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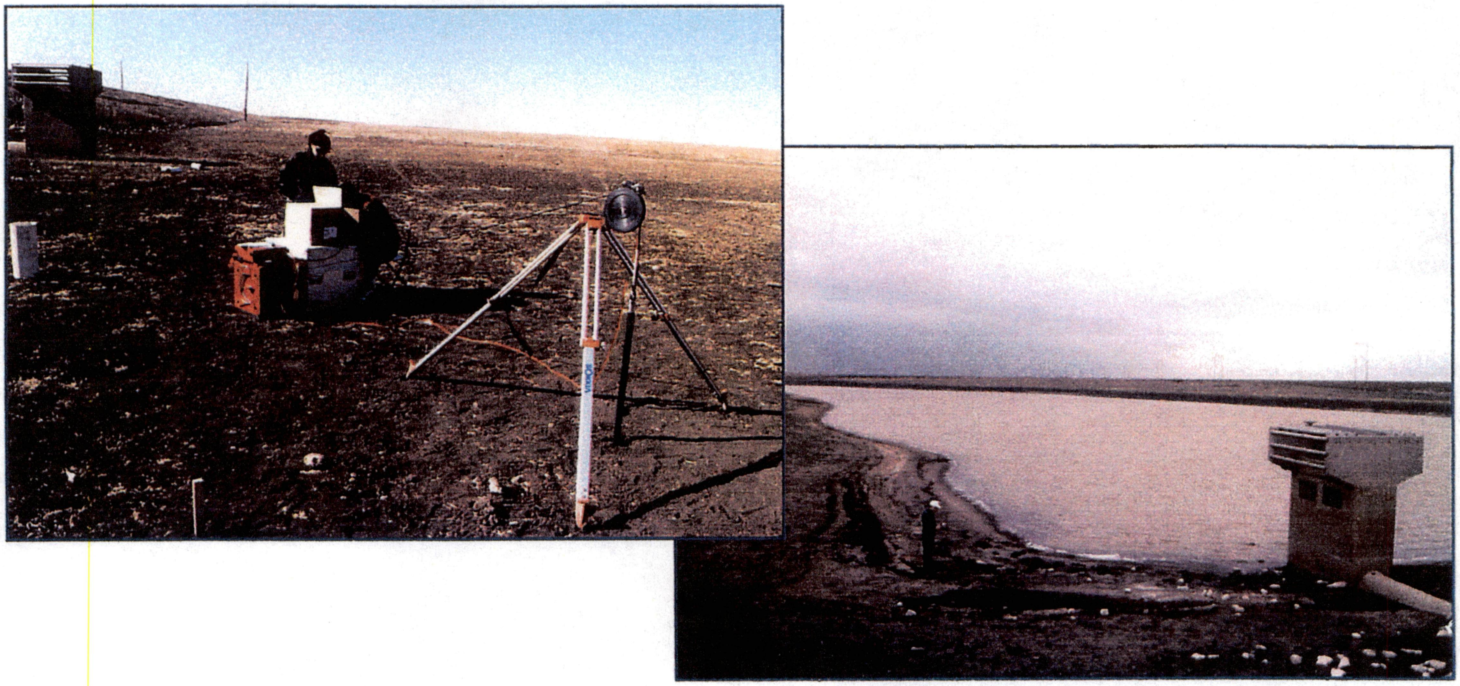

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CONTENTS

Figures

Tables

EXECUTIVE SUMMARY

Preserving, conserving, and optimizing the use of groundwater from the Ogallala aquifer is a critical issue for the Southern High Plains because of continuing demands on groundwater coupled with decreasing groundwater levels. This study evaluates groundwater recharge from Soil Conservation Service (SCS) (currently the Natural Resources Conservation Service) reservoirs to determine if recharge could be enhanced by increasing the storage capacity or by modifying the surfaces of the reservoirs.

There are three phases to this study: a technical evaluation, an engineering feasibility study, and a legal and regulatory analysis. This report presents the technical evaluation and includes the results of surface water modeling and field studies on two of the six reservoirs in Running Water Draw in Hale County, Texas. These reservoirs were installed in 1976 and 1982 by SCS for flood control. Under current state law, reservoirs cannot store more than 200 acre-feet of water unless a permit is obtained from the Texas Natural Resource Conservation Commission (TNRCC).

The SCS 3 reservoir was dry throughout the study period (March 1999-October 2000). Surface water modeling, based on data from 1950 to 1978, shows SCS 3 had runoff ranging from 1 acre-foot in 1976 to 9,380 acre-feet in 1950. This indicates the reservoirs could store much more water during periods of above normal precipitation. Under current regulations, a maximum of 1,200 acre-feet from all six reservoirs is available for storage. Currently, two of the six SCS reservoirs in Running Water Draw have obtained permits and installed plugs to increase storage capacity from 200 acre-feet per reservoir to 424 and 4,427 acre-feet (4,851 acre-feet total). If the area experienced a flood similar to the one in 1941, 24,569 acre-feet of surface water would be available for storage. If the highest recorded annual rainfall (1941) were to occur again, 31,353 acre-feet of surface water would be available for recharge.

Inflows of irrigation return flows into the SCS 4 reservoir resulted in about 155 acre-feet of ponded water during a six-month period (March-September 2000) during the study. Approximately 35 percent of this water evaporated, while the remaining 65 percent infiltrated. Some of the infiltrated water eventually evaporated from the soil. The rest ultimately will recharge the aquifer. Assuming the average reservoir capacity is 1,985 acre-feet and all reservoirs in Running Water Draw have the same infiltration rate as SCS 4 (65 percent) and the current storage limitations were eliminated from the other four SCS reservoirs, the potential infiltration from a 50- to 100-year flood event would be approximately 7,742 acre-feet for all six reservoirs. Actual recharge would depend on the evaporation rate of the infiltrated water.

SCS 3 and SCS 4 had fine-grained sediments in the upper one to three feet of the reservoirs and coarser sediments at greater depths. Previous studies conducted on playas indicate removing surficial fine-grained sediments could increase recharge by 10 times. Modifying fine-grained sediments in the SCS reservoirs may also increase recharge. Modifying SCS reservoirs would impact local recharge; however, it would not enhance recharge throughout the region.

Senate Bill 1 requires the Regional Water Planning Groups (RWPG) to determine the economic impact of not being able to meet future water needs. The Llano Estacado RWPG has determined the region would lose approximately $340 of output and $68 of income per acre-foot of irrigation water that is not available. A conservative estimate of the cost of obtaining permits for the four SCS reservoirs is $20,000 (includes cost of installing plugs). This is based on TNRCC's maximum fee of $5,000 per permit. Modifying surface sediments to enhance recharge on a flood-event basis is estimated to cost $18,000, or $3,000 per SCS reservoir. Together, the total cost of potentially enhancing recharge from 3,673 to 7,742 acre-feet during a 50- to 100-year flood event would be $38,000, or $9.34 per acre-foot. The cost-benefit analysis of installing plugs in the four remaining SCS structures in the Running Water Draw and modifying surface sediments in all six would be positive, especially if considered on a local basis.

Recommendations for Future Work

Additional studies would be required to assess the feasibility of enhancing recharge by modifying soil profiles. Surface water modeling would also be required to quantify runoff from surface water drainages, such as Running Water Draw, and to help determine the impact of efforts to enhance recharge on downstream surface water rights. Specifically, the additional studies would increase the storage capacity and modify fine-grained sediments in selected reservoirs. Detailed monitoring would be conducted to quantify recharge. General statistics and surface water characteristics would be assessed for all of the 62 reservoirs in the Southern High Plains, and the net impact on recharge would be evaluated.

This study focused on drainages. However, surface water bodies drain only 10 percent of the surface area of the Southern High Plains. Playas drain 90 percent. Previous studies indicate recharge may be enhanced by removing fine-grained sediments in playas. Enhancing recharge in playas could impact recharge to the aquifer to a much greater extent than altering SCS reservoirs. As such, any future studies should also include playas. (Modifications to playas may require a permit from the U.S. Army Corps of Engineers due to the potential for designation of playas as wetlands.)

Upon completion of efforts related to the SCS reservoirs, the next phase of this study could include evaluation of playa modification to enhance recharge. Future studies could include a classification of playas based on Landsat imagery, include color IR photography.

Recharge enhancement could concentrate on playas whose ponding times fall in the midrange based on the length of ponding. About 30 to 50 playas could be identified for recharge enhancements. This would result in about one to two playas per county. If possible, duplicate playas could be identified that have similar characteristics. Recharge enhancement could be conducted at one of the two playas, and the effectiveness of enhancing recharge could be quantified by comparing the results with the recharge evaluation from the control playa. Recharge may be enhanced by removal of surficial fine-grained sediments. If these sediments are thick, trenches could be dug to penetrate the fine-grained zone. Monitoring data from modified playas and comparison with control playas would allow quantification of increased recharge through playas as a result of modifying these structures.

INTRODUCTION

The Ogallala aquifer is the main source of water for the Southern High Plains region of the Texas Panhandle. This region is the agricultural center of Texas. In 1994, 5.9 million acre-feet of water was pumped from the Ogallala, 96 percent of which was used for irrigation. It is vital to preserve and optimize this resource in order to support the farmers and ranchers in the region.

The study area is located in the Southern High Plains, which is characterized by flat to gently rolling terrain that dips slightly to the southeast. Approximately 90 percent of the land surface is drained internally by about 20,000 ephemeral lakes or playas. These playas have an average surface area of 19 acres (Fish and others, 1998).

There are 62 SCS reservoirs in the Southern High Plains (fig. 1). Most (56) of these reservoirs are in the northern portion of the Southern High Plains in the Canadian and Red River Basins. The remaining six reservoirs are in Running Water Draw. Parts of Running Water Draw have flooded in the past. A workplan, Running Water Soil and Water Conservation District (1968), focused on the feasibility of building retention ponds to prevent floodwater damage as was experienced in Plainview in 1941, 1950, 1960, and 1965. U.S. Geological Survey (USGS) stream gauge records from 1939 to 1978 show the 1941 flood caused the highest daily mean stream flow on record. Analysis of the 1941 flood revealed that the peak output was 3,710 cubic feet per second (cfs) that resulted from an estimated 38-year-frequency storm. In addition to reducing flooding, the SCS reservoirs may also recharge the Ogallala aquifer. Recharge may be enhanced if the capacity of these reservoirs is increased beyond the regulated 200 acre-feet and/or if surface fine-grained sediments are removed.

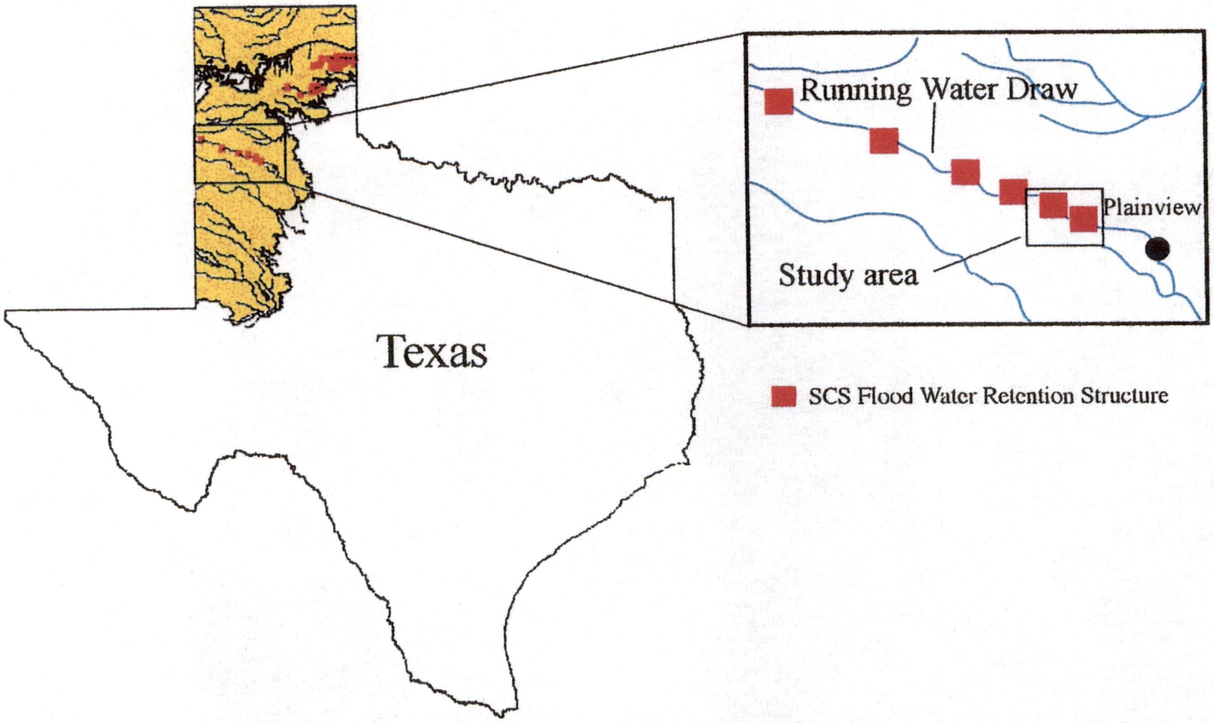

Figure 1. Location of SCS reservoirs in the Southern High Plains. Inset map shows reservoirs along Running Water Draw.

The objective of this project was to evaluate the recharge potential of SCS reservoirs and the feasibility of enhancing recharge by conducting detailed studies of two reservoirs in Hale County, Texas. Potential mechanisms of enhancing recharge evaluated in this study include increasing the reservoir storage capacity beyond the regulated amount of 200 acre-feet and/or modifying the fine-grained sediments present at the surface of these reservoirs. (Note: Reservoirs with <200 acre-feet storage capacity to be used for domestic or livestock purposes are exempt from TNRCC permitting requirements, whereas reservoirs with a storage capacity >200 acre-feet require a permit, regardless of intended use.)

Running Water Draw is one of four drainages in the Texas Panhandle with SCS reservoirs (fig. 1). Three of the drainages, containing a total of 56 SCS reservoirs, are located in the Canadian and Red River Basins. Running Water Draw, located in the Brazos River Basin, with a total of six reservoirs, has the highest average floodwater retention per structure at 4,196 acre-feet. Running Water Draw was the optimum study area, considering the high potential floodwater retention, the low number of reservoirs involved for potential modification, and greater percentage of irrigation water pumped per county from the Ogallala aquifer.

Previous Work

Specific research has not previously been conducted on recharge in SCS reservoirs. However, these reservoirs are similar to playas in that they pond water. Therefore, playa studies may be somewhat applicable to reservoirs.

Natural Recharge

Our understanding of recharge in the Southern High Plains has evolved over time. It is important to describe our conceptual understanding of recharge processes to the Ogallala aquifer to evaluate the potential impact of reservoirs on groundwater recharge. The following provides an account of the evolution of our conceptual understanding of recharge in the Southern High Plains that is primarily updated from a similar account provided by Mullican and others (1997). A vast amount of research has been conducted on recharge in the Southern High Plains. Most regional recharge values are 0.04 to 1 inch/year (Mullican and others, 1997; table 1). From about 1900 to 1965, recharge was considered to be focused through playas. However, from mid-1960s to 1980, playas were considered evaporation pans. Data from many studies from 1980 to the present indicate that playas are focal points of recharge.

Studies dating back to the early 1900s (Johnson, 1901) suggested that recharge is not uniformly distributed and that playas focus recharge. Gould (1906) proposed that recharge to the Ogallala aquifer occurs by downward percolation of rain through playas and noted the existence of perched water tables above the Ogallala aquifer. An improved understanding of recharge to the Ogallala aquifer was developed by Baker (1915), who recognized that desiccation cracks in the playa bottoms might serve as recharge conduits. A comprehensive study that included

Table 1. Published recharge values, Southern High Plains (modified from Mullican and others, 1997).

Author	Areal or focused recharge	Recharge (in/ yr)	Recharge (mm/ yr)
Johnson (1901)	Regional	3–4	76–102
Gould (1906)	Regional	5.98	152
Theis (1937)	Regional	0.13–0.67	3.2–17.0
Cronin (1961)	Regional	0.51	13
Havens (1966)	Regional	0.81	20.6
Aronovici and Schneider (1972)	Interplaya	0.00	0
Brown and Signor (1973)	Regional	0.02–0.08	0.6–2.0
Bell and Morrison (1979)	Regional	0.51	13
Klemt (1981)	Regional	0.19	4.8
U.S. Bureau of Reclamation (1982)	Regional	0.94	24
Wood and Osterkamp (1984)	Regional	0.10	2.5
Wood and Osterkamp (1984)	Playa	1.57	40
Wood and Petraitis (1984)	Regional	0.10	2.5
Wood and Petraitis (1984)	Playa	1.57–1.97	40–50
Knowles (1984)	Regional	0.20	5.1
Knowles and others (1984)	Regional	0.06–0.25	1.5–6.3
Gutentag and others (1984)	Regional	0.06–0.11	1.4–2.8
Stone (1984)	Sand hills	0.05	1.25
Stone (1984)	Nonirrig. cover sand	0.01	0.24
Stone and McGurk (1985)	Playa	0.48	12.2
Stone and McGurk (1985)	Interplaya	0.03	0.75
Nativ (1988)	Playa	0.51–3.15	13–80
Stone (1990)	Interplaya	0.03	0.75
Nativ (1992)	Regional	1.18	30
Mullican and others (1994)	Playa	8.62	219
Mullican and others (1994)	Regional	0.24	6
Dugan and others (1994)	Regional	0.51–1.5	13–38
Wood and Sanford (1995)	Regional	0.43±0.08	11±2
Wood and Sanford (1995)	Playa	3.03±.31	77±8
Scanlon and others (1997)	Playa	2.36–4.72	60 – 120
Mullican and others (1997)	Interplaya	<.004	< 0.1

drilling of monitoring wells, coring, and stream gauging was undertaken in 1942 by Broadhurst. According to this study, exceptionally high rainfall in 1941 caused water levels in wells located adjacent to the playas to rise more than 10 ft, whereas water levels in wells located in upland or interplaya settings showed little change. Broadhurst's results were consistent with the findings of Theis (1937), who suggested that recharge by infiltration of rainwater is not uniform across the Southern High Plains but is focused through the playa lakes. White and others (1946) confirmed the direct relationship between changes in Ogallala aquifer water levels and recharge through playa lakes. The authors collected detailed rainfall and water-level data in Deaf Smith, Hale, Floyd, and Lubbock Counties and noted local water-level increases of as much as 6 ft due to heavy rains. Barnes and others (1949) attributed variable recharge rates within individual playas to the extent of caliche development and the configuration and structure of the materials lining the playa floors. Subsequent studies by Cronin (1961) and Havens (1966) identified various factors impacting the infiltration and quantified the recharge rates. Cronin (1961) estimated that 35 percent of the water accumulated in playas reaches the Ogallala aquifer. He proposed that increased recharge rates are caused by the "annular ring" of playas, a belt of permeable sediments surrounding the playas. Havens (1966) suggested that 20 to 80 percent of the water collected on the playa floors reached the Ogallala aquifer as recharge and confirmed Cronin's (1961) theory of increased percolation rates through the permeable playa slopes. According to Havens (1966), seepage from irrigation also contributes to the overall recharge. Clyma and Lotspeich (1966) agreed that playa lakes were the principal source of aquifer recharge but thought the infiltration amounts suggested by Havens (1966) and Cronin (1961) were too great. On the basis of a comparison of pan evaporation rates and volumetric changes measured in water ponding in a Bushland playa, Clyma and Lotspeich (1966) estimated that only 15 percent of the water in the lake reaches the aquifer. This estimate conflicts with an earlier estimate by Redell and Rayner (1962), who reported that at five playa lakes around Lubbock, 54 to 84 percent of the surface water reached the Ogallala aquifer.

The conceptual model of recharge to the Ogallala aquifer changed markedly in the mid 1960s to about 1980. During this period recharge through playas was thought to be negligible because of thick clay soils, and playas were considered evaporation pans. Ward and Huddleston (1972) looked at how local playa geology impacts downward percolation of water and concluded that infiltration rates in 11 Lubbock County playa lakes were strongly dependent on the clay content in the top foot of soil. The authors estimated that about 90 percent of surface water evaporated while the remainder percolated through the playa floor at a sharply declining rate before reaching a steady state. Bell and Sechrist (1972) also concluded that most of the playa water was being lost to evaporation so that "water in the shallow lakes could only be expected to remain for a few days." However, in 1979, Bell and Morrison argued that changes in the topsoil structure caused by agricultural practices have led in recent times to higher and faster aquifer recharge. A 1982 report by the U.S. Bureau of Reclamation concluded that although playa lakes are the largest contributor of recharge to the Ogallala aquifer, most of the water that accumulates in them is lost through evaporation. Field monitoring techniques and satellite imagery were employed in an effort to determine the percentage of High Plains playa lakes that held water in the wet and dry periods. The authors discovered that 15 percent of the playas held water during the wet period, and 2 percent of the playas held water during the dry season.

Beginning in the early 1980's, the conceptual model of recharge to the Ogallala aquifer shifted back to the original model of the system, which indicated that playas focus recharge. Wood and Osterkamp (1984, 1987) conducted detailed studies of recharge to the Ogallala aquifer. They used historical water level records, tritium data, vadose zone geochemistry under playa and interplaya settings, lake water chemistry, vegetation data, chloride mass-balance profiles, and water budget studies. Wood and Osterkamp (1987) proposed that most infiltration occurs through the annulus surrounding the playa. Wood and Petraitis (1984) monitored groundwater levels after rainfall events and investigated the pore-water chemistry in the unsaturated zone. They concluded that most of the Ogallala aquifer recharge occurs predominantly through playas. The soil-water chloride mass-balance approach was used by Stone (1984, 1990,) and by Stone and McGurk (1985) in playas and interplayas to estimate recharge rates. They concluded that playa lakes furnish most of the recharge and that nonirrigated interplaya land had the lowest percolation rates. Nativ (1988) studied the isotopic composition of groundwater below playa lakes and concluded that the Ogallala aquifer is most likely recharged by focused percolation of partly evaporated playa-lake water rather than by slow regional diffusive percolation of precipitation. On the basis of chemical and isotopic data in the Southern High Plains, Nativ (1992) suggested recharge rates of 1.2 inches/year to the Ogallala aquifer.

Mollhagen and others (1993) evaluated the potential for nonpoint source pollution at 99 playa lakes in the Brazos River Basin by comparing the levels of chloride in local precipitation with chloride concentrations in soil water. Their results suggest that playa lakes are flushing chloride through the vadose zone, thus recharging the aquifer. Scanlon and Goldsmith (1997) and Scanlon and others (1997) conducted a detailed study to quantify spatial variability in recharge beneath playa and interplaya settings. Water contents, water potentials, and tritium concentrations were much higher and chloride concentrations were much lower beneath playas than in interplaya settings, which indicated that playas focus recharge. The results refute previous hypotheses that playas act as evaporation pans or that recharge is restricted to the annular region around playas. Water fluxes estimated from environmental tracers ranged from 2.4 to 4.7 inches/year beneath playas and ≤0.004 inches/year beneath natural interplaya settings not subjected to ponding or irrigation. To reconcile the apparent inconsistency between high recharge rates and thick clay layers beneath playas, ponding experiments were conducted, which showed preferential flow along roots and desiccation cracks through structured clays in the shallow subsurface in playas. Wood and others (1997) used a water budget approach combined with chemical data to show that 60 to 80 percent of recharge to the Ogallala aquifer occurs through macropore flow. Mullican and others (1997) numerically simulated groundwater flow and showed that the playa-focused recharge theory is hydrologically plausible.

Several other researchers (Knowles and others, 1984; Weeks and Gutentag, 1984) suggested that recharge to the Ogallala aquifer occurs chiefly by infiltration of precipitation on formation outcrops and streams' seepage, thus discounting the playa theory. Knowles and others (1984) indicated the caliche layers overlying the Ogallala aquifer may impede the recharge and emphasized the recharge rates are not uniform but vary as a function of local soil composition. Stone (1990) also concluded that water reaches the aquifer by infiltration through dry channels.

Enhanced Recharge

The possibility of using water ponding in the playas to enhance the recharge to the Ogallala aquifer has been considered since it became clear more groundwater was being removed from the aquifer than was being returned through natural recharge. Numerous field experiments, dating back at least to 1955, have been undertaken to test the feasibility of artificial recharge of groundwater. The most popular methods of artificial recharge were (1) the use of water-spreading basins from which water infiltrates to the water table and (2) the use of injection wells to pump water into the aquifer. The most common problem encountered with the use of surface runoff water was clogging of the recharge basins by the sediments suspended in the water. Dvoracek and Peterson (1969) achieved recharge rates of as much as 1.5 ft per day from pits located on the outer perimeter of a playa near Lubbock. However, continued infiltration of high-sediment-content waters reduced rates to 0.1 ft per day. The authors concluded "some clarification of water is required for economical and efficient artificial recharge."

Aronovici and others (1972) conducted several tests on recharge basins excavated beneath Pullman clay soils (depth ~4 ft) adjacent to a playa near Amarillo, Texas. Two model basins (A and B) were excavated. Each basin was 66 ft^2 in area. Basin A was filled with turbid water from the nearby playa and was flooded for 65 days, whereas Basin B was filled with clear water and was flooded for 46 days. The flooding depth ranged from 1 to 1.5 ft. Initial water contents in the sediments were 0.19 ft^3/ft^3, and final water contents were 0.37 ft^3/ft^3. The wetting front advanced at about 0.45 ft/day in both basins. The percolation rate changed from 1.5 ft/day to 2.0 ft/day and gradually increased to 4 ft/day on the 26th day. Percolation rates in Basin A decreased after that to a minimum of 1 ft/day because of surface sealing, whereas rates in Basin B continued to increase to 7 ft/day. The total percolation for Basin A was 147 ft in 65 days, and for Basin B was 196 ft in 46 days. As a result of these studies a 1-acre prototype basin (C) was built (Schneider and Jones, 1988) that was 660 ft long by 66 ft wide. The total recharge in Basin C was ~230 ft over 187 days as a result of various tests conducted between 1971 and 1978. The average recharge rate over this period was 0.37 ft/day. In contrast, excavation of a basin in a playa (Signor and Hauser, 1968) resulted in recharge rates that decreased to 1.5 inch/day because of low-permeability sediments. Various basin management techniques were also investigated, including scraping the surface and using organic mats. Corrugations up and down the slopes combined with a drain allowed the basin to recharge over the 7-year period without any other type of invasive management.

Irrigation return flow may also provide a significant amount of recharge to the Ogallala aquifer; however, studies have not been conducted specifically to quantify the contribution of irrigation return flow to recharge. Recharge from irrigation water may greatly exceed natural recharge in interplaya settings.

The current conceptual model of groundwater recharge in the Southern High Plains is that most recharge is focused beneath playas with very little recharge beneath interplaya settings. This would suggest that recharge should also be focused beneath reservoir impoundments. Studies of enhanced recharge indicate that basin modification can significantly increase recharge rates in playas. Similar modifications in reservoirs may also increase recharge beneath these reservoirs.

Site Description

The study area is in the Running Water Draw catchment in the Southern High Plains region of Texas (figs. 2 and 3). It is a subbasin of the Brazos River Basin and the uppermost headwater tributary of the Brazos River. Parts of Hale, Lamb, Swisher, Castro, and Parmer Counties are within the basin. The basin land use and land cover are predominantly agricultural. The upper part of the basin is in New Mexico. A USGS gauging station (08080700) is located in Plainview, Texas, which is the basin outlet. The drainage area upstream of the Plainview gauging station is 1,291 mi^2. Daily flow records are available from 1939 through 1978. The

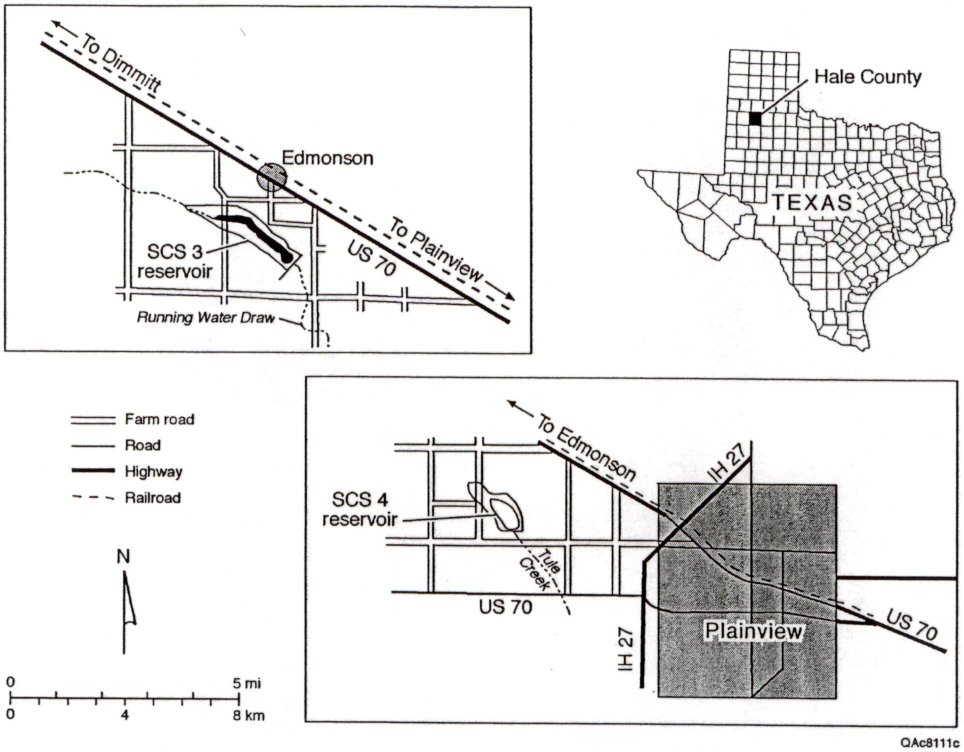

Figure 2. Location of study area that includes Soil Conservation Service (SCS) reservoirs.

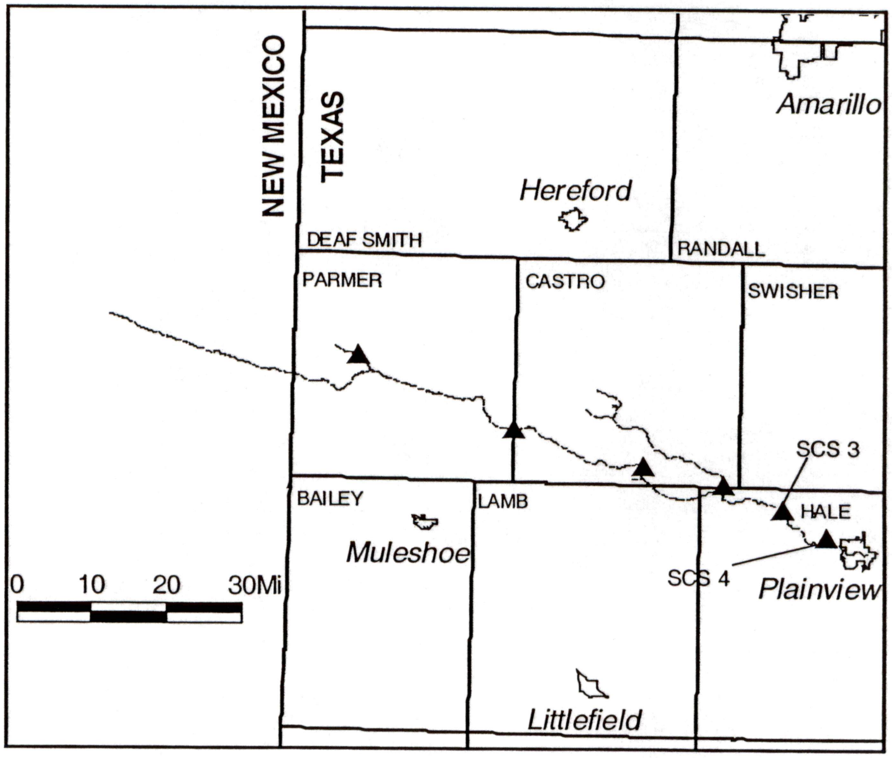

Figure 3. The catchment for Running Water Draw upstream of the Plainview gauging station.

average annual stream flow from 1939 to 1978 is 3.06 cfs, and maximum flow if 3,710 cfs. However, the records for 1954 and 1955 are missing, and records for some years are incomplete.

Six reservoirs were installed along Running Water Draw for flood mitigation in northwest Hale County (latitude 34.2N, longitude 101.8W), approximately 45 miles from Lubbock, Texas (app. B). The SCS 3 reservoir is located approximately 2.5 miles southeast of the city of Edmonson (fig. 2). It has a drainage area of about 28,000 acres. SCS 3 reservoir began operating on February 2, 1982. SCS 4 reservoir is located approximately 3 miles west of Plainview and 1 miles north of State Highway 70. This reservoir was placed on a tributary to Running Water Draw, which intercepts drainage from approximately 6,200 acres. SCS 4 reservoir began operation November 29, 1976. SCS 4 reservoir also receives irrigation return flow from nearby farm plots. The floor of the reservoir is often muddy. Information on surface area, capacity, release rate, and estimated hydraulic conductivity of reservoir floor is listed in table 2. Local farmers indicate that historically more water was available from irrigation return flow in the 1970s and 1980s and SCS reservoirs were frequently filled during this time period.

Table 2. Areas, capacities, and release rates for SCS 3 and SCS 4 reservoirs.

Reservoir number	Emergency spillway		Principal spillway (1)		Principal spillway (2)		Release rate (cfs)	
	Area (acre)	Capacity (acre-feet)	Area (acre)	Capacity (acre-feet)	Area (acre)	Capacity (acre-feet)	(1)	(2)
SCS 3	775	8,213	408	2,959	580	5,362	946	2,404
SCS 4	228	1,712	92	424	Only one spillway		95	

The drainage area upstream of the Plainview gauging station is 1,291 mi^2. Daily flow records are available from 1939 through 1978. The average annual stream flow from 1939 to 1978 was 3.06 cfs, and maximum flow was 3,710 cfs. However, the records for 1954 and 1955 are missing, and records for some years are incomplete.

The climate is semiarid with long-term mean annual precipitation of 17.3 inches, according to precipitation records for Hart, Texas (fig. 2, ID 413972) collected from 1955 to 1979 (fig. 4). Rainfall is highest during the summer months and peaks in June (fig. 4). In addition, the SCS reservoirs also receive irrigation return flow.

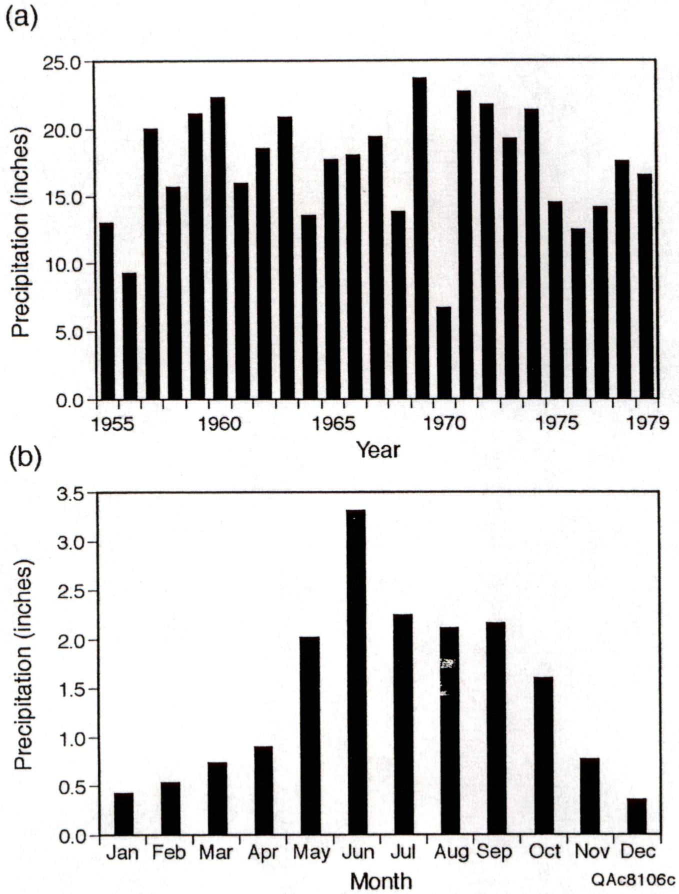

Figure 4. Mean (a) annual and (b) monthly precipitation measured at the Hart weather station from 1955 to 1979.

A mapping study conducted by Texas Tech University indicates that the average playa surface area is about 19 acres (Fish and others, 1998). Playa lakes are concentrated in the study area (fig. 5). Table 3 lists the number and combined area of playa lakes in the counties in the Running Water Draw watershed. The depth to groundwater in the vicinity of the reservoirs ranges from 180 to 240 ft, according to a synoptic water-level survey conducted in January 2000.

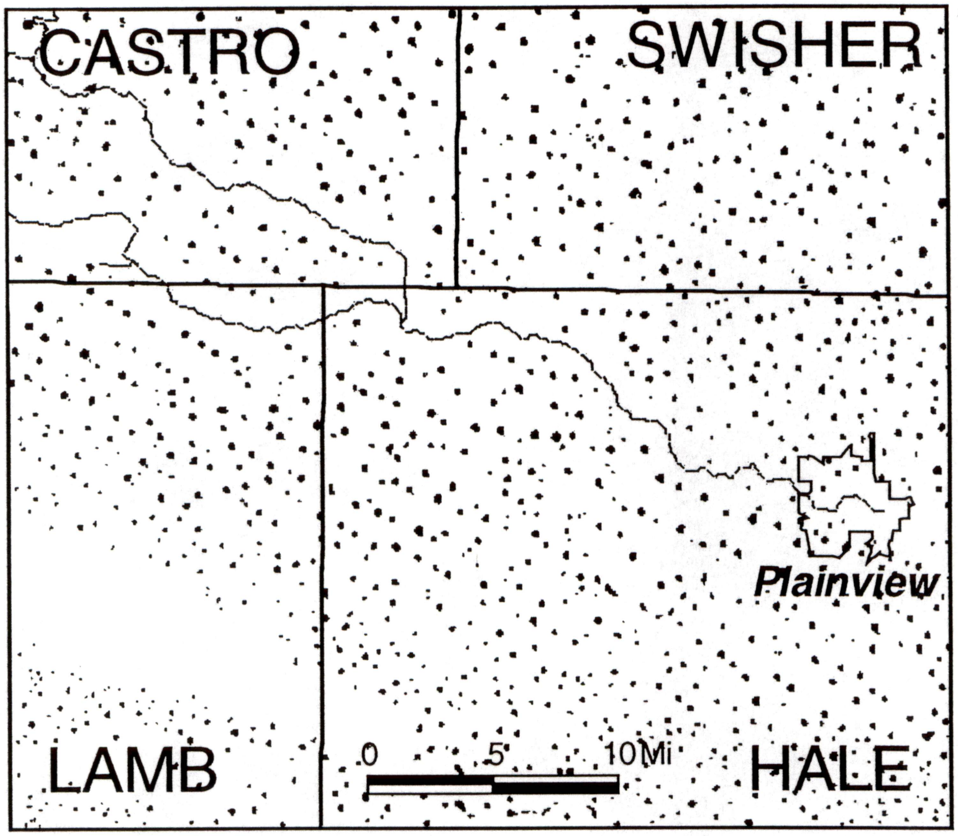

Figure 5. Location of playa lakes in the study area (from Fish and others, 1998).

Table 3. Playa statistics for the study area (from Fish and others, 1998).

County	No. of playas	Total playa floor area (acres)	Percent of county
Castro	610	19,100	3
Lamb	1,150	13,000	2
Hale	1,249	26,000	4
Parmer	433	9,800	1

METHODS

A variety of different approaches were used to evaluate recharge beneath SCS reservoirs. Surface-water modeling was conducted with Soil and Water Assessment Tool (SWAT) (Arnold and others, 1994) to estimate surface-water inflow to the reservoirs. Field studies included electromagnetic induction to evaluate spatial variability in soil texture, salinity, or water content. Boreholes were drilled and soil samples analyzed for soil texture, water content, and chloride. Textural analyses were used to determine if there is a surficial layer of fine-grained sediments that might greatly reduce infiltration beneath SCS reservoirs. Spatial variability in water content was used to estimate areas of low and high infiltration. Chloride concentrations in soil pore water were used to estimate infiltration rates. If chloride input to a system is uniform, then low chloride concentrations generally indicate high water fluxes as chloride is flushed out of the sediments, whereas high chloride concentrations indicate low water fluxes where chloride accumulates as a result of evapotranspiration. Permeability tests were also conducted to determine if permeability of the sediments increases with depth. Such analyses helped assess whether removal of surficial sediments would impact infiltration.

Surface-Water Modeling

Version 99.2 of SWAT (Neitsch and DiLuzio, 1999) that uses a Geographic Information System (GIS) interface (ArcView) was used in this study to evaluate surface runoff in the Running Water Draw catchment and to estimate the amount of water reaching the reservoirs. Surface-water simulations were conducted for 1950 through 1978 because of the availability of climatic data for that time period. The USGS surface-water gauge was removed from Plainview in 1979. SWAT uses daily input data for the simulations. Stream flow was calibrated using gauge data from the USGS Plainview station (8080700).

The main features of SWAT are

- Surface runoff from daily rainfall is predicted. Runoff volume is estimated with a modification of the SCS curve number method (USDA Soil Conservation Service, 1972). The curve number varies nonlinearly from 1 (dry condition at wilting point) to 3 (wet condition at field capacity) and approaches 100 at saturation.
- Peak runoff rate predictions are based on a modification of the Rational Formula. The runoff coefficient is calculated as the ratio of runoff volume to rainfall. The rainfall intensity during the watershed time of concentration is estimated for each storm as a function of total rainfall using a stochastic technique. The watershed time of concentration is estimated using Manning's Formula.
- The percolation component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone.
- Lateral subsurface flow in the soil profile (0 to 6 ft) is calculated simultaneously with percolation. A kinematic storage model is used to predict lateral flow in each soil layer.
- The model offers three options for estimating potential evapotranspiration—Hargreaves, Priestley-Taylor, and Penman-Monteith.
- Channel losses are a function of channel width and length and flow duration. Both runoff volume and peak rate are adjusted when transmission losses occur.
- The required inputs for ponds/reservoirs are capacity and surface area for emergency and principal spillways.

The weather inputs required by SWAT include daily precipitation and maximum/minimum air temperature. Solar radiation, wind speed, and relative humidity are calculated in the code.

To create a SWAT dataset, the interface needs to access ArcView map themes and database files that provide certain types of information about the watershed. The Running Water Draw watershed delineation included a Digital Elevation Model (DEM) for the study area. The scale of the DEM was 1:250,000, where terrain elevations are recorded for ground positions on an evenly spaced grid at intervals of 328 ft. The SWAT ArcView interface delineates drainage basins on the basis of the principle that water always moves downhill. Streams are defined by specifying a minimum threshold drainage area that contributes flow to a particular channel. The accuracy of the watershed delineation was improved using a "burn-in" process. This process combines a coverage of stream networks digitized from aerial photographs with the DEM to force the stream definition to agree more closely with reality. The DEM is shown in figure 6.

Digital maps of soils and land use are used to quantify a variety of watershed properties that control the relationship between rainfall and runoff. STATSGO soil coverages were obtained from the USDA NRCS (http://www.ftw.nrcs.usda.gov/stat_data.html). STATSGO map units are geographically referenced areas containing similar types of soils. Based on these map units, the SWAT ArcView interface derives important information such as hydraulic conductivity and water holding capacity for each subbasin.

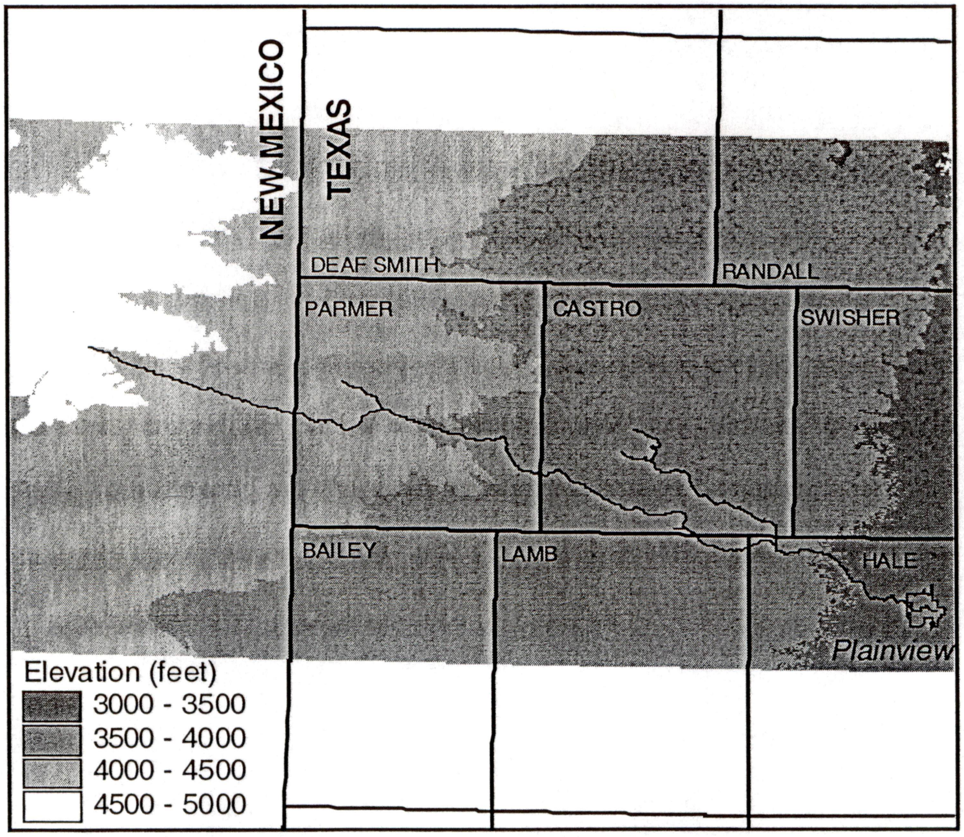

Figure 6. Topography of the catchment based on 1:250,000 DEM.

There are two primary types of soils in the study area. Map unit TX055, which tends to follow the course of Running Water Draw, is characterized by a mixture of loam and clay-loam soils. These soils fall into hydrologic group B and have moderate infiltration rates. The other map units lying farther away from the stream have finer textures and lower infiltration rates. Map unit TX376, which comprises more than 70 percent of the watershed, is categorized as hydrologic group C and has slow infiltration rates. The area just west of Plainview has clay-like soils having very low infiltration rates (TX439). Figure 7 shows the STATSGO map units in the study area.

A grid of USGS land use and land cover classification codes was developed using land use/land cover maps downloaded from the Texas Natural Resources Information System. USGS classification codes are translated into SWAT land cover types with defined hydrologic properties such as SCS curve numbers and leaf area indexes. More than 80 percent of the study area is categorized as agricultural. Rangeland comprises another 15 percent. A map showing the location of different land cover types in the study area is provided in figure 8.

Historical precipitation and temperature data were input into the model. Observed daily data were obtained from the National Climatic Data Center (NCDC) weather database for seven stations in the vicinity of the study area (fig. 9). Precipitation data sets were compiled from observations at six stations, and temperature data sets were developed from measurements at two stations. Precipitation and temperature data for missing records were generated by SWAT.

Surface-water simulations should generally be more accurate as the number of subwatersheds or hydrologic response units (HRUs) used increases. To examine the influence of different numbers of HRUs on the outflow hydrographs, the calculations were conducted using 9, 13, 17, 24, and 42 HRUs. The simulated hydrographs using different numbers of HRUs do not vary appreciably. Water-balance parameters including average annual precipitation, water yield, recharge, evapotranspiration, and channel losses for each of the simulations are listed in table 4.

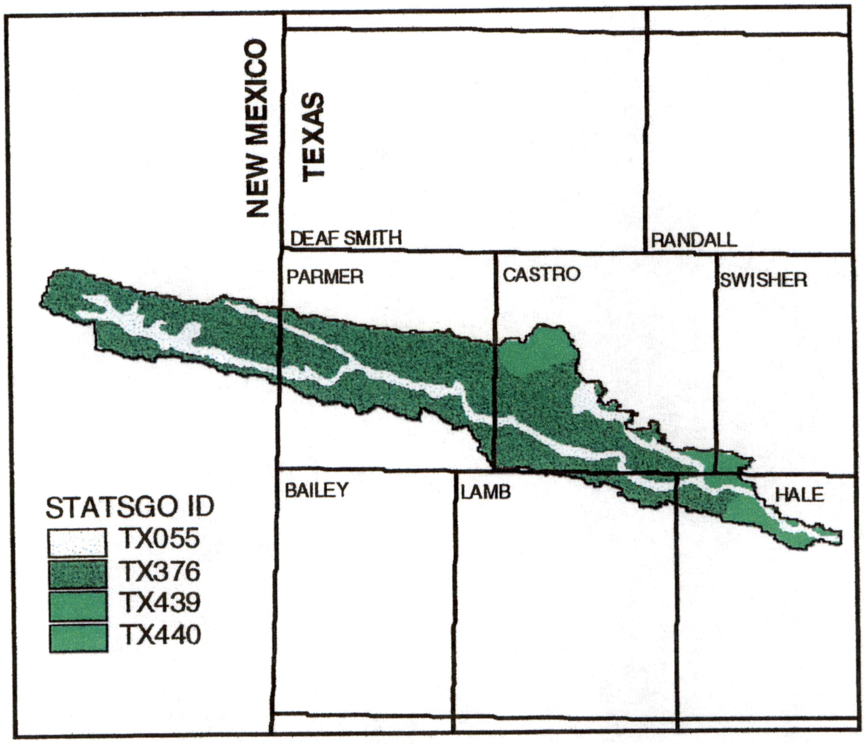

Figure 7. Soil cover data for the study area based on STATSGO.

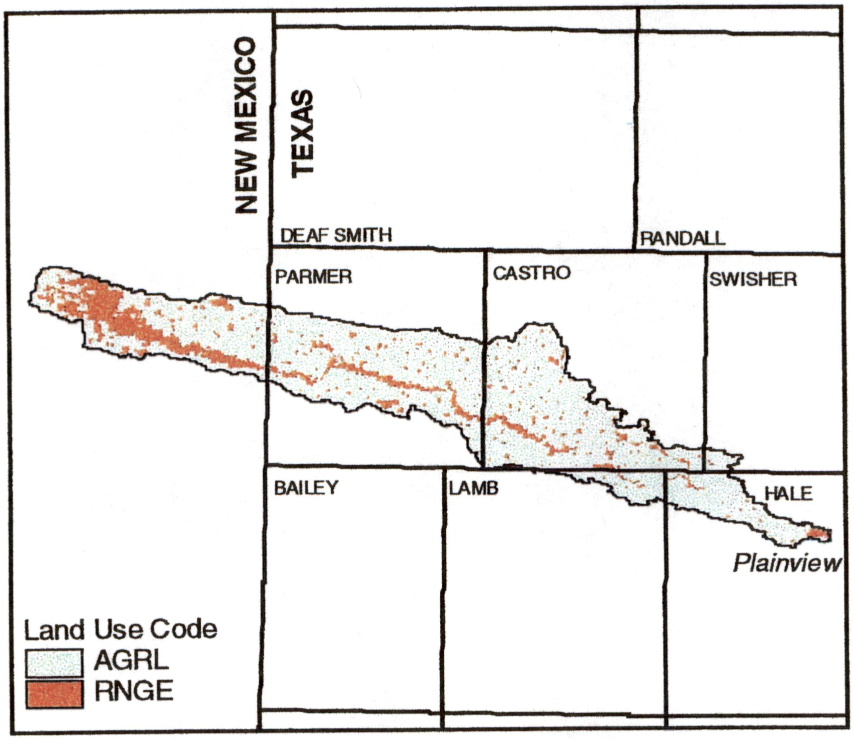

Figure 8. Spatial variability in land cover in the study area.

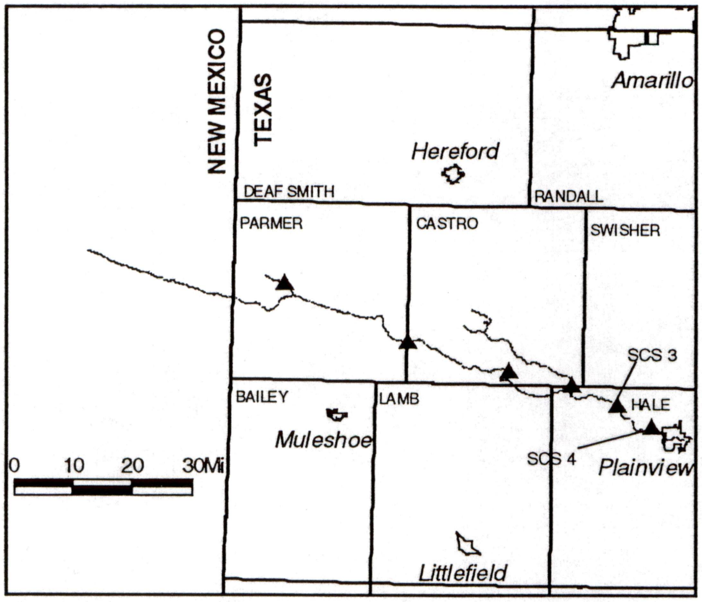

Figure 9. Location of weather stations in the study area.

Table 4. Water balance results for the different densities of hydrologic response units (HRUs).

HRUs	9	13	17	24	42
Precipitation (inches)	1.63	1.64	1.642	1.639	1.641
Water yield (inches)	0.057	0.057	0.057	0.055	0.057
Recharge (inches)	0	0	0	0	0
ET (inches)	1.567	1.58	1.581	1.582	1.582
Channel losses (inches)	0.005	0.004	0.003	0.002	0.002

Because the simulations were not very sensitive to the number of HRUs, a total of 17 HRUs was used in the final simulations (fig. 3). Number 15 HRU is the watershed outlet; the 16th and 17th HRUs were set at the SCS 3 and SCS 4 reservoirs. ArcView interface for SWAT 99.2 allows users to conduct reservoir routing by inserting a reservoir in a particular subbasin. Each subbasin can only contain a single reservoir. In order to calculate the reservoir inflow, the reservoir location should be selected as the outlet of a subbasin. A reservoir subbasin cannot be delineated for an off-channel reservoir. The ArcView-SWAT interface only allows the outlet of a subbasin to be selected at river channel locations that are delineated by the ArcView-SWAT interface. There is no stream delineated for the SCS 4 reservoir in this study; therefore, a subbasin for SCS 4 reservoir could not be delineated and flow to this reservoir could not be calculated.

The model was calibrated by adjusting the SCS curve numbers until simulated and measured average annual stream flow was similar. The simulated flow was adjusted by modifying the SCS curve numbers for each of the HRUs. Initial estimates of SCS curve numbers were generated by SWAT.

EM Induction

Electromagnetic induction is a noninvasive technique that measures a depth-weighted average of the electrical conductivity called the apparent electrical conductivity (EC_a) (McNeill, 1992). Apparent electrical conductivity of the subsurface generally varies with clay content and mineralogy, water content, salinity, porosity, and structure (McNeill, 1992). Variations in electrical conductivity may indicate spatial or temporal differences in infiltration. The various frequency-domain conductivity meters manufactured by Geonics differ in the distances between the transmitter and receiver coils, the frequency at which they operate, and their effective exploration depths (table 5). The instruments can be operated with transmitter and receiver coils horizontal (vertical dipole [VD] mode) or vertical (horizontal dipole [HD] mode). The EM31 and EM38 ground conductivity meters (Geonics Ltd., Mississauga, Ontario) were used to measure EC_a of the subsurface (McNeill, 1992). Apparent electrical conductivity was measured using surface EM meters along transects perpendicular to the margin of reservoir (figs. 10 and 11). Measurement locations were spaced 33 ft apart, and all measurements were taken at the ground surface in both the HD and VD orientations.

Table 5. Characteristics of electromagnetic induction conductivity meters including above ground EM38 and EM31 meters and the downhole EM39 meter used in this study (McNeill, 1992). Exploration depths for the different instruments correspond to approximately 70% of instrument response (McNeill, 1992).

Instrument	Intercoil spacing (m)	Frequency (Hz)	Exploration depth (ft)	
			Horizontal dipole mode	Vertical dipole mode
EM38	1	14,600	2.46	4.92
EM31	3.7	9,800	9.84	19.68
EM39	0.5	39,200	Radial distance = 2.95 ft	

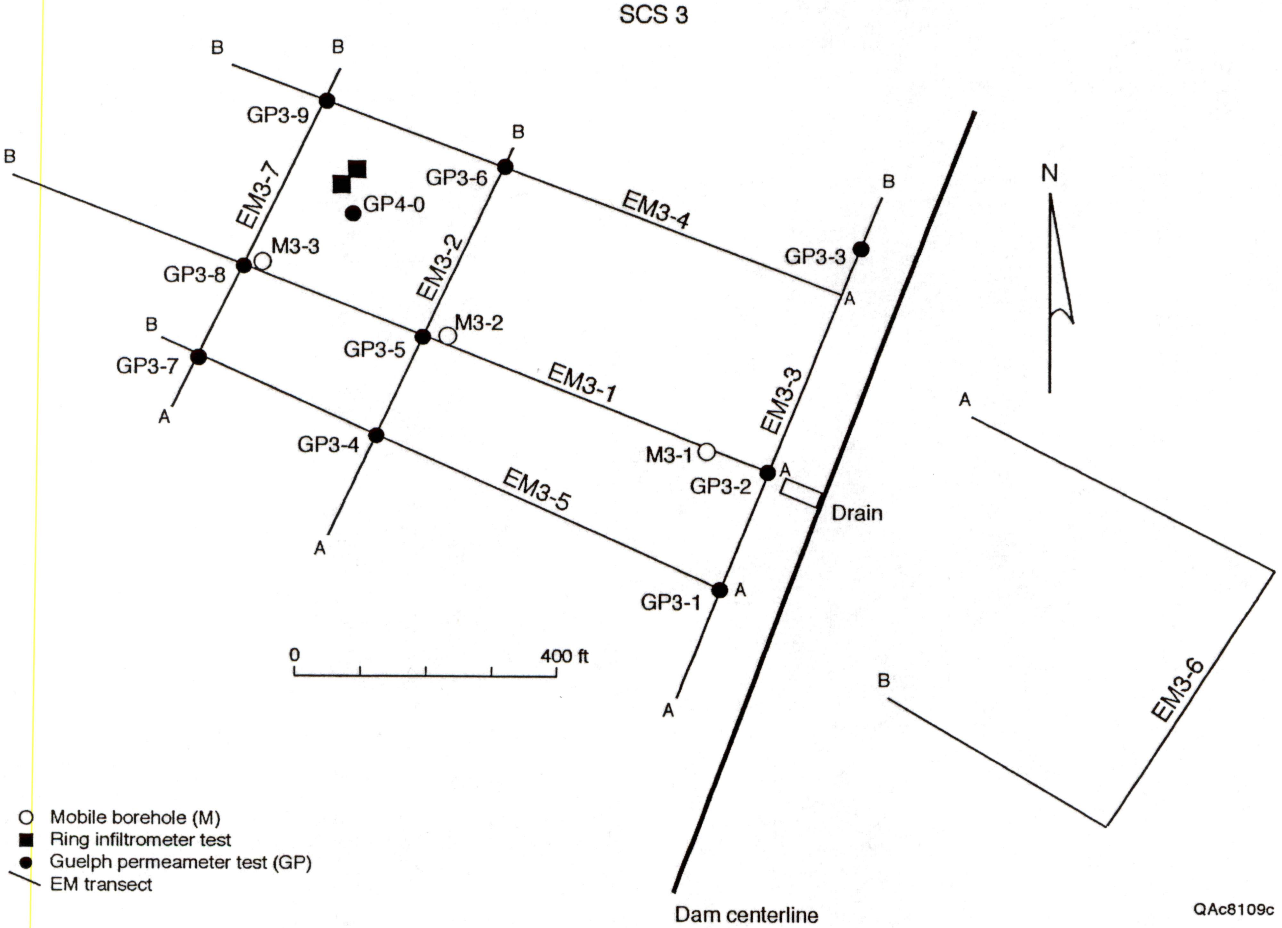

Figure 10. Location of EM transects, boreholes (Giddings, Mobile), Guelph permeameter tests and ring infiltrometer tests in SCS 3 reservoir.

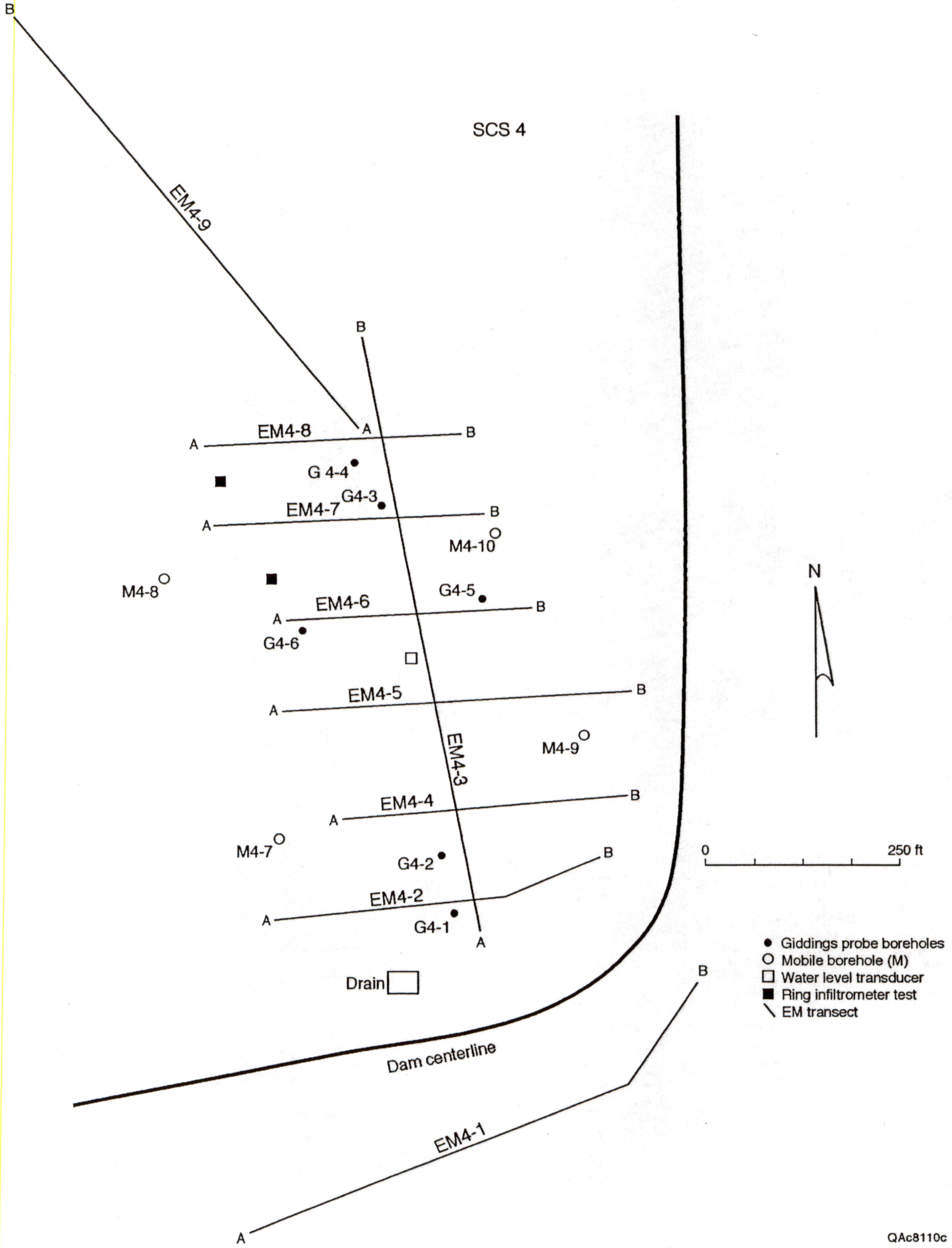

Figure 11. Location of EM transects, boreholes (Giddings, Mobile), and ring infiltrometer tests in SCS 4 reservoir.

Soil Texture, Water Content, and Chloride

A total of six boreholes were drilled at SCS 4 using a Giddings probe (fig. 11). The Giddings probe could not be used to drill boreholes beneath SCS 3 reservoir because the soils were too dry. A Mobile rig was used to drill deeper boreholes in SCS 3 and SCS 4 reservoirs (figs. 10 and 11). Because of ponding at SCS 4 reservoir, these boreholes could not be located in the center of the reservoir. Cores were collected during drilling for analysis of soil texture, water content, and chloride concentration.

Particle-size analyses were conducted on sediment samples from 13 boreholes (table 6). Sediment samples from the initial shallow boreholes drilled with the Giddings rig in SCS 4 were not pretreated; however, all other samples were pretreated to remove carbonate. Percent sand, silt, and clay were determined by hydrometer analysis (Gee and Bauder, 1986). Sediment texture was classified according to the U.S. Department of Agriculture (1975) system. Gravimetric water content was measured on samples from 13 boreholes (table 6). The samples were weighed the same day that they were collected as a precaution against sample drying before measurement.

Core from 13 boreholes was sampled for chloride concentrations (table 6). We extracted chloride from the pore water by adding double-deionized water to the dried sediment sample in a 3:1 ratio. Samples were agitated on a reciprocal shaker table for 4 hours. We then analyzed chloride in the supernatant by potentiometric titration using a 672 Titroprocessor and a 655 Dosimat (Metrohm, Inc., Switzerland) or by ion chromatography (Model 2010i chromatograph, Dionex Corp., Sunnyvale, California) on samples filtered through 0.45-μm filters.

Table 6. Summary of boreholes drilled (G, Giddings drill rig; M, Mobile drill rig), date drilled, analyses conducted on soil samples, and tests conducted (downhole EM39 measurements and Guelph permeameter tests).

SCS 3 reservoir

Borehole number	Date drilled	Soil description	Texture analysis	Water content	Chloride content	Guelph permeameter test
GP3-1	5/9/00	X				X
GP3-2	3/2/00	X				X
GP3-3	4/26/00	X				X
GP3-4	5/9/00	X				X
GP3-5	4/25/00					X
GP3-6	4/26/00	X				X
GP3-7	5/10/00	X				X
GP3-8	4/25/00	X				X
GP3-9	5/10/00	X				X
GP3-10	5/11/00	X				X
M3-1	7/11/00	X	X	X	X	
M3-2	7/12/00	X	X	X	X	
M3-3	7/13/00	X	X	X	X	

SCS 4 reservoir

Borehole		Soil description	Textural analysis	Water content	Chloride	Guelph permeameter Test
GP4-1	2/29/00					X
GP4-2	3/1/00					X
GP4-3	2/21/00					X
GP4-4	2/21/00					X
G4-1	12/1/99		X	X	X	
G4-2	12/1/99		X	X	X	
G4-3	12/1/99		X	X	X	
G4-4	12/2/99		X	X	X	
G4-5	12/2/99		X	X	X	
G4-6	12/2/99		X	X	X	
M4-7	7/13/00	X	X	X	X	
M4-8	7/13/00	X	X	X	X	
M4-9	7/14/00	X	X	X	X	
M4-10	7/14/00	X	X	X	X	

Hydraulic Conductivity

Hydraulic conductivity is a critical parameter that controls infiltration of ponded water into the shallow subsurface and recharge to the underlying Ogallala aquifer. It is important to evaluate the spatial variability in hydraulic conductivity to determine future potential of SCS reservoirs to recharge the Ogallala aquifer. Depth variations in hydraulic conductivity provide valuable information on the feasibility of enhancing recharge by modifying surficial sediments in SCS reservoirs. Hydraulic conductivity was calculated from temporal variations in measured ponding depths in SCS 4, from ring infiltrometer tests, and from Guelph permeameter tests.

Reservoir Infiltration

Variations in water levels in SCS 4 reservoir may be considered a large infiltration test. The SCS 4 reservoir filled with water toward the end of March, and water levels declined until early June when the reservoir refilled to a depth of about 8.6 ft. A pressure transducer was installed in early April toward the center of the reservoir to continuously monitor the stage at SCS 4 reservoir. The pressure transducer was attached to a data logger (Instrumentation Northwest), and water levels were monitored at 30-minute intervals. Pan evaporation data were obtained from a meteorological station in Lubbock and were reduced by a factor of 0.7 to estimate lake evaporation. Water-level changes were corrected for evaporation to estimate net infiltration.

Ring Infiltrometer Tests

The ring infiltrometer is a device used to calculate field-saturated hydraulic conductivity. A metal ring was driven into the ground and filled with water to a specified depth. This depth was maintained until infiltration reached steady state. Field-saturated hydraulic conductivity was calculated from the data. Data collected throughout the test included the volume of water released into the ring and the length of time required for the test. To visually inspect flow beneath the ponded area, a blue food coloring was added to the tanks containing the input water for the ring test. After each test, the ground under the test area was excavated using a backhoe, and the area of influence of the test was visually inspected and photographed. The ring used in the tests for this project was 3 ft in diameter by 2 ft high. The ring was inserted into the ground to a depth of approximately 4 to 6 inches. During the test, the water input to the ring was monitored and controlled by electronic means. Two float switches were installed inside the ring to maintain a constant head of about 2 to 4 inches. Two test sites were selected in each reservoir, one at the surface and a second site at depth (figs. 10 and 11). At SCS 3 reservoir the subsurface test was conducted at a depth of 2 ft, and at SCS 4 the second site was at a depth of 4 ft. The sites were selected to be representative of the reservoir as a whole. Each test was run for 24 hours or until infiltration stabilized. The field-saturated hydraulic conductivity was calculated using a one-ponding-depth approach and a two-ponded-depth approach (Reynolds and Elrick, 1990).

Guelph Permeameter Tests

A Guelph permeameter Model 2800K1 was used to estimate the field-saturated conductivity of surficial sediments in SCS 3 and SCS 4 reservoirs. The Guelph permeameter is an in-hole constant-head permeameter, based on the Mariotte Principle. The method involves measuring the steady-state rate of water recharge into unsaturated soil from a cylindrical test hole, in which a constant depth (head) of water is maintained. The tests were conducted by hand augering 2.4-inch-diameter boreholes to various depths. At approximately 1-ft intervals the borehole was cleaned using a sizing auger followed by a "well prep brush" to clean the borehole walls. The permeameter was inserted and centered in the boring, and the test was performed. After testing, the permeameter was removed, and the borehole was further advanced to repeat the procedure at various depths. Testing continued until a depth of 5 ft was reached or the borehole could no longer be advanced. Water heights of 2 and 4 inches were maintained during the tests. The flow rate from the permeameter was measured at timed intervals until a steady-state rate of fall was observed. The first test was conducted at 2 inches of water until a steady-state flow condition was observed, at which time the height of water was raised in the borehole to 4 inches. The test was completed when steady-state flow rate was reached at 4 inches of water. Field-saturated hydraulic conductivity was determined on the basis of analysis of the data as described in Reynolds and Elrick (1985).

RESULTS

Surface-water simulations demonstrate that the amount of water reaching the reservoirs exceeds the 200 acre-feet regulatory limit; therefore, increasing the storage capacity of the reservoirs should provide more water for recharge to the Ogallala aquifer. Water ponded in SCS 4 reservoir during the study, whereas SCS 3 reservoir remained dry. Ponding in SCS 4 reservoir was attributed to irrigation return flow. Apparent electrical conductivity measured with the electromagnetic induction meters was higher beneath SCS 4 reservoir where water ponded during the study than in SCS 3 reservoir. Textural analysis of surficial sediments indicated that fine-grained sediments are found in the shallow subsurface (~ upper 3 ft). Water contents in sediments were higher beneath SCS 4 reservoir as a result of ponding. Chloride concentrations were low in both reservoirs and indicate that water percolates through the floors of the reservoirs. The rate of percolation could not be estimated because of uncertainty in the chloride input to the system. Measurements of the stage in SCS 4 reservoir during the study indicated that the average infiltration rate was 0.5 acre-foot/day. The average area that was ponded was 12.2 acres, which results in an average infiltration rate of 0.5 inch/day. Results of infiltration tests and hydraulic conductivity tests indicated marked spatial variability in hydraulic conductivity and suggest that the best method of estimating the average infiltration rate is from monitoring water-level changes in the reservoir as a result of ponding.

Surface-Water Model Simulations

The simulations were carried out for the 1950 through 1978 period. The effect of playas on surface runoff was not simulated explicitly; however, the simulated runoff was reduced by the ratio of the catchment area to playas (382 mi^2) to the catchment area of the entire basin (1,291 mi^2). Precipitation and temperature data for individual weather stations were processed by the ArcView-SWAT interface to generate input files for the SWAT model. The SCS curve number was varied until good correspondence was found between measured and simulated flow in Plainview. The simulation generally reproduced the temporal variability in flow; however, the magnitude of the flows differed from measured values. There is no obvious bias in the simulation results because peak flows are underestimated or overestimated at different times. Peak flow in 1960 in response to heavy precipitation was 13 cfs. The simulated average annual stream flows at Plainview are shown in figure 12.

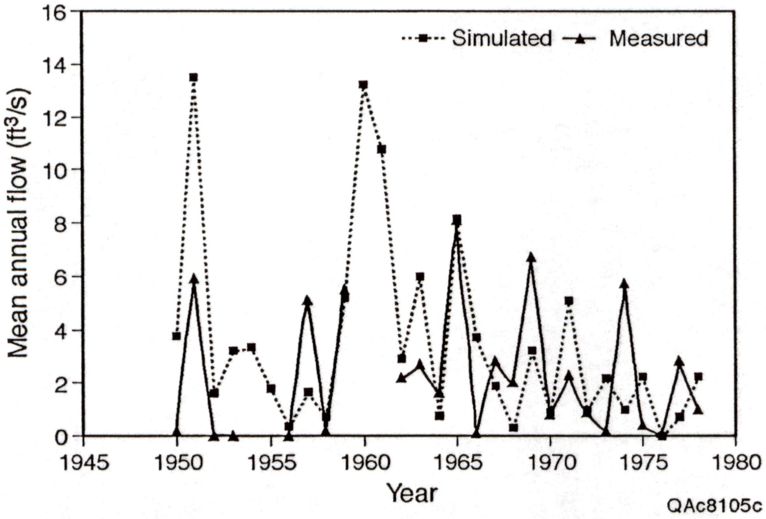

Figure 12. Simulated and measured mean annual stream flow at Plainview, Texas.

Comparison of measured and simulated flows at Plainview indicates fairly good correspondence between the two (root mean square error for annual flow from 1962–1978, 0.54 cfs). SWAT could not simulate flow to SCS 4 reservoir because it is a tributary to Running ranged from 1 acre-foot in 1976 to 9,380 acre-feet in 1951 (table 7). The average total annual inflow from 1950 through 1978 was 2,180 acre-feet. These data indicate that the reservoirs can store much more water than the regulated 200 acre-feet. A subbasin for SCS 3 reservoir was delineated, and the reservoir routing simulation was conducted. Comparison of simulated stream flows at SCS 3 with those at Plainview showed that the outflow hydrograph for SCS 3 reservoir had exactly the same pattern as the hydrograph without reservoir routing. The timing and amplitude of peak flows in the hydrograph were only slightly modified when the reservoir was included. The simulation results did not demonstrate the regulating effect of the reservoir on stream flow. The amplitude of the peaks should be reduced, and the timing of the peaks should be lagged relative to simulated hydrographs without a reservoir.

Table 7. Simulated flows to SCS 3 reservoir.

Year	Annual Inflow rate (cfs)	Total annual Inflow (acre-feet)	Year	Annual Inflow rate (cfs)	Total annual Inflow (acre-feet)
1950	3.67	2,658	1965	6.76	4,898
1951	12.96	9,380	1966	3.45	2,498
1952	1.02	737	1967	1.39	1,003
1953	2.37	1,715	1968	0.16	118
1954	2.99	2,164	1969	2.84	2,055
1955	1.56	1,128	1970	0.87	632
1956	0.32	230	1971	4.29	3,103
1957	1.28	925	1972	0.74	536
1958	0.71	513	1973	1.79	1,297
1959	5.06	3,667	1974	0.56	404
1960	11.33	8,223	1975	0.91	657
1961	10.41	7,539	1976	0.00	1
1962	2.05	1,487	1977	0.22	162
1963	5.68	4,115	1978	1.14	825
1964	0.75	545	Ave.	3.01	2,180

Observed stream flows are available from 1939 through 1978 for USGS gage (08080700) at Plainview, which excluded the missing years of 1954 and 1955. Observed precipitation is available from 1950 through 1979. Thus, the simulated period was selected from 1950 through 1978.

EM Induction

Because borehole data only provide point estimates of hydraulic and hydrochemical parameters, it is important to evaluate interborehole variability using noninvasive techniques such as electromagnetic induction (EMI). Apparent electrical conductivity measured by an electromagnetic meter varies with water content, salt content, sediment texture, structure, and mineralogy. A linear model can be used to describe variations in apparent conductivity of the subsurface:

$$EC_a = EC_w \theta \tau + EC_s \tag{1}$$

where EC_w is pore water conductivity, θ is volumetric water content, τ is tortuosity, and EC_S is surface conductance of the sediment (Rhoades and others, 1976).

Apparent electrical conductivities (EC_a) measured by the Geonics EM31 meter in SCS 3 were lower than those in SCS 4 by about a factor of about 1.5 (mean EM 31 V: SCS 3, 27 mS/m; SCS 4, 44 mS/m; figs. 13 and 14). Values of EC_a in SCS 3 were generally uniformly low (fig. 13). The transect conducted outside the reservoir (3-6) had similar values of EC_a to transects conducted within the reservoir (table 8). Vertical variability in EC_a can be evaluated by comparing EM38 and EM31 transects and vertical and horizontal dipole mode transects. Values of EC_a were higher in EM31 transects than in EM38 transects, which suggests increasing conductivity with depth. In addition, vertical dipole readings were slightly higher in horizontal than in vertical dipole mode, which is consistent with increasing conductivity with depth. Temporal variability in EC_a in SCS 3 was also negligible. Transects were conducted at five different times from November 1999 through May 2000, and EC_a values did not vary significantly (table 8).

In contrast, values of EC_a in SCS 4 were spatially variable and were highest toward the center of the reservoir and lowest near the margins of the reservoir (fig. 14). The mean value of EC_a in the transect outside the reservoir (EM31 V; 27 – 29 mS/m) was much lower than the mean values of EC_a for all other transects (47 – 63 mS/m) (table 8). High values of EC_a in

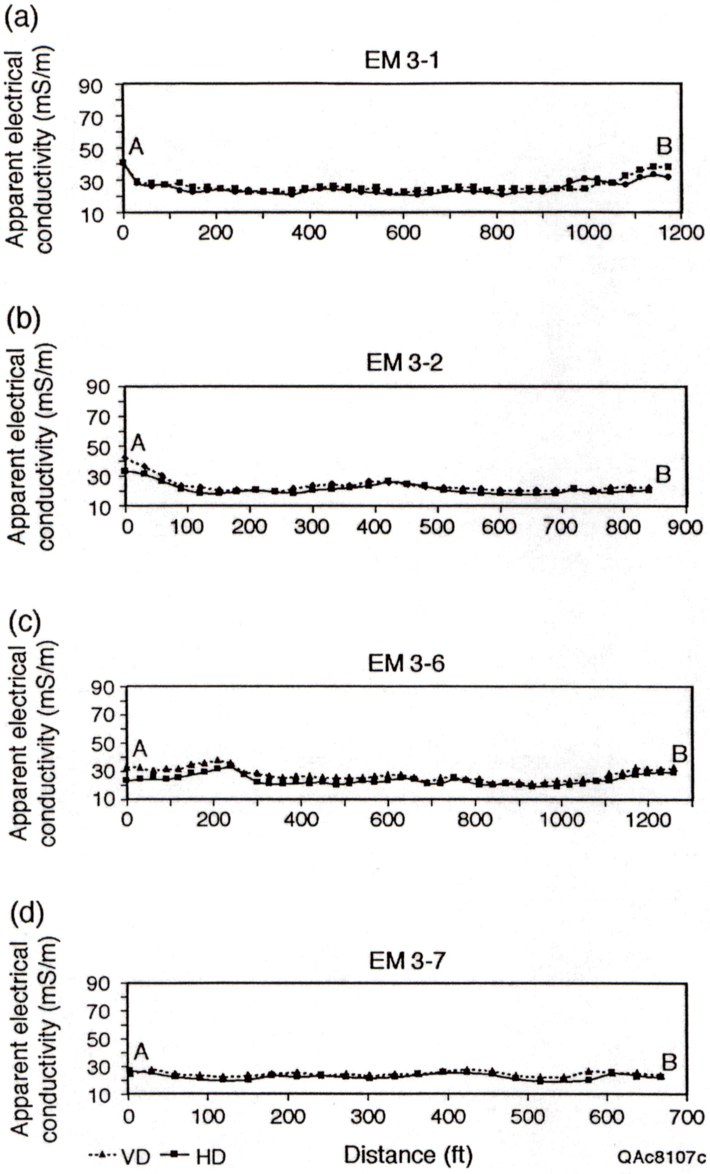

Figure 13. Apparent electrical conductivity measured with the EM 31 meter in the vertical and horizontal dipole mode in representative transects in SCS 3. For location of transects see figure 10.

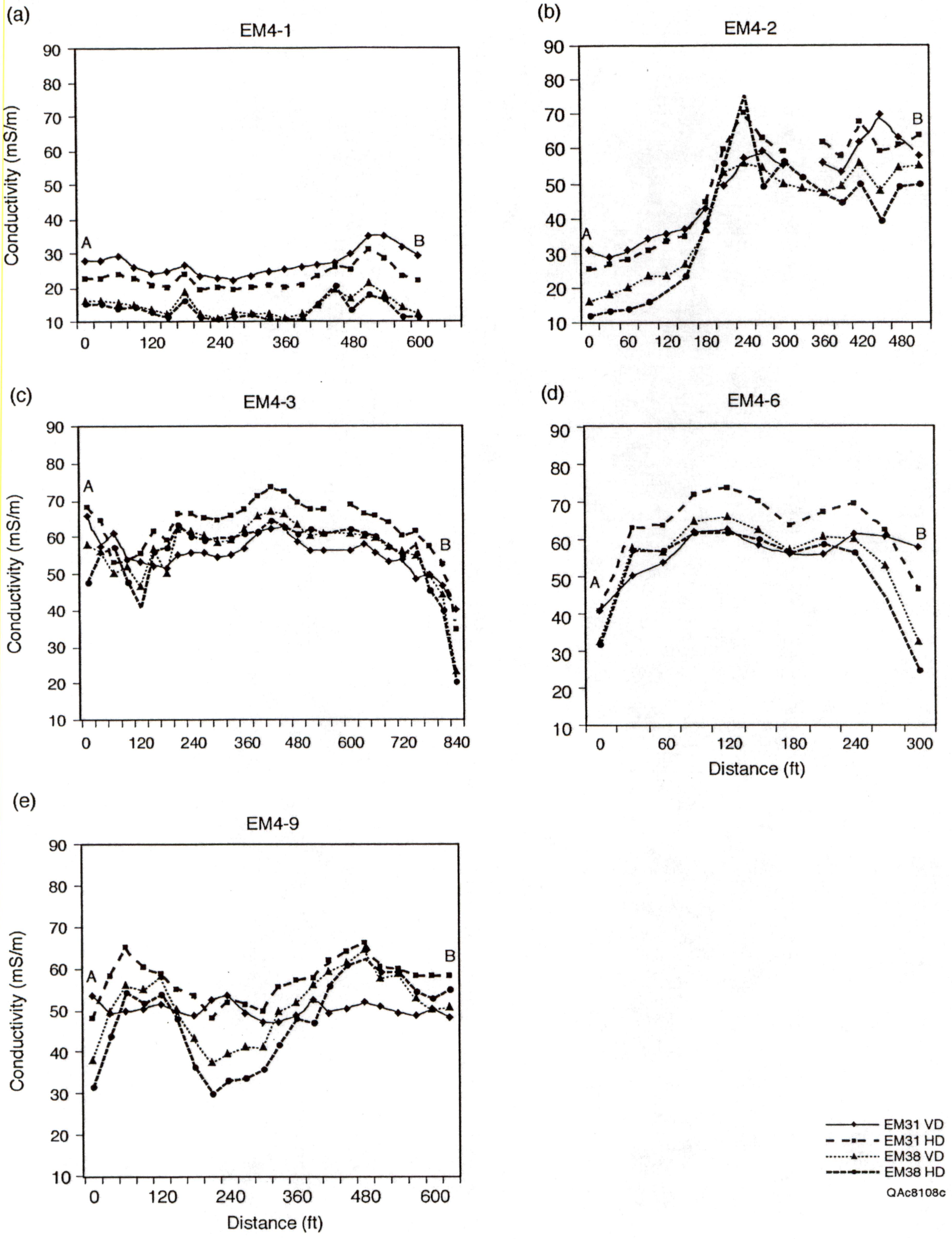

Figure 14. Apparent electrical conductivity measured with the EM 31 meter in the vertical and horizontal dipole mode in representative transects in SCS 4. For location of transects see figure 11.

Table 8. Mean apparent electrical conductivity for EM transects in SCS 3 and SCS 4 reservoirs. For location of transects, see figures 10 and 11.

SCS 3

			Mean Apparent Electrical Conductivity (mS/m)						
		Trans.	**EM3-1**	**EM3-2**	**EM3-3**	**EM3-4**	**EM3-5**	**EM3-6**	**EM3-7**
Nov-99	EM31	HD	24.1	23.6	28.0	-	-	-	-
		VD	27.2	27.1	31.8	-	-	-	-
Dec-99	EM31	HD	25.2	23.7	31.5	22.1	22.5	24.2	22.3
		VD	28.7	27.9	36.0	24.8	25.9	29.5	25.8
Feb-00	EM38	HD	17.2	24.3	24.3	18.3	22.9	16.8	23.8
		VD	18.6	25.4	26.5	20.0	24.7	19.5	25.5
	EM31	HD	25.2	22.5	30.6	21.4	22.2	24.1	22.7
		VD	26.6	24.6	33.1	22.6	23.9	27.7	24.4
Apr-00	EM38	HD	21.7	21.0	22.3	17.8	20.7	16.9	19.6
		VD	19.5	19.1	20.7	15.0	18.7	13.0	17.6
	EM31	HD	29.2	25.7	35.6	25.2	24.2	28.8	25.8
		VD	27.4	25.8	35.4	24.3	24.8	29.5	24.5
May-00	EM31	HD	24.3	22.1	30.8	20.7	21.7	22.8	21.2
		VD	26.6	25.0	33.5	22.5	24.3	27.0	24.0

SCS 4

				Mean Apparent Electrical Conductivity (mS/m)								
			Trans.	**EM4-1**	**EM4-2**	**EM4-3**	**EM4-4**	**EM4-5**	**EM4-6**	**EM4-7**	**EM4-8**	**EM4-9**
Mean AEC	Nov-99	EM31	HD	24.1	50.6	-	53.8	-	-	-	-	-
			VD	29.3	50.9	-	50.7	-	-	-	-	-
	Dec-99	EM31	HD	23.8	49.5	71.8	60.8	52.3	72.8	70.3	65.5	63.6
			VD	29.3	51.6	61.5	55.9	55.0	62.5	61.1	54.8	55.2
	Feb-00	EM38	HD	13.4	39.1	55.5	46.6	43.0	51.8	47.0	48.0	47.8
			VD	14.3	40.7	56.4	47.7	46.1	54.8	47.6	47.6	51.1
		EM31	HD	22.3	49.7	62.8	55.7	54.3	62.9	59.0	54.7	57.1
			VD	26.6	48.1	54.9	51.7	53.4	56.1	52.9	47.4	50.0

transect 9 occur because water flows into the reservoir along a drainage in the vicinity of this transect. Conductivity transects were only measured for 3 months in this reservoir (November 1999 through February 2000) because this reservoir ponded in February. Values of EC_a were fairly uniform over time (table 8).

Variations in EC_a can be attributed to differences in clay content and water content. Lower EC_a values in SCS 3 relative to SCS 4 result from lower clay contents and corresponding lower water contents in this reservoir. Higher EC_a values toward the center of SCS 4 reservoir correspond to higher clay and water contents.

Soil Texture and Water Content

Sediments in SCS 3 reservoir generally ranged from sandy loam to loamy sand with higher clay content in the upper 1 to 2 ft (app. A, fig. 15). Surficial sediments toward the center of SCS4 reservoir are much more clay rich (app. A, fig. 16), the amount of clay generally ranging from 40 to 90 percent. The thickness of the fine-grained zone generally ranges from 1 to 3 ft. The dominant texture below this surficial fine-grained zone is sandy clay loam. Sediments in these shallow boreholes drilled with the Giddings rig were not pretreated to dissolve carbonate; therefore, silt and clay content may be higher than those in all the other profiles that were pretreated. The profiles toward the margins of SCS 4 reservoir were much sandier, and the dominant texture is sandy loam.

Water contents in SCS 3 (mean: 0.09 to 0.15 g/g) were generally lower than those measured in SCS 4 (mean 0.10 to 0.46 g/g) (Table 9). The low water contents in SCS 3 reservoir are similar to those from the deep profiles adjacent to SCS 4 reservoir (mean 0.10 to 0.17 g/g). Water contents were higher in the upper 1 to 4 ft near the center of SCS 4 reservoir (0.42 to 0.66 g/g). High mean water contents in profiles G4-3 and G4-6 result because these boreholes are shallow and the mean values are strongly weighted toward high water contents near the surface. Mean water contents generally decrease away from the center of the reservoir, and the deep

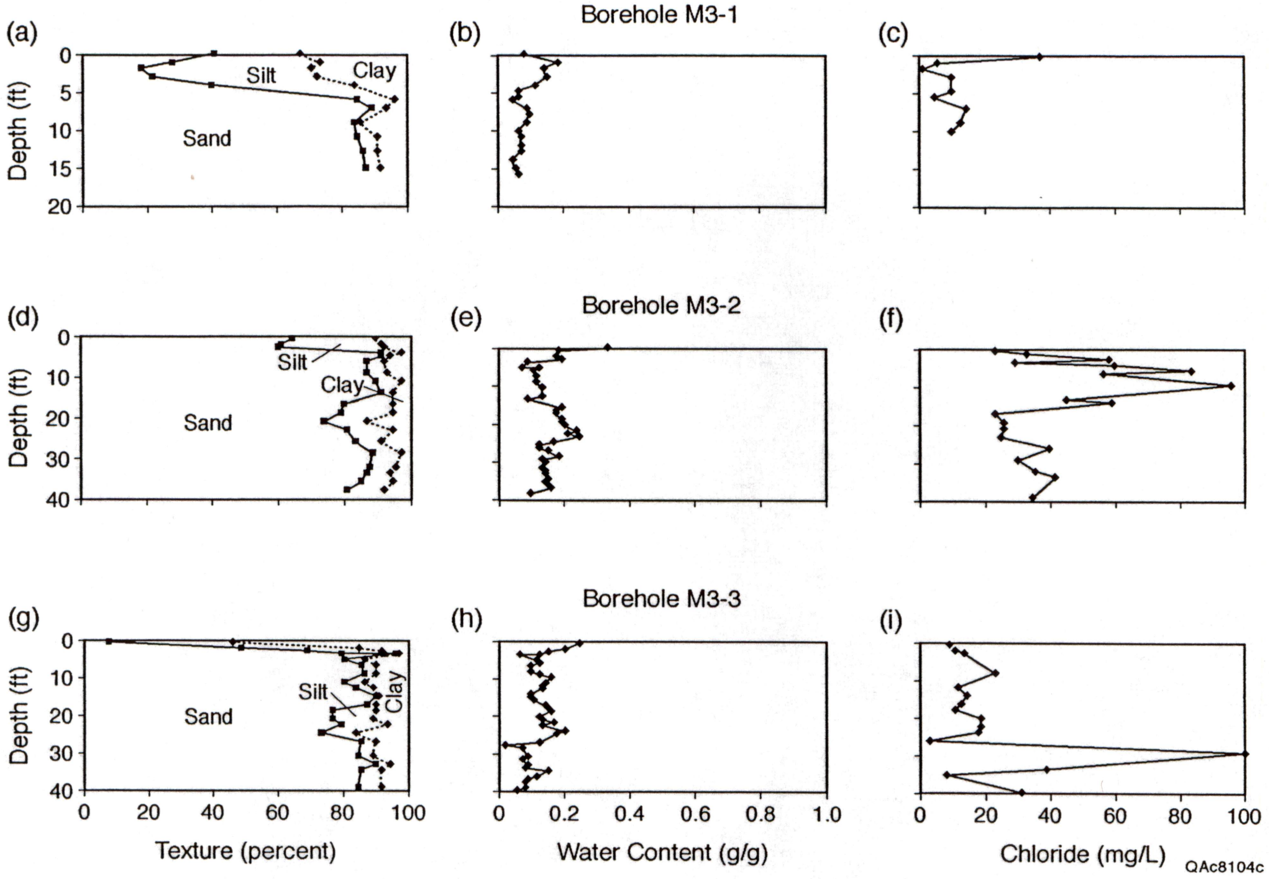

Figure 15. Profiles of soil texture, gravimetric water content, and chloride for boreholes in SCS 3 reservoir. For location of boreholes see figure 10.

profiles toward the margin of the reservoir have mean water contents ranging from 0.10 to 0.17 g/g (M4-7 through M4-10). Water contents in the deep profiles along the margins of the reservoir are uniformly low. These differences in water content are attributed to higher rates of water movement in the center of the ponded area and do not simply reflect variations in water storage associated with textural variations. Clay contents in surficial sediments were similar in G4-1 and G4-2; however, water contents were much higher in G4-2 than in G4-1. Below the shallow subsurface, water contents were lower and generally ranged from 0.1 to 0.3 g/g.

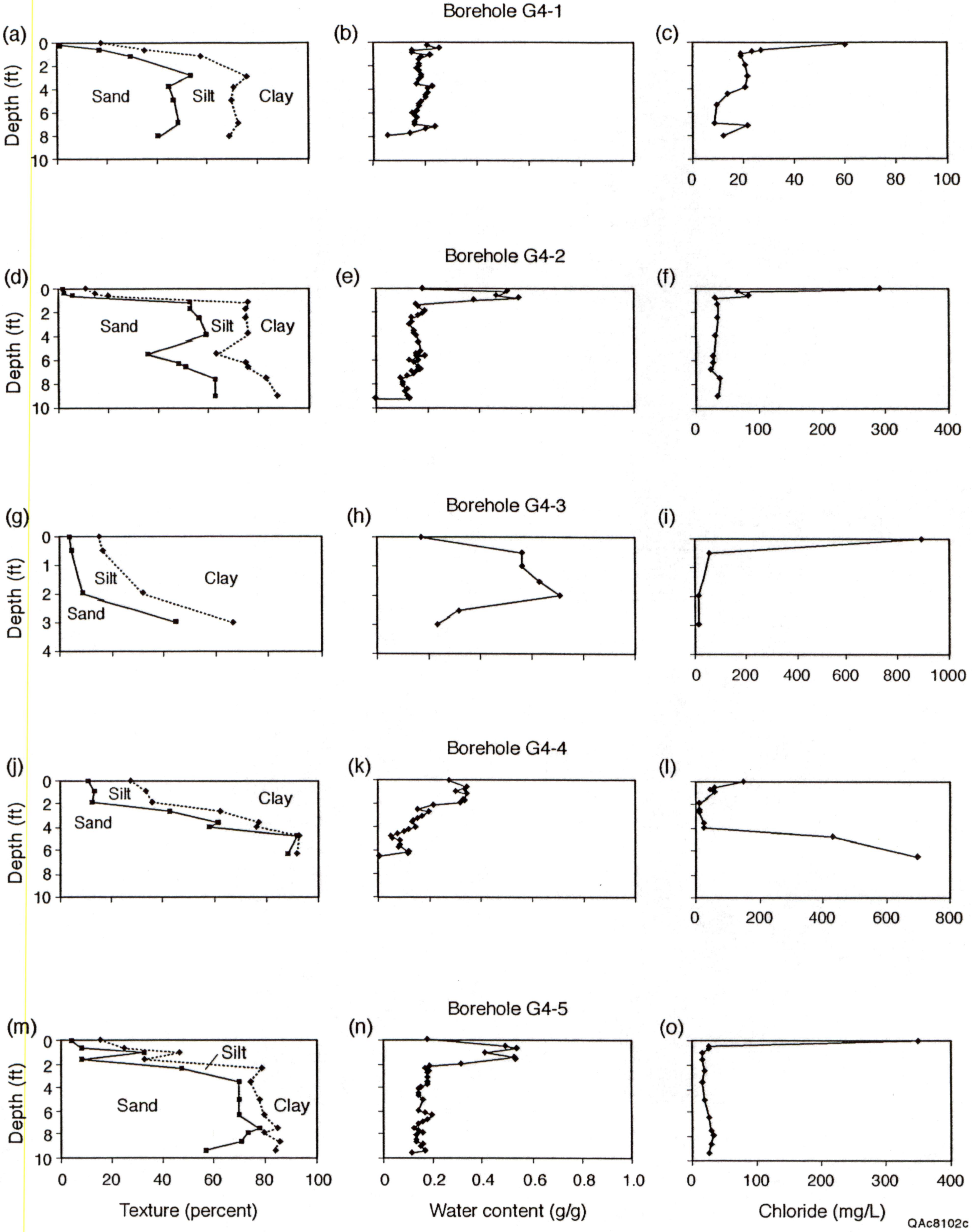

Figure 16. Profiles of soil texture, gravimetric water content, and chloride for boreholes in SCS 4 reservoir. For location of boreholes see figure 11.

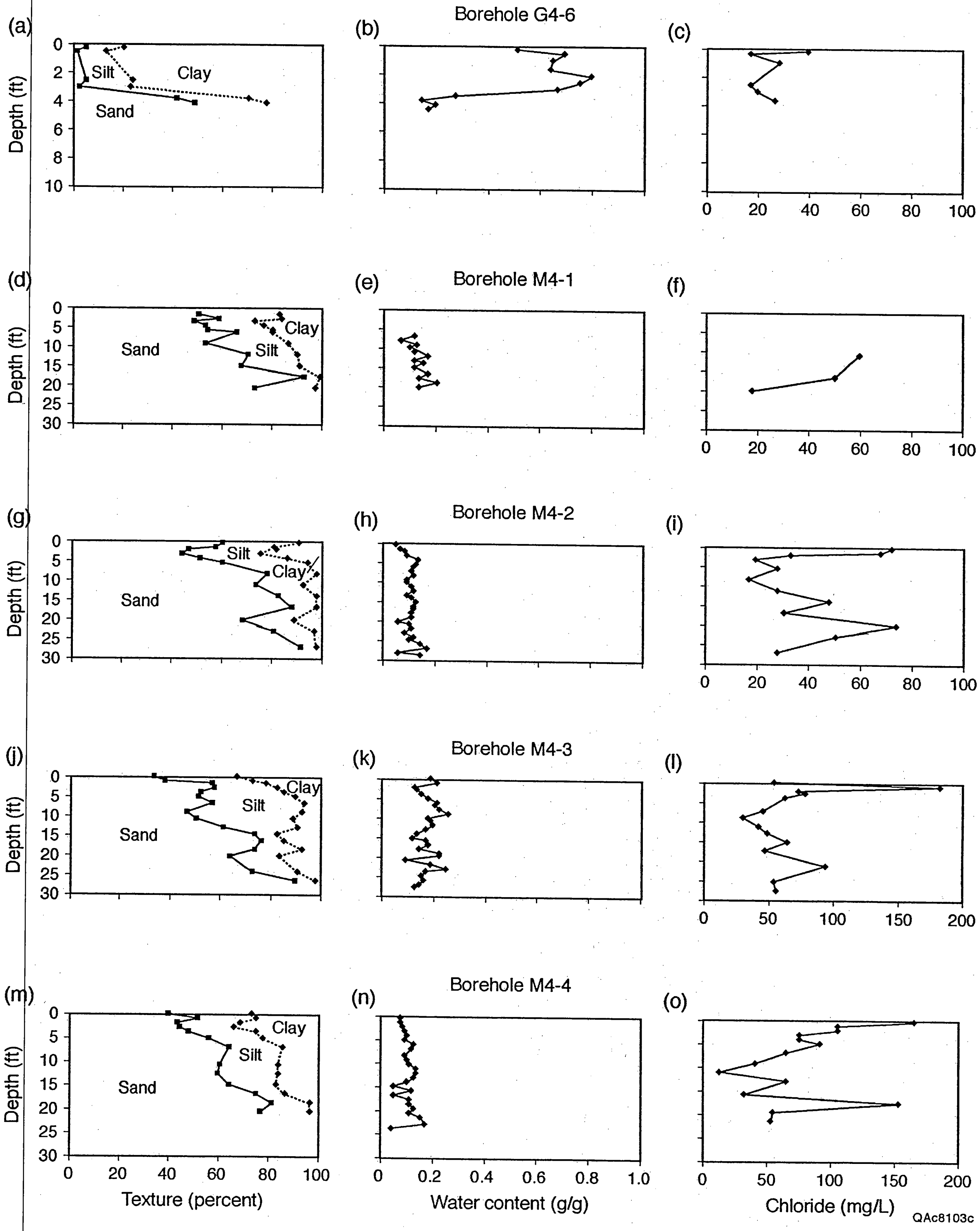

Figure 16. Continued.

Chloride Tracer

Chloride concentrations in pore water from SCS 3 were generally low (mean 12 to 35 mg/L) relative to those in SCS 4 (mean 21 to 250 mg/L) (table 9). The high mean chloride concentrations near the center of the SCS 4 reservoir generally reflect very high concentrations in the upper meter of sediments (mean Cl concentration: 29 to 478 mg/L), whereas mean chloride concentrations below this zone were up to 10 times lower (mean 21 to 30 mg/L) (app. A). Chloride concentrations were uniformly higher throughout the profiles adjacent to the reservoir (M4-7 – M-10; mean: 42 to 77 mg/L) relative to those toward the reservoir center.

It is difficult to estimate water fluxes from the chloride data because of uncertainties in the chloride input to the system. The chloride concentration in ponded water in SCS 4 reservoir was 12 mg/L which is about 10 times higher than chloride concentrations in precipitation. Calculating water fluxes from chloride input from precipitation would result in a lower bounding estimate for water flux. If the chloride input to the system were uniform for both reservoirs, then variations in chloride concentrations in subsurface pore water would be inversely related to water flux and would suggest that water fluxes are higher in SCS 3 reservoir.

Reservoir Infiltration

Variations in water levels in SCS 4 reservoir (fig. 17) were used to estimate net infiltration, which should ultimately result in recharge to the Ogallala aquifer. Water levels in SCS 4 reservoir ranged from 5.5 ft toward the end of March 2000 and decreased to 1.3 ft toward the end of May. They increased to a maximum of 8.6 ft at the beginning of June and decreased to 0.8 ft at the end of September. The cumulative increase in water level was 12.5 ft. Water levels were converted to water volumes using relations between stage, area, and capacity from engineering specifications for the dam. The average maximum depth of water was calculated to be 2 ft. A total of 155 acre-feet ponded in the reservoir over the 6-month period from March to September 2000. About 55 acre-feet evaporated from the reservoir, and 100 acre-feet infiltrated.

Table 9. Borehole number; mean percentage values of sand, silt, and clay; mean and range water content, chloride concentration, and carbonate content for SCS 3 and SCS 4 reservoirs.

	Texture %			Water Content (g/g)			Chloride (mg/l)			Carbonate Content (%)		
Bore-hole	Mean Sand	Mean Silt	Mean Clay	Mean	Maximum	Minumum	Mean	Maximum	Minumum	Mean	Maximum	Minumum
G4-1	35.63	23.13	41.25	0.18	0.26	0.06	20.85	60.32	8.27	No Data	No Data	No Data
G4-2	41.17	20.00	38.83	0.18	0.56	0.00	61.89	25.50	26.24	No Data	No Data	No Data
G4-3	15.75	17.00	67.25	0.46	0.71	0.17	249.64	895.06	20.71	No Data	No Data	No Data
G4-4	48.00	15.00	48.00	0.17	0.35	0.00	143.00	698.85	13.04	No Data	No Data	No Data
G4-5	49.00	15.00	36.00	0.22	0.55	0.12	50.33	351.15	16.96	No Data	No Data	No Data
G4-6	17.00	20.00	62.00	0.49	0.79	0.13	25.25	40.36	17.28	No Data	No Data	No Data
M4-7	60.91	23.45	15.64	0.12	0.19	0.05	42.49	59.50	2.71	32.63	85.38	3.12
M4-8	68.46	22.54	9.00	0.10	0.16	0.04	41.69	74.37	16.86	30.02	72.50	3.50
M4-9	60.06	26.19	9.00	0.17	0.25	0.08	66.36	182.54	29.66	23.44	79.40	3.50
M4-10	59.00	21.92	19.08	0.11	0.17	0.04	77.41	164.14	12.05	26.72	53.00	9.70
M3-1	61.64	22.91	15.45	0.09	0.19	0.04	12.13	2.97	1.90	26.72	23.06	0.16
M3-2	77.75	12.95	9.30	0.15	0.32	0.06	34.47	2.98	25.25	27.19	54.01	10.10
M3-3	79.05	10.14	10.81	0.12	0.24	0.02	21.65	100.12	2.71	17.89	46.71	1.02

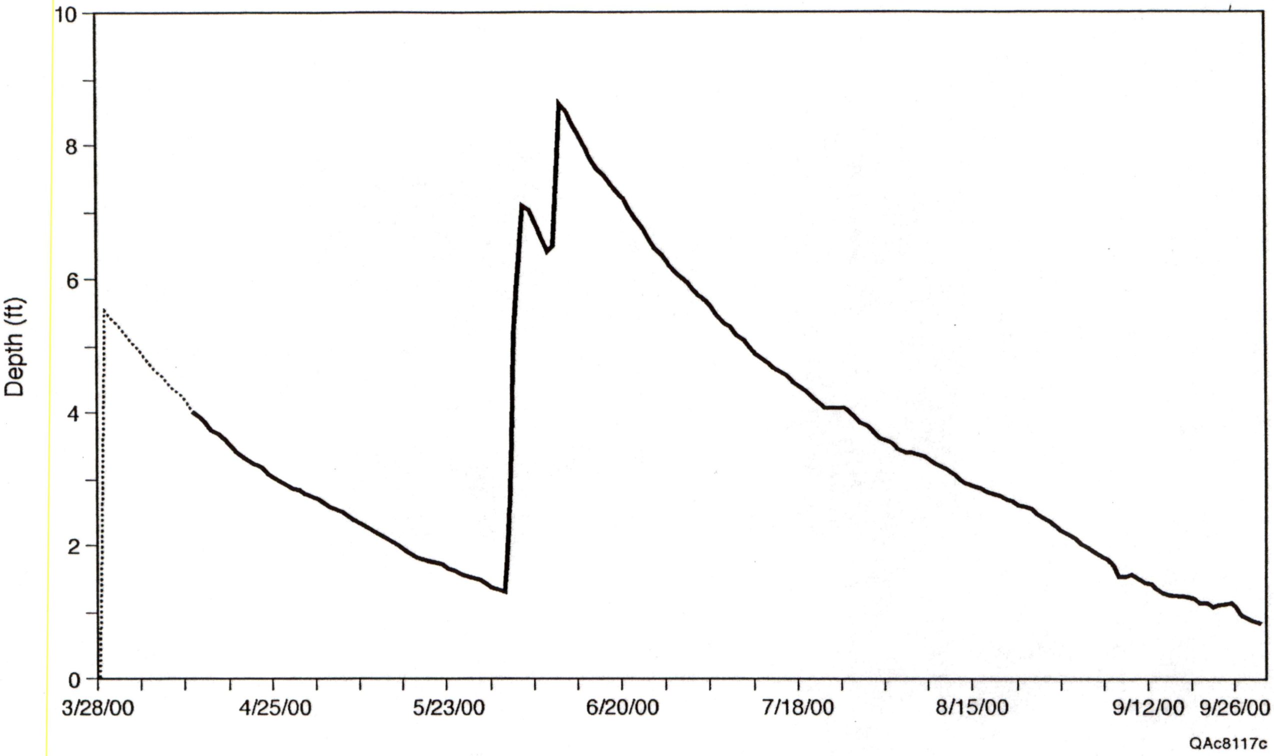

Figure 17. Variations in water levels in SCS 4 reservoir from March through September 2000 and corresponding precipitation. Dashed line was estimated by projecting trend backwards to the beginning of ponding.

The average infiltration rate was 0.5 acre foot/day. The average area of the basin was estimated to be 12 acres; therefore, the average infiltration rate was about 0.5 inch/day. This infiltration rate is much lower than infiltration rates (~1 to 1.3 ft/day) recorded in basins modified to enhance recharge adjacent to playas described by Schneider and Jones (1988).

Hydraulic Conductivity

Ring infiltration tests were conducted at SCS 3 and SCS 4 reservoirs. After completing the tests, the area under the ring was excavated using a truck-mounted backhoe. In SCS 3 reservoir the soil profile consisted of 12 inches of clay loam that graded into carbonate-rich clay. We observed that the sphere of influence of the pond was 42 inches wide and 10 to 15 inches deep.

The upper 2 to 3 inches of sediment was uniformly dyed, whereas below this zone, the dyed area looked mottled. Dye traveled along preferred pathways where the soil texture was coarser and, to a lesser extent, along root paths. Some areas within 4 inches of the surface received no dye, as the material was very dense and compacted.

The ring infiltration test conducted at the 2-ft depth in SCS 3 reservoir had a sphere of influence 42 inches wide and 8 to 14 inches deep. The soil was a carbonate-rich clay. The dye again had a mottled appearance, but the flow paths were predominantly along roots that penetrated the clay. As the dye traveled along the roots, it seeped into the clay.

The ring test conducted at the surface in SCS 4 reservoir consisted of a loamy clay 4 ft thick with silty clay at the base. The area of influence of the test extended out 15 ft from the sides of the ring and penetrated to a depth of 1.5 to 3 ft. The first 6 inches of soil was uniformly dyed, whereas below this zone the dye moved along fractures and some rootlets. At a depth of 16 inches a low-permeability bedding surface resulted in lateral movement of water to a distance of 15 ft from the ring. Along this surface, the dye traveled back up to the surface in some places. The second test conducted at 4-ft depth showed that penetration of dyed water was restricted to the upper 0.25 inch of the clay material.

The ponding tests conducted at the surface in both reservoirs could not be analyzed using the two ponding-depth approaches because of the very small differences in flow rates at the two ponded depths and the small negative changes in flow rates as the ponded depths increased. These tests were then analyzed using the single-ponding-depth approach (table 10). An alpha value of 0.1/inch was used in the single-depth analyses and is the value for clay soil (Reynolds and Elrick, 1990). The resultant K_{fs} ranged from 0.1 to 6 inches/day. The relatively large K_{fs} value for the SCS 4 surface test was attributed to preferential flow as evidenced by the subsurface distribution of blue dye beneath the ponded surface. The K_{fs} value for the ring infiltration test conducted at 2-ft depth in SCS 3 ranged from 0.04 to 0.1 inch/day. In contrast, the ring infiltration test conducted at 4-ft depth in SCS 4 indicates very low permeability because water penetrated only 0.25 inch in 24 hours.

Table 10. Results of ring infiltrometer tests. Depth of borehole, duration of test, diameter of borehole, H1 and H2 are ponding depths, Q1 and Q2 are infiltration rates corresponding to H1 and H2, respectively, Kfs is the field saturated hydraulic conductivity based on two-ponded depth analysis, and Kfs1 and Kfs2 are field saturated hydraulic conductivities based on one ponded depth analysis correspond to heads H1 and H2, respectively.

Location	Depth	Duration	Diam.	H_1	H_2	Q_1	Q_2	K_{fs}	K_{fs1}	K_{fs2}
	ft	hr	ft	in	in	gal/min	gal/min	in/day	in/day	in/day
SCS 3	0	41	3	2.25	4.25	0.019	0.019	-	0.10	0.10
SCS 3	2	22	2	2.5	4.5	0.004	0.008	0.14	0.04	0.07
SCS 4	0	6	3	3.0	6.0	1.12	1.11	-	5.9	5.9
SCS 4	4	24	3	3.0	-	-	-	-	-	-

The results of the Guelph permeameter field-testing are provided in table 11. The rate of water outflow generally ranged from 0.0 to 12.6 inches/minute. Steady-state flow was generally attained within 60 minutes. Calculated hydraulic conductivities using the Richards analysis ranged from 0.3 to 463 inches/day. Some tests resulted in negative values of K_{fs} because the analysis is not well conditioned; that is, the K_{fs} solution is dependent on the ratio of Q_2 to Q_1. These tests were analyzed using data from each head separately with the LaPlace analysis. The Guelph permeameter data suggest that there is no systematic variation in K_{fs} spatially (either with horizontal or vertical location). The high conductivities may result from preferential flow caused by cracking of the surficial sediments.

DISCUSSION

Results of this study suggest that current recharge is higher in SCS 4 reservoir than in SCS 3 reservoir. Analysis of water levels after ponding in the reservoir, high apparent electrical conductivities, and high water contents in subsurface sediments are evidence of recharge in SCS 4 reservoir. Water-level fluctuations, indicating that 100 acre-feet of water infiltrated over a 6-month period, provide the most direct evidence of net infiltration and recharge. The average

Table 11. Field saturated hydraulic conductivity results based on the Guelph permeameter measurements. Q_1 and Q_2 correspond to fluxes calculated from head measurements of 2 and 4 inches, respectively.

	Depth	Steady-state outflow rate (inches/min)		K_{fs} Richards eq. (inches/day)	K_{fs} LaPlace eq. (inches/day)	K_{fs} LaPlace eq. (inches/day)
Test ID	ft	Q_1	Q_2	K_{fs}	(2 inches head)	(4 inches head)
GP4-1	1.0	0.12	0.20	0.51		
	1.5	0.00	0.04	0.43		
	2.5	0.51	NA	NA	0.06	NA
	2.6	0.04	0.59	111.81		
GP4-2	1.0	0.01	0.04	0.31		
	2.0	0.01	0.01		0.06	0.02
GP4-3	1.0	0.04	0.06	1.50		
	2.0	0.06	0.16	16.57		
	2.8	0.06	0.12	8.39		
GP4-4	1.0	0.08	0.14	0.43		
	2.0	0.10	0.10		0.51	0.02
GP3-1	1.0	0.04	0.06	1.50		
	2.2	0.06	0.12	8.39		
	3.2	0.04	0.06	1.50		
	4.3	0.02	0.24	2.65		
	5.4	0.20	0.30	7.48		
GP3-2	1.0	0.20	0.43	36.14		
	2.0	0.10	0.24	22.17		
	2.6	0.08	0.12	2.99		
	3.9	No Flow	No Flow			
	5.2	0.04	0.10	9.69		
GP3-3	1.0	0.02	0.04	2.80		
	2.0	0.02	0.02		1.81	0.67
	3.0	0.08	0.20	19.37		
	3.9	0.01	0.24		12.68	8.15
	5.1	0.10	0.22	18.07		
GP3-4	1.1	1.33	1.81e	20.79e		
	2.2	7.02	CNE		651.97	
	3.2	7.80	12.60e	463.39	724.41	435.83
	4.3	CNE	CNE			
	4.9	4.29e	5.51		398.43e	190.55
GP3-5	1.0	0.06	0.14	12.48		
	2.0	0.06	0.12	8.39		

Table 11. Continued

	Depth	Steady-state outflow rate (inches/min)		K_{fs} Richards eq. (inches/day)	K_{fs} LaPlace eq. (inches/day)	K_{fs} LaPlace eq. (inches/day)
Test ID	ft	Q_1	Q_2	K_{fs}	(2 inches head)	(4 inches head)
GP3-5	3.2	0.04	0.04		3.62	1.34
	4.1	0.14	0.43	52.36		
GP3-6	1.0	0.06	0.06		5.43	2.05
	2.0	0.62	0.79		57.87	27.17
	3.0	CNE	CNE			
	3.9	CNE	CNE			
	5.1	CNE	CNE			
GP3-7	1.1	0.14	0.30	23.66		
	2.2	0.39	0.55	6.81		
	3.2	1.40e	2.01e	29.37e		
	5.4	CNE	CNE			
GP3-8	1.0	0.16	0.24	5.98		
	2.0	0.16	0.30	18.27		
	3.0	0.08	0.12	2.99		
	4.3	3.32	CNE	NA	307.87	
	4.6	0.39	0.98e	96.85e		
GP3-9	1.0	0.08	0.10		7.24	3.39
	2.0	0.10	0.14	1.69		
	3.2	0.12	0.20	8.58		
	4.3	0.16	0.30	29.06		
	5.4	0.55	0.79	12.80		
GP4-10	1.1	0.86e			79.53e	
	2.2	1.95e	CNE		181.10e	
	3.2	4.29e	CNE		398.43e	
	4.3	1.56e	CNE		144.88e	

CNE = Could Not Establish a rate

E = estimate

maximum depth of water was calculated to be 2 ft. The calculated average infiltration rate was about 0.5 inch/day. The volume of recharge in SCS 4 reservoir is attributed to large amounts of irrigation return flow reaching this reservoir. In contrast, current recharge in SCS 3 reservoir is low as shown by low apparent electrical conductivities and low water contents in subsurface sediments. Low chloride concentrations in pore water suggest that recharge rates were higher in the past when more irrigation was conducted in the vicinity of this reservoir.

Textural analysis of the sediments indicated a fine-grained zone in the upper 1 to 3 ft of the reservoirs. Surface-water modeling using the SWAT code indicated that high flow rates reach SCS 3 reservoir, much greater than the regulated amount of water that can be stored in this reservoir (200 acre-feet). These data would suggest that installing the plugs in these reservoirs could enhance recharge by increasing the amount of water available for recharge. Another possible mechanism of enhancing recharge would be to remove surficial (1- to 3-ft depth) fine-grained sediments; however, a single infiltration test conducted at 4-ft depth resulted in very low conductivities at this depth. The current infiltration rates based on water-level fluctuations in SCS 4 reservoir (0.5 inch/day) are low compared with calculated recharge rates in basins excavated adjacent to playas (Aronovici and others, 1972; Schneider and Jones, 1988).

RECOMMENDATIONS

To fully evaluate the potential for enhancing recharge by increasing the regulated storage capacity of SCS reservoirs and/or by modifying the surface of these would require additional studies. There are 62 SCS reservoirs in the Southern High Plains. Information on flow into these reservoirs would be required to assess the availability of water for recharge in these reservoirs. Data on soils would be required to evaluate the permeability of subsurface sediments and the feasibility of modifying surficial sediments to increase subsurface permeability. Testing could be conducted at selected reservoirs that would include removal of surficial fine-grained sediments. Water levels in these reservoirs could be monitored to estimate evaporation and infiltration. Such field-scale testing is much more appropriate than conducting point-scale permeability tests and ring infiltrometer tests because the effects of preferential flow and of heterogeneity could be averaged at the scale of the reservoir. Finally, the effect of enhancing recharge by altering SCS reservoirs could be compared with that achieved by altering playas. Studies conducted in playas near Amarillo, Texas, indicated that recharge rates could be increased markedly by removing surficial fine-grained sediments.

We recommend selecting at least two reservoirs from the 62 existing reservoirs to conduct an engineering feasibility analysis. Surficial sediments could be modified from the floor of these reservoirs to increase the infiltration rate. Plugs on these reservoirs could be installed to increase the capacity of the reservoirs. Detailed monitoring could be conducted on these reservoirs to evaluate whether recharge has significantly increased and to quantify such recharge. Detailed surface-water modeling could be conducted to predict input to the reservoir. Monitoring may be required over several years to capture high-runoff events. Regional modeling could be conducted to assess the potential of runoff from surface drainages off the Southern High Plains. Such studies will help determine potential impacts of the proposed modifications of SCS reservoirs on downstream water users and lakes.

The approximately 20,000 playas in the Southern High Plains represent a much greater source of water than the 62 SCS reservoirs. More thorough studies examining the potential of enhancing recharge in playas should be conducted. One component of such studies could include numerical simulation of the field experiments previously conducted near Amarillo and additional modeling studies to understand recharge processes in playas. Geomorphic studies could be conducted to evaluate the distribution of different soil types in and adjacent to playas and their associated hydraulic properties. Playas could be selected to conduct engineering feasibility studies similar to those described for SCS reservoir alterations. Results of such studies would provide the required information to determine whether playa modifications would greatly enhance recharge to the Ogallala aquifer. Regulatory approval may be required prior to conducting enhanced recharge studies in or adjacent to playas.

Future studies of playas could include a classification of playas based on Landsat imagery including color IR photography. Based on analysis of these data, playas may be grouped according to the length of time they remain ponded with water. Those playas that are ponded most of the time should probably be excluded from recharge enhancements because they may function as effective wetlands. Similarly, playas that are ponded the least amount of time may also be excluded from recharge enhancements because they are probably effectively recharging the aquifer naturally. Recharge enhancement should concentrate on playas that fall in the midrange based on the length of ponding. About 30 to 50 playas could be identified for recharge enhancements. This would result in about one to two playas per county. If possible, duplicate playas could be identified that have similar characteristics. Recharge enhancement could be conducted at one of the two playas, and the effectiveness of enhancing recharge can be quantified by comparing the results with the recharge evaluation from the control playa. Recharge may be enhanced by removal of surficial fine-grained sediments. If these sediments are thick, trenches could be dug to penetrate the fine-grained zone.

CONCLUSIONS

The primary purpose of this study was to assess the recharge potential of SCS reservoirs and determine whether recharge could be enhanced by increasing the regulated storage capacity or modifying the surface of these reservoirs. Detailed studies were conducted at two reservoirs in Hale County, Texas. Results of surface-water modeling using the SWAT code indicate that large amounts of water may inflow into these reservoirs (mean 2,180 acre-feet/year; range 1 to 9,380 acre-feet/year in SCS 3 reservoir). SCS 3 reservoir on the main Running Water Draw channel did not pond during the study, whereas ponding occurred in SCS 4 reservoir on a tributary to Running Water Draw. Ponding in SCS 4 reservoir is attributed to irrigation return flow and runoff related to precipitation. EM induction and water content data from boreholes indicate that subsurface water fluxes beneath SCS 3 reservoir are currently low, which is consistent with the lack of ponding. In contrast, EM induction and water content data from SCS 4 reservoir indicate wetter conditions and higher fluxes as a result of ponding. Low chloride concentrations in pore water beneath SCS 3 reservoir suggest higher water fluxes in the past when irrigation return flow was greater. Analysis of stage data from SCS 4 reservoir during the study suggests an average infiltration rate of about 0.4 inch/day. Hydraulic conductivity tests conducted using blue dye indicate preferential flow in surficial sediments and much lower conductivity at depth.

The results of this study indicate that recharge could be enhanced by increasing the storage capacity of the reservoirs beyond the currently regulated value of 200 acre-feet based on the surface-water modeling. Textural analysis indicates that there is a fine-grained zone in the upper 1 to 3 ft. Removal of this fine-grained zone may further increase recharge; however, the limited infiltration tests suggest that permeabilities at depth are low.

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Appendix A. Borehole number, sand, silt, and clay percentages, textural classification, gravimetric water content, chloride content in soil samples, and chloride concentrations in pore water.

Borehole	Depth (ft)	Sand (%)	Silt (%)	Clay (%)	Soil Texture	Water content (g/g)	Chloride (mg/kg)	Chloride (mg/L)
G4-1								
	0.0	1	17	82	clay	0.21	12.75	60.32
	0.5	18	17	65	clay	0.26	6.85	26.67
	0.7					0.15	3.54	23.21
	0.9					0.16	2.97	18.88
	1.1	30	28	42	clay	0.23	4.23	18.75
	1.4					0.19		
	1.5					0.18		
	1.8					0.18		
	2.0					0.18	3.63	20.46
	2.3					0.18		
	2.5					0.18		
	2.8	54	22	24	sandy clay loam	0.19	3.96	21.31
	3.0					0.19		
	3.3					0.18		
	3.5					0.17		
	3.8	45	26	29	clay loam	0.23	4.68	20.43
	4.0					0.22		
	4.3					0.21		
	4.5					0.21	2.64	12.78
	4.8					0.20		
	5.0	47	23	30	sandy clay loam	0.19		
	5.3					0.18	1.62	9.06
	5.5					0.18		
	5.8					0.17		
	6.0					0.16		
	6.3					0.16		
	6.5					0.17		
	6.8					0.16		
	7.0	49	24	27	sandy clay loam	0.16	1.32	8.27
	7.2					0.24	4.68	19.24
	7.4					0.21		
	7.8					0.15	1.74	11.78
	8.0	41	28	31	clay loam	0.06		
	Mean	**36**	**23**	**41**		**0.18**	**4.20**	**20.86**
	Min					**0.06**	**1.32**	**8.27**
	Max					**0.26**	**12.75**	**60.32**

Appendix A. Borehole number, sand, silt, and clay percentages, textural classification, gravimetric water content, chloride content in soil samples, and chloride concentrations in pore water.

Borehole	Depth (ft)	Sand (%)	Silt (%)	Clay (%)	Soil Texture	Water content (g/g)	Chloride (mg/kg)	Chloride (mg/L)
G4-2								
	0.0	2	9	89	clay	0.19	55.01	295.50
	0.2					0.52	34.88	67.64
	0.5	3	12	85	clay	0.47	39.54	83.74
	0.8	6	14	80	clay	0.56	18.10	32.59
	1.0					0.38		
	1.3	53	23	24	sandy clay loam	0.16	5.77	36.46
	1.5					0.17		
	1.8	53	22	25	sandy clay loam	0.19		
	2.0					0.18		
	2.3					0.17		
	2.5	57	18	25	sandy clay loam	0.14	4.77	34.17
	2.8					0.13		
	3.0					0.13		
	3.5					0.15		
	3.7					0.15		
	4.0	59	17	24	sandy clay loam	0.15	5.01	32.91
	4.5					0.16		
	5.3					0.17		
	5.5					0.16		
	5.6	35	29	36	clay loam	0.19	5.64	29.40
	5.8					0.15		
	6.0					0.13		
	6.1					0.16		
	6.3	49	26	25	sandy clay loam	0.14	4.23	29.49
	6.6					0.16		
	6.7	51	25	24	sandy clay loam	0.17	4.53	26.24
	6.9					0.16		
	7.0					0.14		
	7.2					0.15		
	7.3					0.12		
	7.5	63	20	17	sandy loam	0.10	4.05	40.58
	8.0					0.10		
	8.2					0.10		
	8.5					0.12		
	8.7					0.12		

Appendix A. Borehole number, sand, silt, and clay percentages, textural classification, gravimetric water content, chloride content in soil samples, and chloride concentrations in pore water.

Borehole	Depth (ft)	Sand (%)	Silt (%)	Clay (%)	Soil Texture	Water content (g/g)	Chloride (mg/kg)	Chloride (mg/L)
	9.1	63	25	12	sandy loam	0.12	4.08	34.00
	9.2					0.13		
	9.3					0.00		
	Mean	**41**	**20**	**39**		**0.18**	**15.47**	**61.89**
	Min					**0.00**	**4.05**	**26.24**
	Max					**0.56**	**55.01**	**295.50**
G4-3								
	0.0	4	11	85	clay	0.17	155.66	895.06
	0.5	5	12	83	clay	0.57	34.43	60.86
	1.0					0.57		
	1.5					0.64		
	2.0	9	23	68	clay	0.71	14.71	20.71
	2.5					0.32		
	3.0	45	22	33	clay loam	0.23	5.13	21.92
	Mean	**16**	**17**	**67**		**0.46**	**52.48**	**249.64**
	Min					**0.17**	**5.13**	**20.71**
	Max					**0.71**	**155.66**	**895.06**
G4-4								
	0.0	11	17	11	clay loam	0.28	42.39	152.51
	0.5					0.35	22.69	65.15
	0.8					0.33	17.07	50.99
	1.0	14	20	14	clay loam	0.30	20.04	66.27
	1.2					0.35		
	1.5					0.33		
	1.7					0.34		
	2.0	13	23	13	loam	0.32	5.25	16.59
	2.2					0.21		
	2.5					0.15	1.92	13.04
	2.7	43	20	43	clay	0.19	3.13	16.18
	3.0					0.17		
	3.2					0.15		
	3.5					0.13		
	3.7	62	16	62	clay	0.12	3.51	28.35
	4.0	59	18	59	clay	0.14	3.72	25.73
	4.2					0.12		
	4.5					0.10		
	4.7					0.07		
	4.9	92	1	92	sandy clay	0.05	20.94	434.38

Appendix A. Borehole number, sand, silt, and clay percentages, textural classification, gravimetric water content, chloride content in soil samples, and chloride concentrations in pore water.

Borehole	Depth (ft)	Sand (%)	Silt (%)	Clay (%)	Soil Texture	Water content (g/g)	Chloride (mg/kg)	Chloride (mg/L)
	5.0					0.06		
	5.2					0.08		
	5.5					0.08		
	5.7					0.07		
	6.2					0.11		
	6.4	89	3	89	sandy clay	0.11		
	6.6					0.00	2.96	698.85
	Mean	**48**	**15**	**48**		**0.17**	**13**	**143**
	Min					**0.00**	**1.92**	**13.04**
	Max					**0.35**	**42.39**	**698.85**
G4-5								
	0.0	4	12	84	clay	0.19	67.57	351.15
	0.5					0.50	14.40	28.76
	0.7	9	16	75	clay	0.55	14.81	26.95
	1.2	33	14	53	clay	0.42	7.92	18.68
	1.5					0.54		
	1.7	9	24	67	clay	0.55	9.37	17.08
	2.0					0.33		
	2.2					0.19		
	2.5	48	31	21	loam	0.18	3.81	21.69
	2.7					0.20		
	2.9					0.19		
	3.2					0.19		
	3.5	70	5	25	sandy clay loam	0.19	3.26	16.96
	3.7					0.19		
	4.0					0.16		
	4.2					0.16		
	4.5					0.15		
	4.7					0.16		
	5.0	70	8	22	sandy clay loam	0.17	3.33	19.70
	6.0					0.16		
	6.2					0.18		
	6.5	70	10	20	sandy clay loam	0.21	5.74	27.58
	6.7					0.19		
	6.9					0.17		
	7.0					0.17		
	7.2					0.15		
	7.5	78	7	15	sandy loam	0.13	4.08	31.21

Appendix A. Borehole number, sand, silt, and clay percentages, textural classification, gravimetric water content, chloride content in soil samples, and chloride concentrations in pore water.

Borehole	Depth (ft)	Sand (%)	Silt (%)	Clay (%)	Soil Texture	Water content (g/g)	Chloride (mg/kg)	Chloride (mg/L)
	7.7					0.16		
	7.9					0.17	5.64	33.02
	8.0	74	6	20	sandy clay loam	0.16		
	8.2					0.15		
	8.5					0.14		
	8.7	71	15	14	sandy loam	0.14	4.74	32.74
	8.9					0.17		
	9.1					0.16		
	9.4	57	27	16	sandy loam	0.18	5.20	28.76
	9.6					0.12		
	Mean	**49**	**15**	**36**		**0.22**	**11.53**	**50.33**
	Min					**0.12**	**3.26**	**16.96**
	Max					**0.55**	**67.57**	**351.15**
G4-6								
	0.0	5	15	80	clay	0.50	20.28	40.36
	0.5	2	11	87	clay	0.68	12.18	17.80
	1.0					0.64	18.56	28.97
	1.5					0.63		
	2.0					0.79		
	2.5	5	19	76	clay	0.75	12.90	17.28
	3.0	3	20	77	clay	0.66	13.24	20.03
	3.5					0.25		
	3.7	41	28	31	clay loam	0.13	3.43	27.05
	4.1	48	28	24	loam	0.18		
	4.3					0.15		
	Mean	**17**	**20**	**63**		**0.49**	**13.43**	**25.25**
	Min					**0.13**	**3.43**	**17.28**
	Max					**0.79**	**20.28**	**40.36**
M3-1								
	0.0	42	26	32	clay loam	0.08	2.97	37.69
	1.0	29	46	25	loam	0.19	1.07	5.71
	2.0	19	53	28	silty clay loam	0.14	0.27	1.90
	3.0	23	51	26	silty loam	0.15	1.50	10.19
	4.0	41	44	15	loam	0.11	1.19	10.48
	5.0					0.06		
	5.5					0.06	0.31	5.07
	6.0	86	11	3	loamy sand	0.05	0.72	14.85
	7.0	90	5	5	sand	0.09		

Appendix A. Borehole number, sand, silt, and clay percentages, textural classification, gravimetric water content, chloride content in soil samples, and chloride concentrations in pore water.

Borehole	Depth (ft)	Sand (%)	Silt (%)	Clay (%)	Soil Texture	Water content (g/g)	Chloride (mg/kg)	Chloride (mg/L)
	8.0					0.10	1.24	12.84
	9.0	85	2	13	loamy sand	0.08		
	10.0					0.06	0.64	10.46
	11.0	86	6	8	loamy sand	0.07		
	12.0					0.07		
	13.0	88	4	8	loamy sand	0.07		
	14.0					0.04		
	15.0	89	4	7	sand	0.05		
	16.0					0.06		
	Mean	**62**	**23**	**15**		**0.09**	**1.10**	**12.13**
	Min					**0.04**	**0.27**	**1.90**
	Max					**0.19**	**2.97**	**37.69**
M3-2								
	0.0	4	32	64	clay	0.32	7.47	23.42
	1.0	65	25	10	sandy loam	0.17	5.68	33.01
	2.0	61	30	9	sandy loam	0.17	9.87	58.25
	3.0	60	32	8	sand	0.18	5.41	29.64
	4.0	91	6	3	sand	0.08	4.72	59.63
	5.0	91	3	6	loamy sand	0.06	4.77	83.91
	5.5					0.11		
	6.5	87	5	8	loamy sand	0.09	5.21	56.37
	8.0					0.11		
	9.0	87	6	7	sand	0.11	10.10	95.34
	11.0	90	7	3	sand	0.12		
	13.0					0.12	5.39	45.40
	14.0	91	4	5	loamy sand	0.08	4.42	58.91
	16.0					0.18		
	17.0	80	15	5	loamy sand	0.17	3.93	23.67
	18.0					0.16		
	19.0	79	16	5	sandy loam	0.19	4.91	26.41
	20.0					0.18		
	21.0	74	13	13	sandy loam	0.19	4.98	26.51
	22.0					0.22		
	23.0	81	14	5	loamy sand	0.20	4.95	25.25
	24.0					0.23		
	25.0					0.16		
	26.0	84	7	9	loamy sand	0.11	4.38	39.92
	27.0					0.12		
	28.0					0.14		
	29.0	89	8	3	sand	0.17	5.33	30.48
	30.0					0.13		

Appendix A. Borehole number, sand, silt, and clay percentages, textural classification, gravimetric water content, chloride content in soil samples, and chloride concentrations in pore water.

Borehole	Depth (ft)	Sand (%)	Silt (%)	Clay (%)	Soil Texture	Water content (g/g)	Chloride (mg/kg)	Chloride (mg/L)
	31.0					0.13		
	32.0	88	8	4	sand	0.13	4.41	35.26
	33.0					0.13		
	34.0	87	7	6	loamy sand	0.13	5.28	41.36
	35.0					0.14		
	36.0	85	10	5	loamy sand	0.13		
	37.0					0.14		
	38.0	81	11	8	loamy sand	0.15		
	39.0					0.09	2.98	34.53
	Mean	**78**	**13**	**9**		**0.15**	**4.56**	**34.47**
	Min					**0.06**	**2.98**	**25.25**
	Max					**0.32**	**5.33**	**41.36**
M3-3								
	1.0	9	38	53	clay	0.24	2.01	8.35
	2.0	50	36	14	loam	0.20	2.07	10.19
	3.0	70	23	7	sandy loam	0.15	2.01	13.36
	3.8	81	13	6	loamy sand	0.13		
	4.0	97	1	2	sand	0.06		
	5.0	82	6	12	sandy loam	0.11		
	6.0					0.12		
	7.0	87	4	9	loamy sand	0.10		
	8.0					0.09	2.19	22.05
	9.0	88	3	9	loamy sand	0.12		
	10.0					0.16		
	11.0	82	6	12	sandy loam	0.14		
	12.0					0.13	1.59	11.62
	13.0	85	5	10	loamy sand	0.13		
	14.0					0.10	1.86	13.98
	15.0	91	1	8	sand	0.10		
	16.0					0.10	1.17	11.93
	17.0	89	2	9	loamy sand	0.14		
	18.0					0.15	1.41	9.97
	19.0	78	13	9	sandy loam	0.16		
	20.0					0.12	2.82	18.10
	21.0	78	12	10	sandy loam	0.13		
	22.0					0.16	2.37	18.39
	23.0	81	14	5	loamy sand	0.13		
	24.0					0.20	2.34	17.40
	25.0	75	10	15	sandy loam	0.18		
	26.0						0.48	2.71
	27.0	87	4	9	loamy sand	0.12		

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Borehole	Depth (ft)	Sand (%)	Silt (%)	Clay (%)	Soil Texture	Water content (g/g)	Chloride (mg/kg)	Chloride (mg/L)
	28.0					0.02		
	29.0					0.07	2.13	100.12
	30.0							
	31.0	86	4	10	loamy sand	0.09		
	32.0					0.07		
	33.0	91	5	4	sand	0.08	2.67	37.62
	34.0					0.08		
	35.0	87	6	7	loamy sand	0.15	0.58	7.53
	36.0					0.11		
	37.0					0.08		
	38.0					0.08		
	39.0	86	7	7	loamy sand	0.08		
	40.0					0.05	2.34	29.75
	Mean	**79**	**10**	**11**		**0.12**	**1.87**	**21.65**
	Min					**0.02**	**0.48**	**2.71**
	Max					**0.20**	**2.82**	**100.12**
M4-1								
	0.0	49	33	18	loam	sample compromised	8.34	
	1.0	57	26	17	sandy loam	sample compromised	2.76	
	2.0	47	25	28	sandy clay loam	sample compromised	1.53	
	3.0	51	24	25	sandy clay loam			
	4.0	52	27	21	sandy clay loam	sample compromised	2.01	
	5.0	64	15	21	sandy clay loam			
	6.0							
	7.0					0.11		
	8.0	51	34	15	loam	0.05		
	9.0					0.12		
	10.0					0.09		
	11.0	69	20	11	sandy loam	0.10	6.04	59.50
	12.0					0.15		
	13.0					0.10		
	14.0	66	24	10	sandy loam	0.14		
	15.0					0.10		
	16.0							
	17.0	92	6	2	sand	0.16	7.77	50.03
	18.0					0.12		

Appendix A. Borehole number, sand, silt, and clay percentages, textural classification, gravimetric water content, chloride content in soil samples, and chloride concentrations in pore water.

Borehole	Depth (ft)	Sand (%)	Silt (%)	Clay (%)	Soil Texture	Water content (g/g)	Chloride (mg/kg)	Chloride (mg/L)
	19.0					0.19		
	20.0	72	24	4	sandy loam	0.12	2.20	17.93
	Mean	**61**	**23**	**16**		**0.12**	**4.38**	**42.49**
	Min					**0.05**	**1.53**	**2.71**
	Max					**0.19**	**8.34**	**59.50**
M4-2								
	0.0	61	30	9	sandy loam	0.04	3.18	72.07
	1.0	58	23	19	sandy loam	0.06	3.86	67.84
	2.0	47	35	18	loam	0.08	2.64	33.82
	3.0	45	31	24	loam	0.09	1.77	19.76
	4.0	52	35	13	loam	0.13		
	5.0	61	34	5	sandy loam	0.12	3.39	28.16
	6.0					0.11		
	7.0					0.11		
	8.0	79	19	2	loamy sand	0.11	1.83	16.86
	9.0					0.09		
	10.0					0.09		
	11.0	74	19	7	sandy loam	0.10	2.93	28.78
	12.0					0.11		
	13.0					0.08		
	14.0	83	15	2	loamy sand	0.10	5.06	48.28
	15.0					0.12		
	16.0					0.11		
	17.0	88	10	2	sand	0.11	3.48	31.18
	18.0					0.10		
	19.0					0.10		
	20.0	69	20	11	sandy loam	0.05	3.78	74.37
	21.0					0.09		
	22.0					0.10		
	23.0	81	16	3	loamy sand	0.08	4.05	50.52
	24.0					0.11		
	25.0					0.10		
	26.0					0.14		
	27.0	92	6	2	sand	0.16	4.63	28.59
	28.0					0.05		
	29.0					0.14		
	Mean	**68**	**23**	**9**		**0.10**	**3.38**	**41.69**
	Min					**0.04**	**1.77**	**16.86**
	Max					**0.16**	**8.34**	**74.37**

Appendix A. Borehole number, sand, silt, and clay percentages, textural classification, gravimetric water content, chloride content in soil samples, and chloride concentrations in pore water.

Borehole	Depth (ft)	Sand (%)	Silt (%)	Clay (%)	Soil Texture	Water content (g/g)	Chloride (mg/kg)	Chloride (mg/L)
M4-3	0.0	34	33	33	clay loam	0.18	9.86	53.57
	1.0	38	35	27	clay loam	0.21	37.57	182.54
	2.0	57	22	21	sandy clay loam	0.12	8.63	72.42
	3.0	58	25	17	sandy loam	0.13	10.20	78.46
	4.0	53	33	14	sandy loam	0.15	9.22	62.96
	5.0	52	38	10	loam	0.18		
	6.0					0.21		
	7.0	57	37	6	sandy loam	0.20	8.90	44.90
	8.0					0.21		
	9.0	47	46	7	loam	0.25	7.42	29.66
	10.0					0.17		
	11.0	51	38	11	loam	0.18	7.53	41.57
	12.0					0.19		
	13.0	62	29	9	sandy loam	0.17	8.10	48.54
	14.0					0.13		
	15.0	74	9	17	sandy loam	0.11	7.22	63.95
	16.0					0.16		
	17.0	77	9	14	sandy loam	0.17	7.92	47.07
	18.0					0.13		
	19.0	74	19	7	sandy loam	0.22		
	20.0					0.21		
	21.0	64	20	16	sandy loam	0.08	7.82	94.41
	22.0					0.18		
	23.0					0.24		
	24.0					0.16		
	25.0	73	18	9	sandy loam	0.14	7.73	54.22
	26.0					0.16		
	27.0	90	8	2	sand	0.14	7.65	54.80
	28.0					0.12		
	Mean	**60**	**26**	**14**		**0.17**	**10.41**	**66.36**
	Min					**0.08**	**7.22**	**29.66**
	Max					**0.25**	**37.57**	**182.54**
M4-4	0.0	40	33	27	clay loam	0.08	12.78	164.14
	1.0	52	23	25	clay loam	0.08	8.03	103.52
	2.0	44	25	31	sandy loam	0.08	8.62	103.77
	3.0	45	21	34	sandy loam	0.09	7.01	75.46

Appendix A. Borehole number, sand, silt, and clay percentages, textural classification, gravimetric water content, chloride content in soil samples, and chloride concentrations in pore water.

Borehole	Depth (ft)	Sand (%)	Silt (%)	Clay (%)	Soil Texture	Water content (g/g)	Chloride (mg/kg)	Chloride (mg/L)
	4.0	48	27	25	sandy loam	0.10	7.49	75.19
	5.0	56	22	22	loam	0.09	8.44	90.73
	6.0					0.13		
	7.0	64	22	14	sandy loam	0.12	7.71	64.68
	8.0					0.09		
	9.0					0.11	4.15	39.45
	10.0					0.11		
	11.0	61	23	16	loam	0.13	1.61	12.05
	12.0					0.13		
	13.0	60	24	16	loam	0.13	8.54	64.86
	14.0					0.10		
	15.0	64	19	17	sandy loam	0.05		
	16.0					0.12	3.86	31.31
	17.0	75	12	13	sandy loam	0.05		
	18.0					0.11	16.82	151.95
	19.0	81	15	4	sandy loam	0.11		
	20.0					0.13	6.98	53.75
	21.0	77	19	4	sandy loam	0.11		
	22.0					0.15	8.11	52.87
	23.0					0.17		
	24.0					0.04		
	Mean	**59**	**22**	**19**		**0.11**	**7.87**	**77.41**
	Min					**0.04**	**1.61**	**12.05**
	Max					**0.17**	**16.82**	**164.14**

Appendix B. Summary of Running Water Draw reservoirs.

County	Dam name	Year completed	Permitted storage (acre-feet)	Low stage principal spillway volume (acre-feet)	TNRCC permit numbers
PARMER	RUNNING WATER DRAW WS SCS SITE 2 DAM	1973	≤ 200	1,232*	NA
PARMER	RUNNING WATER DRAW WS SCS SITE 3 DAM	1979	4,427*	4,427*	12-367(1,2,3,4)
CASTRO	LOWER RUNNING WATER DRAW WS SCS SITE 1 DAM	1980	≤ 200	1,489*	(4,383 application no.)
HALE	LOWER RUNNING WATER DRAW WS SCS SITE 2 DAM	1977	≤ 200	1,377	NA
HALE	LOWER RUNNING WATER DRAW WS SCS SITE 3 DAM	1982	≤ 200	2,959	NA
HALE	LOWER RUNNING WATER DRAW WS SCS SITE 4 DAM	1976	424	424	12-3875

*Information combined from communication with TNRCC and USDA's NRCS
NA= Not applicable
WS = watershed