous formations in the study area are small and limited to narrow bands around playa lakes and to a few small exposures in eastern New Mexico. Some saline lakes in Texas are surrounded by small Cretaceous outcrops but probably function as drains rather than recharge areas into the aquifer, as the evaporation of the exposed groundwater is probably greater than the recharge from direct precipitation on the lakes. As a result, direct recharge from outcrops into the aquifers is probably insignificant.

Percolation from Quaternary sand dunes and alluvium in eastern New Mexico (Lansford and others 1982), where the Ogallala Formation is absent (Figure 9), is another viable recharge source into the Cretaceous aquifers. Tritium in groundwater of the Cretaceous aquifers ranges from 1.1 to 68.2 TU. The highest tritium concentration was found in the Trinity sandstone aquifer at the western part of the northern Cretaceous subcrop. Fast recharge into the Quaternary sand dunes, followed by percolation into the Cretaceous aquifer, probably accounts for the high tritium content in groundwater there. Low tritium concentration was observed far from the suggested recharge zone—in the Trinity sandstone and Edwards limestone aquifers in the eastern parts of the study area. More groundwater samples from beneath the sand dunes area need to be analyzed for tritium to test the relative importance of this area as a major recharge zone for the Cretaceous aquifers.

Dockum Aquifer

The location of groundwater divides in the Dockum aquifer, according to Dutton and Simpkins (1989), precludes any significant recharge from the Dockum outcrops along the Pecos and Canadian rivers into the Southern High Plains. Because depletion in $\delta^{18}O$ and δD cannot be the result of any known mechanism of isotopic evolution of flowing groundwater, recharge from the overlying Ogallala or Cretaceous aquifers containing groundwater that is relatively enriched in $\delta^{18}O$ and δD also has to be insignificant (Nativ and Smith 1987). Dutton and Simpkins (1989) suggested that the depleted isotopic composition of water stored in the Dockum aquifer reflects the influence of Pleistocene climatic variations and the altitude effect of the previous recharge zone of the Dockum aquifer in eastern New Mexico, before it was cut off by the incising Pecos and Canadian rivers. Low transmissivities of the aquifer helped preserve these features, whereas higher transmissivities in the overlying Ogallala and Cretaceous

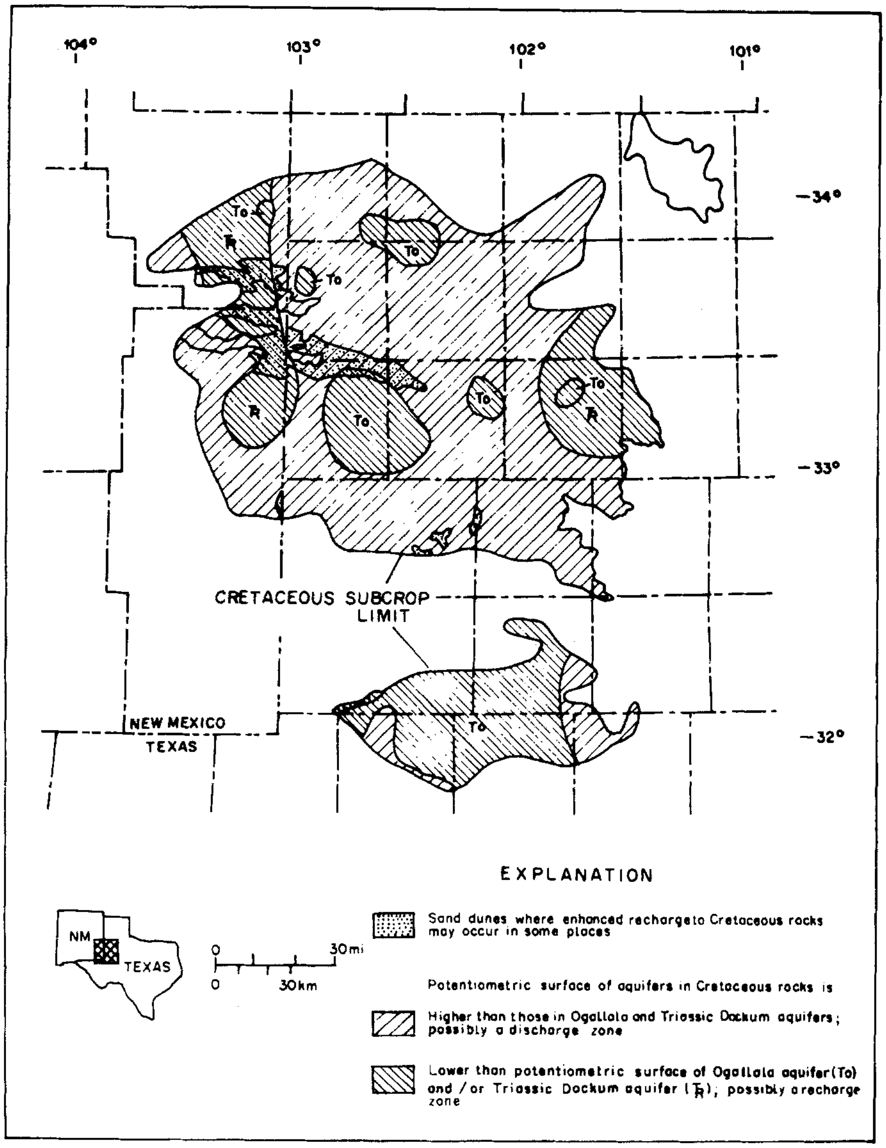

Figure 9. Schematic map of possible recharge and discharge zones of Cretaceous aquifers.

aquifers allowed continued recharge and flushing during the Holocene.

Carbon-14 dating of groundwater in the Ogallala, Cretaceous, and Dockum aquifers could support the above-mentioned suggestions. Within the Dockum aquifer, groundwater dating has to be carried out near the suggested water divide to support the assumption that the outcrop areas do not contribute much recharge into the aquifer beneath the Southern High Plains. Groundwater sampling also needs to be carried out at different depth intervals within the Dockum Group (in the Upper Dockum aquifer and in the Lower Dockum aquifer) to test the assumption that leakage from above is insignificant. If groundwater in the Dockum aquifer is of Pleistocene age, then percentage of modern carbon should be very low or nil.

Conclusions

The Ogallala aquifer has traditionally been considered to recharge the underlying Cretaceous and Triassic aquifers in the Southern High Plains. Estimates of the natural recharge into the Ogallala vary by two orders of magnitude (0–41 mm/yr). On the basis of hydrologic, chemical, and isotopic evidence, Cretaceous aquifers may have independent recharge sources, whereas the Triassic aquifer may not receive any current recharge. In places, both the Cretaceous and the Triassic aquifers may contribute groundwater and solutes into the Ogallala aquifer. Because playa lakes seem to have a major role in recharging the Ogallala aquifer, the higher estimates of focused recharge rates are more realistic than the lower values of diffuse recharge.

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