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Soil-water movement under natural-site and waste-site conditions: A multiple-year field study in the Mojave Desert, Nevada

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Abstract. Soil-water movement under natural-site and simulated waste-site conditions were compared by monitoring four experimental sites in the Mojave Desert, Nevada, during a 5-year period: one vegetated soil profile, one soil profile where vegetation was removed, and two nonvegetated test trenches. Precipitation ranged from 14 to 162 mm/yr. Temporal changes in water content measured by neutron probe were limited to the upper 0.5–1 m; values ranged from 0.01 to 0.19 m^3/m^3. Water potential and temperature were measured by thermocouple psychrometers; 77% remained operable for ≥4.5 years. For vegetated soil, precipitation that accumulated in the upper 0.75 m of soil was removed by evapotranspiration: water potentials decreased seasonally by 4 to >8 MPa. During 2 years with below-average precipitation, water potentials below the apparent root zone decreased by 2.3 (1.2-m depth) to 0.4 MPa (5-m depth), and the gradients became predominantly upward. Water potentials then rebounded during 2 years with near- and above-average precipitation, and seasonally variant water potential gradients were reestablished above the 4.2-m depth. Under nonvegetated waste-site conditions, data indicated the long-term accumulation and shallow, but continued, penetration of precipitation: water potentials showed moisture penetration to depths of 0.75–1.85 m. The method of simulated-waste drum placement (stacked versus random) and the associated differences in subsidence showed no measurable influence on the water balance of the trenches: subsidence totaled ≤13 mm during the study. Water potentials below the trenches and below the 2-m depth for the nonvegetated soil remained low (≈−5.5 to −7.5 MPa) and indicated the persistence of typically upward driving forces for isothermal water flow. Water fluxes estimated from water potential and temperature data suggested that isothermal liquid, isothermal vapor, and nonisothermal vapor flow need to be considered in the conceptualization of unsaturated flow at the field sites. Below the depth of temporal water content change, the estimated liquid fluxes ranged from 10^{-10} to 10^{-15} cm/s, isothermal vapor fluxes ranged from 10^{-10} to 10^{-13} cm/s, and the nonisothermal vapor fluxes ranged from 10^{-8} to 10^{-10} cm/s.

Introduction

Arid environments often are considered ideal areas for waste isolation [*Winograd*, 1981; *Reith and Thomson*, 1992] because the natural environment has features that can minimize the risk of waste migration to the underlying water table (e.g., low precipitation, high evapotranspiration, thick unsaturated zone). On this premise, sites in the arid western United States are increasingly being sought for isolation of the nation's radioactive and other hazardous wastes for periods ranging from 100 to 10,000 years. Volumes of locally generated municipal, industrial, and mining wastes also are increasing because of rapid population growth, industrialization, and the importance of mining in the arid West. Thus concern about the potential effect of contaminants on the environment in the region is being raised.

The suitability of a burial site or landfill for isolating wastes will depend largely on the processes and factors that control water movement. The complex processes influencing water movement in arid environments, however, are not well understood and can be affected in dramatic ways by temporal and spatial changes in precipitation, vegetation, and soils [*Gee and Hillel*, 1988; *Nativ*, 1991]. Water that contacts the waste can enhance the release of contaminants for subsequent transport by liquid water, water vapor, or other gases. Although it is recognized that under desert conditions movement in the vapor phase may be an important transport mechanism for certain contaminants (e.g., ^3H, ^{14}C, ^{222}Rn), few comprehensive data have been available to test assumptions about the relative contributions of the liquid- and vapor-flow components to total water flow. The lack of data is the result of (1) the technical complexity of hydraulic characterization and monitoring of the dry, often heterogeneous soils and sediments, and (2) insufficient field studies that account for the large interannual variation in precipitation in arid regions and its effect on soil-water response under natural-site and waste-burial conditions.

Environmental tracer techniques (e.g., Cl, ^{36}Cl, ^3H) are increasingly being used to evaluate long-term flow processes in arid environments [*Allison et al.*, 1994; *Nativ et al.*, 1995; *Phillips*, 1994; *Prudic*, 1994; *Scanlon*, 1992]. *Phillips* [1994] noted that such tracer techniques should be powerful tools in characterizing waste sites because the results from a limited number of profiles can, with some degree of confidence, be extrapolated to similar geomorphic settings in the immediate vicinity. In the absence of a geomorphic setting that mimics features of

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the waste-burial facility, however, the tracer information may not describe the flow and transport processes that will ultimately determine the potential for long-term isolation of contaminants from the environment.

Soil physics approaches, which rely on measurements of hydrologic conditions and properties, typically provide invaluable insight into the factors and processes affecting flow in the unsaturated zone. However, standard soil-water balance and Darcy's law (or Richards' equation) approaches, which are commonly used in the field study of water flow under agricultural or irrigated conditions, are problematic when applied under natural desert climate and dry soil conditions. In arid systems, precipitation and evapotranspiration may be nearly equal, and small errors in the estimation of either of these quantities will result in large errors in the calculated deep percolation [*Gee and Hillel*, 1988]. Neutron-probe measurements often are used to estimate water storage changes in desert soils and to deduce evapotranspiration and deep percolation from them [e.g., *Anderson et al*., 1993; *Nichols*, 1987]. It is sometimes assumed that the apparent absence of measured water content changes at depth is an indication of no deep percolation. This assumption disregards the possibility of steady flow under a unit hydraulic gradient and does not consider the accuracy of neutron-probe measurements, which typically are insufficient to detect small fluxes in desert soils. Lysimeters have successfully been used to estimate evapotranspiration and deep percolation at arid sites [*Gee et al*., 1994]. Because of disturbance and scale effects, however, lysimeters are limited in their ability to reproduce features of a native soil profile, and they may induce artificial boundary conditions that can affect flow processes [*Allison et al*., 1994]. The application of Darcy's law to field studies of water flow in desert soils has been limited by difficulties in determining the unsaturated hydraulic conductivity and the hydraulic gradients in dry soils. Few experimental determinations of the hydraulic conductivity relations in dry soils have been made because standard methods are difficult and time consuming [*Mehta et al*., 1994; *Mehuys et al*., 1975], and more rapid methods (e.g., centrifugation) require specialized equipment [*Khaleel et al*., 1995; *Nimmo et al*., 1992]. In addition, field instrumentation that is well established in agricultural soils (e.g., tensiometers) cannot be used to measure the low water potentials typical of desert soils. Thermocouple psychrometers are suitable for use in dry soils (≈ -0.2 to -8 MPa), but difficulties in calibration, installation, and data interpretation have limited the application of these instruments in field studies of water movement in desert unsaturated zones. Thus the operational life span of these instruments is largely unknown but sometimes is anticipated to be less than a few years. Finally, reliance on Darcy's law alone also is problematic because vapor flow may dominate over liquid flow where soils are dry and large temperature fluctuations occur [*Campbell*, 1985].

Present regulations governing the licensing of proposed waste sites require an assessment of water fluxes into and out of the landfill or burial facility before disposal operations can begin. Numerical models commonly are relied on for such predictive assessments. Although significant advances have been made in the development of soil-water flow models during the past 10 to 20 years, the lack of appropriate laboratory and long-term field data has resulted in these models remaining largely untested as to how well they represent the complex flow systems at arid sites. Recently, *Scanlon and Milly* [1994] used field data to test numerical simulations of water (liquid and vapor) and heat flow in response to an annual climate cycle at a site in the Chihuahuan Desert of Texas. Good agreement was found between simulated and measured water potentials and temperatures, but model results indicated an unexplained accumulation of water at all depths below 0.3 m. One hypothesis was that the year under consideration was somehow anomalous relative to preceding years. Insufficient data were available, however, to determine whether such a trend occurred in the field. The work by *Scanlon and Milly* [1994] has increased our knowledge of the complexity of flow processes that can occur at an arid site, but their study was limited to a single setting (bare, undisturbed soil), and the results further demonstrated the need for multiple-year field data.

The work presented here was prompted by the need to better understand how and to what degree the natural unsaturated-flow system may be altered by the installation of a waste facility in an environment where precipitation averages less than 150 mm/yr. Results of the laboratory characterization component of the study showed that disturbances caused by the construction of waste-burial trenches significantly altered the properties and variability of the natural-site environment [*Andraski*, 1996]. This paper describes the experimental design and presents results of the multiple-year field component of the study. Four sites were monitored during a 5-year period: one soil profile with undisturbed, native vegetation; one undisturbed soil profile where vegetation was removed; and two nonvegetated test trenches (in one trench, simulated-waste drums were stacked; in the other trench drums were randomly placed). The specific objectives of the field study were to (1) describe and compare seasonal and year-to-year changes in soil properties (water content, water storage, water potential, and temperature) under natural-site and simulated waste-site conditions, (2) assess the effects of drum placement (stacked versus random) on the accumulation and movement of water in the test trenches, and (3) document the operability of thermocouple psychrometers under extended field use. Soil properties were monitored to a maximum depth of 5.5 m. Because the field study was designed to evaluate site-to-site differences in the soil-water response to natural variations in climate, no artificial wetting or irrigation was used. The field results, in combination with the earlier laboratory characterization results, provide information important to the conceptualization and understanding of subsurface flow both under natural-site conditions and under simulated waste-site conditions. Rigorous evaluation of the strongly coupled processes of liquid and vapor flow requires the use of numerical models. The third component of the study is designed to combine the laboratory and field data with numerical simulations to further evaluate the mechanisms affecting unsaturated flow at the site. The laboratory and field data will provide the material-property information and the initial conditions for the simulations, and the field-monitoring data will be used to evaluate the simulation results. Work on this study component is in progress.

Study Site and Methods

Site Description

The study site is adjacent to the commercial waste-burial facility on the Mojave Desert, about 40 km east of Death Valley, near Beatty, Nevada (Figure 1). The site is in one of the most arid areas of the United States. On the basis of disposal-facility records (R. Marchand, personal communication, 1991) and data collected at the study site [*Wood*, 1996], annual pre-

cipitation during 1981–1992 averaged 108 mm and ranged from 14 mm during 1989 to 225 mm during 1983. About 70% of the precipitation that falls is associated with frontal systems that cover large areas during October through April, when temperature and potential evapotranspiration are least. Snow, however, is rare. Summer rainfall occurs predominantly during localized, short-duration, convective storms. Annual potential (pan) evaporation is about 1900 mm [*Nichols*, 1987]. Monthly mean air temperatures range from 3°C during December to 33°C during July [*Andraski et al.*, 1995]. The study area is approximately 845 m above sea level. Depth to the water table ranges from 85 to 115 m below land surface [*Fischer*, 1992]. Sediments are primarily fluvial deposits [*Nichols*, 1987]. Surface soils are mapped as the Yermo-Arizo association; Yermo soils are classified as loamy-skeletal, and Arizo soils are sandy-skeletal (W. E. Dollarhide, USDA-NRCS, personal communication, 1987). Vegetation in the area is sparse; creosote bush (*Larrea tridentata* (DC.) Cov.) is the dominant species. The rooting depth for creosote bush closely corresponds to the depth of penetrating moisture [*Wallace and Romney*, 1972]. Edaphic factors that influence the depth of moisture penetration (e.g., soil texture, petrocalcic (caliche) layers) also can influence plant-water relations in the Mojave Desert [*Smith et al.*, 1995].

The waste facility has been used for the burial of low-level radioactive waste (LLRW) (1962–1992) and hazardous chemical waste (1970 to present). The LLRW facility was the first such commercially operated site in the United States. Regulations governing burial of LLRW do not require that trenches be lined with impervious materials. Steps used in construction of the LLRW burial trenches included excavation and stockpiling of native soil, emplacement of waste, and backfilling with previously stockpiled, uncompacted soil. The surfaces of completed burial trenches and perimeter areas are kept free of vegetation. Dimensions of the 18 LLRW trenches constructed until the mid-1970s ranged from about 1 to 20 m wide, from 2 to 6 m deep, and from 100 to 200 m long; the four trenches constructed later are about 30–90 m wide, 9–15 m deep, and 200–250 m long. Excavation, waste emplacement, and backfilling were generally done progressively and concurrently along the axis of a trench. For the trenches constructed until the mid-1970s the time between commencement of excavation at one end of a trench and final backfilling at the other end averaged about 9 months for 100-m-long trenches and 24 months for the 200-m-long trenches. For the larger trenches that were constructed later, this time period averaged about 68 months. The bulk of the solid LLRW material was packaged in 0.21-m^3 steel drums. Drums were placed into the trenches both in an orderly fashion and in a random fashion, depending on the type of equipment used for waste emplacement. Liquid LLRW could also be shipped to the facility, but the operating license required that liquids be solidified with portland cement before disposal. A 1976 U.S. Nuclear Regulatory Commission (USNRC) investigation, however, indicated that liquid wastes delivered to the site between 1962 and 1975 were disposed directly into the trenches [*USNRC*, 1976].

Figure 1. Location of waste-burial site, Death Valley, and Mojave Desert of the southwestern United States.

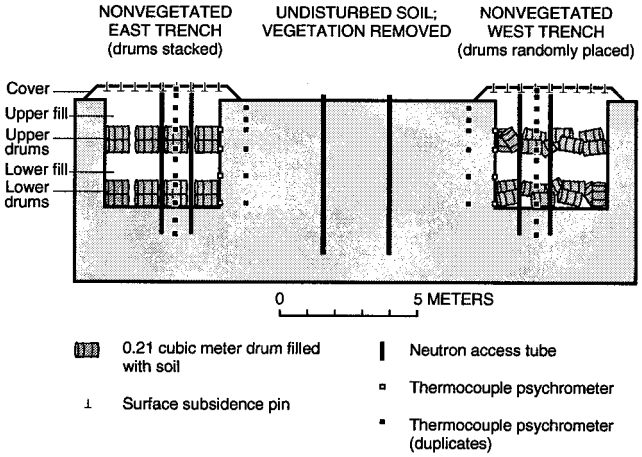

Figure 2. General design and instrumentation of three disturbed sites that simulate solid-waste-burial and nonvegetated-surface conditions.

Experimental Design and Monitoring

Four experimental sites were monitored during a 5-year period (October 1987 through September 1992): one undisturbed, vegetated soil profile; one undisturbed soil profile where vegetation was removed; and two nonvegetated test trenches (in one trench, simulated-waste drums were stacked; in the other trench drums were randomly placed). Monitoring at the undisturbed, vegetated site began in 1984 [*Fischer*, 1992]. The three disturbed sites (Figure 2) were established in September 1987, about 40 m from the undisturbed site, and were designed to simulate solid-LLRW-burial and nonvegetated-surface conditions [*Andraski*, 1990]. The test trenches were excavated to about 4 m in all three dimensions. A total of 104 soil-filled drums were buried in each test trench. The bulk density of soil in the drums ($\approx$1.65 g/m^3) was similar to the estimated density of waste materials in the LLRW trenches (1.60 g/m^3) [*US Ecology, Inc.*, 1989]. Vegetative top growth was removed from a 10-m-wide perimeter area around the three disturbed sites at the time of construction; herbicide was used to keep the three sites and the perimeter area free of vegetation. A raised plastic border was installed around the central area of the trench cover surfaces (26 m^2) to eliminate runoff; runoff was assumed to be negligible at the other sites. Construction of the test trenches was completed in 12 days. The

depth and width of the test trenches were chosen to be within the range of LLRW trenches that were constructed until the mid-1970s. No attempt was made to duplicate the length of the LLRW trenches because it was felt that reasonable results could be obtained without such duplication. On the basis of the dimensions and the time between initial excavation and final backfilling, the test trenches are considered representative of a segment of an actual, full-length burial trench. Field data collected during the 5-year study did not indicate that any artificial boundary effects were induced by the reduced length of the test trenches.

Precipitation and air temperature data presented in this paper were continuously monitored at the study-site weather station [e.g., *Wood*, 1996].

To assess the effects of drum placement on water accumulation and movement in the trenches, surface subsidence was monitored using a series of pins that were placed in a 0.5- by 0.5-m grid and covered the central, 16-m^2 area of the trench cover (Figure 2). Each pin consisted of a steel base plate (51-mm diameter, 2 mm thick) welded to a rod (13-mm diameter, 152 mm long). The base of each pin was buried about 90–120 mm below the surface of the trench cover. Pin elevations (relative to a site benchmark) were measured monthly or bimonthly using a rod and level. Cumulative subsidence was determined as the change in elevation with time.

Water content was monitored to a depth of 5.25 m using a neutron-moisture probe (model 503, Campbell Pacific Nuclear Corp., Martinez, California) and steel access tubes. (The use of trade names is for identification only and does not constitute endorsement by the U.S. Geological Survey.) For the test-trench sites, 51-mm-OD tubes with a 3.0-mm wall thickness were installed during trench construction; the tubes were placed into holes that were hand-augered below the trench floor prior to backfilling. Larger-diameter access tubes (140-mm OD, 6.4-mm wall thickness) were installed at the vegetated-soil site (July 1984) and the nonvegetated-soil site (September 1988) using a pneumatically driven downhole-hammer system [*Tyler*, 1988]. Two access tubes were used at each of the three disturbed sites (Figure 2), and three tubes were used at the vegetated-soil site. Although neutron attenuation by steel access tubes can be about 40% greater than that for aluminum tubes [*Abeele*, 1978], the steel tubes were used because of their durability.

The neutron probe was calibrated for both sizes of access tube using steel cylinders filled with soil that had been excavated during trench construction. An access tube was placed in the center of the cylinder (760- or 910-mm diameter), and the annular space between the tube and cylinder wall was filled with soil to a depth of 1 m. The soil was wetted and subsequently dried to differing degrees to attain a range of water contents for the calibration: average water contents ranged from 0.02 to 0.19 m^3/m^3. For the wet end of the calibration range, water was ponded on the surface, and the soil was irrigated and allowed to drain until neutron-probe readings indicated a uniform water content distribution. Neutron-probe calibration readings then were taken at depths of 0.15, 0.25, and 0.50 m, and the soil-water content distribution in the cylinders was determined using samples collected by the rubber-balloon method (a description of the rubber-balloon method is provided by *Andraski* [1991]). To attain progressively lower calibration water contents, all the soil was removed from the previously sampled cylinder, some soil was added to replace that removed by rubber-balloon sampling, and, following a period of air drying and thorough mixing, this soil then was placed back into the cylinder. Calibration equations were developed using count ratios calculated for measurements at a depth of 0.15 m and for depths greater than 0.15 m. All calibration equations had coefficients of determination (r^2) > 0.96. For the small-diameter tubes the standard error of estimate (SE) was 0.017 m^3/m^3 for measurements at the 0.15-m depth, and the SE was 0.012 m^3/m^3 for measurements at greater depths. For the large-diameter tubes the SEs were $\leq$0.009 m^3/m^3 for measurements at all depths. The adequacy of the cylinder calibrations was tested by comparing water contents determined for field samples collected during instrumentation of the disturbed sites with those predicted from neutron-probe measurements that were made immediately afterwards. Results showed little difference between the field-measured and predicted values: for the small-diameter tubes, measured values averaged 0.002 m^3/m^3 greater than the predicted values; for the large-diameter tubes, measured values averaged 0.003 m^3/m^3 less than the predicted values.

Water content was monitored monthly and also after precipitation of $\geq$5 mm. Concurrent monitoring of water content at the trenches and the vegetated-soil site began in October 1987; monitoring at the nonvegetated-soil site began in September 1988. Cumulative changes in water storage were calculated from water content measurements. The initial water storage values for nonvegetated soil were estimated using soil samples collected when vegetation was removed. For selected dates, differences in cumulative changes in water storage among the four sites were analyzed using a one-way analysis of variance procedure (PROC GLM [*SAS Institute*, 1981]). Mean values were compared using Fisher's least significant difference test [*Steel and Torrie*, 1980].

Water potential and temperature were monitored with screen-caged thermocouple psychrometers (TCPs) (model 74, J. R. D. Merrill Speciality Equipment, Logan, Utah) and data loggers (Model CR-7, Campbell Scientific, Inc., Logan, Utah). The osmotic component of water potentials at the field site ranges between 0 and −0.5 MPa [*Fischer*, 1992]. The TCPs were individually calibrated in the laboratory using procedures described by *Fischer* [1992] and the calibration data were analyzed using stepwise regression techniques [*Meyn and White*, 1972]. A total of 100 TCPs were calibrated for possible use at the three disturbed sites and, on the basis of individual calibration results, 92 TCPs were retained and used in the development of a common regression equation; the coefficient of multiple determination (R^2) for the regression equation was 0.99 and the SE was 0.2 MPa. For the vegetated-soil site an individual calibration equation was developed for each TCP; R^2 values were $\geq$0.98 and the SEs were $\leq$0.3 MPa.

A total of 80 TCPs were installed at the three disturbed sites during trench construction (Figure 2). The TCPs in the undisturbed soils beneath and adjacent to the trenches were installed in holes that were made perpendicular to the exposed floor or wall of the trench. Below the 2-m depth, where the native soil was very cohesive, a steel rod (10-mm OD) was driven into the soil, the rod was removed, a TCP was placed into the resulting hole, and the hole was backfilled to the extent possible to form a soil seal around the lead wire. Above the 2-m depth, where the native soil was prone to collapse, a steel pipe (22-mm OD) fitted with a drive-point insert (4.8-mm carriage bolt) was driven into the soil, the pipe was retracted slightly to remove the drive point, a TCP was inserted to the end of the pipe, and the pipe was removed, allowing soil to

collapse around the TCP and lead wire. The TCPs in the trenches were simply laid horizontally at the desired depth during backfilling. Duplicate TCPs in the trench fill and the underlying native soil were about 1 m apart, and duplicates in the nonvegetated soil adjacent to the trench were about 0.35 m apart. The installation procedures minimized the disturbance of native soil surrounding the TCPs and reduced the potential for preferential flow along the lead wires in the soil and trench fill. Horizontal emplacement of TCPs also was used to minimize potential thermal-gradient effects on water potential estimates in the near-surface soil/fill [*Merrill and Rawlins*, 1972].

A total of 15 TCPs at the undisturbed, vegetated-soil site were monitored and evaluated in conjunction with this study. For the TCPs in the upper 0.75 m of soil, installation was done in the manner described for the undisturbed soil adjacent to the trenches, but a small pit was dug to provide access for horizontal emplacement. After installing the TCPs the pit was backfilled with the original soil. Single TCPs that were installed in the upper 0.75 m of soil during October 1985 were replaced by duplicate TCPs (placed ≈0.3 m apart) during January 1991. Water potential and temperature data reported for greater depths (1.2–5 m) are from TCPs that were installed prior to, but continuously monitored during, this field study. Single TCPs at depths of 1.2, 1.6, 2.8, 3.4, and 4.2 m were emplaced as part of a 12-m-deep borehole installation that was drilled and instrumented during June 1986 [*Fischer*, 1992]. The single TCP at the 5.0-m depth was one that was installed (February 1987) horizontally outward from a 1.5-m-diameter, 13-m-deep instrument shaft [*Fischer*, 1992]. The borehole installation was drilled using the same downhole-hammer system that was used for installation of the large-diameter neutron-access tubes, but the tubes were withdrawn after TCPs were emplaced and as the hole was backfilled with drill cuttings and layers of bentonite. The bentonite was used to minimize the potential for preferential movement of water or air into the borehole and between TCPs in the borehole [*Fischer*, 1992]: a small amount of wetted bentonite was placed midway between TCPs installed at depths of 1.2, 1.6, 2.8, and 3.4 m; dry bentonite was placed between TCPs installed at depths of 3.4 and 4.2 m. The installation was completed by plugging the uppermost 0.5 m of the borehole with wetted bentonite. *Fischer* [1992] noted that the use of wetted bentonite could possibly increase water potential readings, but a comparison between borehole and instrument-shaft measurements made at similar depths indicated no positive bias in the borehole values: borehole values averaged −4.5, −4.5, and −4.6 MPa at depths of 2.8, 3.4, and 4.2 m, respectively; instrument-shaft values averaged −4.0 and −4.6 MPa at depths of 3.0 and 4.0 m, respectively.

The TCP data reported in this paper represent daily mean values that were calculated using noon and midnight measurements. This procedure was used to minimize the potential effect of diurnal variation in soil temperature gradients on TCP measurements [*Merrill and Rawlins*, 1972]. The TCP measurements were adjusted in the data logger for variations in zero offset. This adjustment was used to correct water potential estimates for temperature gradients within the TCP; under field conditions, most zero offsets are within the range of −60 to +60 μV [*Brown and Bartos*, 1982]. The zero offsets measured using the field installation and data processing procedures described for this study typically ranged from −2.5 to +2.5 μV. Water potential and temperature monitoring at the vegetated-soil site was ongoing at the start of this field study, and concurrent monitoring at all four sites began in May 1988.

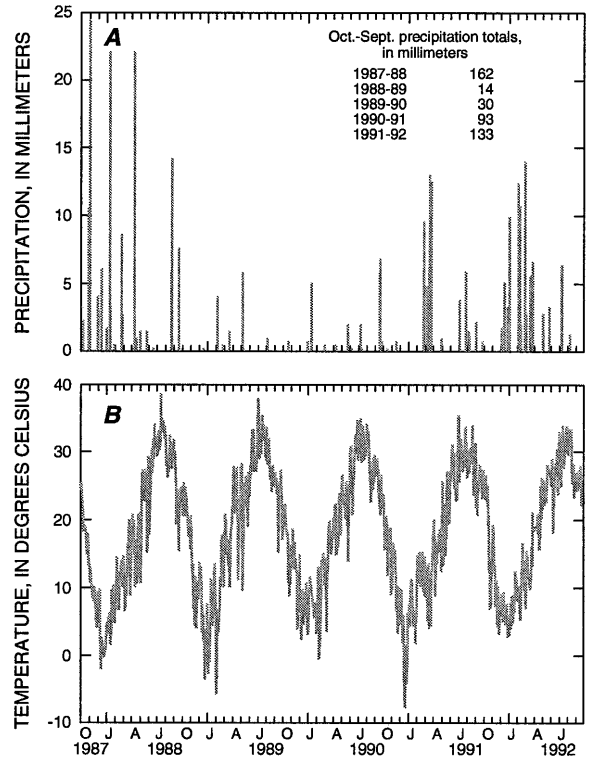

Figure 3. (a) Daily and annual precipitation and (b) daily mean air temperature.

All data logger data were retrieved through a telecommunications link between the study site and the project office, 540 km away.

Results

Precipitation and Air Temperature

Precipitation and air temperature during October 1987 through September 1992 are shown in Figure 3. Precipitation during the year prior to this study totaled 103 mm, and 81% was measured during October–April. On the basis of the similarity between these values and the long-term average values for quantity (108 mm/yr) and distribution (70%), the initial conditions for this study were considered to be representative of average conditions. Precipitation during the wettest year of this study (1987–1988) totaled 162 mm, and during the driest year (1988–1989) precipitation totaled 14 mm. During the first, fourth, and fifth years of the study, 80–88% of the precipitation fell during October–April, when air temperatures were least. During each of the two dry years, however, only 47% of the total precipitation was measured during these 7 months.

Drum Placement Effects on Subsidence of Test Trench Covers

Subsidence totaled 10 mm for the east trench and 13 mm for the west trench (Figure 4). About 50% of the total subsidence was observed during the first year following trench construction. Subsidence measured during this period was probably due to settling of the uncompacted fill material in response to precipitation and freeze-thaw cycles. After 1988, greater subsidence was observed for the west trench, where drums were randomly placed. General trends in cumulative subsidence were similar for the two trenches and the rates of subsidence

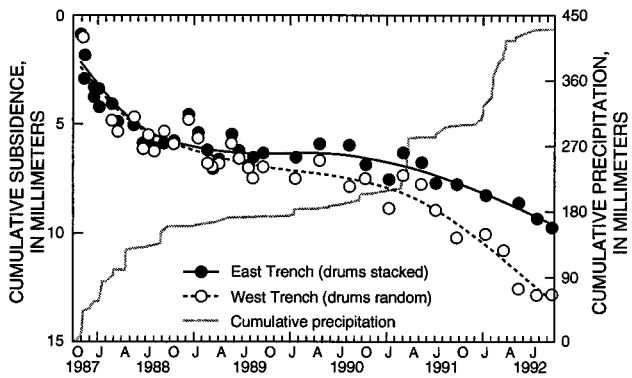

Figure 4. Cumulative surface subsidence of trench covers and cumulative precipitation.

appeared to be correlated with cumulative precipitation (Figure 4).

Deep Water-Content Profiles

Variation in water content with depth for selected dates is shown in Figure 5. Water content values for the depth intervals 1.5–2.5 m and 3.5–4.5 m at the trench sites were not determined because of the influence of simulated-waste drums on neutron-probe readings. The March 1991 data show the maximum water content value (measured at the 0.15-m depth) that was observed for each site; these data were collected in response to 29 mm of precipitation that fell during a 3-day period and measurements were made to a maximum depth of 2 m.

For the vegetated- and nonvegetated-soil sites (Figures 5a and 5b) water contents below a depth of 0.75–1 m ranged from about 0.04 to 0.10 m^3/m^3, and vertical variations corresponded with variations in soil texture. *Andraski* [1996] characterized five major soil layers in the upper 5 m of native soil at the study site. Layers were designated 1 (surface) to 5 (deepest). The thickness of the uppermost layer varied from 0.75 m (vegetated-soil site) to 1 m (nonvegetated-soil site), and each of the four underlying layers was about 1 m thick. The textural classification for the five layers was 1, loamy sand; 2, gravelly coarse sand; and 3, 4, and 5, gravelly coarse sandy loam. Water contents for the gravelly coarse sand were about 0.03–0.06 m^3/m^3 less than those for the underlying soil.

The initial (October 1987) water content for the trench fill was relatively uniform with depth (Figures 5c and 5d) and averaged about 0.05 m^3/m^3 for the east trench and 0.04 m^3/m^3 for the west trench. These values were similar to the average initial water content that was measured for the upper 1.5 m of vegetated soil ($\approx$0.04 m^3/m^3). The uniformity of water content throughout the body of the trenches, however, reflected the homogenizing and drying effects of trench construction on fill properties. Textural classification of the fill was gravelly loamy coarse sand [*Andraski*, 1996]. Water content for the soil beneath the trenches (i.e., >4.5 m deep) was, on average, about 0.02 m^3/m^3 greater than the initial trench-fill values.

Water Storage and Water Content Changes

Temporal variations in near-surface (0- to 1.25-m depth) water storage and water content are shown in Figure 6. The results of statistical analyses to evaluate site-to-site differences

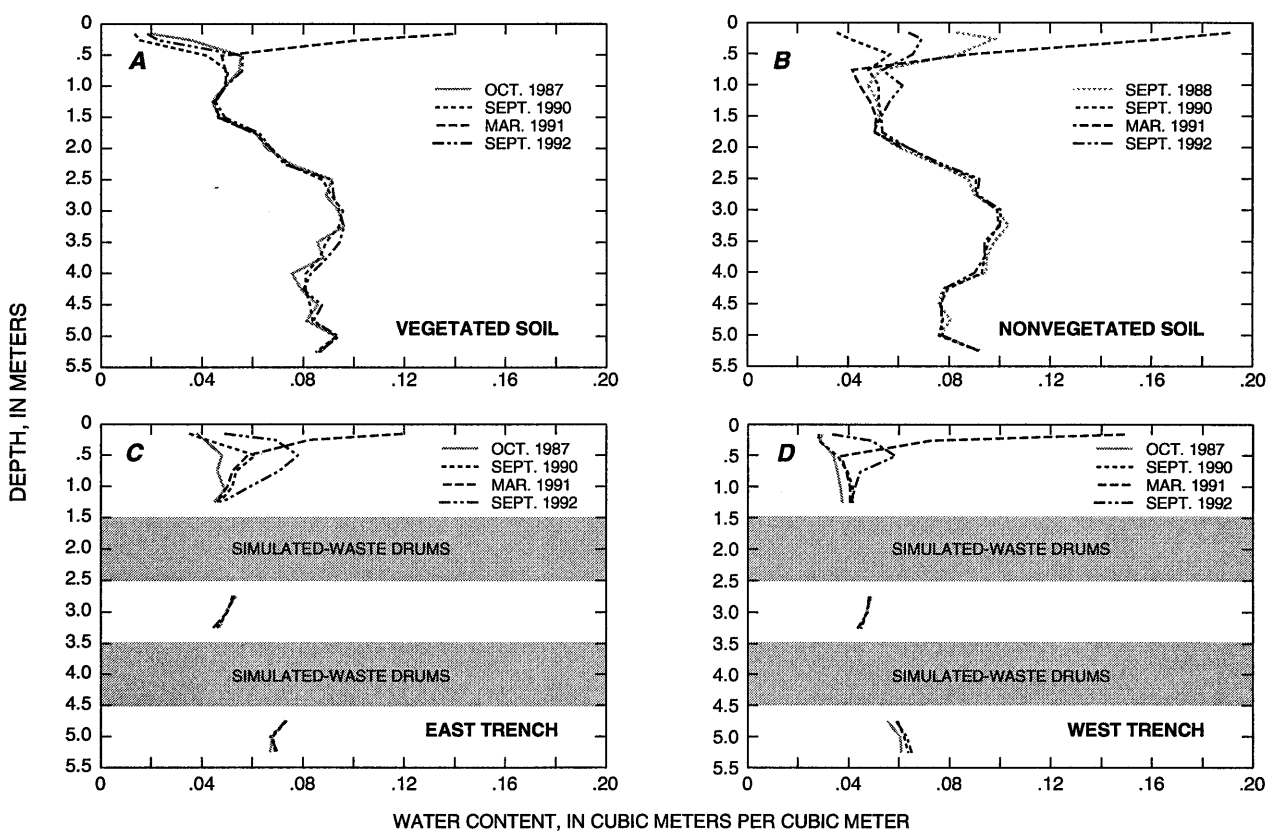

Figure 5. Water content variations with depth for selected dates for the (a) vegetated, native soil profile, (b) nonvegetated, native soil profile, (c) east trench, and (d) west trench. Monitoring of nonvegetated soil began in September 1988.

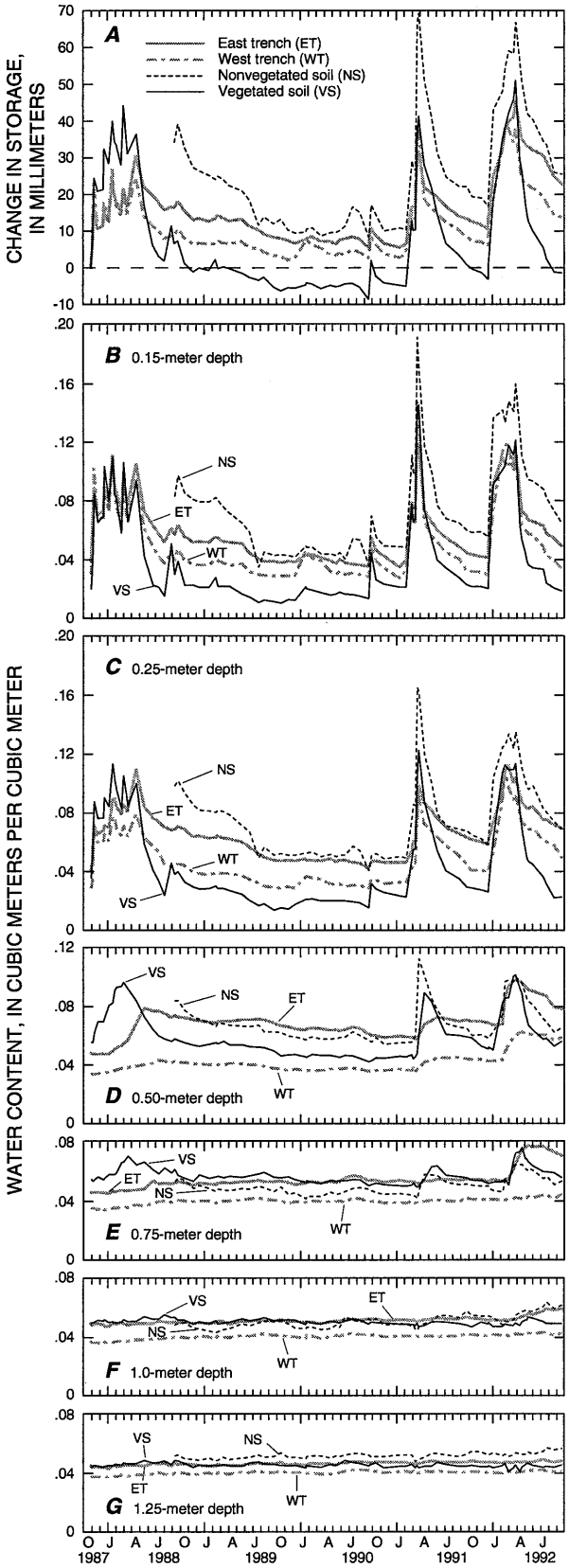

Figure 6. Cumulative changes in water storage (Figure 6a) and water content (Figures 6b–6g) with time in the upper 1.25 m at four sites. Continual monitoring of nonvegetated soil began in September 1988.

Table 1. Cumulative Changes in Water Storage for Depth Intervals Between Land Surface and 5.25 m for Selected Dates Relative to Initial Values

Site	Nov. 21, 1988	Sept. 21, 1989	Sept. 18, 1990	Dec. 18, 1991	Sept. 24, 1992
0- to 1.25-m Depth					
Vegetated soil	−1 a	−5 a	−9 a	−3 a	−1 a
Nonvegetated soil	27 b	12 b	8 b	17 b	26 b
East trench	13 c	8 b	6 b	11 b	23 b
West trench	6 c	3 b	3 b	6 b	14 b
1.25- to 2.75-m Depth					
Vegetated soil	−4 a	−1 a	−1 a	0 a	1 a
Nonvegetated soil	8 a	11 a	11 a	10 a	13 a
East trench	...	...	...	...	...
West trench	...	...	...	...	...
2.75- to 3.25-m Depth					
Vegetated soil	−1 a	1 a	0 a	1 a	0 a
Nonvegetated soil	−1 a	0 a	1 a	0 a	2 a
East trench	−1 a	−1 a	0 a	−1 a	0 a
West trench	0 a	0 a	0 a	−1 a	0 a
3.25- to 4.75-m Depth					
Vegetated soil	0 a	4 a	1 a	2 a	5 a
Nonvegetated soil	−2 a	0 a	1 a	−1 a	−1 a
East trench	...	...	...	...	...
West trench	...	...	...	...	...
4.75- to 5.25-m Depth					
Vegetated soil	0 a	1 a	0 a	1 a	0 a
Nonvegetated soil	2 a	2 a	3 a	2 a	3 a
East trench	0 a	0 a	0 a	0 a	0 a
West trench	0 a	1 a	1 a	1 a	2 a

Values given in millimeters.

Within dates and depth intervals, column values followed by the same letter are not significantly different at the 0.10 probability level, as determined by Fisher's least significant difference test. Ellipses denote values not determined because of the influence of simulated-waste drums on neutron-probe readings.

in long-term water storage changes between land surface and 5.25 m are summarized in Table 1.

Cumulative changes in water storage showed pronounced increases during October 1987 through January 1988, February through March 1991, and December 1991 through March 1992 (Figure 6a). The net change in water storage that occurred between the beginning and the end of these periods indicated that net increases for the native-soil sites were, on average, about 1.5 to 2 times greater than those for the trenches. Water that accumulated at the vegetated-soil site, however, was seasonally depleted by evapotranspiration and, by the fall or early winter of each year, water storage values were similar to, or less than, those measured initially. In contrast, water storage values for the three nonvegetated sites remained greater than those measured initially. Statistical analyses showed that long-term water accumulation in the upper 1.25 m of the nonvegetated sites was significantly greater than that for vegetated soil (Table 1).

Water content measurements in the upper 1.25 m of the four sites indicated water penetration in response to precipitation was more rapid for the native soil than for the trench fill. For example, a comparison of water content data for the 0.50- and 0.75-m depths during October 1987 through March 1988 and March through April 1991 shows that the rate and magnitude of water content increases for the undisturbed soils (vegetated or nonvegetated) were greater than those for the trenches (Figures 6d and 6e). The enhanced water penetration for the

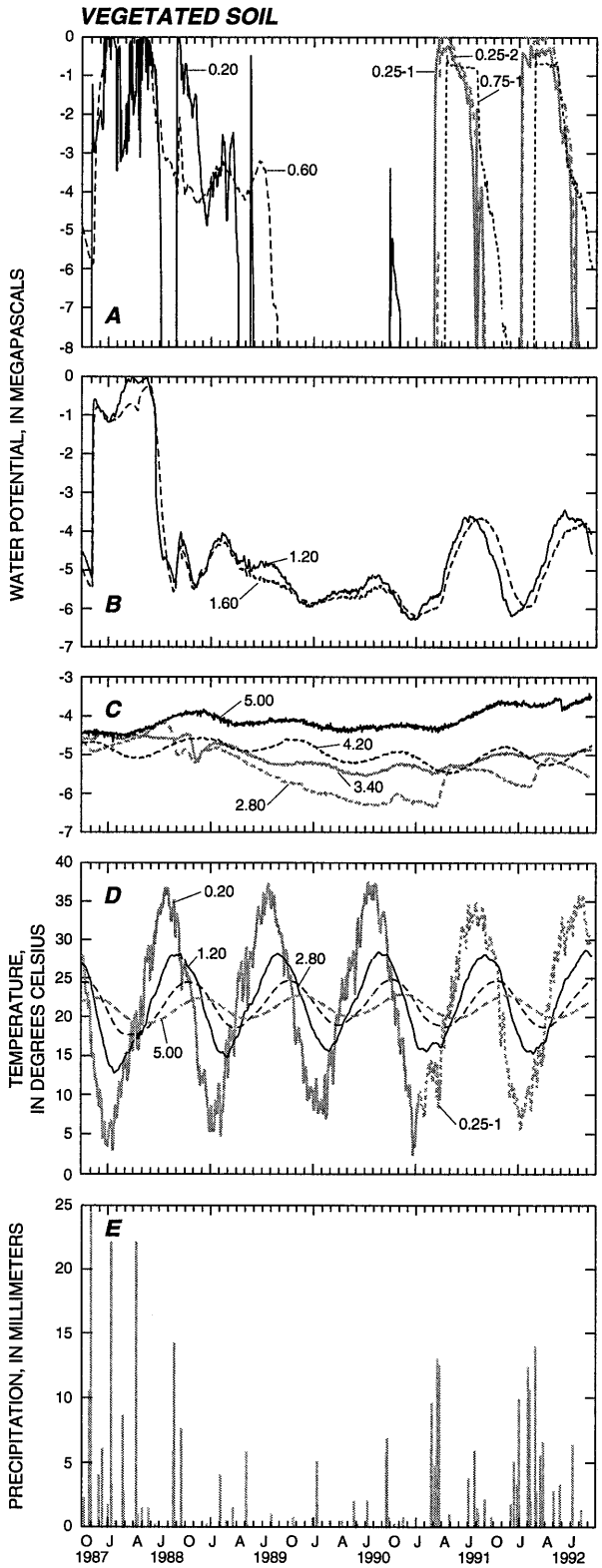

Figure 7. Daily water-potential changes (Figures 7a–7c) and temperature changes (Figure 7d) with time at the vegetated-soil site, and daily precipitation (Figure 7e). Single thermocouple psychrometers (TCPs) at the 0.20- and 0.60-m depths were replaced by duplicates during January 1991. Lines are identified by TCP depth (in meters) and, where applicable, duplicate number (1 or 2).

vegetated and nonvegetated soil was attributed to the structure of the uppermost native-soil layer. In contrast, trench construction produced a structureless fill that was denser than the uppermost soil layer [*Andraski*, 1996]. Among the four sites, maximum depth to which temporal changes in water content were observed increased in the following order: west trench (0.50 m), east trench and vegetated soil (0.75 m), and nonvegetated soil (1 m) (Figures 6d, 6e, and 6f). Below these depths, temporal changes in water content were within the error of the neutron-probe measurements. Cumulative changes in water storage for depth intervals between 1.25 and 5.25 m showed no significant differences among the four sites (Table 1).

For the native soil profiles, temporally invariant water contents below 0.75–1 m indicated that the textural discontinuity between the two uppermost soil layers (loamy sand over gravelly coarse sand) provided a natural capillary break that impeded percolation. This observation is supported by laboratory results that showed, except for water potentials near zero, liquid hydraulic conductivities for the coarse soil layer are about 4 orders of magnitude less than those for the uppermost soil layer [*Andraski*, 1996]. For the trench sites the depth of water penetration was apparently limited by the hydraulic characteristics of the structureless, homogeneous fill and the dryness of the fill ahead of the wetting front: liquid hydraulic conductivity at a water content of 0.04 m^3/m^3 is about 10^{-13} cm/s [*Andraski*, 1996].

Water Potential and Subsurface Temperature

Thermocouple psychrometer measurements. The TCP data were used to document the operability of these instruments under extended field use. A total of 95 TCPs were monitored, but 25 of these were in locations where water potentials remained outside the TCP range (<-8 MPa). Of the remaining 70 TCPs, 64 were monitored for $\geq$4.5 years, and 49 (77%) of these were still operable during September 1992. Another six TCPs were installed during January 1991 and were monitored during the last 21 months of the study. Of all the TCPs that were monitored for $\geq$21 months, 86% were still functional during their 21st month of operation. A general observation, made on the basis of this and other monitoring done at the Mojave Desert site, is that TCPs that remain operational during the first 6 months of field use typically remain operable for several years. This observation also appears to be supported by the monitoring data that were shown by *Scanlon* [1994]; in that study, 14 of 20 TCPs (70%) remained operational during a 20-month monitoring period.

Water potential and temperature data collected at the four sites are shown in Figures 7, 8, 9, and 10. Direct comparisons of TCP data were not always possible because of out-of-range water-potential measurements, instrument failure, and (or) differences in measurement depths among sites. As a consequence, it is difficult to describe and characterize the TCP data succinctly, and the following overview is provided to describe how and what data are presented. Within the limits of the available data, water potentials presented for each site were grouped according to three depth intervals (0–1 m, 1–2 m, and >2 m). For the undisturbed-soil sites these depth intervals generally correspond with the three-soil-layer model of vertical variation that was proposed by *Andraski* [1996]. Where more than one TCP was used for a given site and depth, replicate water potential data are shown to provide information on the agreement between replicates. For the nonvegetated soil, duplicate TCPs were placed in two vertical arrays, one near each

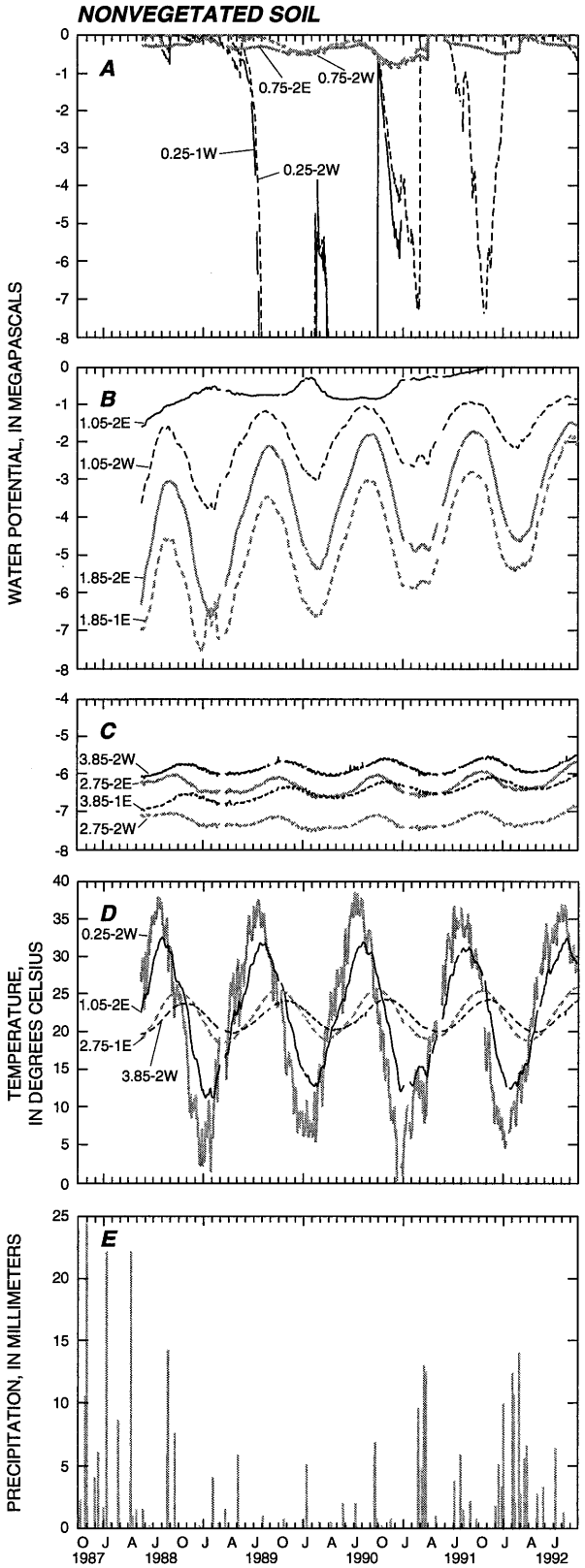

Figure 8. Daily water-potential changes (Figures 8a–8c) and temperature changes (Figure 8d) with time at the nonvegetated-soil site, and daily precipitation (Figure 8e). Lines are identified by thermocouple psychrometer depth (in meters), duplicate number (1 or 2), and location (E designates vertical array near east trench; W designates the array near west trench (Figure 2)).

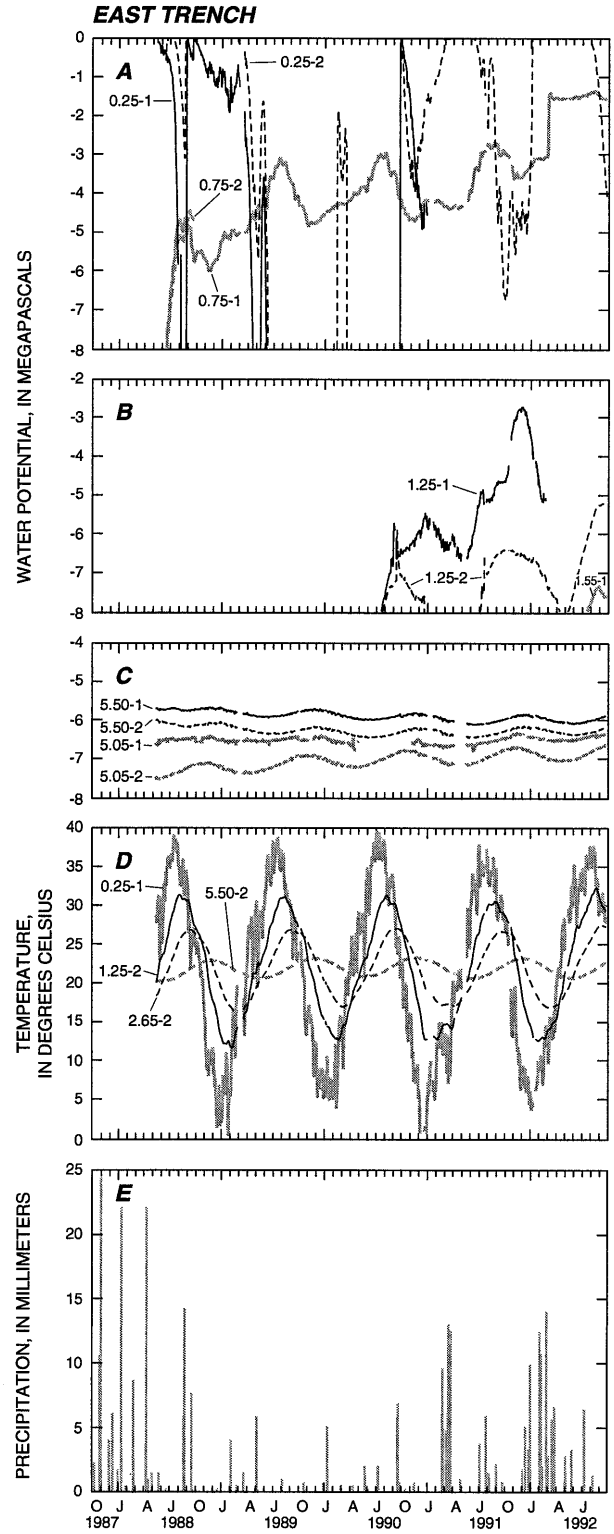

Figure 9. Daily water-potential changes (Figures 9a–9c) and temperature changes (Figure 9d) with time within and below the east trench, and daily precipitation (Figure 9e). Lines are identified by thermocouple psychrometer depth (in meters) and duplicate number (1 or 2). Water potentials for fill between the 1.55- and 4.5-m depths remained <-8 MPa.

trench (Figure 2); within arrays the difference in water potential between duplicates was typically ≤ 0.5 MPa. Therefore, except where otherwise noted, data for a TCP from each array are shown to provide information on the spatial variation in

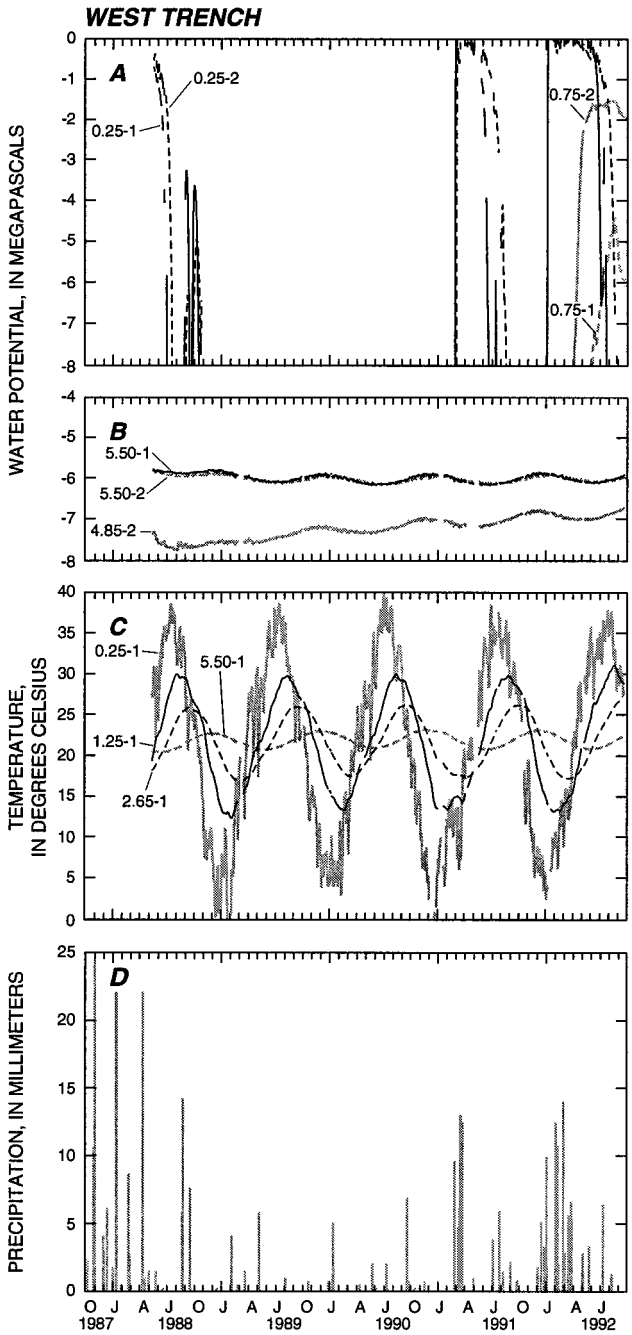

Figure 10. Daily water-potential changes (Figures 10a and 10b) and temperature changes (Figure 10c) with time within and below the west trench, and daily precipitation (Figure 10d). Lines are identified by thermocouple psychrometer depth (in meters) and duplicate number (1 or 2). Water potentials for fill between the 0.75- and 4.5-m depths remained <-8 MPa.

water potentials measured at the nonvegetated-soil site. Nearly all TCPs provided continuous subsurface temperature data for the duration of the study. Where replicate temperature data were available, the difference between replicate values typically was <0.2°C. Thus the temperature data shown for a given site and depth are based on measurements by individual TCPs.

Vegetated- and nonvegetated-soil sites. Water potential and temperature data for the vegetated- and nonvegetated-soil sites are shown along with precipitation in Figures 7 and 8. Rapid penetration of precipitation in the uppermost native-soil layer is reflected by the large increases in water potential at depths of 0.6–0.75 m for the vegetated soil during 1987, 1991, and 1992 (Figures 7a and 7e). The subsequent decreases in water potentials at these depths illustrated the efficiency of root-zone water depletion by native plants. *Odening et al.* [1974] have shown creosote bush to be capable of extracting soil water and maintaining small, positive net photosynthesis when xylem-sap potentials, measured at dawn, are as low as −7.8 MPa. Water potentials for vegetated soil (0.6- to 0.75-m depths) decreased below this value during 1989, 1991, and 1992; potentials remained outside the TCP range during 1990. In contrast, the persistence of elevated water potentials at the 0.75-m depth for the nonvegetated soil indicated precipitation that penetrated to a relatively shallow depth was not removed by evaporation (Figure 8a).

For vegetated soil the magnitude of variation in water potentials between the 1- and 2-m depths markedly differed from year to year (Figure 7b). The changes in water potential for the 1.2- and 1.6-m depths (in the coarse soil layer) during November 1987 through June 1988 were inconsistent with other data collected in the upper 2 m of native soil. For example, the large water potential response to precipitation for the 1.2- and 1.6-m depths during November 1987 preceded that for the 0.4-m (data not shown) and 0.6-m depths by about 4 days. In addition, water potentials measured by these TCPs prior to this study ranged from −3.5 to −5.5 MPa and showed no abrupt changes in response to a similar-sized storm during March 1987 [*Fischer*, 1992]. The cause of the large and, apparently, premature increase in water potentials for the 1.2- and 1.6-m depths during November 1987 is unknown, but it may be related to preferential flow of water down the instrument borehole. The large November storm may have coincided with a period of low antecedent soil moisture conditions that were conducive to the development of a preferential flow path along the bentonite plug in the upper 0.5 m of the borehole. During 1990–1992 the magnitude of the water potential increases for the coarse soil layer appeared to be largely dependent on seasonal, but often short-lived, accumulation of meteoric water in the uppermost soil layer. For example, data in Figures 7a, 7b, and 7e show that during 1990, low precipitation and low-moisture conditions in the uppermost soil layer corresponded with a small (0.8 MPa) increase in water potential at the 1.2-m depth. In contrast, during 1991 and 1992, increased precipitation and relatively high moisture conditions in the uppermost soil layer for a period of 3 to 4 months corresponded with a water potential increase of about 2.7 MPa. The 1990–1992 data also indicate that seasonal fluctuations in water potential were generally in phase with seasonal temperature fluctuations; values were greatest during the summer and least during the winter (Figures 7b and 7d). This trend in water potentials is the opposite of what one would expect if plant-water uptake was actively occurring in the coarse soil layer because evaporative demand is greatest during summer. A second indication of the absence of plant roots in the coarse layer is that the minimum water potential values never decreased below −6.3 MPa, even during 1989–1990, when values showed a long-term decrease of about 2.3 MPa in response to low precipitation (Figures 7b and 7e).

For nonvegetated soil, water potentials between the 1- and 2-m depths showed no evidence of rapid preferential movement of water into the coarse soil layer, but the long-term increase displayed by the data indicated that water did con-

tinue to penetrate slowly downward (Figure 8b). The difference between water potentials measured by the two TCPs at the 1.05-m depth was attributed to spatial variation in depth to the interface between the two soil layers: TCP 1.05-2E was at the interface; TCP 1.05-2W was below the interface. Water potential gradients between the 1- and 2-m depths indicated a consistently downward driving force for isothermal flow: water potential and temperature gradients were in the same direction during the summer but were diametrically opposed during the winter (Figures 8b and 8d).

Below the 2-m depth the vegetated- and nonvegetated-soil sites also showed marked differences in soil-water response to year-to-year changes in precipitation. For vegetated soil, during the 2 years with low precipitation, water potentials all showed measurable decreases and indicated the establishment of a consistently upward driving force for isothermal flow between the 2.8- and 5-m depths (Figures 7c and 7e): water potential decreases ranged from 1.4 MPa (2.8-m depth) to 0.4 MPa (5-m depth). Water potentials then rebounded during two years with near- and above-average precipitation, but the recovery was incomplete: for example, values at the 2.8-m depth during 1992 were about 0.5 MPa less than those measured before the dry period. For nonvegetated soil, however, water potentials at the 2.75- and 3.85-m depths typically showed little long-term change ($\leq$0.3 MPa) and, on average, indicated the persistence of an upward driving force for isothermal flow (Figure 8c). In addition to these temporal differences between sites, a comparison of water potentials shown in Figures 7c and 8c indicates that values for vegetated soil were, on average, about 1 to 2 MPa greater than those for nonvegetated soil. The lower water potentials for nonvegetated soil is contrary to what one might expect in response to the removal of plants from that site during September 1987. The reason for the difference in water potentials cannot be readily explained, but it may be related to spatial and (or) instrument-installation differences between the vegetated and nonvegetated sites.

East and west trench sites. Water potential and temperature data for the trench sites are shown along with precipitation in Figures 9 and 10. The large changes in water potential with time at the 0.25-m depth reflected infiltration and redistribution of moisture in response to precipitation and evaporation (Figures 9a, 9e, 10a, and 10d). In contrast with the native-soil sites, however, the downward penetration of water below the 0.25-m depth was quite slow. *Andraski* [1996] estimated that the water potential for trench fill at the time of trench construction was about −8.5 MPa. Therefore the initial increases in field-measured water potentials for the east trench show that the moisture front reached the 0.75-m depth during June 1988, and water potentials for the west trench show that the moisture reached the 0.75-m depth during 1992 (Figures 9a and 10a). The timing of responses to initial wetting by duplicate TCPs also suggested that the downward advancement of the moisture front in trench fill was relatively uniform. The persistence of elevated water potentials at the 0.75-m depth of the east trench indicated water that penetrated to a relatively shallow depth was not removed by evaporation; the seasonal changes in water potential generally corresponded with seasonal changes in temperature (Figure 9a and 9d).

Water potentials between the 1- and 2-m depths for the east trench showed that the moisture front reached 1.25 m during July 1990 and reached 1.55 m during July 1992: the maximum value observed at the 1.55-m depth was −7.2 MPa (Figure 9b). The TCP measurements for the west trench, however, indicated that the moisture front did not reach the 1.25-m depth during the study.

Below the 2-m depth, water potentials in the trench fill remained <-8 MPa. Water potentials for the native soil beneath the trenches (below the 4.5-m depth) ranged from about −5.7 to −7.5 MPa, and replicate measurements were in good agreement (values usually differed by <0.4 MPa) (Figures 9c and 10b). Seasonal fluctuations in water potentials for the soil beneath the trenches generally corresponded with seasonal fluctuations in temperature (Figures 9c, 9d, 10b, and 10c).

General trends in the direction of driving forces for water movement at the trench sites were similar to those observed for nonvegetated soil. Although the exact extinction depth for bare soil evaporation is not known, water potential data for the east trench indicate that a consistently downward driving force for isothermal flow developed in the near-surface fill soon after trench construction. Below the evaporative zone, water potential and temperature gradients were in the same direction during the summer, but during the winter, water potential gradients opposed the temperature gradients (Figures 9a, 9b, and 9d). In contrast, data for the soil below the trenches showed that the water potential and temperature gradients were less steep, and the water potential gradients provided a consistently upward driving force for isothermal flow: water potential and temperature gradients were in the same direction during midwinter to midsummer but were diametrically opposed during midsummer to midwinter (Figures 9c, 9d, 10b, and 10c). The lack of any measurable water potential increase for all TCPs placed 0.15 m above the trench floors, however, implied that the upward flux of water into the trenches was negligible during the monitoring period.

Potential Mechanisms of Water Transport

Although it is recognized that the processes of liquid and vapor flow are strongly coupled and that rigorous evaluation of these processes cannot be done without the use of numerical models, calculations were made to estimate the relative magnitude of liquid and vapor fluxes at the field sites. The calculations were based on field data collected during this study and results from the earlier material-property characterization [*Andraski*, 1996].

The large, intermittent increases in water potential to near 0 MPa in the upper 0.25 m for the trench sites and the upper 0.75 m for the native-soil sites reflected infiltration and redistribution of precipitation. If a unit-gradient condition above the wetting front is assumed, the maximum downward liquid flux may be estimated from the saturated hydraulic conductivity value (K_s): K_s for the uppermost native soil layer is 5.0×10^{-4} cm/s; K_s for the trench fill is 2.9×10^{-4} cm/s.

For greater depths, average vertical fluxes of isothermal liquid (q_L), isothermal vapor (q_{iv}), and nonisothermal vapor (q_{Tv}) were estimated on the basis of field data collected at the ends of the third and fifth years of the study. The September 1990 data reflect conditions following 2 years with low precipitation, and the September 1992 data reflect conditions following 2 years with near- or above-average precipitation. For each time period the average water potential and temperature was first determined from TCP measurements at the top and bottom of the depth intervals given in Table 2. The q_L was calculated as

$$q_L = -K_L(d\psi/dz + 1) \tag{1}$$

Table 2. Average Vertical Fluxes of Isothermal Liquid, q_L; Isothermal Vapor, q_{iv}; and Nonisothermal Vapor, q_{Tv}, Estimated for Selected Depth Intervals at the End of the Third and Fifth Years of the Study

Site	Depth Interval, m	September 1990			September 1992		
		q_L	q_{iv}	q_{Tv}	q_L	q_{iv}	q_{Tv}
			cm/s				
Vegetated soil	1.20–1.60	-3.0×10^{-15}	-2.0×10^{-11}	-3.0×10^{-9}	1.2×10^{-14}	4.5×10^{-11}	-5.0×10^{-9}
	2.80–3.40	5.9×10^{-11}	7.0×10^{-11}	-2.0×10^{-9}	6.0×10^{-11}	5.7×10^{-11}	-2.0×10^{-9}
	4.20–5.00	5.6×10^{-11}	3.8×10^{-11}	-3.7×10^{-10}	1.3×10^{-10}	6.7×10^{-11}	-5.2×10^{-10}
Nonvegetated soil	1.05–1.85	-1.1×10^{-13}	-4.5×10^{-11}	-3.0×10^{-9}	-1.7×10^{-13}	-4.4×10^{-11}	-3.0×10^{-9}
	2.75–3.85	4.3×10^{-11}	5.4×10^{-11}	-1.0×10^{-9}	4.4×10^{-11}	6.2×10^{-11}	-2.0×10^{-9}
East trench	0.75–1.25	-2.0×10^{-10}	-5.1×10^{-10}	-2.0×10^{-9}	-8.8×10^{-10}	-5.7×10^{-10}	-1.0×10^{-9}
	5.05–5.50	3.5×10^{-11}	5.1×10^{-11}	-7.6×10^{-10}	3.2×10^{-11}	4.5×10^{-11}	-8.0×10^{-10}
West trench	4.85–5.50	4.8×10^{-11}	7.1×10^{-11}	-4.9×10^{-10}	3.8×10^{-11}	5.1×10^{-11}	-5.7×10^{-10}

Fluxes given in centimeter per second.

Sign convention is that downward fluxes are negative and upward fluxes are positive. Water potential and temperature data used in the analysis are from the following thermocouple psychrometers: vegetated soil, 1.20, 1.60, 2.80, 3.40, 4.20, and 5.00 (Figure 7); nonvegetated soil, 1.05-2W, 1.85-2E, 2.75-2W, and 3.85-2W (Figure 8); east trench, 0.75-1, 1.25-2, 5.05-2, and 5.50-2 (Figure 9); and west trench, 4.85-2 and 5.50-2 (Figure 10).

where K_L is unsaturated hydraulic conductivity corrected for the effects of in situ temperature and calculated as a geometric mean for the two depths in the interval; $d\psi/dz$ is the water potential gradient expressed in units of length; and $(d\psi/dz + 1)$ is the hydraulic gradient. The q_{iv} was calculated as

$$q_{iv} = -K_{iv}(d\psi/dz) \tag{2}$$

where K_{iv} is isothermal vapor conductivity corrected for the effects of in situ temperature and calculated as an arithmetic mean for the two depths in the interval. The q_{Tv} was calculated as

$$q_{Tv} = -D_{Tv}\eta(dT/dz) \tag{3}$$

where D_{Tv} is thermal vapor diffusivity [*Philip and de Vries*, 1957] corrected for the effects of in situ temperature and calculated as an arithmetic mean for the two depths in the interval; η is an enhancement factor that was calculated as a function of clay content and water content [*Campbell*, 1985]; and dT/dz is the temperature gradient. The average fluxes calculated by these methods are given in Table 2.

For vegetated soil, q_L for the 1.20- to 1.60-m interval (in the coarse soil layer) was at least 3 orders of magnitude less than the vapor fluxes (Table 2). The downward isothermal fluxes estimated for the 1.20- to 1.60-m interval during September 1990 resulted from a water potential difference between depths that was within the measurement error (<0.2 MPa) of the TCPs. Within each of the two lower depth intervals the q_L and q_{iv} values were similar but were less than q_{Tv} (Table 2).

For nonvegetated soil, q_L for the 1.05- to 1.85-m interval (in the coarse soil layer) was at least 2 orders of magnitude less than the vapor fluxes (Table 2). In contrast, for the 2.75- to 3.85-m interval, there was little difference between the q_L and q_{iv} values, but the isothermal fluxes were about 1 order of magnitude less than q_{Tv}. Within depth intervals the calculated fluxes showed little difference between time periods. However, moisture accumulation in the coarse soil layer at the nonvegetated-soil site did result in q_L values that were ≥1 order of magnitude more than those for the coarse soil layer at the vegetated site (Table 2).

For the trench sites, within dates and depth intervals, the isothermal fluxes differed by less than a factor of 3; however, the isothermal fluxes for the 0.75- to 1.25-m interval at the east trench were, on average, about 1 order of magnitude greater than those for the soil below the trenches (Table 2). The calculations also showed that the accumulation of moisture in the 0.75- to 1.25-m interval between September 1990 and September 1992 was sufficient to increase q_L by a factor of >4, but the other fluxes showed little difference between time periods. Below the trenches, water fluxes were similar to those estimated for the 4.20- to 5.00-m interval at the vegetated site (Table 2). Water fluxes in the lower 3 to 4 m of trench fill could not be calculated directly using (1), (2), and (3) because water potentials remained <−8 MPa. However, on the basis of results from *Andraski* [1996] and September temperature data measured by TCPs at the 2.65- and 3.25-m depths (3.25-m data not shown), values for K_L and K_{iv} were estimated to be on the order of 10^{-13} cm/s, and D_{Tv} was about 10^{-8} cm^2/(s°C). If water potential gradients are assumed to be small, these K_L and K_{iv} values should approximate the magnitude of the isothermal fluxes in the body of the trenches, and q_{Tv} for the 2.65- to 3.25-m interval would be about -10^{-9} cm/s.

Because of the simplicity of the calculations used here, definitive comparisons of water transport mechanisms at the field sites are not possible, but some qualitative observations can be made. First, for the duration of this experiment, the liquid fluxes typically were small and, below the depth of temporal water content changes, were minimized in the native, coarse soil layer and in the trench fill ahead of the advancing moisture front. Second, the results given in Table 2 suggest that the overall magnitude of water fluxes below the surface active zone may be greatest for nonisothermal vapor flow. This observation and the nonisothermal flux values estimated here are consistent with the results of previous work that was done by *Fischer* [1987] at the vegetated-soil site. In that study the magnitude and direction of monthly average nonisothermal vapor fluxes varied down to a depth of 9 m in response to seasonal temperature variations: for the 1.2- to 1.6-m interval, maximum values ranged from -10^{-8} cm/s (July) to 10^{-8} cm/s (December); for the 7.9- to 9-m interval, maximum values ranged from -10^{-10} cm/s (January) to 10^{-10} cm/s (June). Finally, differences between the water fluxes given in Table 2 must also be viewed in relation to the potential sources of uncertainty associated with the estimated values. Probably the greatest source of uncertainty is in the unsaturated hydraulic conductivity function, particularly in the dry range. The accuracy of the Rossi and Nimmo–Mualem predictive model used by *An-*

draski [1996] has not been tested at low water contents. However, *Khaleel et al*. [1995] recently compared measured and predicted unsaturated hydraulic conductivities that were estimated using the fitted moisture retention curve, measured K_s, and the van Genuchten–Mualem model. They found that deviations between measured and predicted values were particularly severe at low water contents ($\leq$0.10 m^3/m^3); for some samples, differences were in excess of 2 orders of magnitude. Because of such uncertainties, it is difficult to assess the relative importance of the liquid and vapor transport mechanisms. However, the results do suggest that isothermal liquid, isothermal vapor, and nonisothermal vapor flow need to be considered in the conceptualization of unsaturated flow at the field sites.

Discussion

Thermocouple Psychrometer Measurements

In contrast with neutron-probe data, the greater sensitivity of TCP measurements in the dry range allowed for better definition of the actual extent of water movement and provided information on the direction of driving forces for water movement. The TCPs typically provided several years of water potential and temperature data. Recognizing the variability in electrical-output characteristics among TCPs, the generally good agreement between water potentials determined by replicate units also provided confidence in the field-measured values: differences often were $\leq$0.5 MPa.

Past research has indicated that the calibration of TCPs can shift with time. For example, *Brown and Johnston* [1976] evaluated changes in the sensitivity of screen-covered TCPs by recalibrating uncleaned units that had been buried in the field for as long as 3.3 years: 86% of the TCPs showed an average change in sensitivity of 6%, and the remainder showed no change. *Brown and Collins* [1980] performed a similar experiment with screen-caged TCPs like those used in this study and reported a calibration drift of 2.9% after 1 year of field exposure. No periodic calibration of TCPs was done in the present study because, with the exception of the one unit installed at the instrument shaft (5-m depth for vegetated soil), the units could not be removed without disturbing the soil/fill. However, recalibration of TCPs at the Mojave Desert site was done as part of the instrument-shaft studies by *Fischer* [1992]. In that work, retrievable TCPs were recalibrated after 1–2 years of field use. The maximum change in calibration was 0.5 MPa, but it was also noted that some of the observed changes could have been caused by the installation procedures. For the present study the greatest apparent long-term changes, or drift, in water potentials that cannot be readily explained were increases of about 0.5–0.7 MPa for three TCPs (3.85-1E, Figure 8c; 5.05-2, Figure 9c; and 4.85-2, Figure 10b). These unexplained changes represented long-term increases of about 7–9% and may be related to a drift in TCP sensitivity away from its original calibration. Because TCP performance can depend on their design (e.g., screen caged, ceramic cup) and how they are used, as well as the environmental conditions to which they are exposed, additional work is needed to evaluate the effects of specific installation procedures and field conditions on temporal changes in TCP sensitivity.

Water Movement Under Natural-Site and Simulated Waste-Site Conditions

Cumulative precipitation measured from October 1987 through September 1992 totaled 432 mm. Annual precipitation ranged from 1.5 times greater than the long-term average (108 mm/yr) to 8 times less than the long-term average. This episodic precipitation pattern is common to desert regions, and it was useful in identifying soil-water-response differences among the field sites.

Data collected at the undisturbed, vegetated-soil site showed no evidence of long-term accumulation or continued downward penetration of precipitation during the 5-year study. The large, intermittent increases in water potentials in the upper 0.75 m of soil suggested that downward liquid fluxes in the near-surface may approach 10^{-4} cm/s during infiltration events, but the data typically showed that percolation of precipitation was effectively impeded by the natural capillary break in the soil profile (loamy sand over gravelly coarse sand). On an annual basis, all of the water that accumulated in the uppermost soil layer was removed by evapotranspiration. The efficiency of root-zone water depletion by native plants was illustrated by the substantial seasonal decreases in water potentials (4 to >8 MPa) in the uppermost soil layer.

The field data for the vegetated-soil site indicated the absence of plant roots below the uppermost soil layer. This observation is in concurrence with the field observations of *Wallace and Romney* [1972], who stated that the rooting depth for creosote bush closely corresponds with the depth of penetrating moisture. However, the year-to-year variations in water potentials that were measured at depth during this study also implied that plant activity in the uppermost soil layer may have an effect on soil moisture conditions well below the apparent root zone. During the 2-year dry period, when low-moisture conditions persisted in the uppermost soil layer, water potentials for all depths below 0.75 m showed measurable decreases, and the resultant gradients established between the depths of 2.8 and 5 m provided a consistently upward driving force for isothermal flow. Water potentials then rebounded during 2 years with near- and above-average precipitation and, although the recovery was incomplete, seasonally variant water potential gradients were reestablished above the 4.2-m depth. Temperature gradients also may be important in controlling the direction of water flow in the soil profile: the thermal driving force was predominantly downward during the summer and upward during the winter. Isothermal liquid and isothermal vapor fluxes that were estimated below a depth of 1 m typically were on the order of 10^{-11} cm/s; however, liquid fluxes as low as 10^{-15} cm/s were calculated for the coarse soil layer. Results from this study and those of *Fischer* [1992] indicated that the magnitude of the nonisothermal vapor flux at the vegetated-soil site decreased with depth and was estimated to be on the order of 10^{-8} to 10^{-10} cm/s.

Results suggested not only that under present climatic conditions, the natural soil-plant system provides effective controls on the annual near-surface water balance but that the upper boundary conditions imposed by plant activity in the uppermost soil layer may also provide for the imposition of a second control on subsurface water flow that results in episodic, deep drying during periods of below-average precipitation. These results support, and may help to explain, the indirect evidence for negligible deep percolation that has been inferred from other studies at the vegetated-soil site. For example, studies of chloride concentration profiles have estimated that deep percolation below a depth of 10 m has been minimal or nonexistent for at least 6000 years [*Fouty*, 1989] to 15,000 years [*Prudic*, 1994]. Recent (1993) TCP measurements [*Andraski and Prudic*, 1997] also indicate that water potential gradients and a

geothermal gradient of 0.06°C/m [*Prudic*; 1994] provide upward driving forces for water movement between depths of 10 and 50 m.

In contrast with results for the vegetated soil, data collected at the nonvegetated-soil site indicated the long-term accumulation and shallow, but continued, penetration of precipitation. The cumulative change in near-surface water storage showed a net increase of 26 mm between October 1987 and September 1992. Assuming no runoff, this suggests that 94% of the total precipitation that fell on the nonvegetated-soil site was evaporated back to the atmosphere. Similar to the vegetated-soil site, rapid percolation of precipitation out of the uppermost soil layer was impeded by the natural capillary break in the native soil profile. However, long-term increases in water potentials ($\approx$1–3 MPa) for the coarse soil layer at the nonvegetated site suggested that water did continue to penetrate slowly and uniformly downward.

Unlike the results for vegetated soil, the water potential data for the nonvegetated-soil site suggested little, if any, year-to-year change in the direction of driving forces for isothermal flow below the 0.75-m depth. Water potentials between the depths of 0.75 and 2 m showed the persistence of downward driving force for isothermal flow during the monitoring period: water potential and temperature gradients were in the same direction during the summer but were diametrically opposed during the winter. In contrast, water potentials measured at and below the 2.75-m depth, on average, indicated the persistence of an upward driving force for isothermal flow: water potential and temperature gradients were in the same direction during the winter–spring period but were diametrically opposed during the summer–fall period. Water fluxes that were estimated below a depth of 1 m indicated that moisture accumulation in the coarse soil layer at the nonvegetated site was sufficient to result in isothermal liquid fluxes that were $\geq$1 order of magnitude more than those for the coarse soil layer at the vegetated site. However, the magnitude of the vapor (isothermal and nonisothermal) fluxes, as well as the liquid fluxes deeper in the nonvegetated-soil profile, were similar to the values estimated for equivalent depths at the vegetated site.

Steps used in the construction of the two nonvegetated test trenches (excavation, stockpiling excavated materials, and backfilling) produced a homogeneous fill material with a uniform water content (0.04–0.05 m^3/m^3). Similar to results for the nonvegetated soil, data collected at the trench sites indicated the accumulation and shallow, but continued, penetration of precipitation. Temporal changes in water content measured by the neutron probe were limited to the upper 0.50 m for the west trench and the upper 0.75 m for the east trench. The cumulative change in near-surface water storage for the trench sites between October 1987 and September 1992 showed a net increase of 14 mm for the west trench and 23 mm for the east trench. This suggests that 95–97% of the total precipitation that fell on the trenches was evaporated back to the atmosphere. Water potential data indicated water penetration to a depth of 0.75 m for the west trench and 1.55 m for the east trench; below these depths, water potentials in the trench fill remained <-8 MPa. In contrast with the natural capillary break that impeded percolation in the native-soil profiles, the depth of long-term water penetration at the trench sites was apparently limited by the hydraulic characteristics and the dryness of the fill ahead of the advancing moisture front. Advancement of the moisture front appeared to occur as the result of slow, and relatively uniform, redistribution of infiltrated water.

The method of drum placement and the associated differences in subsidence showed no positive relation with differences in water accumulation or penetration at the trench sites. Subsidence for the east trench, where drums were stacked, totaled 10 mm, and subsidence for the west trench, where drums were randomly placed, totaled 13 mm. Although subsidence did not have a measurable influence on water movement at the trench sites during the monitoring period, the general trends in subsidence suggested a positive relation with cumulative precipitation. This implies that subsidence could become a factor in the long-term water balance of the trenches, particularly if the subsidence were to result in localized ponding and the development of preferential flow paths. Further study is needed to verify this hypothesis.

The observed differences in water accumulation and penetration between the two trenches may be related to the quantity of rock fragments in the near surface cover materials (rock fragments (kg/kg): east trench = 0.45, west trench = 0.23). A greater quantity of rock fragments in the near surface of the east trench versus that for the west trench could have retarded evaporation and enhanced internal drainage. The apparent influence of rock-fragments on water accumulation is in general agreement with the results of *Waugh et al*. [1994]. In their study, done in southeastern Washington, it was found that bare soils with gravel mixed into the near surface consistently retained more water than bare soils with no gravel.

Similar to the results for nonvegetated soil, data for the trench sites indicated water that accumulated in the near surface provided for the development of a consistently downward driving force for isothermal flow: water potential and temperature gradients were in the same direction during the summer but were diametrically opposed during the winter. In contrast, water potential data for the soil below the trenches showed the persistence of an upward driving force for isothermal flow: water potential and temperature gradients were in the same direction during midwinter to midsummer but were diametrically opposed during midsummer to midwinter. The isothermal liquid and isothermal vapor fluxes estimated below the 0.75-m depth in the trench fill were on the order of 10^{-10} to 10^{-13} cm/s. The nonisothermal vapor fluxes for the trench sites, as well as the isothermal fluxes for the soil below the trenches, were similar to the values estimated for equivalent depths at the vegetated-soil site. In relation to the direction of driving forces, it also is of interest to note that the low (<-8 MPa) water potentials in the main body of the trenches versus those measured by TCPs in the adjacent soil profile (Figures 2 and 8) suggests an horizontal driving force for water movement toward the trenches.

Implications for Arid-Site Waste Disposal

Data collected under natural-site conditions identified two features that in combination may serve as important components of a waste-cover system that is designed to minimize the potential for downward movement of precipitation into a landfill or waste-burial facility: texturally stratified soils and native plants. The restoration of native plants, however, may be difficult because the disturbance caused by construction of a waste-burial facility will not only remove plants but will also destroy the fragile "fertile island" structure of desert surface soils. Natural revegetation of disturbed land in some arid areas, such as the Mojave Desert, may require decades or cen-

turies; more-rapid revegetation may be possible but only through the use of extensive soil manipulation and plant husbandry techniques that can help, but do not guarantee, restoration of a disturbed site [*Wallace et al*., 1980]. Thus additional work is needed to evaluate and develop cost-effective revegetation strategies if plants are to be successfully incorporated into waste-cover systems in such areas. Further study also is needed to define the soil-plant-atmosphere interactions that caused the deep drying observed at the vegetated-soil site during the present study and to evaluate how such interactions could affect the potential for release of contaminants to the terrestrial environment as well as to groundwater.

Results of the study also suggest that under nonvegetated conditions, precipitation can accumulate and penetrate downward, thereby increasing the potential for water to come in contact with and enhance the release of contaminants for subsequent transport by liquid water, water vapor, or other gases. For the duration of this experiment, however, the slow downward advancement of the moisture front at the nonvegetated sites was limited to the upper 1–2 m and, for greater depths the water potential data indicated the persistence of an upward water flux of a magnitude similar to that observed under natural-site conditions. In contrast to these observations, *Nativ et al*. [1995] observed rapid percolation of water and solutes through a 20- to 60-m-thick unsaturated zone at an arid site underlain by fractured chalk. It was concluded that preferential flow through the fractures made the chalk inefficient as a hydrologic barrier to contaminant migration because it allowed water and solutes to bypass the low-permeability matrix and escape much of the near-surface exposure to evapotranspiration. In addition to such differences in the hydrologic characteristics of the subsurface environment, the potential for downward movement of water at an arid waste-burial site could also be enhanced if precipitation and runoff were allowed to collect in open trenches during construction or if liquids were disposed directly into unlined trenches. Under such conditions the effectiveness of the positive surface and subsurface waste-isolation features that were identified under the objectives of this study would be diminished. In relation to this, another study is presently investigating the distribution of contaminants in the unsaturated zone at the Mojave Desert site and initial analyses have suggested that liquid wastes disposed into the LLRW trenches during 1962–1975 contributed to the observed contamination [*Striegl et al*., 1996].

Conclusions

In contrast with neutron-probe data, water potential and temperature measurements by thermocouple psychrometers were needed to define the extent of water movement and to provide information on driving forces for water movement at the Mojave Desert site in Nevada. Thermocouple psychrometers typically provided several years of water potential data: 77% were still operable after $\geq$4.5 years of use. Recognizing the variability in electrical-output characteristics among TCPs, the generally good agreement between water potentials determined by replicate units also provided confidence in the field-measured values: differences often were $\leq$0.5 MPa.

Under undisturbed, vegetated-soil conditions, no long-term accumulation or continued downward penetration of precipitation was observed. Percolation was impeded by a capillary break in the upper 1 m of the native soil profile (loamy sand over gravelly coarse sand). On an annual basis, all of the water that accumulated in the uppermost soil layer was removed by evapotranspiration; the efficiency of root-zone water depletion by native plants was illustrated by substantial seasonal decreases in water potentials (4 to >8 MPa). Below the uppermost soil layer, water contents remained low (0.04–0.10 m^3/m^3) and temporally invariant; however, the typically low water potentials (≈ -3.5 to -6.5 MPa) showed both seasonal and year-to-year variations. During a 2-year period with 44 mm of total precipitation, water potentials decreased by 2.3 (1.2-m depth) to 0.4 MPa (5-m depth) and the gradients became consistently upward between the 2.8- and 5-m depths. Water potentials then rebounded during 2 years with near- and above-average precipitation, and seasonally variant water potential gradients were reestablished above the 4.2-m depth. Results suggested that the natural soil-plant system not only provides effective controls on the annual near-surface water balance, but the upper boundary conditions imposed by plant activity in the uppermost soil layer may also provide for the imposition of a second control on subsurface water flow that results in episodic, deep drying during periods of below-average precipitation.

Under nonvegetated waste-site conditions, temporal changes in water content were limited to the upper 0.5–1 m and indicated that 94–97% of the total precipitation that fell on the three disturbed sites was evaporated back to the atmosphere. Water potentials indicated water penetration to depths of 0.75–1.55 m at the trench sites and to a depth of 1.85 m at the nonvegetated, native-soil site. The method of drum placement (stacked versus random) and the associated differences in trench-cover subsidence showed no measurable influence on the water balance of the trenches: subsidence totaled 10 mm for the trench in which drums were stacked and 13 mm for the trench in which drums were randomly placed. In contrast with the stratified native soil, the depth of water penetration at the trench sites was apparently limited by the hydraulic characteristics of the homogeneous fill and the dryness of the fill ahead of the advancing moisture front (0.04–0.05 m^3/m^3; <-8 MPa). Water potentials below the trenches and below the 2-m depth for the nonvegetated soil remained low (≈ -5.5 to -7.5 MPa) and indicated the persistence of typically upward driving forces for isothermal water flow.

Water fluxes estimated from water potential and temperature data suggested that isothermal liquid, isothermal vapor, and nonisothermal vapor flow need to be considered in the conceptualization of unsaturated flow at the Mojave Desert site. Liquid fluxes may approach 10^{-4} cm/s in the near-surface soil/fill during infiltration events. Below the depth of temporal water content change, the estimated magnitude of the isothermal liquid and isothermal vapor fluxes for the vegetated- and nonvegetated-soil sites typically were on the order of 10^{-11} cm/s; however, liquid fluxes as low as 10^{-15} cm/s were calculated for the coarse soil layer. At the trench sites the estimated isothermal fluxes in the fill ranged from about 10^{-10} to 10^{-13} cm/s and, for the soil below the trenches, fluxes were about 10^{-11} cm/s. Temperature gradients were predominantly upward during the winter and downward during the summer. The magnitude of the nonisothermal vapor flux decreased with depth and, below 1 m, was estimated to range from about 10^{-8} to 10^{-10} cm/s.

The results of this field study provide a greater understanding of how, and to what degree, the natural unsaturated-flow system may be altered by the installation of a waste-disposal

facility. Such information is important to the hydrologic assessment and design of arid-site disposal systems.

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