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Field study of spatial variability in unsaturated flow beneath and adjacent to playas

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Abstract. We quantified unsaturated flow beneath playa and adjacent interplaya settings at a site in the Southern High Plains (United States) to resolve issues related to where and how water moves through the unsaturated zone. This is the first study in which the data density (39 boreholes) and the variety of techniques used (physical, chemical, and isotopic) were sufficient to quantify spatial variability in unsaturated flow. 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. These 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 60 to 120 mm yr^{-1} beneath playas and were $\leq$0.1 mm yr^{-1} during the past 2000–5000 years beneath natural interplaya areas not subjected to ponding. To evaluate the apparent inconsistency between high recharge rates and thick clay layers beneath playas, we applied bromide and FD&C blue dye to evaluate flow processes. These applied tracer experiments showed preferential flow along roots and desiccation cracks through structured clays in the shallow subsurface in playas.

Introduction

Many studies in arid and semiarid regions have been conducted to evaluate groundwater resources, although in the past two decades the emphasis has shifted from groundwater resource evaluation to contaminant transport. Depending on the circumstances, spatial variability in water fluxes through the unsaturated zone may or may not be important for volumetric water resource evaluation; however, such variability is critical for contaminant transport in areas of nonuniform flow. Use of spatially averaged water fluxes in the unsaturated zone to predict contaminant transport in areas of focused flow or in areas of preferential flow greatly underestimates transport velocities.

Playa basins in the Southern High Plains provide an appropriate setting to examine the effect of spatial variability in unsaturated flow because of the range in geomorphic settings (playas/interplayas), variations in texture (structured clays in playas versus clay loam in interplayas), and range in boundary conditions (episodic ponding in playas versus nonponding in most natural interplayas). Playa basins have been divided into (1) the playas, which mark the flat floor of the playa basin, (2) the annulus, which is considered the break in slope at the playa margin, and (3) the interplaya, which marks the region between the playas and includes the slope and upland settings described by *Hovorka* [1995].

Where does unsaturated flow occur in playa/interplaya settings? Conceptual models regarding the role of Southern High Plains playas as recharge features have varied over the past few decades. Previous studies suggested (1) that playas act as evaporation pans [*Lehman*, 1972; *Claborn et al.*, 1985], (2) that recharge is restricted to the annular region around playas [*Osterkamp and Wood*, 1987; *Wood and Osterkamp*, 1987], or (3) that playas focus recharge [*Broadhurst*, 1942; *White et al.*, 1946; *Wood and Sanford*, 1995]. *Claborn et al.* [1985] suggested that clays in playas act as a liner and that natural recharge occurs only when water levels in playas rise above the level of the clay to the silty loam in the annular region around the playa. *Osterkamp and Wood* [1987] and *Wood and Osterkamp* [1987] also indicated that recharge occurred primarily in the annular regions surrounding playas. Evidence for high recharge is provided by higher water level responses in wells beneath playas than in adjacent upland areas [*Broadhurst*, 1942; *White et al.*, 1946] and by high tritium concentrations and low chloride concentrations in the unsaturated zone beneath playas [*Stone and McGurk*, 1985; *Wood and Sanford*, 1995].

The debate about whether playas act as evaporation pans or whether they concentrate recharge has focused on the nature of water movement through clay soils in the playa floors. Clay sediments are generally used in engineered waste disposal facilities as liners to minimize water movement through the unsaturated zone to the groundwater. Recent studies in many areas, however, indicate that macropore flow is dominant in structured, fine-grained sediments [*Steenhuis and Parlange*, 1991; *Flury et al.*, 1994]. Macropore flow, referring to flow along noncapillary-size openings, such as fractures, cracks, and root tubules, is a type of preferential flow. Although some researchers refer to focused recharge beneath playas as macroscopic scale preferential flow [*Gee and Hillel*, 1988], most researchers restrict the use of the term preferential flow to much smaller scales and do not include focused flow beneath topographic features such as playas. Dye-tracing experiments by *Flury et al.* [1994] showed that the episodic ponding, upper-boundary condition greatly enhances preferential flow in structured sediments. Thick clay zones and seasonal wetting and drying of clays in playas predispose this system to preferential flow.

Essential to evaluating the significance of preferential flow is the vertical continuity of preferred pathways. Whereas most pathways, such as desiccation cracks and root tubules, are

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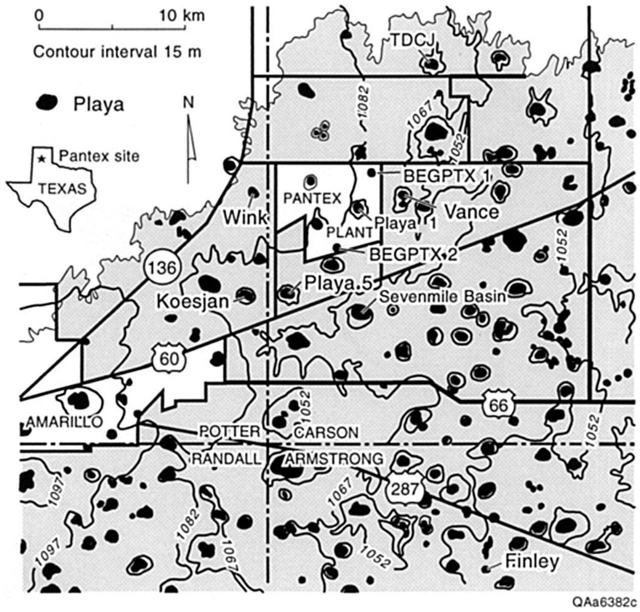

Figure 1. Location of the seven playas (TDCJ, Wink, Vance, Playa 5, Koesjan, Sevenmile Basin, and Finley) in the study area (35°20′N, 102°22′W; ~25 km northeast of Amarillo, Texas). The playas range in area from 0.2 km^2 (Finley playa) to 1.3 km^2 (Sevenmile Basin (SMB) playa), and corresponding basin areas range from 4 km^2 (Finley) to 47 km^2 (SMB). Maximum topographic relief from interplaya to playa settings is 8 m [*Scanlon et al.*, 1997].

found in the shallow subsurface (a few meters deep), these pathways could extend to great depths. Subsurface stratigraphy beneath playas indicates that as many as five paleosols lie beneath the present playas, which mark periods of surface stability when soil development occurred [*Hovorka*, 1995]. These paleosols could extend the types of preferred pathways generally associated with surface soils to much greater depths. Geologic evidence of long-term transport along these preferred pathways includes organic matter and iron- and manganese-oxide staining, gleying, and clay illuviation. Slickensided fractures are also found at depth.

The basic issues that need to be resolved are (1) What is the spatial variability in unsaturated flow in playa/interplaya settings?, (2) What is the direction and rate of water movement through the playa and interplaya settings?, and (3) How does water move through the unsaturated zone, particularly the thick clay sections beneath the playas?

The objective of this study is to resolve the above issues. Spatial variability was examined both at large scales (playa-interplaya) and small scales (desiccation crack–root tubule). The direction of water movement was evaluated using physical data such as water potential measurements, and the rate of water movement was quantified using the distribution of environmental tracers such as chloride and tritium. Applied tracer experiments were specifically designed to evaluate flow processes through the unsaturated zone beneath playas.

This study differs from previous studies in that physical, chemical, and isotopic data were integrated, whereas many of the previous studies of the unsaturated zone generally relied on chemical data alone [*Wood and Sanford*, 1995; *Stone and McGurk*, 1985]. The variety of tracers, including environmental (Cl, ^{36}Cl, and ^{3}H) and applied ($CaBr_2$ and FD&C blue dye), and integration with physical measurements, such as water content and water potential, provide a much more comprehensive investigation of spatial variability in unsaturated flow in these settings than any previously conducted. This is the first study where the number of playas studied (seven) and the data density (39 boreholes; Figure 1; Table 1) have been sufficient to accurately delineate where recharge is occurring and to quantify the rates of water movement in both playa and interplaya settings. Most of this paper focuses on Texas Department of Criminal Justice (TDCJ; playa, 0.5 km^2; basin, 11 km^2) and Wink (playa, 0.3 km^2; basin, 8 km^2) playa basins because these playa basins were studied most intensively. Previous studies of unsaturated flow in interplaya settings have been minimal and qualitative [*Aronovici and Schneider*, 1972]. Although some studies have suggested preferential flow as a possible transport mechanism beneath playas in the Southern High Plains [*Zartman et al.*, 1994; *Wood and Sanford*, 1995], detailed studies of preferential flow were not previously conducted in this setting.

There is no integrated drainage network on the Southern High Plains. All surface water drains internally into the playas. Because the catchment area of playas is generally large, surface runoff from the surrounding basin is sufficient to account for ephemerally ponded water in the playa. This is substantiated by water budget studies conducted in playas at the nearby Pantex Plant [*Reed*, 1994].

Physical Techniques

Physical techniques provide information on current-flow processes. Water contents measured in the laboratory provide information on how dry the sediments are. Neutron probes cannot be used to monitor volumetric water content in shrink-swell media such as the clays beneath playas. The direction of water movement can be estimated from the energy potential. Energy potential is continuous across the interfaces between sediment types under steady flow conditions, and it is typically used to infer flow direction. Potential energy in the unsaturated zone includes capillary, adsorptive, osmotic, and gravitational components. Capillary and adsorptive components are combined to form the matric potential, which is the component associated with the soil matrix. The osmotic potential is generally negligible in unsaturated media and can usually be ignored. In areas of moderate to high unsaturated water fluxes, gravity is the dominant driving force and matric potential gradients are generally close to zero. In addition to using the gradient in potential energy to evaluate the direction of water movement, the position of the measured matric potentials relative to a static equilibrium matric potential can be used to assess the flow direction under steady state [*Bear*, 1972, Figure 9.4.16, pp. 506].

Environmental and Applied Tracers

Environmental tracers generally provide information on cumulative water flux over time periods longer than those represented by hydraulic data. Chloride concentrations in pore water have been widely used to evaluate water fluxes in semiarid systems [*Allison and Hughes*, 1978]. According to the chloride mass balance approach, sources of chloride are generally assumed to be precipitation and dry fallout; however, if other sources exist (such as runon), such sources should be accounted for. Chloride concentration increases through the root zone as a result of evapotranspiration. Chloride transport through the unsaturated zone is described by the following:

Table 1. Geomorphic Location of 29 of the 39 Drilled Boreholes; Mean Values of Sand, Silt, Clay, and Carbonate Content; Range and Mean Water Content; Mean and Maximum Chloride Concentration; and Minimum Water Potential

Borehole	Geomorphic Setting	Borehole Location	Date Drilled	Borehole Depth, m	Sand, Mean %	Silt, Mean %	Clay, Mean %	Carbonate, Mean Wt. %	Water content, $g\ g^{-1}$			Wp Minimum, MPa	Depth WP Minimum, m	Cl, $g\ m^{-3}$		Depth Cl, Maximum, m
									Minimum	Maximum	Mean			Mean	Maximum	
BEGPTX 1	interplaya	101°32′30; 35°21′11	Jan. 1, 1992	24.4	···	···	···	···	0.09	0.20	0.14	−5.50	0.79	···	806	1.5
BEGPTX2	interplaya	101°34′43; 35°18′25	Jan. 2, 1992	22.1	···	···	···	···	0.06	0.27	0.12	−3.40	1.10	···	1166	1.0
Finley 1	interplaya	101°27′12; 35°6′24	Sept. 9, 1991	4.2	27	42	31	27	0.08	0.26	0.13	−7.97	0.52	1201	1706	2.0
Finley 2	annulus	101°27°22; 35°6′27	Sept. 10, 1991	12.2	41	29	30	18	0.06	0.27	0.14	−5.16	0.24	67	152	11.3
Finley 3	playa	101°27′32; 35°6′25	Sept. 13, 1991	14.2	41	27	32	14	0.07	0.30	0.19	−1.43	0.37	19	43	0.3
Koesjan 2	interplaya	101°37′32; 35°17′16	Aug. 28, 1992	13.4	33	37	30	···	0.09	0.17	0.13	−5.94	6.72	465	641	2.2
Koesjan 4	annulus	101°37′47; 35°17′52	Aug. 27, 1992	31.5	39	29	32	···	0.08	0.27	0.17	−1.19	4.04	78	142	1.9
Playa 5 no. 7	playa	101°36′27; 35°16′30	Oct. 12, 1994	27.0	17	···	···	···	0.15	0.31	0.26	−0.75	0.66	305	451	11.5
Playa 5 no. 8	playa	101°36′42; 35°16′35	Oct. 20, 1994	25.4	54	···	···	···	0.06	0.29	0.14	···	···	231	343	4.7
Playa 5 no. 26	interplaya	101°36′43; 35°16′2	Oct. 24, 1994	17.7	···	···	···	···	0.05	0.14	0.10	−13.60	0.05	726	2516	1.7
SMB 2	playa	101°33′11; 35°15′39	Aug. 30, 1992	27.0	20	33	47	···	0.08	0.37	0.27	−0.81	6.23	29	39	4.5
SMB 3	interplaya	101°33′14; 35°15′8	Sept. 13, 1992	22.0	49	34	17	···	0.05	0.24	0.13	−1.94	0.23	324	893	9.5
SMB 7	interplaya	101°32′32; 35°16′5	Sept. 15, 1992	20.6	···	···	···	···	0.03	0.16	0.11	−6.19	1.84	326	1245	1.9
TDCJ 1	interplaya	101°29′44; 35°24′49	Sept. 16, 1991	4.5	26	42	32	23	0.08	0.23	0.11	−6.42	0.67	836	2117	1.6
TDCJ 2	annulus	101°47′35; 35°24′52	Sept. 24, 1991	9.0	34	30	36	12	0.09	0.18	0.14	−5.01	0.52	306	657	2.8
TDCJ 3	annulus	101°29′49; 35°24′52	Sept. 27, 1991	24.4	42	26	32	10	0.06	0.29	0.15	−2.81	2.53	326	1118	5.4
TDCJ 4	annulus	101°30′19; 35°24′59	Dec. 3, 1991	26.2	37	35	30	11	0.06	0.34	0.18	−1.84	4.94	15	35	3.0
TDCJ 5	interplaya	101°29′36; 35°24′50	Dec. 4, 1991	18.6	33	38	29	19	0.08	0.16	0.12	−5.19	0.52	384	689	4.5
TDCJ 9	drainage	35°25′10; 101°29′56	Aug. 7, 1992	29.9	···	···	···	···	0.06	0.22	0.16	−0.67	1.75	179	737	2.1
TDCJ 11	interplaya	101°29′19; 35°24′46	Aug. 25, 1992	23.3	···	···	···	···	···	···	···	−3.64	0.91	···	···	···
TDCJ 28	playa	101°30′0; 35°25′2	Apr. 2, 1993	21.4	12	36	52	2	0.12	0.41	0.30	−0.71	11.76	16	37	17.5
Vance 2	playa	101°31′20; 35°19′47	Oct. 11, 1993	25.5	51	25	24	···	0.05	0.28	0.17	−0.99	5.68	129	338	11.0
Vance 6	interplaya	101°31′17; 35°19′41	Oct. 13, 1993	12.2	30	34	36	···	0.09	0.17	0.12	−13.16	0.27	320	488	8.6
Wink 1	interplaya	101°38′14; 35°19′22	Sept. 1, 1992	26.3	33	36	31	15	0.07	0.27	0.13	−7.37	0.90	848	4171	1.0
Wink 5	annulus	101°38′6; 35°20′18	Aug. 26, 1992	32.0	57	23	20	···	0.02	0.28	0.16	−0.39	25.80	54	62	2.5
Wink 7	playa	101°37′42; 35°20′5	Feb. 23, 1993	33.8	38	32	30	3	0.13	0.26	0.18	−1.34	2.00	17	23	3.2
Wink 13	playa	101°37′52; 35°20′11	Sept. 22, 1993	30.7	39	36	25	···	0.04	0.34	0.22	···	···	17	245	0.5
Wink 14	playa	101°37′52; 35°20′11	Sept. 26, 1993	29.8	51	27	22	···	0.03	0.23	0.15	···	···	···	···	···
Wink 17	interplaya	101°38′14; 35°19′22	Oct. 7, 1993	18.0	···	···	···	···	···	···	···	−30.10	0.05	···	···	···

Eight of the remaining 10 drilled boreholes were not listed because only water potential was measured, and thermocouple psychrometers were installed in the other two drilled boreholes that were not sampled.

$$q_{Cl} = c_{Cl}q_w - D_h \frac{\partial c_{Cl}}{\partial z} \tag{1}$$

where q_{Cl} is the chloride deposition flux at the surface ($M\ L^{-2}\ T^{-1}$), c_{Cl} is the pore water chloride concentration ($M\ L^{-3}$), q_w is the volumetric water flux below the root zone ($L\ T^{-1}$), and D_h is the hydrodynamic dispersion coefficient ($L^2\ T^{-1}$), which is a function of θ (the volumetric water content) and v (the average pore water velocity). The first term on the right represents the chloride flux that results from advection, and the second term represents the flux from dispersion. At low water velocities (<7 m yr^{-1}) the hydrodynamic dispersion coefficient can be approximated by the effective molecular diffusion coefficient (D_e) [*Olsen and Kemper*, 1968]. D_e includes the effects of tortuosity and water content. Water content data from the profiles were used to calculate D_e on the basis of the relationship between water content and D_e from *Kemper and van Shaik* [1966] and from *Olsen and Kemper* [1968]:

$$D_e(\theta) = D_0 a \exp{(b\theta)} \tag{2}$$

where D_0 is the diffusion coefficient of chloride in free water (0.006 m^2 yr^{-1} [*Kemper*, 1986]), a is a constant that ranges from 0.001 for clay to 0.005 for sandy loam, and b is 10. In many arid systems only the advective flux is considered [*Allison and Hughes*, 1978] and (1) is simplified to

$$q_w = q_{Cl}/c_{Cl} \tag{3}$$

The chloride deposition flux at the surface can be estimated either by multiplying chloride concentration in precipitation by the mean annual precipitation or by dividing the atmospheric fallout of ^{36}Cl by the prebomb ^{36}Cl/Cl ratio. The chloride concentration in precipitation (0.6 g m^{-3}) was estimated on the basis of data from wet precipitation collectors by *Lodge et al.* [1968] and also from bulk precipitation collectors (wet precipitation and dry fallout) by R. Nativ as described by *Wood and Sanford* [1995]. The long-term mean annual precipitation is 500 mm, and the resultant chloride deposition flux is 300 mg m^{-2} yr^{-1}. Estimation of chloride deposition flux from ^{36}Cl data requires information on variations in ^{36}Cl fallout with latitude, which were calculated by *Andrews and Fontes* [1991]. Dividing the atmospheric ^{36}Cl fallout for the latitude of the site (18 atoms m^{-2} s^{-1}) by the prebomb ^{36}Cl/Cl ratio for the study area (430 × 10^{-15}) results in a chloride deposition flux of 77 mg m^{-2} yr^{-1}. Recent studies indicate that ^{36}Cl fallout should also vary with precipitation [*Knies*, 1994]; such variation with precipitation is already well documented for bomb fallout. An estimate of the variation in ^{36}Cl fallout with precipitation is provided by [*Scanlon et al.*, 1997; F. M. Phillips, personal communication, 1996].

$$q_{^{36}Cl} = AP + B \tag{4}$$

where $q_{^{36}Cl}$ is the ^{36}Cl deposition flux in atoms per square meter per second, P is mean annual precipitation (meters), A is the slope coefficient (51.7 atoms m^{-3} s^{-1}), and B is the dry deposition component (10.4 atoms m^{-2} s^{-1}). Details of the derivation of this equation have been given by *Scanlon et al.* [1997]. Applying this formula to our study area, having 500 mm annual precipitation, gives 36.2 atoms m^{-2} s^{-1} (atmospheric fallout), which is divided by the measured prebomb ^{36}Cl/Cl ratio of 430 × 10^{-15} to give a chloride deposition flux of 157 mg m^{-2} yr^{-1}. This value implies an average chloride concentration in precipitation of 0.31 g m^{-3}.

The previous discussion outlines the uncertainties in estimating the Cl deposition flux at a site. The value of 157 mg m^{-2} yr^{-1} is probably most representative of chloride deposition flux in the study area, whereas the value of 77 mg m^{-2} yr^{-1} may be considered a lower limit because the atmospheric fallout values estimated by *Andrews and Fontes* [1991] did not account for variations in ^{36}Cl fallout with precipitation. On the other hand, the value of 300 mg m^{-2} yr^{-1} can be considered an upper limit because chloride recycles in precipitation collectors. Uncertainties in chloride deposition flux range from a factor of −0.5 to a factor of +2 at this site, resulting in corresponding uncertainties in the calculated water fluxes because (3) is linear. The average age of the chloride (t), and by implication that of the water, can be estimated from

$$t = \int_0^z \theta c_{Cl}\, dz \bigg/ q_{Cl} \tag{5}$$

This equation ignores hydrodynamic dispersion. If the chloride deposition flux is assumed uniform at a site, then chloride concentration in the pore water is inversely proportional to the water flux; low chloride concentrations indicate high water flux, and high chloride concentrations indicate low water flux.

Chloride concentrations in pore water are insensitive to preferential flow along roots or fractures [*Nativ et al.*, 1995]. In contrast, pulse-type tracers, such as bomb-pulse ^{36}Cl (half-life 301,000 years) and tritium (half-life 12.4 years), are generally used to evaluate preferential flow in arid and semiarid regions. Nuclear weapons tests conducted in the Pacific Ocean from 1952 through 1958 resulted in ^{36}Cl concentrations in precipitation that were as much as 10,000 times greater than natural fallout levels [*Bentley et al.*, 1986]. Tritium concentrations increased from 10 to ≥2000 tritium units (TU) during atmospheric nuclear testing [*International Atomic Energy Agency*, 1983], which began in 1952 and peaked in 1963. Deep penetration of ^{36}Cl and tritium (as deep as ~440 m) at Yucca Mountain [*Liu et al.*, 1995; I. C. Yang, personal communication, 1995] and of tritium (as deep as ~60 m) in the Negev desert in Israel [*Nativ and Nissim*, 1992] has been attributed to preferential flow along fractured rock. Because bomb-pulse-type tracers, such as ^{36}Cl and tritium, are generally required to evaluate preferential flow, these tracers were analyzed in this study.

Site Description

The Southern High Plains of Texas and New Mexico are internally drained by ~25,000 playas, each of which is generally <1.5 km^2 in area [*Sabin and Holliday*, 1995]. The study area is characteristically flat (elevation ranges from 1045 to 1100 m). The regional semiarid climate has a long-term mean annual precipitation of 500 mm (Amarillo precipitation record from 1948 through 1992). Approximately 70% of the precipitation falls from May through September. The natural vegetation is grass, but much of the region is used for agriculture. Perched aquifers, which are found beneath some areas of the study region, range in depth from 76 to 107 m [*Mullican et al.*, 1994]. The main aquifer in the region is the Ogallala, with a water table depth from 46 to 137 m in the study area [*Mullican et al.*, 1994].

The Pleistocene Blackwater Draw Formation, which hosts

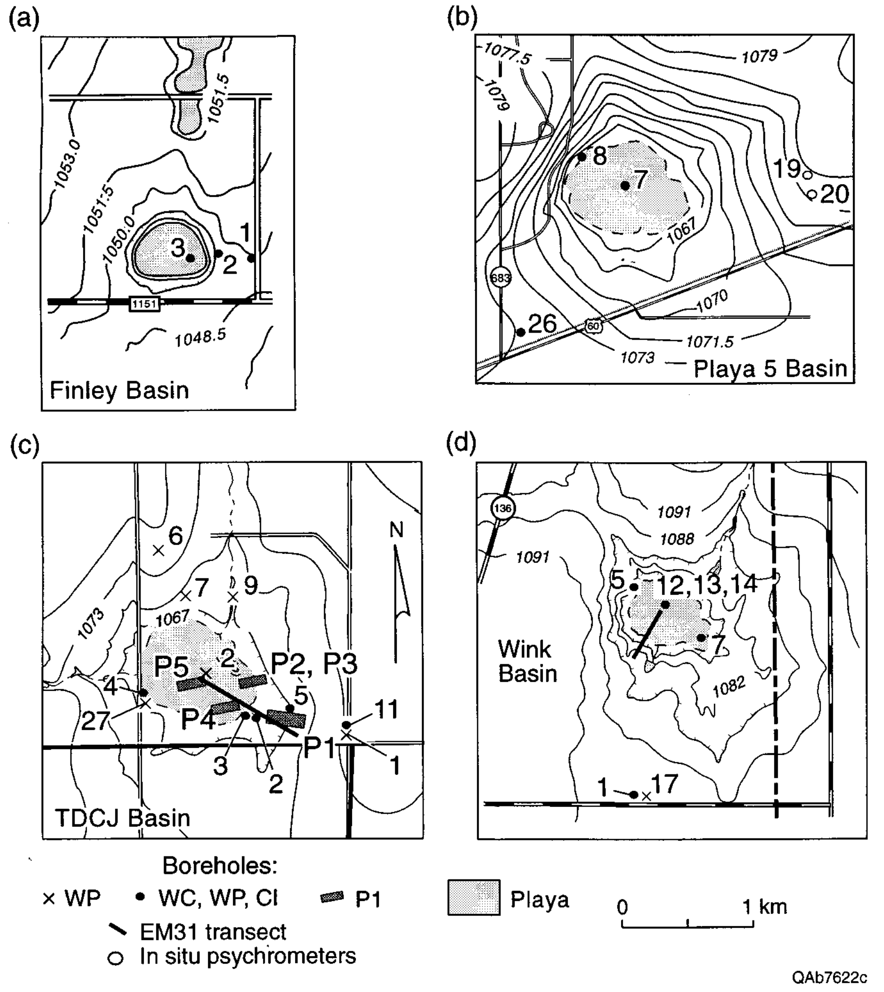

Figure 2. Location of sampled boreholes and monitoring equipment in (a) Finley, (b) Playa 5, (c) TDCJ, and (d) Wink playa basins. WC, water content; WP, water potential; Cl, chloride; and P1, ponding test. Borehole Wink 14 was also sampled for tritium analyses. Contour intervals for Figures 2a and 2b are 1.5 m and for Figures 2c and 2d are 3 m.

the playa sediments, consists of silty clay loam of eolian origin [*Holliday*, 1989]. The playas contain Randall clay soils (Vertisols) in the upper 1–2 m [*Jacquot*, 1959] that are underlain by clay-rich lacustrine sediments (5–18 m thick). A sand unit underlying the lacustrine sediments at a depth of 10–20 m records migration of sand sheets across the playa [*Hovorka*, 1995]. The modern and older clays have well-developed soil structures that include roots, peds, and slickensided vertic structures, which provide evidence of soil formation [*Hovorka*, 1995]. The annular region has a generally complex interbedding of clay and loam, which reflects past variations in lake size [*Hovorka*, 1995]. In the interplaya settings Pullman and Estacado soil series developed that consist of a silty clay loam having a well-developed Stage III calcic horizon [*Jacquot*, 1959]. The underlying sediments consist of clayey silt and sand of eolian origin that have as many as 12 buried calcic soil horizons [*Hovorka*, 1995].

Methods

Detailed descriptions of methods have been given by *Scanlon* [1994] and *Scanlon et al.* [1997]. Particle-size analyses were conducted on sediment samples from 20 boreholes, which were classified according to the *U.S. Department of Agriculture* [1975] system. Sediment samples were collected from 34 boreholes for water potential measurements in the laboratory (26 listed in Table 1; remaining 8 tabulated by *Scanlon et al.* [1997]). Many of the samples were collected from the same boreholes as were those sampled for texture. Sample intervals were variable and generally ranged from ≤0.3 m in the upper 5 m and increased with depth generally to 1- to 2-m intervals. We measured water potential in the laboratory using a thermocouple psychrometer that had a sample changer (model SC-10a; Decagon Devices, Inc., Pullman, Washington). Sediment samples were collected adjacent to borehole TDCJ 28 for laboratory measurement of saturated hydraulic conductivity using a constant head flexible wall permeameter [*American Society of Testing Materials*, 1990].

A total of 27 boreholes were sampled for gravimetric water content and 26 for chloride concentrations (Table 1). We extracted chloride from the pore water by adding double-deionized water to the dried sediment sample in a 3:1 ratio. All chloride concentrations are expressed as g Cl m^{-3} pore water. Three ^{36}Cl samples were collected from borehole Wink 1 (Figure 2d) at depths of 2.8, 4.4, and 10.9 m. Analysis for ^{36}Cl by

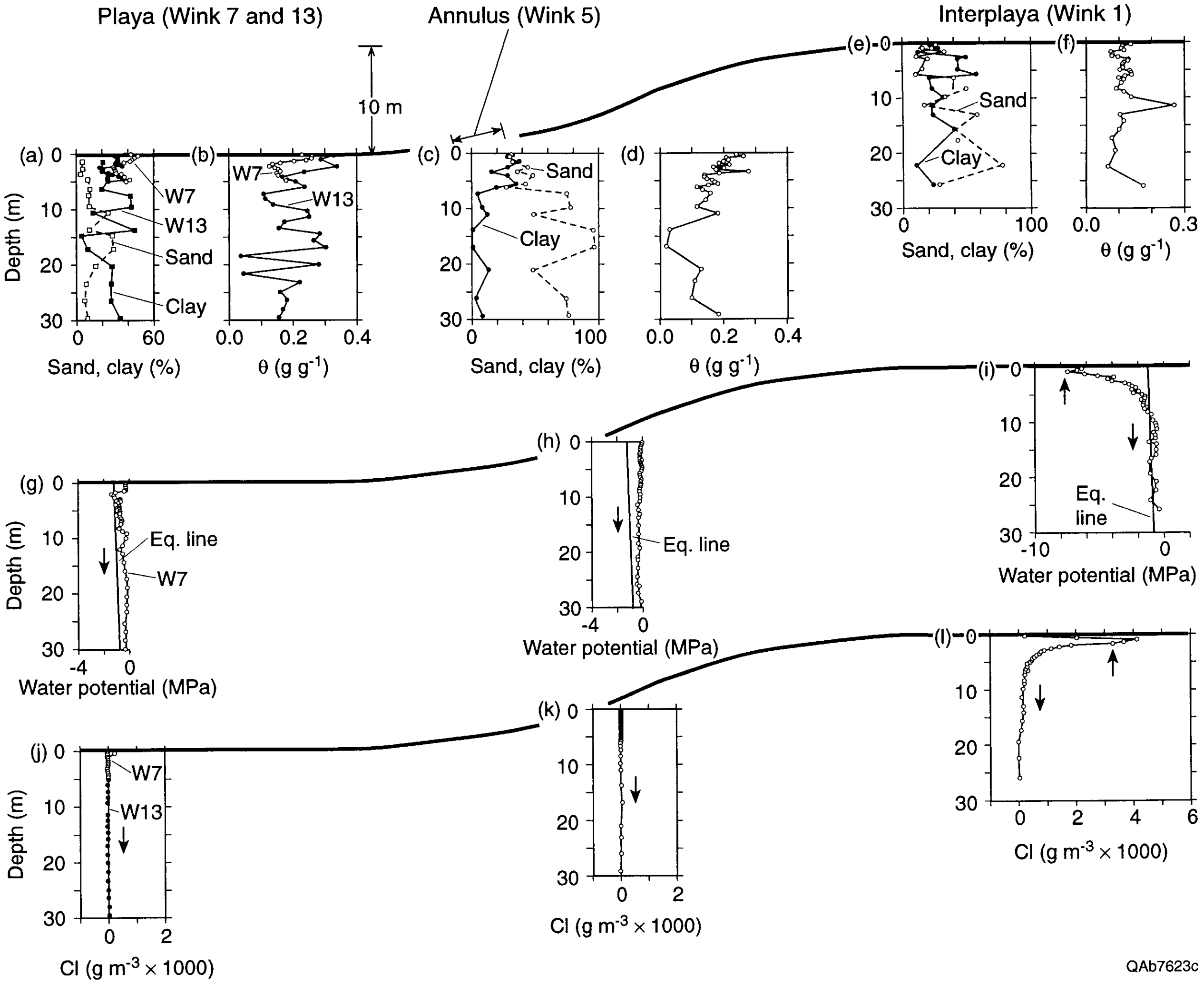

Figure 3. Profiles of texture, gravimetric water content, water potential, and chloride in relation to surface topography for boreholes in Wink playa basin. Texture, water content, and chloride for Wink 7 are plotted for the upper 5 m; water potential for Wink 7 was plotted for the entire profile (0.3–29.9 m); and texture, water content, and chloride for Wink 13 were plotted for the entire profile. Equilibrium line (Eq. line) marks the no flow line where matric and gravitational potentials are balanced. Arrows indicate the flow direction.

accelerator mass spectrometry was conducted at Lawrence Livermore National Laboratory according to procedures outlined by *Elmore et al.* [1984]. Samples for tritium analysis were collected from borehole Wink 14 in 1993 (Figure 2d). The pore water samples were extracted by toluene azeotropic distillation and were analyzed both enriched and unenriched according to standard direct scintillation methods at the University of Arizona Tritium Laboratory. We installed thermocouple psychrometers (model 74, PST 66; J. R. D. Merrill Specialty Equipment, Logan, Utah) in the interplaya setting adjacent to Playa 5 (borehole 19, 22.5 m deep; borehole 20, 23.0 m deep; Figure 2b) to monitor temporal variations in water potential and temperature daily. Calibration and installation procedures are similar to those described by *Scanlon* [1994].

Five ponding tests (2–2.6 m^2 in area) were conducted at TDCJ playa basin (Figure 2c): test 1 in the interplaya in May 1993, tests 2 and 3 in the annulus in June 1993, and tests 4 and 5 in the playa in December 1994. The procedures for all ponding tests were generally similar. First, dyed water was applied until a head of 100 to 180 mm was attained in various ponds. Then the ponded water was allowed to infiltrate. After infiltration was complete, a trench was excavated through the ponded area to allow visual inspection of the vertical distribution of dye in the subsurface and to permit sediment-sample collection for water-content and bromide analyses. The dye patterns were photographed and traced. Gravimetric water content was measured in the laboratory, and we analyzed bromide. Wick samplers similar to those described by *Boll et al.* [1992] were installed at a depth of 1.1 m beneath ponds 4 and 5 to evaluate temporal variations in preferential flow. Water collected in the samplers was analyzed for dye and bromide.

Results and Discussion

Results of analyses from selected profiles of Finley, TDCJ, and Wink playa basins are shown in Figures 3 and 4, and mean values and ranges of various parameters from most profiles are provided in Table 1. The remainder of the results are tabulated by *Scanlon et al.* [1997].

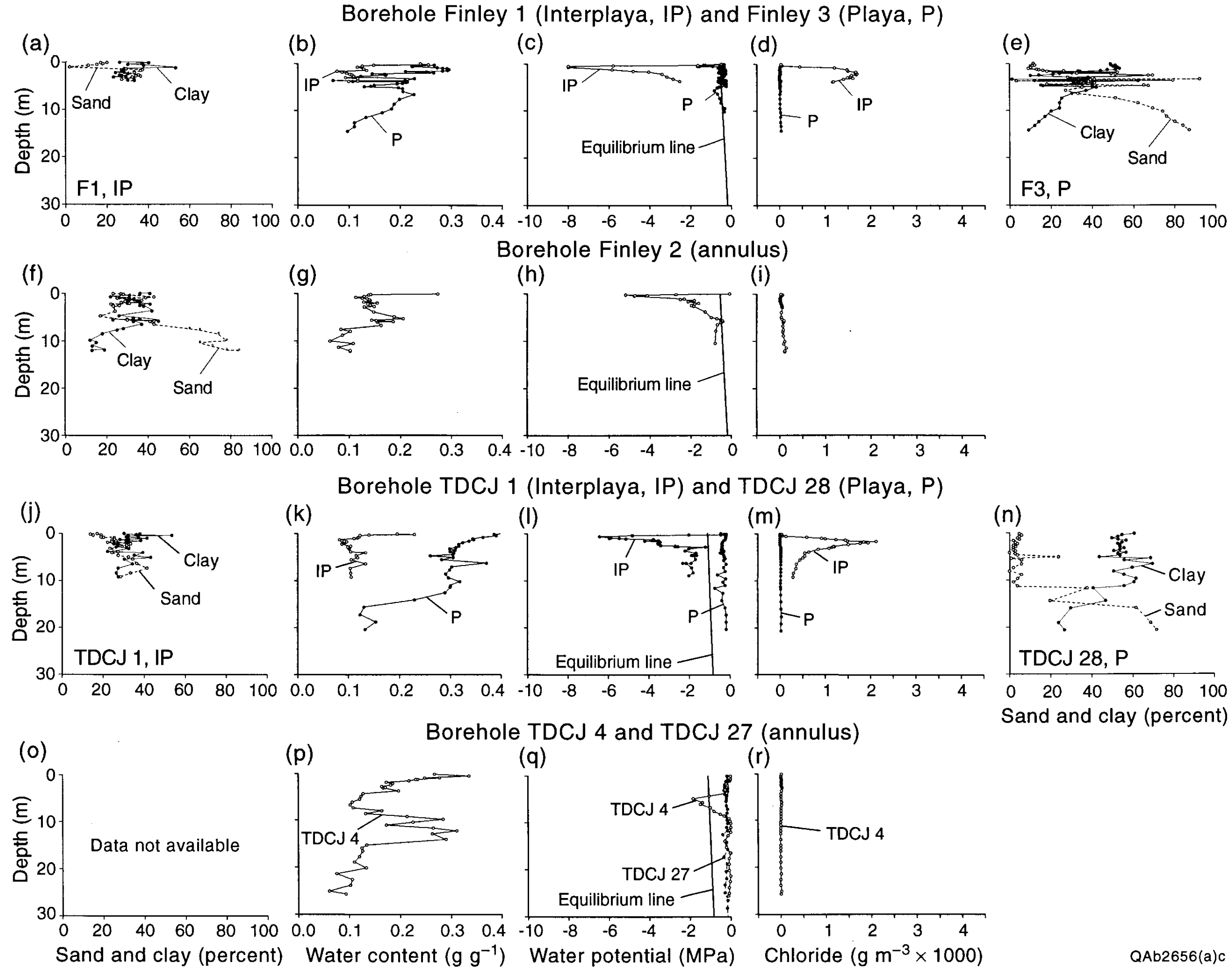

Figure 4. Profiles of texture, gravimetric water content, water potential, and chloride of boreholes in Finley and TDCJ playa basins.

Sediment Texture

Clay content in surficial sediments in many playas ranged generally from 40 to 60%. The depth of this clay-rich zone varied widely among the playas: fairly shallow in some playas (~1.5 m, Finley 3 (Figure 4e) and Wink 7 (Figure 3a)) and much deeper in other playas (~14 m, TDCJ 28 (Figure 4n) and SMB 2 [*Scanlon et al.*, 1997]). The clay fraction is predominantly illite-mica (5–45%) and smectite (4–34%) [*Mars*, 1996]. Many playas have a more sand-rich zone (40–91% sand) at depth (~7 m, Finley 3 (Figure 4e); ~11 m, SMB 3 [*Scanlon et al.*, 1997]; ~16 m, TDCJ 28 (Figure 4n); and ~11 m, Vance 2 [*Scanlon et al.*, 1997]). Although many previous studies [*Claborn et al.*, 1985; *Osterkamp and Wood*, 1987; *Wood and Osterkamp*, 1987] suggest that recharge is much higher in the annulus than in the playa because of coarser sediments in the annulus, textural analyses in this study show that surficial sediments in the annular region are only slightly coarser than in corresponding zones beneath the playa. Primarily clay loam was found in the annular region relative to clay in the playa in the upper 1 to 2 m. Interplaya sediments are slightly coarser grained (TDCJ 1 and Wink 1; silty clay loam) than the playa sediments (TDCJ 28, Wink 7, and Wink 13; clay to silty clay) in the shallow subsurface [*Scanlon et al.*, 1997]. The mean carbonate content in profiles beneath TDCJ and Wink playas is ≤3% (TDCJ 28 (range: 0–5%) and Wink 7 (range: 0–9%)) (Table 1). In contrast, mean carbonate content is much higher in the interplaya profiles (Finley 1, 27%; TDCJ 1, 23%; and TDCJ 5, 19%).

Water Content

Water content generally increased from interplaya to playa settings (Figures 3 and 4; Table 1). Although fine-grained sediments such as clays retain more water than coarser grained sediments such as loams, water-content variations among the different settings cannot be explained solely by differences in texture. In Finley playa basin, for example, similar textures (clay loam) had average water contents of 0.10 g g^{-1} in the interplaya borehole (Finley 1), 0.14 g g^{-1} in the annular borehole (Finley 2), and 0.21 g g^{-1} in the playa borehole (Finley 3). These differences are attributed to higher water fluxes beneath playas than in the annular or interplaya settings. Depth variations in water content within individual profiles were generally negatively correlated with percent sand and positively correlated with percent silt and clay [*Scanlon et al.*, 1997].

Water Potential

In playa sediments, laboratory-measured water potentials were much higher than those in the interplaya sediments, par-

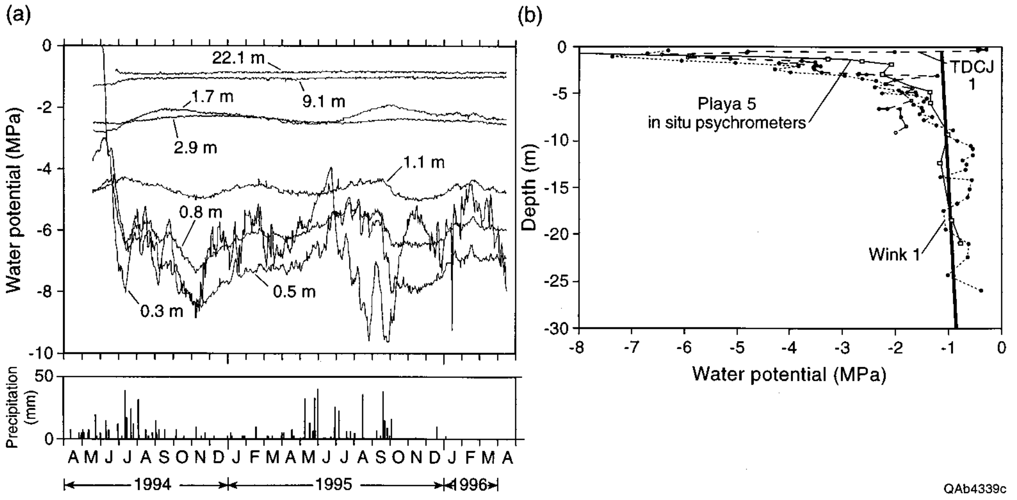

Figure 5. (a) Temporal variations in water potential monitored daily by in situ thermocouple psychrometers adjacent to Playa 5 (interplaya setting, boreholes 19 and 20; Figure 1) for depths of 0.3, 0.5, 0.8, 1.1, 1.7, 2.9, 9.1, and 22.1 m depths; (b) comparison of water potentials measured in situ on July 14, 1994, by thermocouple psychrometers adjacent to Playa 5 with laboratory measured water potentials in sediment samples from TDCJ 1 and Wink 1 interplaya profiles.

ticularly in the upper 5–10 m (Figures 3g, 3i, 4c, and 4l; Table 1), a finding consistent with the high water contents in profiles beneath playas. The water (sum of matric and osmotic) potentials were approximately equivalent to the matric potentials because the magnitude of the osmotic potentials was generally $\leq$0.01 MPa [*Scanlon et al.*, 1997]. The water potential gradient in the playa profiles was close to zero, suggesting that water was draining beneath playas under gravitational head. Water potentials in the playa profiles plot to the right of the equilibrium matric potential, also indicating that under steady flow conditions water was draining in these sediments (Figures 3g, 4c, and 4l). Because water potential gradients can be neglected, water flux can be approximated by hydraulic conductivity, which varies with water content. Saturated hydraulic conductivity estimates based on laboratory measurements in this study ($\sim 2 \times 10^{-10}$ m s^{-1}) provide upper limits on water flux through the soil matrix; however, they ignore preferential flow through cracks and roots.

Water potentials in annular settings show no consistent relationship with water potentials in adjacent playa-interplaya settings. In some cases, water potentials in annular settings (TDCJ 4, TDCJ 27 (Figure 4q); Wink 5 (Figure 3h)) resembled those in adjacent playa settings (TDCJ 28 (Figure 4l); Wink 7 (Figure 3g)), which indicates high water fluxes in these annular settings similar to those in the adjacent playa. However, other annular profiles (TDCJ 2, TDCJ 3) had water potentials that were intermediate between those in adjacent playa (TDCJ 28) and interplaya (TDCJ 1) settings (Table 1), which suggests lower water fluxes in these annular regions relative to those in the adjacent playa.

In the interplaya setting, boreholes sampled after a long dry period had low water potentials in near-surface sediments (as low as -30 MPa, Wink 17; Table 1), indicating that the surficial sediments were extremely dry. Except in the shallow subsurface after rainfall, water potentials generally increased with depth. Gradients were very steep in the shallow zone ($\sim$1.0 to 1.5 MPa m^{-1} in the upper 4 m TDCJ 1 and Wink 1 profiles). The downward increase in water potentials in the top 5–10 m indicates that there is an upward driving force for water movement. Water potentials lie to the left of the equilibrium line in the upper $\sim$10 m, which also indicates upward flow under steady flow conditions in this zone (Figures 3i, 4c, and 4l). Water potential gradients decrease with depth, suggesting drainage of water at depth. At depths $\geq\sim$10 m, water potentials measured in sediment samples from Wink 1 plot close to or to the right of the equilibrium line, further suggesting drainage of water at depth under steady flow conditions (Figure 3i).

Information on temporal variability in water potentials was provided by the field monitored water potentials (Figure 5a). Water potentials in the upper 0.3 m were close to zero initially, which indicates the maximum penetration depth of the wetting front during the monitoring period. Water potentials decreased sharply with depth, particularly at the 0.3- and 0.5-m depths, in June 1994, which indicates rapid drying of the sediments as a result of evapotranspiration. Water potentials in the upper 0.8 m remained fairly low (~ -4 to -10 MPa) throughout the remainder of the monitoring period. Below these depths water potentials remained fairly uniform after the initial equilibration period. The vertical distribution of water potentials shows an upward decrease, which indicates an upward driving force for water movement (Figure 5b). At depths $\geq\sim$10 m, field-monitored water potentials plot close to, or to the right of, the equilibrium line, which suggests drainage of water in this zone under steady flow conditions. Field-monitored water potentials resembled laboratory-measured water potentials of sediment samples collected in similar interplaya settings (Figure 5b).

Environmental Tracers

Meteoric chloride. Mean chloride concentrations in profiles sampled beneath the playas generally ranged from 16 g m^{-3} (TDCJ 28) to 29 g m^{-3} (SMB 2), with the exception of Vance 2 (mean 129 g m^{-3}) and Playa 5 (no. 7, mean 305 g m^{-3}; no. 8, 231 g m^{-3}) (Table 1). The generally low chloride concentrations in playa profiles provide evidence of high water fluxes and indicate either that chloride never accumulated or that it has been flushed out. The low chloride concentrations are consistent with the low carbonate content in sediments beneath playas, which also indicates high water fluxes. Higher chloride concentrations beneath Vance playa, reflecting incomplete flushing beneath this playa, are consistent with carbonate nodules in these sediments [*Hovorka*, 1995]. Vance playa is also densely vegetated by grasses, which suggests infrequent flooding. High chloride concentrations in Playa 5 profiles are attributed to discharge of sewage and waste into the playa from 1968 through 1992.

Water fluxes estimated for playa profiles on the basis of chloride mass balance (equation (3)) ranged from 6 to 10 mm yr^{-1}. These values of water flux for the playas are minimum estimates because runon into the playas has been neglected. The chloride deposition flux used in these equations was 157 mg m^{-2} yr^{-1}; however, as discussed in the introduction, uncertainties in the deposition values range from a factor of -0.5 to 2, which would result in water fluxes of 3 to 20 mm yr^{-1}. We can also estimate water fluxes by including runon [*Wood and Sanford*, 1995]:

$$q_w = \frac{q_{Cl}}{c_{Cl\,uz}} + R_0\left(\frac{A_b c_{Cl\,R_0}}{A_f c_{Cl\,uz}}\right) \tag{6}$$

where q_{Cl} is the chloride flux at the surface, $c_{Cl\,uz}$ is the chloride concentration in the unsaturated zone pore water, $c_{Cl\,R_0}$ is the chloride concentration in the runon, R_0 is runon, A_b is the area of the basin, and A_f is the area of the playa. *Wood and Sanford* [1995] estimated runon into the playas to be ~5% of precipitation on the basis of tritium and chloride data at a site in the central part of the Southern High Plains. A value of 10% was assumed in this study because sediments in the study area are finer grained than those examined by *Wood and Sanford* [1995] [*Sabin and Holliday*, 1995]. *Wood and Sanford* [1995] also assumed that the chloride concentration in runon is the same as that in precipitation; however, the value used in their calculation (2.81 g m^{-3}) was ~4 times greater than the value used in recharge estimates (0.6 g m^{-3}) in their study. We assumed that the chloride concentration in runon is ~4 times higher (1.24 g m^{-3}) than that in precipitation (0.31 g m^{-3}) because of chloride in surficial sediments. The water flux estimates for the playas based on (6) ranged from 60 to 100 mm yr^{-1}, which are an order of magnitude greater than estimates that neglect runon.

Contaminants in Playa 5 can be considered long-term applied tracers and can be used to estimate water fluxes. These water fluxes are representative of playas that receive large quantities of wastewater. The calculated water flux of ~200 mm yr^{-1} was based on chloride concentrations sampled in 1994 to a maximum depth of 25.4 m (no. 7 borehole) that resulted from sewage discharged from 1968 through 1992. Because the sampled borehole did not penetrate the base of the contaminated sediments, calculated water fluxes are minimum estimates. High chloride and nitrate concentrations in groundwater (71 m depth) suggest a water flux of ~600 mm yr^{-1} (A. E. Fryar, personal communication, 1996).

In most cases, mean chloride concentrations in annular settings (TDCJ 4, 15 g m^{-3}; Wink 5, 54 g m^{-3}) were similar to those in adjacent playa settings (TDCJ 28, 16 g m^{-3}; Wink 7 and 13, 17 g m^{-3}), which suggests similar water fluxes in annular and playa regions. Mean chloride concentrations in TDCJ 2 (306 g m^{-3}) and TDCJ 3 (326 g m^{-3}) in the annulus, however, were higher than those in the playa (TDCJ 28; 16 g m^{-3}; Table 1), indicating lower water fluxes in this annular region.

In contrast to the generally low chloride concentrations in playa and most annular settings, maximum chloride concentrations in interplaya settings were high and ranged from 1166 g m^{-3} (1-m depth, BEG PTX 2) to 4171 g m^{-3} (1-m depth, Wink 1) (Table 1). Chloride profiles in interplaya settings had generally low concentrations in the upper 0.1- to 0.5-m depth (Figures 3l, 4d, and 4m). Chloride concentrations increased sharply to maximum concentrations generally at depths of 1 to 2 m and decreased gradually below the peak to low values at depth (as low as 39 g m^{-3} at 26-m depth, Wink 1; Figure 3l).

It is difficult to estimate water fluxes with certainty from chloride data in interplaya profiles because chloride concentrations do not remain constant below the peak. Reduction in chloride concentrations below the peak could result from preferential flow diluting chloride at depth or from higher water fluxes during the past. If preferential flow reduced chloride concentrations below the peak, one would expect bomb-pulse tracers below the chloride peak. The ^{36}Cl/Cl ratios in three samples from Wink 1 (440×10^{-15}, 2.8 m depth; 420×10^{-15}, 4.4 m depth; and 430×10^{-15}, 10.9 m depth) are typical of background ^{36}Cl/Cl ratios found at many sites (450×10^{-15} [*Scanlon*, 1992]; 490×10^{-15} [*Fabryka-Martin et al.*, 1993]), whereas peak bomb-pulse values would be as much as an order of magnitude higher [*Scanlon*, 1992]. Although these data are limited, they suggest that reduction in chloride concentrations is more likely the result of transient conditions resulting in increased water flux in the past than from preferential flow. Lack of preferential flow is supported by low tritium concentrations below chloride peaks in interplaya settings [*Wood and Sanford*, 1995].

The chloride data were smoothed by fitting power functions to the data, and the water flux was calculated from (3) using a chloride deposition flux of 157 mg m^{-2} yr^{-1}. Equation (3) ignores diffusive fluxes of chloride, which is similar to most previous analyses of chloride profiles that neglect diffusive fluxes [*Allison and Hughes*, 1978; *Phillips*, 1994]. The time period represented by the chloride profiles was estimated using (5). The Wink 1 profile represents the longest record in an interplaya setting (9900 years). Estimated water fluxes ranged from ≤0.1 mm yr^{-1} during the past 5000 years and increased below this zone to a maximum value of 4 mm yr^{-1} at the base of the profile (9900 years) (Figure 6c). Similar ranges in water flux were found in the TDCJ 1 profile (from ≤0.1 mm yr^{-1}, ≤2000 years, to 0.5 mm yr^{-1}, ~5500 years; Figure 6b) and in the Playa 5 number 26 profile (from ≤0.1 mm yr^{-1}, ~3000 years, to 1 mm yr^{-1}, 8500 years; Figure 6a). Uncertainties in water fluxes and ages range from a factor of -0.5 to $+2$ (0.1 mm yr^{-1} equivalent to 0.05–0.2 mm yr^{-1}; 5000 years equivalent to 2500–10,000 years) because of uncertainties in the chloride deposition flux.

The periods of higher water flux estimated from chloride data in some of these interplaya profiles are at much shorter timescales than the Pleistocene-Holocene variations in climate (~10,000 years ago) that resulted in higher water fluxes at many sites in the southwestern United States [*Scanlon*, 1991; *Phillips*, 1994]. The interplaya chloride profiles may reflect shorter term climatic fluctuations, with recurrence intervals of approximately thousands of years that are not preserved in the paleoclimatic record. Although chloride can be readily flushed out of the profiles after short-term ponding, several thousands of years are required to accumulate chloride at levels found in

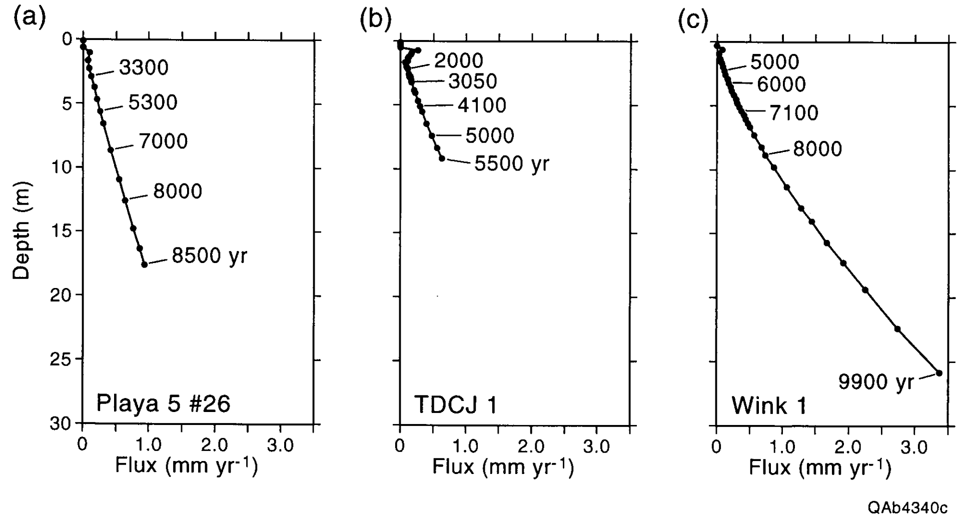

Figure 6. Variations in water flux with depth estimated from playa 5 no. 26, TDCJ 1, and Wink 1 chloride profiles. The corresponding chloride mass balance ages are also shown.

interplaya profiles in this study. Alternatively, chloride profiles may reflect changes in factors other than climate that control unsaturated flow, such as vegetation. The importance of vegetation in removing water from the subsurface has been demonstrated in many areas. At the Hanford site, in Washington, replacement of shrub vegetation with grasses (a result of wildfires) resulted in marked increases in unsaturated flow [*Prych*, 1995]. Higher past water fluxes may also be reflected in the higher water potentials and zero water potential gradients in many interplaya profiles, which indicate drainage at depth. Such water could also provide a source for low upward water fluxes in the shallow subsurface that are indicated by upward water potential gradients, reflecting long-term drying of the sediments in the profiles.

Another explanation for chloride profiles would be that instead of a reduction in water flux with time, the water flux changed from downward to upward. Therefore, below the shallow subsurface active zone, chloride profiles may represent upward water movement with a net sink for water at ~1-m depth because of water extraction by roots and downward chloride diffusion from ~1-m depth. Downward chloride diffusion is supported by the high diffusive chloride fluxes (equation (1)) in the upper 5 m in Playa 5 no. 26, TDCJ 1, and Wink 1. These diffusive fluxes are up to an order of magnitude higher than advective chloride fluxes immediately beneath the chloride peak. At greater depths the diffusive component of the chloride flux decreased and was generally an order of magnitude less than the advective chloride flux at a depth of ~10 m. Uncertainties in calculated effective diffusivities are high, and the applicability of laboratory-derived effective diffusivities to field sites with low water contents is questionable. Upward water flow is consistent with upward water potential gradients in the top 10 m; however, we do not know how long it takes to generate these water potential profiles. In either case, whether water is moving downward or upward, the water fluxes are extremely low in natural interplaya settings.

Tritium. Tritium levels in the pore water beneath Wink playa (Wink 14) ranged from 4.4 ± 0.4 to 77 ± 5 TU (Figure 7b). These values indicate post-1952 water flux to a depth of at least 29 m. The tritium profile had multiple peaks, the highest tritium concentration, 77 TU, at a 21-m depth. The zone of fairly high tritium concentrations (39–77 TU) from 18- to 21-m depth corresponds to a zone of low water content (2.7–4.6 g g^{-1}) and to a laterally extensive sand layer (96–98% sand). This sand layer is also found in borehole Wink 12 (~300 m from Wink 14) from a 18.5- to 22.1-m depth (92–99% sand). This zone of high tritium probably reflects 1964 tritium rain, judging from a comparison with fallout data from Waco, Texas (Figure 7a). Tritium concentrations were low in the base of the profile (4.4 ± 0.4 TU in a sample combined from 28- and 29.1-m depths). The tritium concentration in perched groundwater (~90 m depth) adjacent to Wink playa was 1.8 TU [*Mullican et al.*, 1994].

Multiple tritium peaks could result from variations in tritium

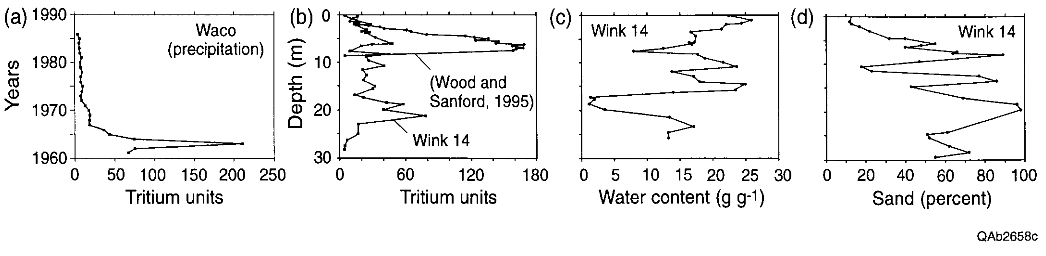

Figure 7. (a) Tritium measured in precipitation at Waco, Texas, decay corrected (to 1993) [*International Atomic Energy Agency*, 1992]; (b) vertical profile of tritium from Wink 14 (playa setting) and TB21 [*Wood and Sanford*, 1995], (c) water content, and (d) sand content from Wink 14.

input to the system over time or from preferential flow. The Waco tritium fallout data are smooth (Figure 7a), and a smooth, single-peaked tritium profile beneath a playa to the south of the study area (Figure 7b) [*Wood and Sanford*, 1995] suggests that the multiple peaks beneath the Wink playa are more likely the result of preferential flow. The occurrence of bomb-pulse tritium as deep as 29 m suggests a water velocity of 710 mm yr^{-1}, which is important for estimating preferential flow. To calculate recharge in areas of preferential flow, *Cook et al.* [1994] suggested that the center of mass rather than the peak concentration should be used to estimate water fluxes because the latter does not conserve mass. A water velocity of 490 mm yr^{-1} was calculated on the basis of the depth of the center of mass of the tritium profile (14.2 m) and the time from the center of mass of the fallout (1964, on the basis of data from Ottawa, Canada, ranging from 1953 to 1987) and sample collection (1992). The resultant water flux was 120 mm yr^{-1}, which was based on an average water content of 0.24 m^3 m^{-3}.

The multipeaked tritium profile beneath Wink playa provides qualitative evidence of preferential flow to 18 m depth. The tritium samples were extracted from large sediment samples, however, and more likely represent a mixture of water from preferred pathways and the matrix. Geologic core description also indicates that the entire section of lacustrine clays has intensely developed structures [*Hovorka*, 1995]. The occurrence of high tritium in a sand layer from a depth of 18 to 21 m beneath Wink playa suggests that structureless sand layers may limit the vertical connectivity of preferred pathways. This hypothesis is supported by *Flury et al.* [1994], who indicated that preferred pathways may terminate in the transition from structured, fine-grained material to structureless, coarse-grained material, as evidenced by the distribution of organic dyes. The sand layers beneath playas may function as a reservoir for volatile contaminants because of their low water content and lack of preferred pathways.

Applied Tracers

All field ponding experiments conducted in TDCJ playa basin showed varying degrees of preferential flow. With the exception of pond 1, in the interplaya setting, all ponded areas had near-surface open cracks before ponding began. Evidence of preferential flow during ponding was provided by dripping dyed water from roots in the ceiling of an access tunnel (1.1 m deep) that was excavated for the wick sampler beneath pond 5. Water had collected in the wick samplers beneath pond 5 between 54 and 72 hours after the test began.

We excavated trenches beneath all ponds to examine the vertical distribution of dye and to collect samples for analyses. All trenches exhibited a uniformly dyed zone that ranged from 70 mm in thickness beneath pond 1 in the interplaya setting (Figure 8) to 10–20 mm in thickness beneath all other ponds. This zone of uniform dye resembles the mixing or distribution zones discussed by *Steenhuis et al.* [1994a, b], and dyes are adsorbed in this zone, which acts as a reservoir for preferred pathways at greater depth. Below the mixing zone, FD&C blue dye was restricted to preferred pathways, including interpedal pores and root tubules in interplaya settings (pond 1, Figure 8); near vertical planar fractures, interpedal pores, and root tubules in the annular region (ponds 2 and 3); and annular spaces around roots and planar vertic structures in playas (ponds 4 and 5). The density of preferred pathways decreased with depth (Figure 8). Many of the dyed areas, particularly in the annular region (ponds 2 and 3), had a two-dimensional planar geometry. The penetration depths of the dye ranged from 0.5 to 1 m, depending on the test. Bromide analyses, which were available for ponds 1, 4, and 5, also provided evidence of preferential flow. Bromide concentrations exceeded the background value of 2.5 g m^{-3} throughout the upper 0.6 m beneath pond 1, a measurement that also corresponded to the vertical extent of the dyed pathways. Extreme variability in bromide concentrations beneath ponds 4 and 5 in the playa suggests preferential flow (Figure 9). The length of time until ponding (15 min, pond 4; 0 min, pond 5), penetration depth of dye and bromide (Figure 9), and the time required for all the water to infiltrate (pond 4, 25 hours; pond 5, 72 hours) suggest that preferential flow was greater beneath pond 4 (300 m from playa center), where the sediments were initially drier and cracks were more evident, than beneath pond 5 (playa center), which was more frequently flooded.

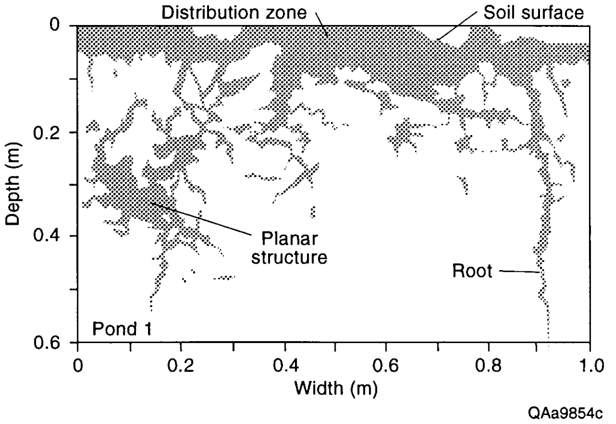

Figure 8. Vertical cross section of FD&C blue dye beneath pond 1 infiltration test at TDCJ playa basin (interplaya setting).

Spatial Variability in Unsaturated Flow

Both physical and chemical data collected in this study indicate that playas focus recharge. High water contents, high water potentials, and low chloride and high tritium concentrations in pore water (Figures 3, 4, and 7; Table 1) all indicate high water fluxes beneath playas. The arrows in Figure 3 indicate direction of water movement and show downward movement in the playa and adjacent annulus. Water flux estimates based on chloride and tritium data ranged from 60 to 120 mm yr^{-1}. Estimates of saturated hydraulic conductivity ($\sim 2 \times 10^{-10}$ m s^{-1} equivalent to ~6 mm yr^{-1}) indicate that even when the playa floor sediments are fully saturated, they are not impermeable. The data from this study are consistent with findings of *Wood and Sanford* [1995], which show low chloride and high tritium concentrations beneath playas. Although the results of this study may appear trivial, it should be realized that prior to this study there was considerable controversy about whether playas focus recharge or act as evaporation pans. In studies that suggested that playas focus recharge, there was debate about whether recharge is restricted to the annular region surrounding the playas or whether recharge also occurs in the playa floor. The concept of playas as evaporation pans is inconsistent with the lack of chloride buildup in the ponded water [*Wood and Osterkamp*, 1987] and water content, water potential, chloride, and tritium data in this study. The restriction of percolation to annular regions [*Osterkamp and Wood*, 1987; *Wood and Osterkamp*, 1987] is also unsup-

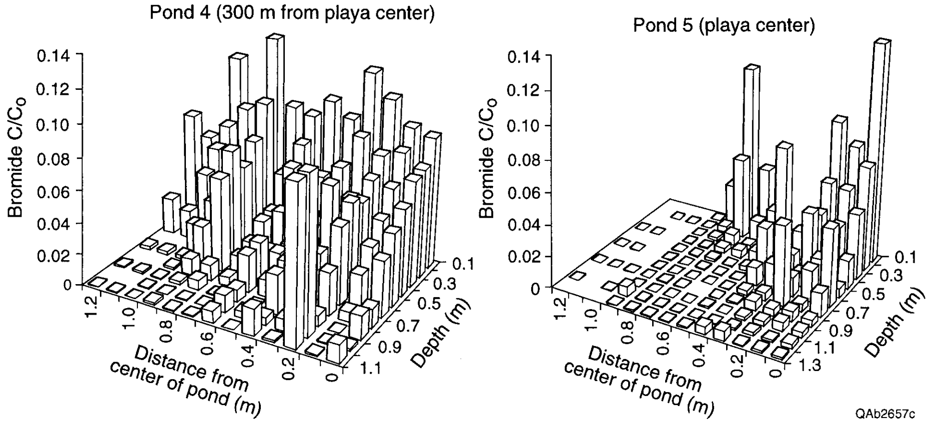

Figure 9. Profiles of bromide concentration in pore water extracted from sediment samples beneath ponds (a) 4 and (b) 5.

ported by data in this study. Some profiles in the annular regions resembled those in the adjacent playas; however, others had lower water potentials and higher chlorides than those in the playas, which suggests lower water fluxes in these annular regions relative to the adjacent playas.

Because the area covered by playas was estimated to be 3% on the basis of GIS analysis of a 5×10^9 m^2 area surrounding the study region [*Mullican et al.*, 1994], the spatial focusing exerted by the playas is extreme. Published estimates of aerially uniform recharge are generally ≤25 mm yr^{-1}; however, recharge estimates beneath playas from this study are approximately an order of magnitude higher. Use of an aerially uniform recharge rate of 20 mm yr^{-1}, an average water content of 0.2 m^3 m^{-3} (velocity 100 mm yr^{-1}), and a water table depth of 70 m would result in a contaminant travel time of ~700 years. Use of playa-focused recharge values from this study of 120 mm yr^{-1} would result in a travel time of ~120 years. Because contaminated sites generally received much more water than did natural playas, the water fluxes through these systems would have to be even greater, as shown by chloride and nitrate data from groundwater beneath Playa 5, which had an estimated maximum travel time of 24 years. High tritium levels in groundwater (44 TU, 61-m depth) reflect 1966 to 1967 tritium fallout and suggest a maximum residence time of 25 years [*Fryar and Mullican*, 1995].

The apparent contradiction between thick clay layers and high recharge rates can be resolved because water moves preferentially through the clay sediments. The ponding experiments conducted in this study provide direct visual evidence of preferential flow. Desiccation cracks, interpedal pores, and root tubules provide pathways through low-permeability clays in the playa. Whereas ponding may greatly increase the occurrence of preferential flow initially after a dry season, continued ponding may reduce preferential flow as the clays swell. Studies by *Bronswijk et al.* [1995] show that leaching of bromide was much greater in the summer when the clay was dry and cracked than in the winter when the clay was wet and expanded. Although ponding test results are generally restricted to the upper meters of sediment, the multipeaked tritium profile beneath Wink playa provides qualitative evidence of preferential flow to an 18-m depth.

In contrast to those in playa settings, unsaturated water fluxes in undisturbed interplaya settings not subjected to ponding under current climatic conditions are negligible. This observation is supported by low water contents, low minimum water potentials, high peak chloride concentrations in pore water (Figures 3 and 4), and high carbonate contents in the sediment (Table 1). The upward decrease in water potentials in the top 5 to 10 m indicates net upward water movement in this zone (see arrows Figure 3). Estimated water fluxes were ≤0.1 mm yr^{-1} during the past 2000 to 5000 years on the basis of chloride data. High water potentials and low chloride concentrations at depth in these profiles suggest drainage of older water that has estimated water fluxes of as much as 4 mm yr^{-1} at a depth of ~25 m (~9900 years).

Low water fluxes estimated for natural interplaya settings suggest that contaminant transport in these areas should be negligible. Alteration of interplaya settings and excavation of ditches for transporting liquid wastes and storm water to playas would result in high transport velocities beneath the ditches similar to the high velocities beneath playas. Low chloride concentrations beneath ditches at the Pantex Plant provide evidence of high water fluxes in these settings (P. C. Bennett, personal communication, 1995). In these altered systems, ditches, like playas, focus water flow and allow rapid transport of contaminants. Typical calcic soils in interplaya settings do not provide a barrier to flow, as evidenced by the artificial recharge experiments conducted in interplaya settings on calcic soils that showed rapid downward water movement [*Aronovici et al.*, 1970; *Schneider and Jones*, 1984].

Although many studies in the past emphasized the importance of soil surveys to the understanding of unsaturated flow processes, the results of this study indicate that ponding, not soil texture, is the primary control on unsaturated flow in these regions and results in high water fluxes and high solute transport velocities through the unsaturated zone.

Conclusions

Playas collect surface runoff from large catchment basins and focus flow through the unsaturated zone. Evidence for high water fluxes through the unsaturated zone is provided by high water contents, high water potentials, low chloride and high tritium concentrations in the pore water, and low carbonate contents in the sediments. Water potentials close to zero suggest drainage of water under unit gradient conditions. Low mean chloride concentrations (16–29 g m^{-3}) indicate high water fluxes (60–100 mm yr^{-1}), which prevent chloride accumulation or flush out previously accumulated chloride. High tritium concentrations to a 29-m depth indicate high water fluxes (~120 mm yr^{-1}). In contrast to the playa setting, unsaturated water movement in interplaya regions not subject to ponding is negligible, as shown by low water contents, low minimum water potentials, high peak chloride concentrations in the pore water, and high carbonate contents in the sediments. Steep upward water potential gradients (≤1.5 MPa m^{-1}) in the top 10 m indicate an upward driving force for water movement. At depths greater than ~10 m, water potential gradients are negligible, suggesting drainage of water. Water fluxes estimated from the chloride data were ≤0.1 mm yr^{-1} and indicate negligible water fluxes during the past 2000–5000 years. Higher water fluxes before that time were up to 4 mm yr^{-1} at ~26-m depth. Higher water fluxes in the past may be attributed to wetter climate or different vegetation and are consistent with drainage indicated by water potential gradients of zero at depth.

Frequent ponding of water in playas and the highly structured nature of the clays predispose the system to preferential flow. Applied tracer experiments that included FD&C blue dye and bromide provided visual evidence of preferential flow along interpedal pores, roots, and desiccation cracks in playas. Additional evidence of deep preferential flow was provided by a multipeaked tritium profile beneath a playa.

The primary control on unsaturated flow is surface ponding of water, which occurs in playas and in ditches and which focuses recharge to the underlying aquifer. Macropores in the structured clays in playas allow rapid transport of contaminants through the system and bypass the buffering capacity of much of the unsaturated matrix.

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