Water Movement in the Unsaturated Zone At a Low-Level Radioactive-Waste Burial Site Near Barnwell, South Carolina

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Water Movement in the Unsaturated Zone At a Low-Level Radioactive-Waste Burial Site Near Barnwell, South Carolina

By KEVIN F. DENNEHY and PETER B. McMAHON

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By Kevin F. Dennehy and Peter B. McMahon

Abstract

Four unsaturated-zone monitoring sites and a meteorologic station were installed at the low-level radioactive-waste burial site near Barnwell, S.C., to investigate the geohydrologic and climatologic factors affecting water movement in the unsaturated zone. The study site is located in the Atlantic Coastal Plain. The unsaturated zone consists of a few centimeters to more than 1 meter of surface sand, underlain by up to 15 meters of clayey sand. Two monitoring sites were installed in experimental trenches, and two were installed in radioactive-waste trenches. Two different trench designs were evaluated at the monitoring sites.

A meteorologic station was used to measure precipitation and to calculate actual evapotranspiration using the Bowen ratio method. Soil-moisture tensiometers, soil-moisture conductance probes, and temperature sensors were used to monitor soil-water movement in and adjacent to the trenches. Tracer tests using sodium chloride were conducted at each monitoring site. Hydrologic properties of unsaturated-zone materials were also determined. Data collection at the monitoring sites began in January 1982 and continued until early May 1984.

Tensiometer data show that the unsaturated materials had their highest percent saturations in winter and spring. Saturations in the backfill sand varied from 20 to 100 percent, and in the adjacent undisturbed and overlying compacted clayey sand, from about 75 to 100 percent. The same pattern generally was observed at all four monitoring sites.

The tracer-test data indicate that water movement occurred mainly during the recharge period, winter and spring. The tracer-test results enabled computation of rates of unsaturated flow in the compacted clayey-sand cap, the compacted clayey-sand barrier, and the backfill sand.

A micro-scale hydrologic budget was determined for an undisturbed part of the site from July 1983 through June 1984. Total precipitation was 144 centimeters, and actual evapotranspiration was 101 centimeters. Additionally, because tensiometer data indicate negligible water-storage changes in the unsaturated zone, it is estimated that approximately 43 centimeters of recharge reached the water table.

During 1984, the rise and fall of ponded water in an experimental trench was continuously monitored with a digital recorder. This water-level record was used to compute the rate of leakage of ponded water from that trench—1×10^{-5} centimeter per second.

A cross-sectional finite-element model of variably saturated flow was used to test the conceptual model of water movement in the unsaturated zone and to illustrate the effect of trench design on water movement into the experimental trenches.

Monitoring and model results show that precipitation on trenches infiltrated the trench cap and moved vertically into the trench backfill material. Precipitation on the undisturbed material adjacent to the trenches moved vertically through the surface sand and continued either downward into undisturbed clayey sand or laterally along the sand/clayey-sand interface into the backfill sand, depending on trench design. The trench construction practice of placing a compacted clayey-sand barrier around the trench greatly inhibits soil water from entering the trench.

INTRODUCTION

At the Barnwell waste-burial site in South Carolina, approximately 45 percent of the Nation's annual production of commercial low-level radioactive waste is buried each year in shallow trenches. Disposal began in 1971 and is scheduled to continue until 1992, when a new burial site elsewhere in the Southeastern States is to be opened.

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The effectiveness of shallow disposal of radioactive waste depends on how well the waste is isolated from the environment over a long period of time. The agent most likely to threaten that isolation is water. If soil water percolating through the unsaturated zone encounters the buried waste, the water could transport radionuclides away from the trench and into the ground-water flow system.

To minimize the potential for contamination, Congress asked the U.S. Geological Survey to conduct a nationwide investigation of the suitability of various environments for shallow disposal of these wastes. The Barnwell site was included in the investigation because of its large volume of buried waste and because it is the Nation's only low-level radioactive-waste burial site that is located in a humid Coastal Plain environment with relatively high rates of precipitation and recharge to the ground-water flow system. Because of these conditions, and because some future sites are likely to be located in similarly humid environments, the movement of water from the land surface to the water table at this site needs to be understood in detail.

This report presents results of a study of water movement at trenches excavated in the unsaturated zone at the low-level radioactive-waste burial site near Barnwell, S.C. Field studies were conducted from 1981 through 1984. The information gathered at the study site can be used in development of hydrologic guidelines for the selection of future burial sites.

Purpose and Scope

This report describes the results of a study of water movement in and adjacent to trenches excavated in the unsaturated zone and assesses the principal factors affecting this movement. The objectives of the study were to (1) determine the parameters that control the relative rates, direction, and timing of water movement from land surface into and out of the waste trenches, (2) estimate a hydrologic budget at the study site, based on direct measurement of precipitation and calculation of actual evapotranspiration using the Bowen ratio/energy budget method, and (3) determine the influence of two different trench designs on water movement into those trenches.

The scope of the study included (1) installation of monitoring sites in two experimental and two radioactive-waste burial trenches, (2) use of tracer tests at each monitoring site to determine rates of soil-water movement, (3) collection and analysis of unsaturated soil samples, (4) collection and analysis of meteorologic data, and (5) qualitative simulation of soil-water movement using a variably saturated numerical flow model.

General Description of Study Area

The study area is located at a low-level radioactive-waste burial site in the Coastal Plain physiographic province about 128 km (kilometers) inland from the Atlantic Ocean in southwestern South Carolina. The burial site covers an area of about 130 hm^2 (square hectometers) and is situated 8 km west of the city of Barnwell, S.C., near the southeastern edge of the Savannah River Plant (fig.1). The burial site is a commerical enterprise operated on property leased to the contractor

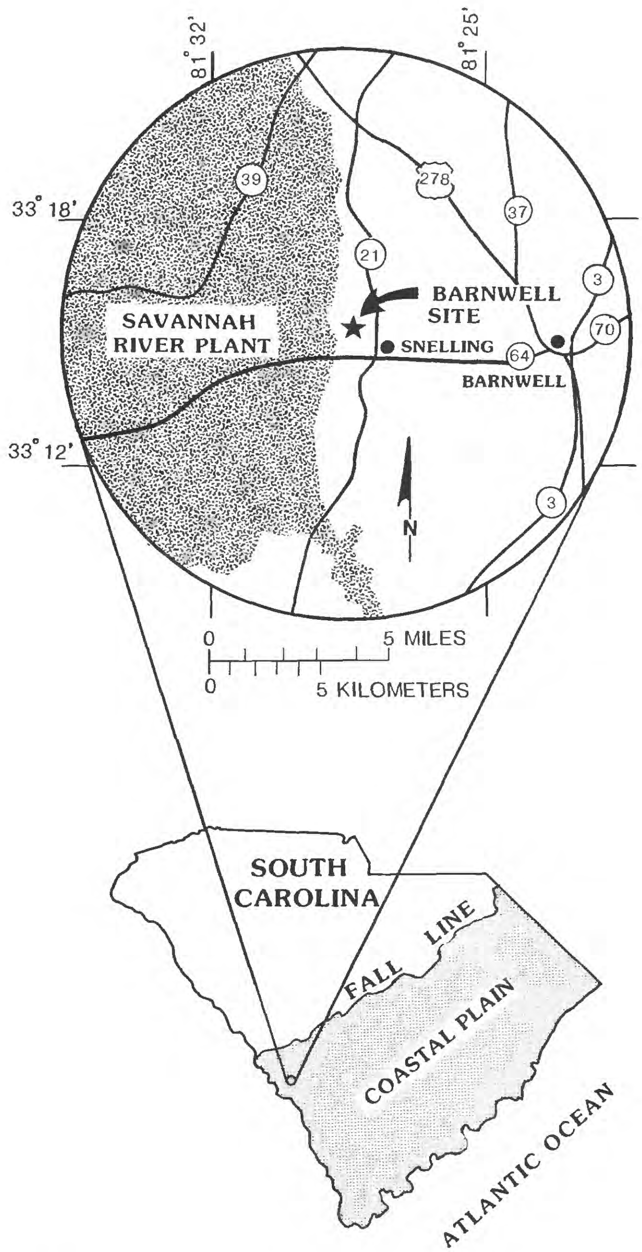


Figure 1. Location of low-level radioactive-waste burial site near Barnwell, S.C.

by the State of South Carolina. Solid waste is buried in rectangular trenches that are excavated in unconsolidated Coastal Plain sediments of the Miocene Hawthorn Formation. The burial area contains about 50 trenches that average about 7 m (meters) in depth, depending on the depth of the water table, 15 to 30 m in width, and 152 to 305 m in length. The water table at the site is generally at a depth of about 10 to 15 m below land surface. Current regulations require that trench bottoms at all times remain at least 1.5 m above the water table.

The topography is generally flat to slightly rolling, with land-surface elevations ranging from 70 m to about 80 m above sea level.

The climate of the area is characterized by warm, humid summers and mild winters. Based on data collected from 1883 to 1983 at the climatological station 12 km northeast of the burial site in Blackville, S.C., mean annual air temperature is 17.6 °C and mean annual precipitation is 121.5 cm (centimeters) (U.S. National Oceanic and Atmospheric Administration, 1984). Mean daily temperatures for the month vary seasonally from 7.8 °C in January to 26.6 °C in July. Average monthly rainfall ranges from a high of 13.4 cm in June to a low of 5.7 cm in November.

Overland runoff at the burial site is observed only during intense rainfall where forest litter and surface sand have been removed (Cahill, 1982). Seventy percent of rainfall is estimated to return to the atmosphere by evapotranspiration (Cahill, 1982). Cahill (1982) and Hung (1982) have estimated from numerical simulation that recharge is about 30 percent of total rainfall.

The geology of the site is typical of the Atlantic Coastal Plain. The sediments, which range in age from Late Cretaceous to Holocene, are relatively unconsolidated and are composed of stratified gravel, sand, silt, clay, and limestone. Thickness of the unconsolidated Coastal Plain sediments ranges from a few meters near the Fall Line to more than 1,200 m along the coast of South Carolina (Siple, 1967). Although the unconsolidated sediments are about 320 m thick in the study area (Cahill, 1982), only the upper 10 to 15 m are unsaturated and, therefore, of interest in this study. For a more detailed discussion of the geology of the unconsolidated sediments below the unsaturated zone in the vicinity of the study area, see Siple (1967), Cahill (1982), and McDonald (1984).

The undisturbed unsaturated zone at the study site is composed of eolian sands of Holocene age, consisting of fine-grained quartz, ranging in thickness from a few centimeters to more than 1 m, underlain by up to 15 m of clayey sand of the Hawthorn Formation. The Hawthorn Formation consists of tan, red, purple, and white clayey sand that contains coarse sand, gravel, and limonitic nodules. Grains of feldspar, partially weathered to kaolinite, are scattered throughout the clayey sand. In most places the sand of the Hawthorn Formation is poorly sorted (Siple, 1967). The formation is intersected by numerous clay-filled clastic dikes that can be observed at trench cut sites.

Acknowledgments

The authors thank James M. Cahill (U.S. Geological Survey, retired) for the project conception, initial design, and installation of the monitoring sites.

TRENCH CONSTRUCTION

Low-Level Radioactive-Waste Burial Trenches

Low-level radioactive waste was first buried at the Barnwell site in May 1971 in trenches at the south end of the facility (fig. 2). These trenches are 152 m or less long,

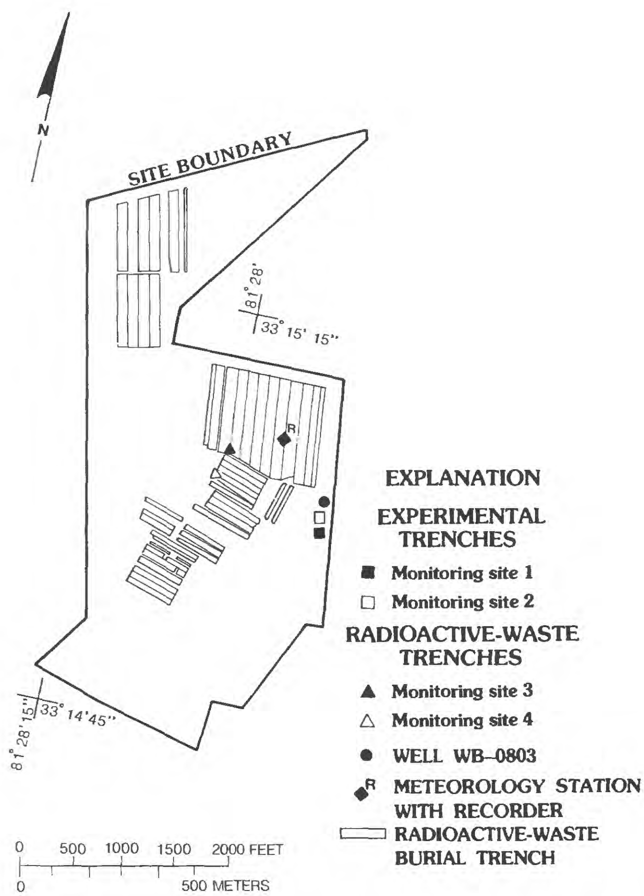


Figure 2. Location of unsaturated-zone monitoring sites and meteorologic station at the low-level radioactive-waste burial site.

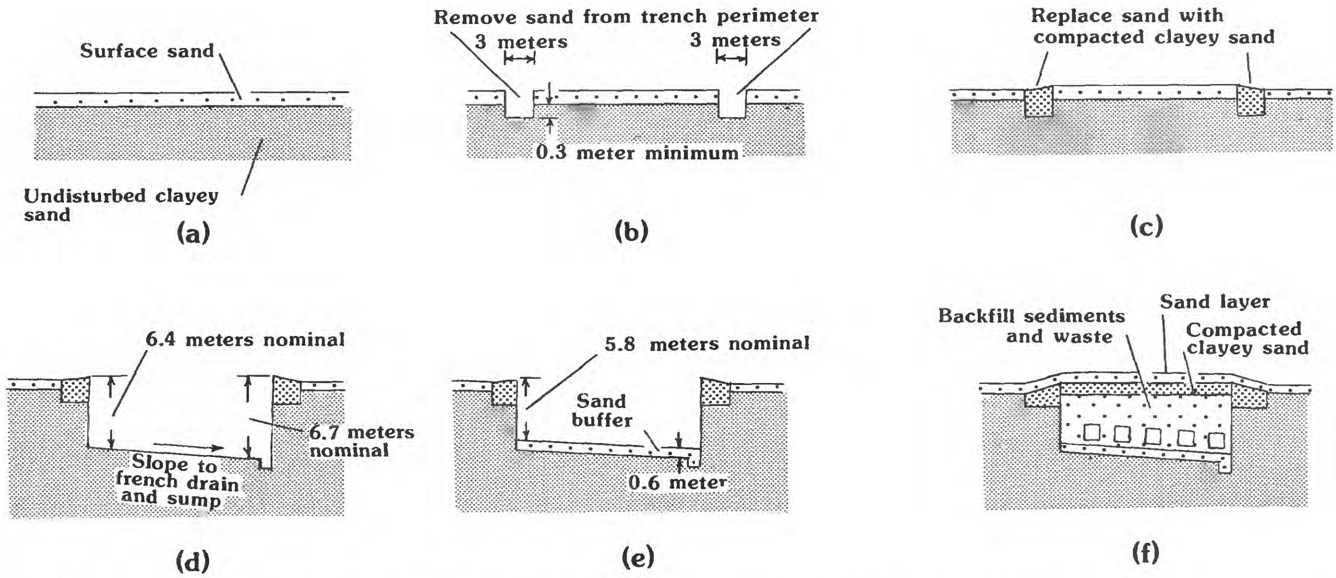


Figure 3. Post-1976 trench construction details: (a) pre-construction, (b) removal of surface sand from trench perimeter, (c) replacement of sand with compacted clayey sand, (d) trench excavation, (e) addition of sand buffer, (f) completion of trench.

15 m wide, and 7 m deep. In 1976 the shallow land burial method used at the Barnwell site was modified. The new trenches, located north of the old trenches near the middle of the site, are approximately 305 m long, 30 m wide, and 7 m deep (fig. 2).

The initial step in construction of a new trench is removal of the surface (sandy) layer of soil from a perimeter around the designated trench area (fig. 3b). Clayey sand is then placed in the excavated area and compacted to construct an upper barrier wall (fig. 3c). The perimeter is shaped to facilitate drainage away from the structure, and the trench is excavated within the exposed undisturbed clayey sand (fig. 3d). The compacted clayey sand prevents the upper walls from caving in and ensures that the trench is surrounded by a low-permeability surface barrier (U.S. Nuclear Regulatory Commission, 1982, p. 2–15). The absence of the compacted clayey-sand barrier is the fundamental difference between the pre- and post-1976 trench designs, although an upper barrier wall has since been emplaced around trenches constructed before 1976 (M.T. Ryan, Chem-Nuclear Systems, Inc., oral commun., 1985).

The trench is excavated so as to maintain at least a 1.5-m separation between the trench bottom and the water table (Chem-Nuclear Systems, Inc., 1980, p. 47). The bottom is sloped, and along the lower side of the bottom, a 0.6-m-deep French drain is constructed and filled with gravel (figs. 3d, 4). Monitoring standpipes are installed at 30-m intervals to facilitate future sampling. Two sumps, 1.2×1.2 m, extending 1.2 m below the trench floor, are placed 152 m apart and filled with gravel to serve as collection points for water. Pipes rising to grade level from the sumps allow removal of any water.

Before the trench is filled with waste, the sandy topsoil previously removed is added to the trench bottom (fig. 3e) to provide (1) a firm and level base for the waste, (2) a relatively permeable porous medium to allow moisture to move easily to the French drain, both before and after trench closure, and (3) a buffer zone in case of an abnormal rise of the water table (U.S. Nuclear Regulatory Commission, 1982, p. 2–17). Radioactive waste is then stacked in the trench, and the trench is backfilled with stockpiled surface sand, now referred to as "trench backfill sand."

Once the trench has been filled with waste and backfilled with surface sand, a minimum of 0.6 m of clayey sand is added at the top of the trench and a vibrating compactor is used to accelerate the settling process. An additional 0.15 m of sandy soil is added over the compacted clayey-sand cap (fig. 3f). The trench cap is contoured for drainage by sloping the adjacent ground away from the structure and establishing a uniform gradient in the longitudinal direction. To control erosion, grass is seeded over the trench (Chem-Nuclear Systems, Inc., 1980, p. 47).

Monitoring sites 3 and 4 were installed in existing low-level radioactive-waste burial trenches constructed using the new (post-1976) trench design (fig. 2). These trenches will be referred to for simplicity as "trenches 3 and 4."

Experimental Trenches

Experimental trenches 1 and 2 were constructed to monitor the effect of old and new trench designs on water movement in the unsaturated zone (fig. 2). Trench 1 was constructed using a design similar to that of a

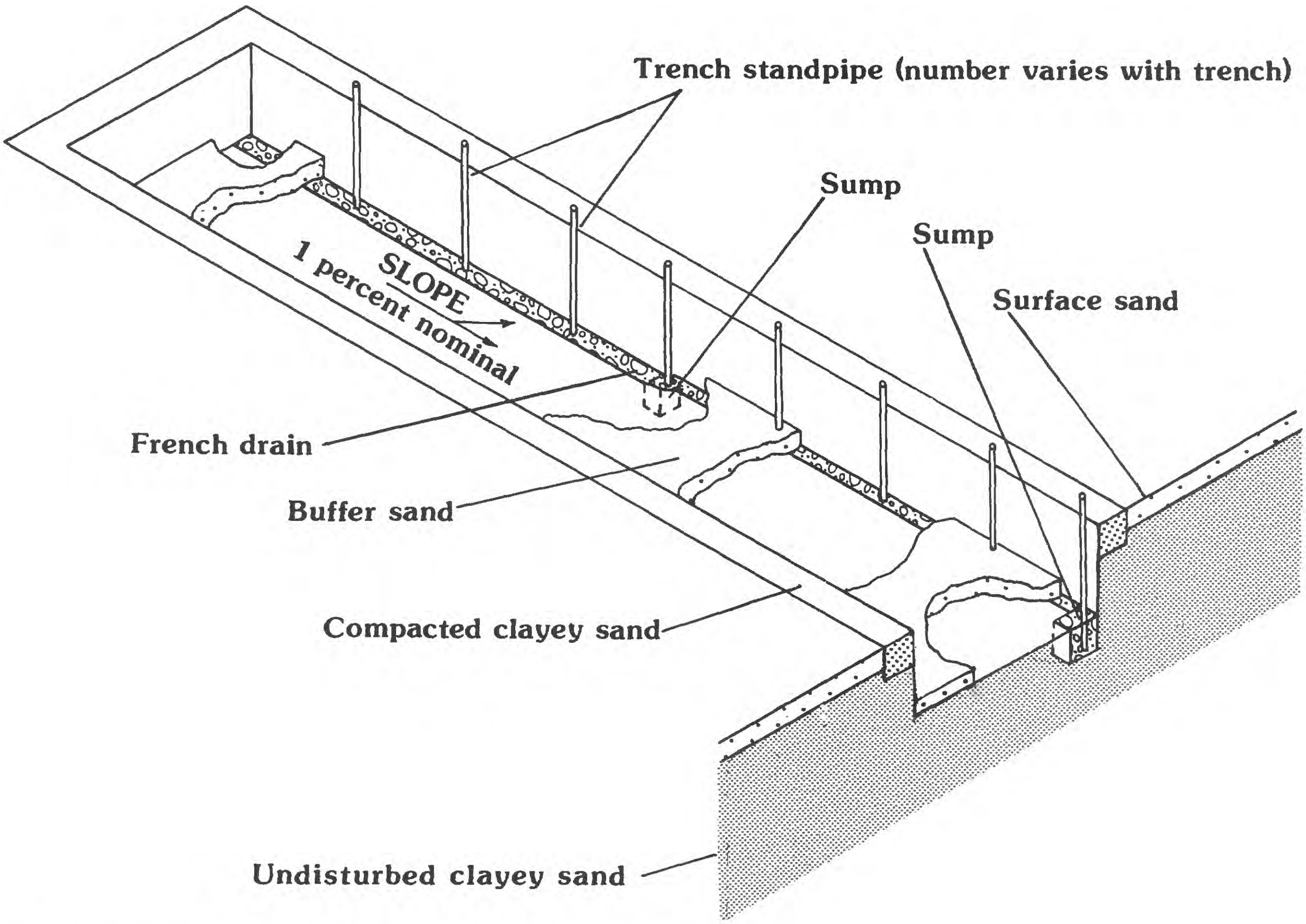


Figure 4. Typical post-1976 burial trench.

typical trench constructed after 1976. Trench 2 was constructed using a design similar to that used prior to 1976.

Trench 1

Trench 1 was constructed according to post-1976 construction design in that the surface sand around the perimeter was replaced by a 3-m-wide compacted clayey-sand barrier. However, the trench contains no monitoring pipes, sumps, or French drain. The trench is 4.2 m wide, 10.4 m long, and 7.0 m deep. After excavation, simulated waste forms were placed on the trench floor, and the trench was backfilled with stockpiled surface sand and capped with 2 m of compacted clayey sand. Monitoring site 1 is located in trench 1.

Trench 2

Trench 2 was constructed to represent the trench design used prior to 1976. It is virtually identical to trench 1 except that surface sand around the perimeter was left in place. Trenches 1 and 2 are 3.4 m apart. Monitoring site 2 is located in trench 2.

In trenches 1–4 the monitoring site was placed in the trench to monitor soil moisture in both the backfill sand and the surrounding undisturbed clayey sand.

APPROACH TO MONITORING EVAPOTRANSPIRATION AND THE UNSATURATED ZONE

Monitoring Actual Evapotranspiration

A meteorologic station (fig. 2) was used to measure precipitation and the variables necessary to estimate actual evapotranspiration using the Bowen ratio/energy budget method (Campbell, 1977; Brutsaert, 1982). Variables measured at the station included incoming and reflected short-wave radiation, incoming and emitted long-wave radiation, net radiation, soil-heat flux and temperature, dry- and wet-bulb temperatures, and windspeed and wind direction. Meteorologic variables, with the exception of precipitation, were scanned every

10 s (seconds) by a Campbell Scientific CR-21[1] micrologger. The 10-s readings were averaged over each hour. The hourly values were then stored on magnetic-tape cassettes. Data stored on cassettes were transferred to computer storage. A paper-tape record was made as a backup. Precipitation data measured with a rain gage were recorded hourly on paper tape. Microclimate measurements were collected during 1983 and 1984. For a detailed discussion of the instruments used at the meteorologic station and the accuracy of each, as well as a complete listing of the data, see Dennehy and McMahon (1985).

The energy budget used in the Bowen ratio method can be expressed as

$$R_n - G - H - \lambda E = 0 \qquad (1)$$

where

R_n = net radiation measured near the ground surface, in watts per square meter;
G = rate of heat storage in the soil or water (soil-heat flux), in watts per square meter;
H = sensible heat loss, in watts per square meter;
λ = latent heat of vaporization, in joules per kilogram; and
E = actual evapotranspiration rate, in kilograms per square meter per second or millimeters per second.

If the Bowen ratio is defined as $\beta = H/\lambda E$, equation 1 can be written as

$$\lambda E = (R_n - G)/(1+\beta) \qquad (2)$$

or, solving for E,

$$E = (R_n - G)/(\lambda(1+\beta)) \qquad (3)$$

The Bowen ratio (Bowen, 1926) can be expressed as the ratio of sensible heat flux to latent heat flux

$$\beta = H/\lambda E = \frac{M_a p c_p (T_1 - T_2)}{M_w \lambda (p_{v1} - p_{v2})} \cdot \frac{r_v}{r_h} \qquad (4)$$

where

β = Bowen ratio, dimensionless;
M_a = molecular weight of dry air, in kilograms per mole;
p = absolute barometric pressure, in kilopascals;
c_p = specific heat of dry air, in joules per kilogram per degree Celsius;
T_1 = air temperature at height Z_1, in degrees Celsius;
T_2 = air temperature at height Z_2, in degrees Celsius;
M_w = molecular weight of water, in kilograms per mole;
p_{v1} = vapor pressure at height Z_1, in kilopascals;
p_{v2} = vapor pressure at height Z_2, in kilopascals;
r_v = vapor transfer resistance between heights Z_1 and Z_2, in seconds per meter;
r_h = heat transfer resistance between heights Z_1 and Z_2, in seconds per meter; and other components are as previously defined.

T_1, T_2, R_n, and G were measured directly at the meteorologic station, and it was assumed that $r_v = r_h$ (Campbell, 1977, p. 137). Vapor pressures were calculated using T_1 and T_2 in conjunction with wet-bulb temperatures, which were measured at the station with nonventilated thermistor psychrometers. By knowing R_n and G, and calculating β by means of equation 4, equation 3 can be used to estimate actual evapotranspiration.

Hourly values of evapotranspiration were estimated for daytime hours using equation 3. Daily evapotranspiration was determined by adding hourly evapotranspiration estimates. Daily values were summed to give monthly evapotranspiration. Dennehy and McMahon (1987) discuss in detail this approach and the errors associated with it.

Monitoring Soil Water

Installation of Trench Monitoring Sites

Soil-water movement was monitored in the vicinity of selected burial trenches with instruments placed in two experimental trenches (monitoring sites 1 and 2) and in two radioactive-waste trenches (monitoring sites 3 and 4). Figure 2 shows the location of the monitoring sites.

Large-diameter (1.83-m) metal shafts consisting of corrugated culvert pipe were used to gain access to the unsaturated zone. One shaft was installed vertically in each trench prior to filling the trenches with simulated waste forms (trenches 1 and 2) or radioactive waste (trenches 3 and 4) and backfill sand. A layer of bentonite clay, 0.3 m wide and 0.15 m thick, was placed along the outside circumference of each shaft where compaction of the cap to restrict water percolation downward along the pipe was not possible. This clay ring did not extend through the entire thickness of the compacted clayey-sand cap but was buried within the cap.

Soil tensiometers, temperature sensors, and soil-moisture conductance probes were installed horizontally throughout the shaft wall at different depths into the undisturbed clayey sand, compacted clayey sand, and trench backfill sand surrounding each shaft. Table 1 gives the depth, orientation, and soil material for the monitoring instruments at each trench. Figures 5 through 8 show the locations of the monitoring instruments at each site.

[1]Use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Table 1. Depth, orientation, and material type for soil-moisture tensiometers, temperature sensors, and soil-moisture conductance probes

Monitoring site number 1
Elevation of ground surface above sea level = 78.52 meters

Probe	Number	Elevation of probe above sea level (meters)	Orientation of probe from north (degrees)	Material
Tensiometer	6	75.55	273	Backfill sand
	10	72.68	201	Backfill sand
Temperature and soil-moisture conductance	3	78.03	301	Compacted clayey-sand cap
	6	77.44	298	Compacted clayey-sand cap
	7	76.58	130	Undisturbed clayey sand
	10	75.82	136	Undisturbed clayey sand
	13	74.93	126	Undisturbed clayey sand
	19	73.30	147	Backfill sand
	20	72.19	154	Backfill sand
	21	72.12	355	Undisturbed clayey sand

Monitoring site number 2
Elevation of ground surface above sea level = 78.65 meters

Probe	Number	Elevation of probe above sea level (meters)	Orientation of probe from north (degrees)	Material
Tensiometer	2	77.98	26	Compacted clayey-sand cap
	3	77.59	84	Compacted clayey-sand cap
	4	77.28	84	Surface sand
	5	76.70	95	Surface sand
	6	75.51	96	Undisturbed sandy clay
	7	75.45	35	Backfill sand
	8	74.87	95	Undisturbed sandy clay
Temperature and soil-moisture conductance	12	74.31	74	Undisturbed clayey sand
	19	72.18	69	Undisturbed clayey sand
	21	71.89	269	Backfill sand

Table 1. Depth, orientation, and material type for soil-moisture tensiometers, temperature sensors, and soil-moisture conductance probes—Continued

Monitoring site number 3
Elevation of ground surface above sea level = 79.15 meters

Probe	Number	Elevation of probe above sea level (meters)	Orientation of probe from north (degrees)	Material
Tensiometer	3	76.32	210	Undisturbed clayey sand
	4	75.54	240	Undisturbed clayey sand
	6	73.44	45	Backfill sand
	8	71.26	270	Undisturbed clayey sand
Temperature and soil-moisture conductance	2	78.32	210	Compacted clayey-sand barrier
	6	77.43	330	Compacted clayey-sand barrier

Monitoring site number 4
Elevation of ground surface above sea level = 78.37 meters

Probe	Number	Elevation of probe above sea level (meters)	Orientation of probe from north (degrees)	Material
Tensiometer	2	76.42	330	Undisturbed clayey sand
	4	75.61	270	Undisturbed clayey sand
	6	73.09	330	Undisturbed clayey sand

Holes were drilled into the side of the metal shaft to install the instruments. The tensiometers were installed by extracting soil using a 2.5-cm-diameter core barrel and then inserting the tensiometers into the cored hole until contact between the tip of the porous cup and the materials was made. Cored holes extended approximately 1 m into the materials, and the last 0.1 m of soil extracted was saved for hydrologic tests. A slurry composed of material that passed through a number 200 sieve (75 micrometers) was jetted into the cored hole to prevent moisture from moving along the cored hole and reaching the instrument. The hose used to jet the slurry into place was slowly pulled out of the horizontal hole as it was being backfilled. Pairs of temperature sensors and soil-moisture conductance probes were installed in horizontal holes similar to holes for the tensiometers. The sensors and probes were inserted the same distance as the tensiometers, and the material extracted from the cored hole was used to backfill the probes by tamping the material into place. No soil samples were taken at these probe locations.

Tensiometers

Unsaturated-zone monitoring site data were recorded daily with a Campbell Scientific CR5 digital recorder. Soil tensions were measured directly with a pressure transducer, which converts a pressure differential into a voltage that is recorded on the data logger. This pressure-transducer type of tensiometer satisfied two necessary criteria; the various tensions measured were well within the range of the pressure-transducer system, and the instrumentation provided a continuous record. A calibration curve was developed for the pressure transducer connected to each tensiometer so that an equivalent soil-moisture tension, expressed as centimeters of freshwater, could be determined for each recorded value. Because of the large quantity of data collected, only data from a few of the most complete instruments are included in this report. For a complete record of the tensiometer data, see the data report by Dennehy and McMahon (1985). Figure 9 illustrates the soil-tensiometer apparatus.

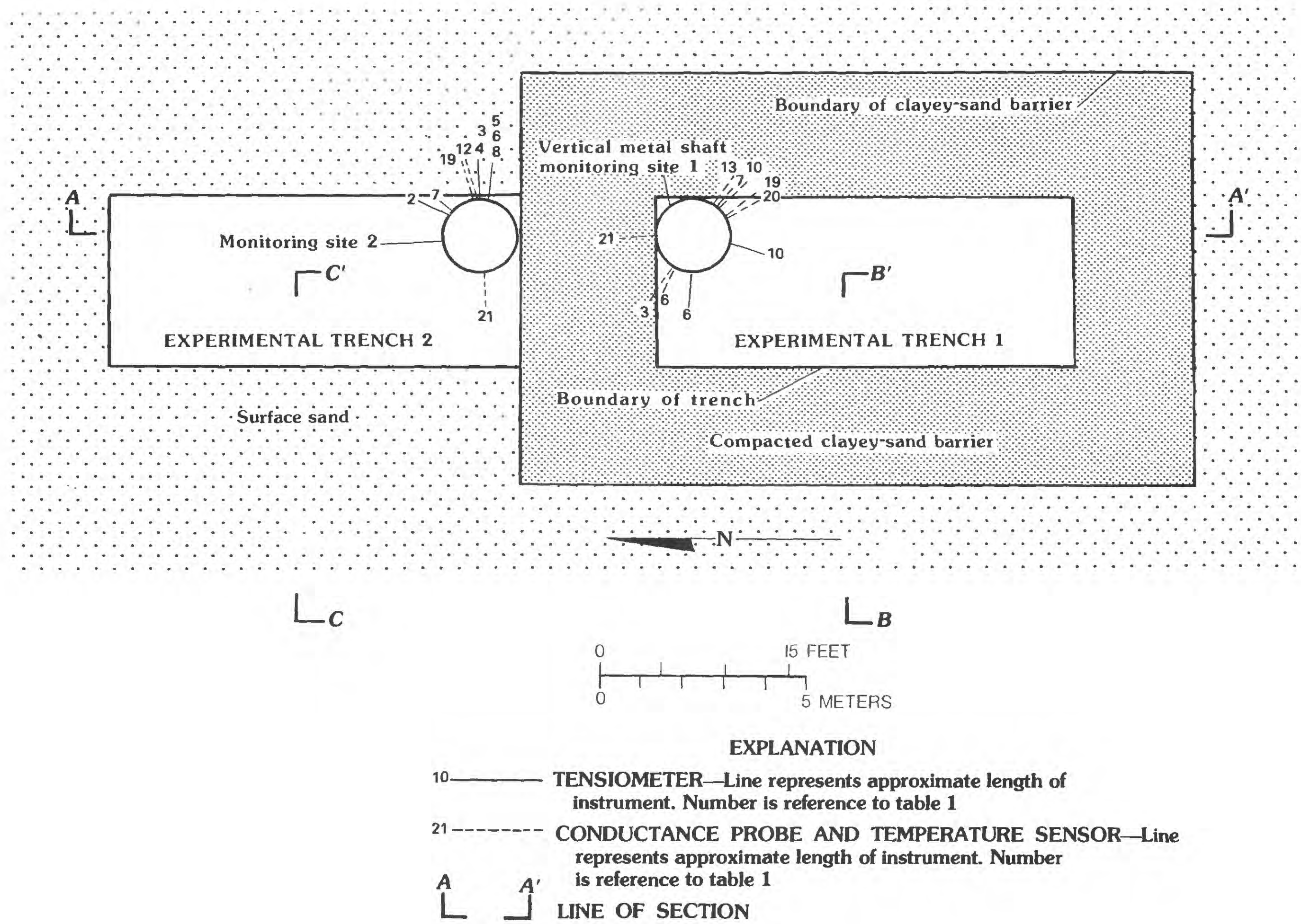


Figure 5. Tensiometer, temperature sensor, and soil-moisture conductance probe distribution at monitoring sites 1 and 2 (plan view).

Tracer Tests

Tracer tests were conducted to determine the movement of water in the unsaturated zone at the four monitoring sites (fig.2). Sodium chloride salt granules were used as a tracer. Salt granules were scattered on the bottom of the two experimental trenches (trenches 1 and 2) prior to their completion in 1981. On November 17, 1981, after completion of all four trenches, salt granules were applied at or near land surface at each monitoring site. At monitoring sites 1 and 2 the salt was placed just below land surface in the trench cap. At monitoring sites 3 and 4 the salt was placed on top of the backfill sand/undisturbed clayey-sand interface and then covered with the trench cap. A second application of salt was made at the four monitoring sites on May 20, 1983. At sites 1 and 2 the salt granules were buried in the trench cap about 0.45 m below land surface. At sites 3 and 4 the salt granules were placed on top of the compacted clayey-sand cap and then additional cap material was placed over the salt. In all cases the salt was distributed in a circular pattern around the monitoring sites approximately 1 m from the perimeter of the vertical shafts so that the salt was above the backfill sand and the undisturbed clayey sand (figs. 5–8).

Movement of the salt from near ground surface to the bottom of the trenches was monitored using soil-moisture conductance probes and temperature sensors located in pairs at various depths (Dennehy and McMahon, 1985). The temperature sensors were used to determine whether changes in soil-moisture conductance readings were due to temperature fluctuation or to salt-tracer contact with the soil-moisture conductance probe. Because soil-moisture conductance measurements were taken in a variably saturated system, soil-moisture conductance values, as discussed in this report, reflect changes in soil-moisture content as well as the presence of the sodium chloride tracer. This is discussed further in the section in which the results of the tracer test are presented.

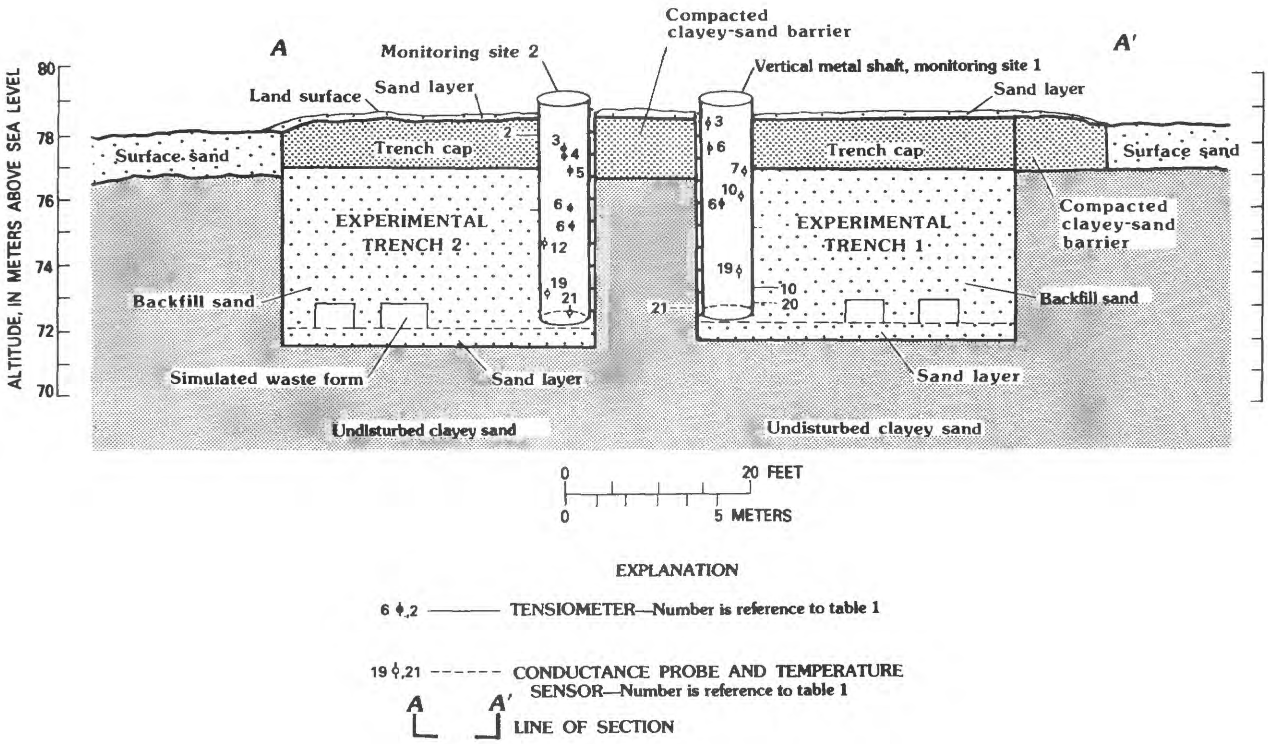


Figure 6. Tensiometer, temperature sensor, and soil-moisture conductance probe distribution at monitoring sites 1 and 2 (cross section). (Line of section A-A' shown in fig. 5.)

The salt was applied to the bottom of the two experimental trenches to gain insight into water movement beneath these trenches. Soil-moisture conductance probes were installed in two clusters at the bottom of each trench. Because of probe failure, the soil-moisture conductance probes produced no usable data.

The period of monitoring extended from January 1982 to May 1984 for monitoring site 1, January 1982 to March 1984 for monitoring site 2, July 1982 to May 1984 for monitoring site 3, and February 1982 to March 1984 for monitoring site 4. For a complete record of the data see Dennehy and McMahon (1985).

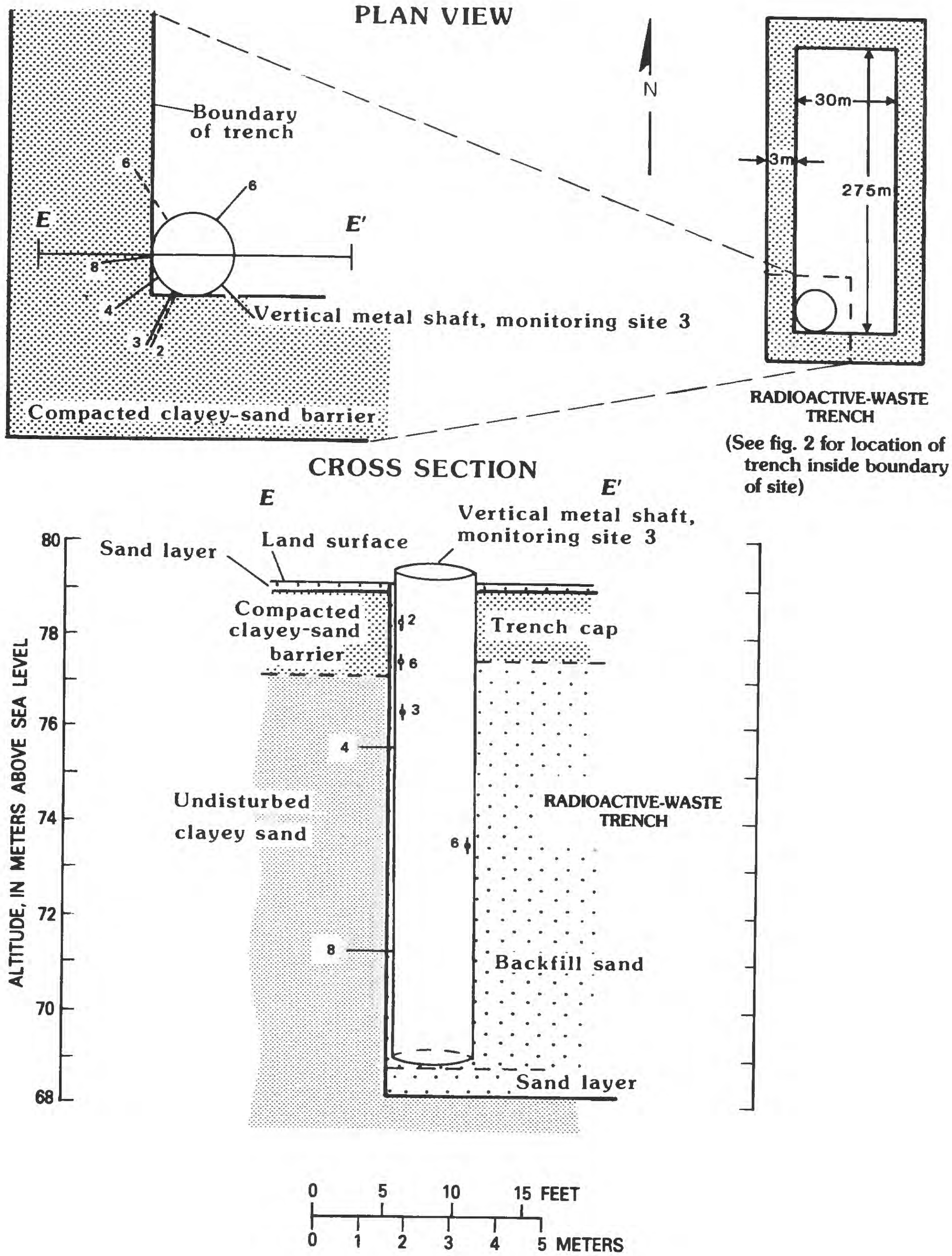
Sampling and Analysis of Unsaturated-Zone Materials

Soil samples were taken at each tensiometer location when the tensiometers were installed and again at the end of the project when the monitoring sites were dismantled. The initial samples were extracted with a 2.5-cm-diameter core barrel. Porosity and the soil-moisture retention characteristics of the materials were determined from these samples. A modified shelby-tube sampler having a 5.1-cm outer diameter (0.32-cm wall thickness) was used to collect the final samples. The sampling device was driven with a hammer or pushed where possible. Although it is recognized that the in situ hydrologic properties of the materials may be disrupted when this method is used, care was taken to disturb the samples as little as possible. Recovery of the samples was generally 100 percent.

Core taken using the modified shelby-tube sampler at each location was separated into four samples. Two samples were used for analyzing the soil moisture for tritium. They were extracted from the sampler, sealed in double-plastic bags, and kept frozen until delivered to the lab. Approximately 100 g (grams) of soil were required for each tritium analysis. Water was azeotropically distilled from soil samples (Thatcher and others, 1977). A scintillation counter was used to measure the tritium concentration in the water. The other two samples were individually cut from the sampler and left within the metal tubing to avoid any additional disturbance of those samples. The samples were then sealed at both ends with double-plastic sheets to keep in moisture. One of these samples was used to determine the saturated hydraulic conductivity and grain-size distribution of the material. The other sample was used to determine the soil-moisture retention characteristics of the material.

Hydrologic Testing and Relative Hydraulic Conductivities

Soil samples taken from the tensiometer locations and those obtained in the vicinity of the monitoring sites were used to measure the variations in the hydrologic



EXPLANATION

3 ⸸ ,3 — **TENSIOMETER—Line in plan view represents approximate length of instrument. Number is reference to table 1**

2 ⸸ ,2 ---- **CONDUCTANCE PROBE AND TEMPERATURE SENSOR—Line in plan view represents approximate length of instrument. Number is reference to table 1**

E E' **LINE OF SECTION**

Figure 7. Tensiometer, temperature sensor, and soil-moisture conductance probe distribution at monitoring site 3.

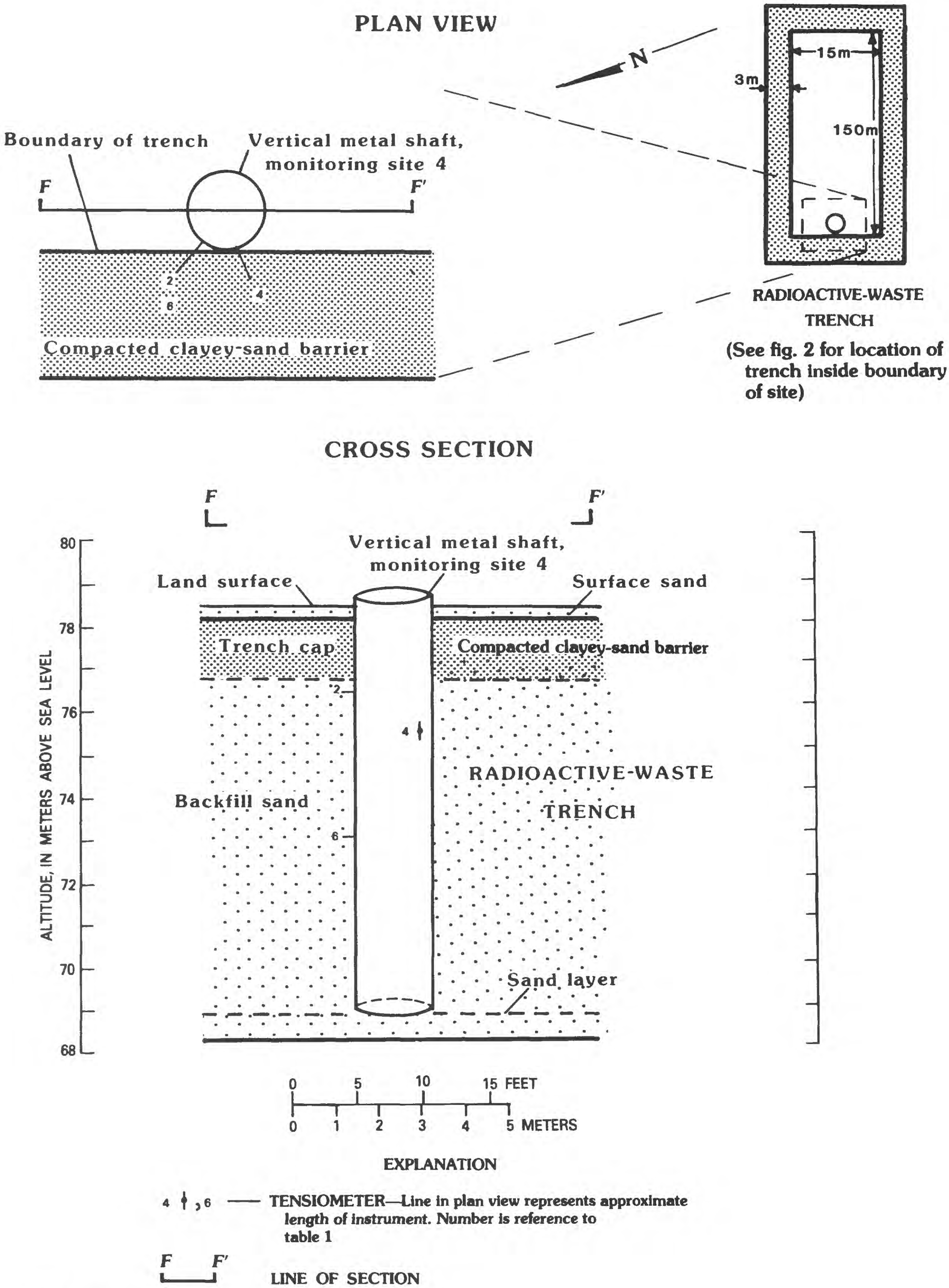


Figure 8. Tensiometer distribution at monitoring site 4.

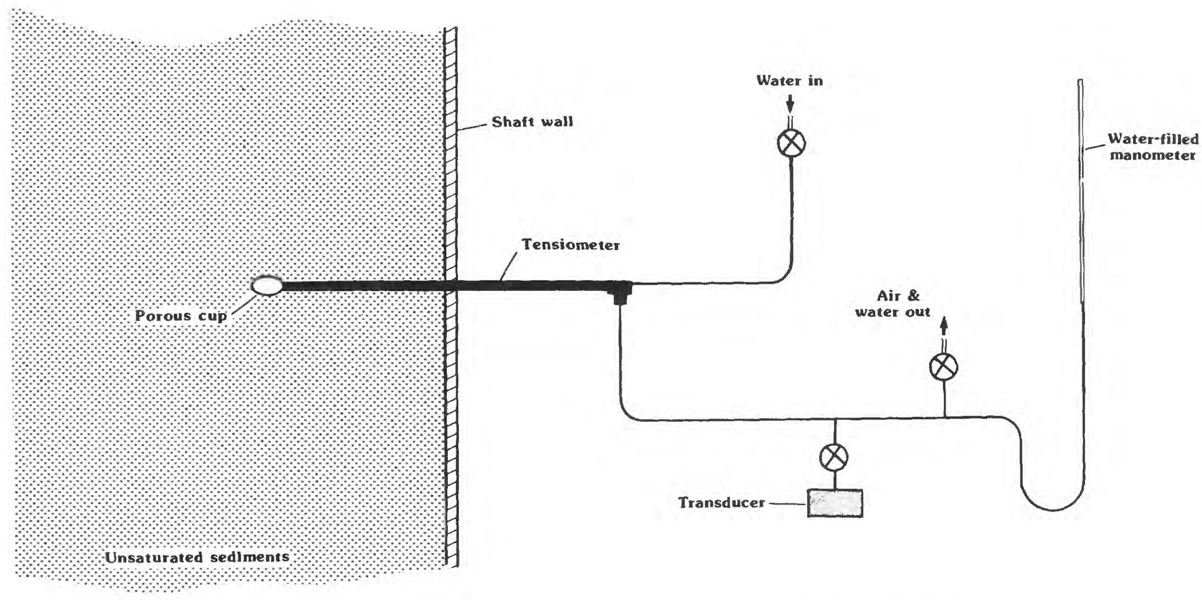


Figure 9. Typical apparatus for monitoring soil-moisture tensions in unsaturated sediments.

properties of the unsaturated-zone materials. Grain-size distributions, soil-moisture-characteristic curves, porosities, residual saturations, and saturated hydraulic conductivities were obtained from the soil samples. In addition, relative hydraulic conductivity versus percent saturation curves based on the Brooks and Corey (1964) relationship are presented.

Mechanical sieve analyses were performed according to American Society for Testing and Materials (ASTM, 1985) test method D422–63 to determine the grain-size distribution of the materials.

Soil-moisture retention data were determined for the different material types by two methods. Data for curves for monitoring site 2 were obtained using ASTM (1985) test method D2325 (capillary-moisture relationships for soils by porous-plate apparatus). The mercury injection technique (Purcell, 1949) was used to obtain data for curves for monitoring sites 3 and 4. A comparison of the two methods for core samples taken at the same location showed similar soil-moisture retention curves. Both methods produce data on the draining part of the soil-moisture retention curve. For testing method D2325, air is the nonwetting liquid that replaces water, which is the wetting liquid. For the mercury injection technique, mercury is the nonwetting liquid that enters an evacuated sample. Porosity and residual saturation data were obtained by both testing methods.

Saturated hydraulic conductivity (K_{sat}) data were obtained from soil samples taken from monitoring site 2. The K_{sat} for undisturbed clayey sand, compacted clayey sand, and undisturbed sandy clay samples were determined using a falling-head permeameter test. The K_{sat} for the surface/backfill sand was determined using a constant-head permeameter test. These tests were performed according to ASTM (1985) test method D2434–68.

Unsaturated hydraulic conductivity data is more difficult to obtain than saturated hydraulic conductivity data. This is because the hydraulic conductivity of an unsaturated porous medium is a function of its saturation (S). Testing procedures exist to measure the functional relation between K and S, but the method is difficult. An alternative approach for obtaining unsaturated hydraulic conductivity values is to use an empirical relation between K and S. Numerous relations of this type exist. In this study, the empirical relation between relative hydraulic conductivity (K_r) and saturation developed by Brooks and Corey (1964) is used. The method is reviewed in the following paragraphs.

Brooks and Corey (1964) found that

$$S_e = (P_b/P_c)^{\lambda} \text{ for } P_c \geq P_b \tag{5}$$

where S_e is the effective saturation, P_b is a measure of the maximum pore size forming a continuous network of flow channels within the medium, P_c is capillary pressure, and λ characterizes the pore-size distribution. Both P_b and λ are determined graphically on a log-log plot of S_e versus P_c, where λ is the slope and P_b is the intercept of the straight line, with the ordinate representing $S_e = 1.0$. Equation 5 following substitution and intergration becomes

$$K_r = K_{unsat}/K_{sat} = S_e^{\,(2+3\lambda)/\lambda} \tag{6}$$

which is the relative hydraulic conductivity versus percent saturation, $K_r(S)$, relation derived by Brooks and Corey. The assumptions on which their empirical relation is based are that (1) the medium is isotropic, (2) it is rigid, and (3) the drainage part of the soil-moisture retention curve is being considered.

WATER MOVEMENT IN THE UNSATURATED ZONE

Evapotranspiration Rates and Potential Recharge

Monthly evapotranspiration estimated using the Bowen ratio method and precipitation during 1983 and 1984 is shown in figure 10. Data were not available to estimate evapotranspiration in June 1983 using the Bowen ratio method. Actual evapotranspiration estimated using the Bowen ratio method was highest in summer and lowest in winter. The greatest monthly evapotranspiration (14 cm) occurred in May 1984, and the smallest (2.4 cm) occurred in December 1984. The greatest average daily evapotranspiration (0.45 cm) occurred in May 1984, and the smallest (0.078 cm) occurred in December 1984.

The potential for recharge exists at the waste burial site when precipitation is in excess of evapotranspiration. Precipitation exceeded evapotranspiration during numerous fall, winter, and spring months (fig. 10); therefore, water was available to infiltrate into the unsaturated materials during these months. Obviously, there are other factors that affect infiltration and, ultimately, recharge to the saturated zone, but these data provide a solid basis for identifying periods during 1983 and 1984 when the potential for recharge was greatest. For a detailed discussion of the microclimate and evapotranspiration at the site, see Dennehy and McMahon (1987).

Hydrologic Properties

Results of hydrologic tests on soil samples obtained during tensiometer installation and final monitoring-site decommissioning are separated with respect to material type. Three different types of material were sampled: undisturbed clayey sand, surface/backfill sand, and compacted clayey sand (cap and barrier). Variations among material types are examined.

Twenty-four mechanical sieve analyses of grain-size distribution were performed on samples of the three materials. The number 40 sieve determined the break between medium- and fine-grained sand, and the number 200 sieve marked the break between fine-grained sand and silt or clay. Analyses showed that 85 to 93 percent of the undisturbed clayey sand passed the number 40 sieve (425 micrometers) and that 20 to 60 percent

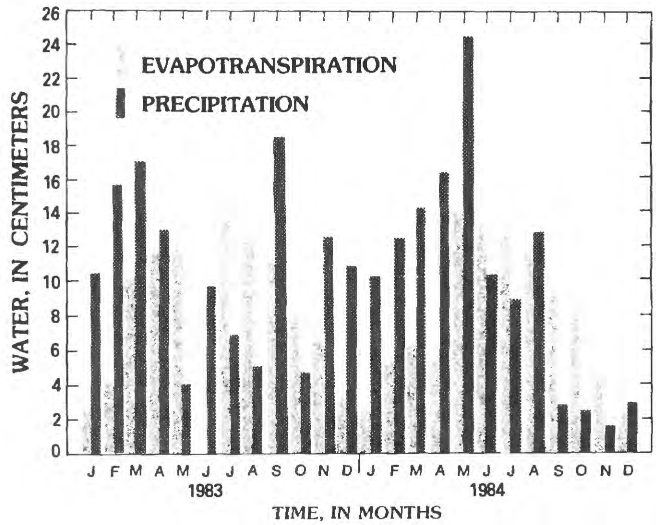


Figure 10. Monthly evapotranspiration and precipitation at Barnwell site for 1983 and 1984.

passed the number 200 sieve (75 micrometers). The undisturbed clayey sand is classified as fine-grained clayey sand to sandy clay. Sixty-five to ninety-three percent of the surface/backfill sand passed the number 40 sieve, and 2 to 12 percent passed the number 200 sieve. This material is classified as medium- to fine-grained sand with small amounts of clay. The trench cap and barrier is clayey sand that has been compacted with heavy machinery. Ninety to ninety-one percent of this material passed the number 40 sieve, and 20 to 30 percent passed the number 200 sieve. This material is classified as a fine-grained clayey sand. As might be expected, the compacted clayey sand has a grain-size distribution similar to that of the undisturbed clayey sand. The differences in the ranges of grain size represent sample variability.

The soil-moisture retention curves for the materials obtained at tensiometer locations at monitoring sites 2, 3, and 4 are presented in figures 11, 12, and 13. Although soil samples were collected from monitoring site 1, attempts to develop soil-moisture retention curves in the laboratory failed as a result of equipment and procedural difficulties. However, a comparison of grain-size distribution curves from monitoring sites 1 and 2 indicate a similarity between the materials. Because of this, the curves developed for materials at site 2 can be applied to the materials at site 1. The retention curves indicate that for a given tension, the surface/backfill sand has a lower percent saturation than either the undisturbed clayey sand or the compacted clayey sand.

Averaging the porosities for each type of material at all four monitoring sites gives a porosity of 0.30 for the undisturbed clayey sand, 0.36 for the surface/backfill sand, and 0.30 for the compacted clayey sand. The average residual saturation taken from the

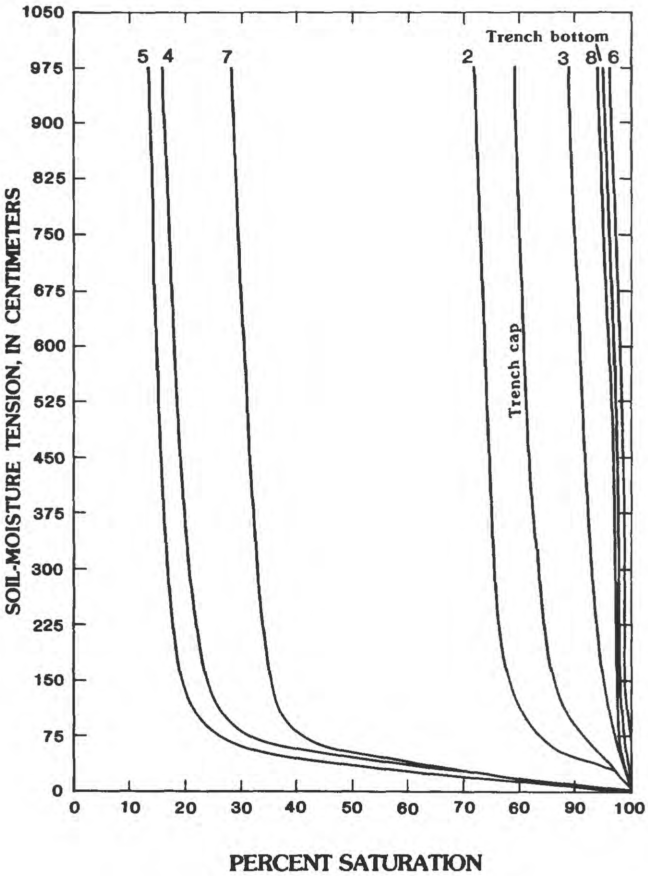


Figure 11. Soil-moisture retention curves for materials obtained at tensiometers 2 through 8, trench cap, and trench bottom at monitoring site 2.

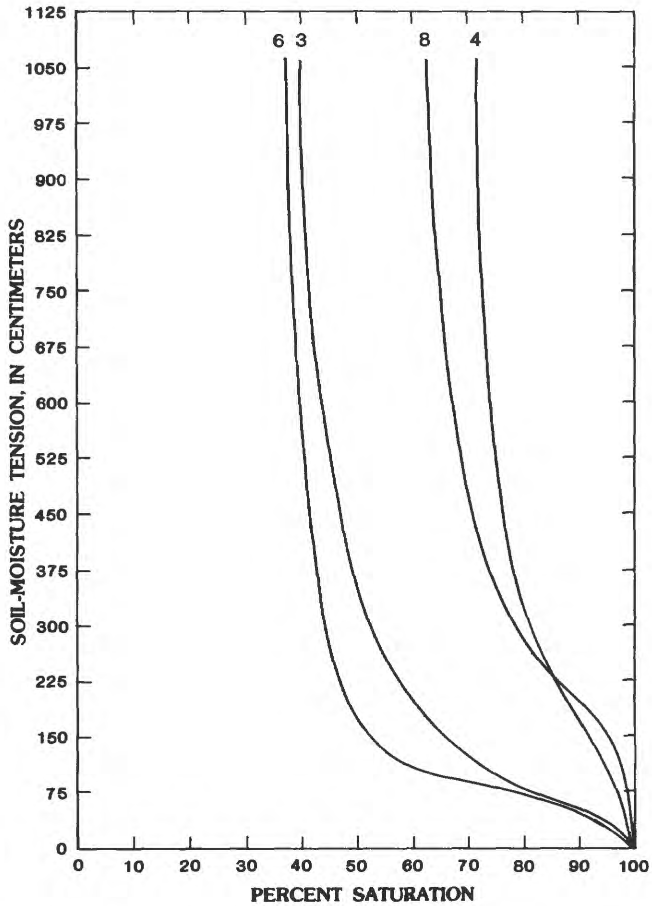


Figure 12. Soil-moisture retention curves for materials obtained at tensiometers 3, 4, 6, and 8 at monitoring site 3.

retention curves is 0.70 for the undisturbed clayey sand, 0.15 for the surface/backfill sand, and 0.72 for the compacted clayey sand.

The saturated hydraulic conductivities are as follows:

	K_{sat}(*cm/s*)		
Material	*Range*	*Geometric mean*	*Number of samples*
Undisturbed clayey sand	6.7×10^{-8} to 4.8×10^{-7}	1.4×10^{-7}	4
Compacted clayey sand	5.0×10^{-7} to 3.5×10^{-6}	1.5×10^{-6}	3
Surface/backfill sand	2.7×10^{-3} to 7.0×10^{-3}	4.0×10^{-3}	5

Figure 14 shows typical relationships between soil-moisture tension and percent saturation, and between K_r and S (as computed from the Brooks and Corey relationship) for backfill sand, undisturbed clayey sand, and compacted clayey sand. The hydraulic conductivity of an unsaturated porous medium increases with the degree of saturation, but it is always less than its saturated hydraulic conductivity. Furthermore, because clays tend to retain more water than sands, K_{unsat}-clay may be greater than K_{unsat}-sand for a given tension. Table 2 lists the components necessary to calculate relative hydraulic conductivity versus percent saturation curves for the core samples using the model suggested by Brooks and Corey (1964), as in equation 6.

Degree of Saturation and Water Movement

Tensiometers

Monitoring Site 1

The soil-moisture tension data collected in the undisturbed clayey sand at monitoring site 1 generally could not be used in this analysis because of their poor quality. Only tensiometers 6 and 10, in backfill sand, provided usable data (fig. 15). For details on possible errors in tensiometer measurements, see the data report by Dennehy and McMahon (1985). Tensiometers 6 and 10 were 2.97 and 5.84 m, respectively, below land surface. Illustrated in figure 15 on the left and right axes of each graph is the relationship between soil-moisture tension and percent saturation. Percent saturation values were determined from laboratory-generated soil-moisture retention curves; for a given tension, the corresponding percent saturation can be read from the

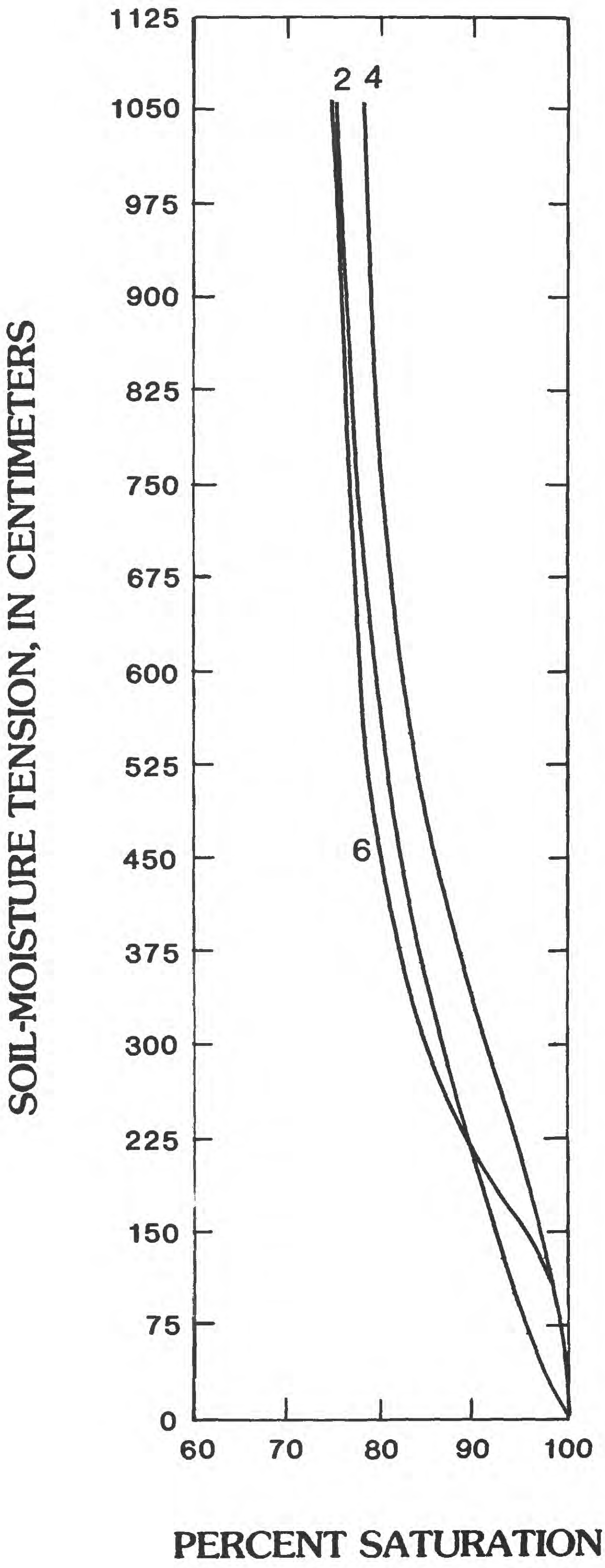


Figure 13. Soil-moisture retention curves for materials obtained at tensiometers 2, 4, and 6 at monitoring site 4.

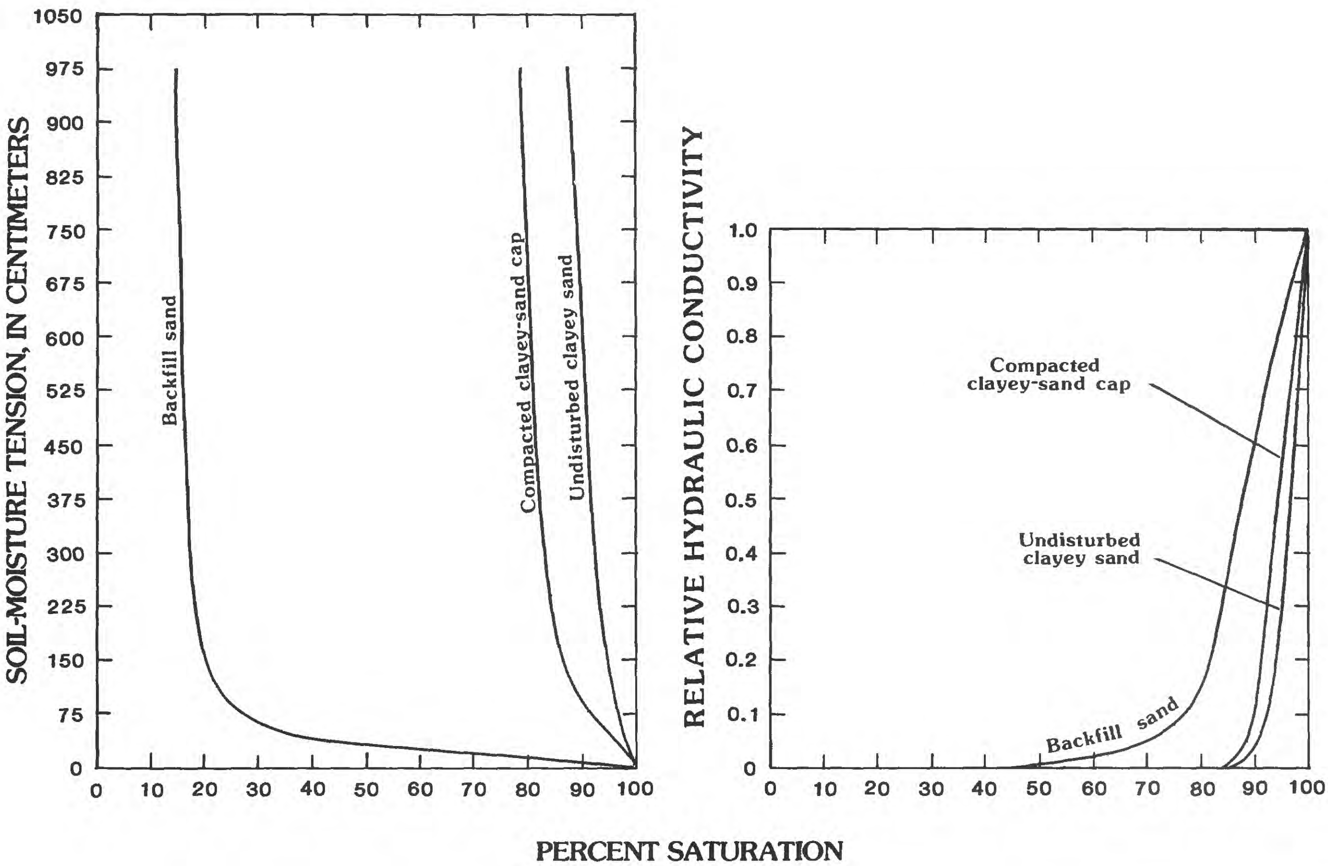


Figure 14. Typical soil-moisture retention and relative hydraulic conductivity curves for backfill sand, undisturbed clayey sand, and compacted clayey-sand cap.

curve. Moisture-characteristic curves for the materials from tensiometers 6 and 10 at site 1 were not available. The moisture-characteristic curve for tensiometer 7 at site 2 was used to determine saturation for these tensiometers because of the similarity in the grain-size distributions of the backfill materials and their proximity to each other.

The data from both tensiometers indicate that materials had their greatest percent saturation in late fall, winter, and early spring. Infiltration during winter and early spring, when precipitation exceeded evapotranspiration, generally drained downward from the unsaturated materials to the saturated sediments without being replaced during summer and early fall, when evapotranspiration exceeded precipitation. This caused the percent saturation of the materials to decrease. During fall and early winter, moisture began to accumulate in the unsaturated materials again. This is indicated in figure 15 by the low tensions in January and February and the steadily increasing tensions from February through September. After September the tensions declined until they reached their low levels again in January.

The greatest saturation observed at tensiometer 6 was approximately 80 percent in January 1983. Materials at tensiometer 10 were about 75 percent saturated in March of the same year. At the end of September the backfill sand at tensiometer 6 was 36 percent saturated and the sand at tensiometer 10 was 43 percent saturated. Throughout the year the near-surface backfill sand had lower percent saturations than the deeper sand. Reliable tension data for the undisturbed clayey sand at monitoring site 1 are not available. However, it is likely that moisture tensions and saturations in the undisturbed clayey sand are similar to those at monitoring site 2, described below.

Monitoring Site 2

Tensiometers 2, 3, 6, and 8 were located in compacted clayey sand and undisturbed sandy clay at depths of 0.67, 1.06, 3.14, and 3.78 m, respectively, below land surface. Soil-moisture tensions measured by these tensiometers are shown in figure 16. Tensiometers 4, 5, and 7 were located in surface sand and backfill sand at depths of 1.37, 1.95, and 3.20 m, respectively, below land surface. Soil-moisture tensions measured by these tensiometers are shown in figure 17. Soil-moisture retention curves from samples obtained at tensiometers 2 through 8 were generated in the laboratory and are presented in

Table 2. Measured values of porosity, residual saturation, lambda, and saturated hydraulic conductivity for samples from monitoring sites 1–4

Location	Sample	Material	Porosity ϕ	Residual saturation S_r	Lambda λ	Saturated hydraulic conductivity K_{sat} $(\frac{cm}{s})$
Monitoring site 1	trench cap	compacted clayey sand	-	-	-	3.5×10^{-6}
	tensiometer 6	backfill sand	-	-	-	3.0×10^{-3}
	tensiometer 10	backfill sand	0.40	-	-	2.7×10^{-3}
	trench bottom	undisturbed clayey sand	-	-	-	1.4×10^{-7}
Monitoring site 2	trench cap	compacted clayey sand	0.31	0.71	0.36	1.9×10^{-6}
	tensiometer 2	compacted clayey sand	0.29	0.66	0.39	-
	tensiometer 3	compacted clayey sand	0.29	0.79	0.18	5.0×10^{-7}
	tensiometer 4	surface sand	0.37	0.010	0.29	3.3×10^{-3}
	tensiometer 5	surface sand	0.36	0.067	0.44	7.0×10^{-3}
	tensiometer 6	undisturbed sandy clay	0.33	0.85	-	6.7×10^{-8}
	tensiometer 7	backfill sand	0.38	0.18	0.44	5.2×10^{-3}
	tensiometer 8	undisturbed sandy clay	0.31	0.84	0.26	4.8×10^{-7}
	trench bottom	undisturbed clayey sand	0.39	0.90	0.44	9.0×10^{-8}
Monitoring site 3	tensiometer 3	undisturbed clayey sand	0.27	0.37	0.63	-
	tensiometer 4	undisturbed clayey sand	0.30	0.67	0.37	-
	tensiometer 6	backfill sand	0.28	0.36	0.66	-
	tensiometer 8	undisturbed clayey sand	0.22	0.55	0.17	-
Monitoring site 4	tensiometer 2	undisturbed clayey sand	0.31	0.71	0.61	-
	tensiometer 4	undisturbed clayey sand	0.29	0.72	0.65	-
	tensiometer 6	undisturbed clayey sand	0.28	0.71	0.68	-

figure 11. Tensiometers located near the trench bottom were rendered inoperative by ponded water which flooded the monitoring site during spring and early summer. In general, few data are available for after August 1983 owing to the lack of access to the monitoring site to service equipment.

Percent saturation generally increased with depth (figs. 16, 17). In the surface sand and backfill sand, tensiometers 4, 5, and 7 were approximately 44, 32, and 69 percent saturated, respectively, in January 1983. Those sands were approximately 29, 27, and 77 percent saturated, respectively, in May 1983. The materials at tensiometers 2, 3, 6, and 8 were 99 percent saturated or greater in January 1983. By the end of May 1983 those materials were approximately 81, 98, 99, and 99 percent saturated, respectively.

Comparison of tensiometer data collected in the undisturbed sandy clay and backfill sand at the same elevation indicates that the undisturbed sandy clay had a higher percent saturation. For example, undisturbed sandy clay at tensiometer 6 was greater than 99 percent saturated in January 1983 while backfill at its counterpart, tensiometer 7, was only 69 percent saturated. Similarly, material at tensiometer 6 was 99 percent saturated in June while material at tensiometer 7 was 55 percent saturated. Even though the undisturbed sandy clay maintained a higher percent saturation than the backfill sand, the flux of water through the backfill sand was greater. This is supported by the fact that more than 2.3 m of water collected in the bottom of monitoring site 2 during the spring and early summer of 1984. This ponding was caused by water moving relatively quickly downward through the backfill sand and then becoming perched by the less permeable undisturbed clayey sand below the trench bottom.

Monitoring Site 3

Tensiometers 3, 4, and 8 were located in the undisturbed clayey sand at depths of 2.83, 3.61, and 7.89 m, respectively, below land surface. Soil-moisture tensions measured by these tensiometers are shown in figure 18. Tensiometer 6 was located in the backfill sand at a depth of 5.71 m below land surface. Soil-moisture tensions measured by this tensiometer are shown in figure 19. Soil-moisture retention curves for tensiometers 3, 4, 6, and 8 are presented in figure 12.

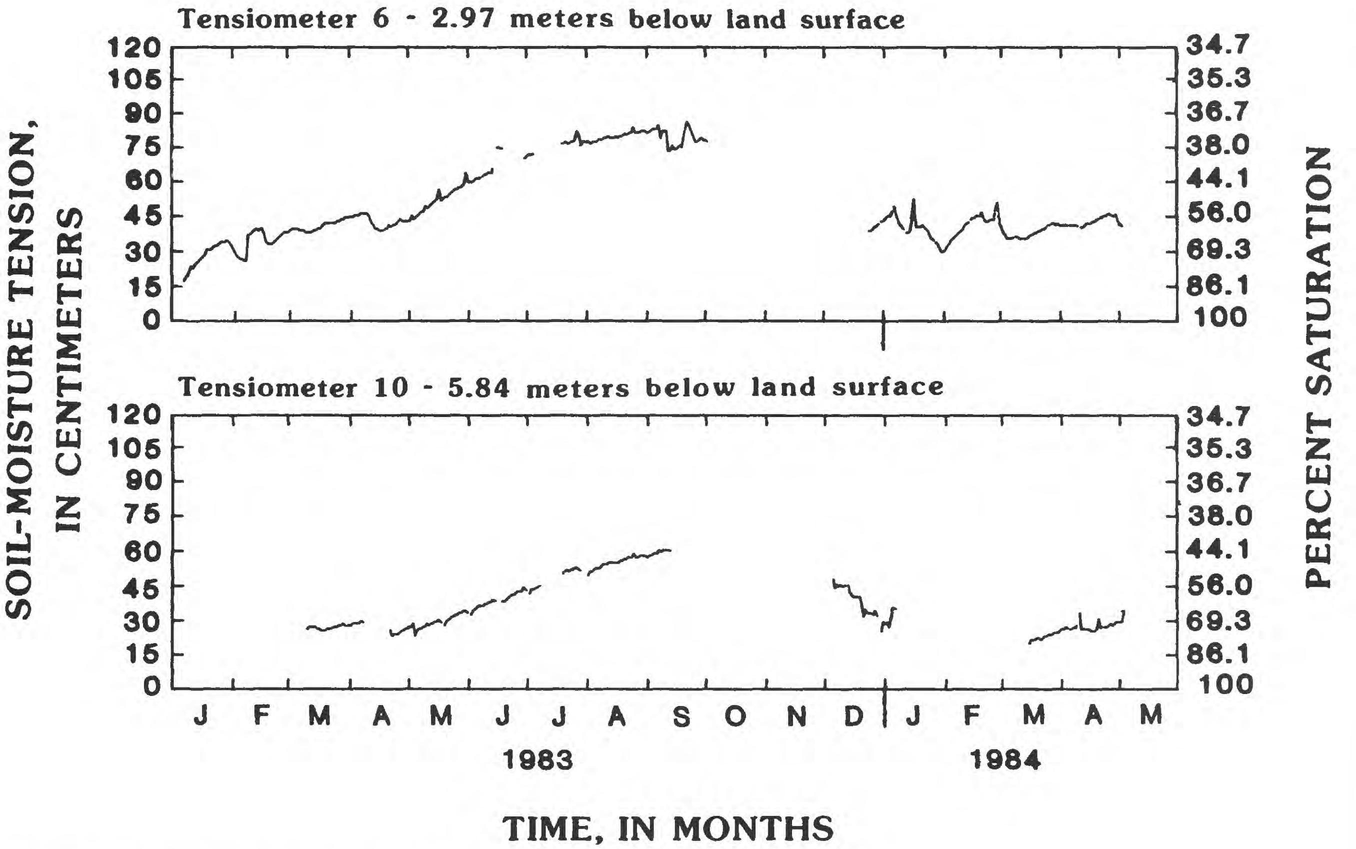


Figure 15. Soil-moisture tensions in backfill sand at monitoring site 1.

As was observed in the unsaturated clayey sand at monitoring sites 1 and 2, saturation of the sediments was high in late winter and early spring. In the undisturbed clayey sand the average percent saturation at tensiometers 3, 4, and 8 was about 97, 95, and greater than 99 percent, respectively, during January through April 1983. Average saturation for tensiometer 6, which was in the backfill sand, was 99 percent for the same period.

The percent saturation of both materials decreased after April. This trend, also seen at monitoring sites 1 and 2, is indicative of that part of the year when the soils drained without being recharged by infiltrating precipitation. The lowest observed value of saturation at tensiometer 4 was about 90 percent at the end of June 1983. Data from tensiometer 4 are incomplete after July 1983 owing to instrumentation problems that were not corrected until September. The deeper materials, at tensiometers 6 and 8, lost very little moisture and remained 94 and 99 percent saturated, respectively.

The undisturbed clayey sand at monitoring site 3 exhibited moisture-retention characteristics similar to those of the same material at monitoring site 2. The clayey sand at both monitoring sites showed an increase in moisture content with depth. In addition, the material at each tensiometer generally remained over 95 percent saturated throughout the period of record. Material at tensiometer 2 at monitoring site 2, at a depth of 0.67 m, did drain to 81 percent saturation in May. There was no tensiometer at a similar depth at monitoring site 3 to verify whether a similar degree of saturation developed in the shallow undisturbed clayey sand at that site.

The moisture-retention characteristics of backfill sand at monitoring site 3 are different from those at monitoring site 2. Although saturation in monitoring site 1 and 2 backfill sand ranged from 36 to 84 and from 36 to 98 percent, respectively, monitoring site 3 backfill sand was 92 to 99 percent saturated. Soil-moisture retention curves for the backfill sands at sites 2 and 3 (figs. 11, 12) illustrate the differences in saturation versus tension. Backfill sand at monitoring site 2 loses water rapidly upon initial pressure application, thereby allowing the material to achieve small saturation percentages. Backfill sand at monitoring site 3 does not lose water rapidly upon initial pressure application. This phenomenon is due to a slight increase in the percentage of clay found in the backfill sand at site 3. Greater tensions are required in monitoring site 3 backfill sand than in monitoring site 2 backfill sand to achieve equivalent saturation percentages.

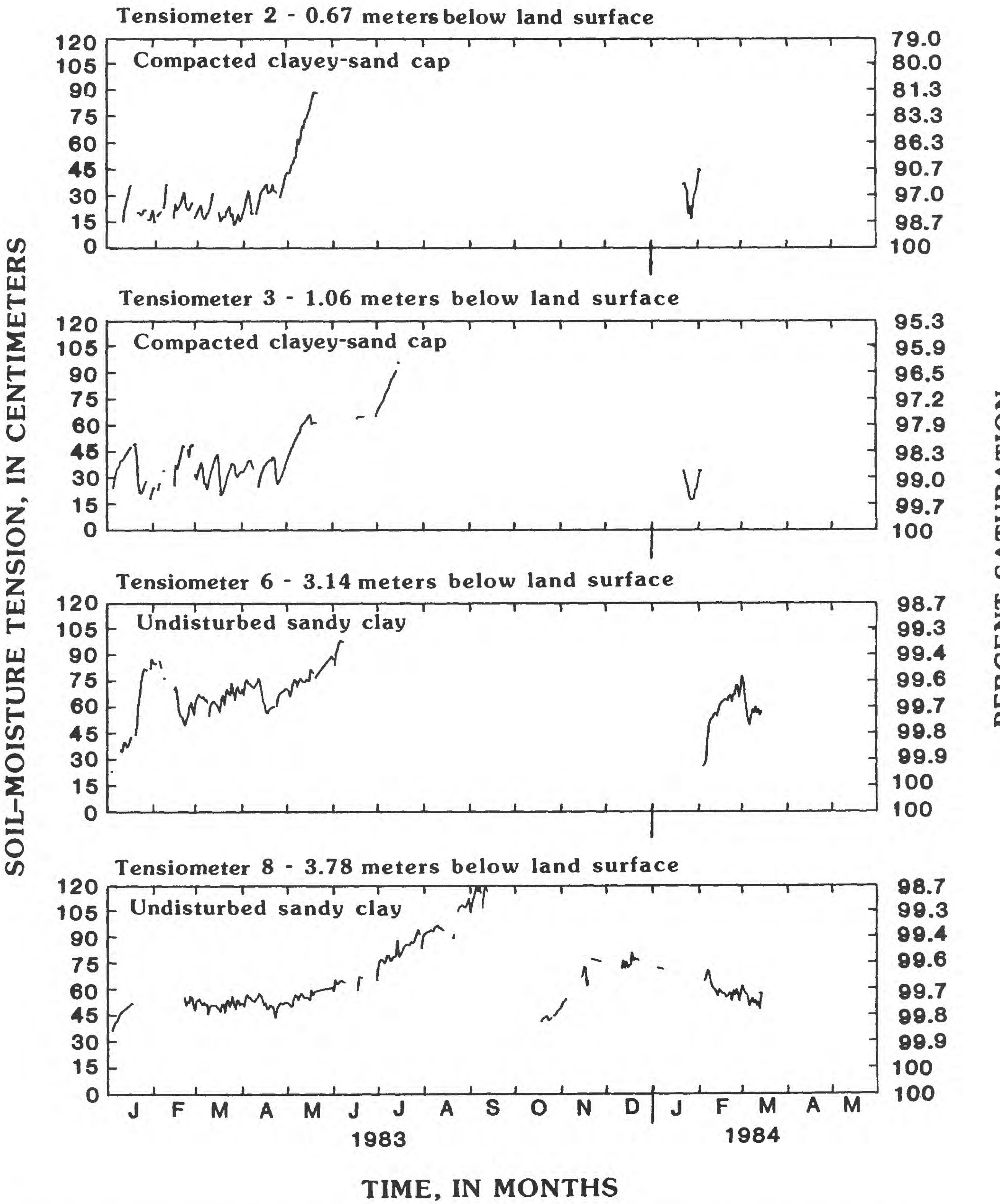


Figure 16. Soil-moisture tensions in compacted clayey-sand cap and undisturbed sandy clay at monitoring site 2.

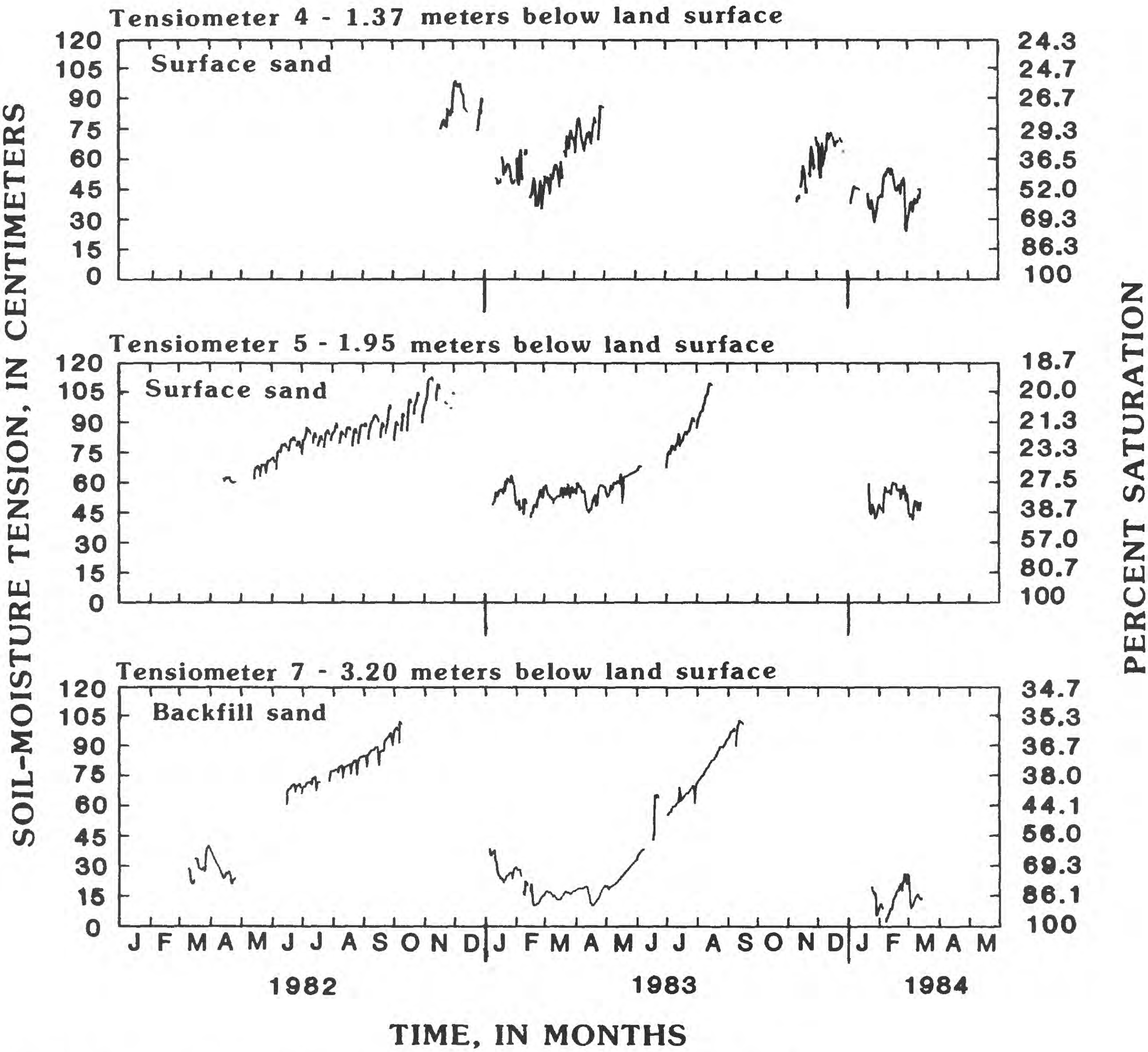


Figure 17. Soil-moisture tensions in surface sand and backfill sand at monitoring site 2.

Monitoring Site 4

Tensiometers 2, 4, and 6 at monitoring site 4 were all located in undisturbed clayey sand. They were 1.95, 2.76, and 5.28 m, respectively, below land surface. Figure 20 shows the soil-moisture tension data for each tensiometer. The soil-moisture retention curves generated for the materials at these tensiometers are presented in figure 13. No reliable data are available for the backfill sand at monitoring site 4.

The variation in the distribution of the percent saturation in undisturbed clayey sand at monitoring site 4 through the year was similar to the variation in undisturbed sediments at the other monitoring sites. The highest saturations occurred in late fall, winter, and early spring. Saturations in the sediments steadily decreased until about the end of September. After September the saturations started increasing until around January through March, when they reached their highest values. Although the tensions in the sediments at the tensiometers fluctuated by 80 cm in some instances, all of the undisturbed sediments remained over 97 percent saturated throughout 1983.

Tracer Tests

One hundred eighty-seven separate soil-moisture conductance probes and temperature sensors were used to monitor sodium chloride tracer movement at the four

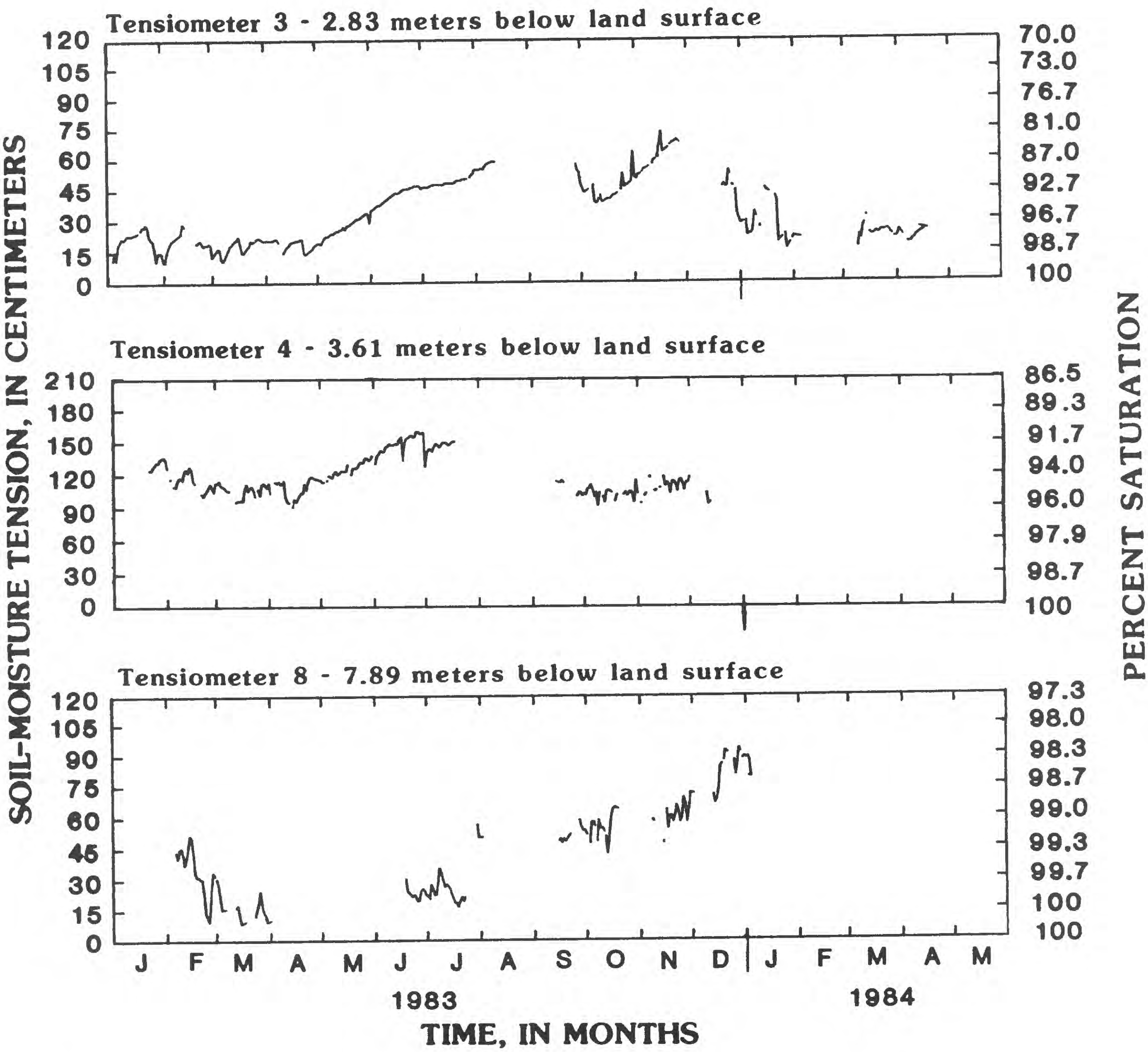


Figure 18. Soil-moisture tensions in undisturbed clayey sand at monitoring site 3.

monitoring sites. Many of the soil-moisture conductance probes failed to function properly during the monitoring phase of the study, thereby limiting the quantity of usable data. Only data from selected probes where the most complete record was collected are presented. The tracer tests were conducted to identify the directions of unsaturated flow in and around the monitoring sites, and to determine relative rates of water movement in the undisturbed clayey sand, compacted clayey sand, and backfill sand.

Two concerns must be addressed in using soil-moisture conductance probes to monitor the movement of sodium chloride in unsaturated clayey sand and sand. First, soil-moisture conductance values referred to in this report reflect changes in soil-moisture content as well as the presence of the sodium chloride tracer. However, the specific conductance of precipitation and shallow ground water at the site is less than 50 μS/cm (microsiemens per centimeter) at 25 °C (Cahill, 1982, p. 71); therefore, soil-moisture conductance readings greater than 50 μS/cm are assumed to have resulted from the presence of the sodium chloride tracer in soil moisture. The second concern is that sodium will react with the clay in the undisturbed and compacted clayey sand, causing a reduction in the hydraulic conductivity of these materials (Drever, 1982, p. 73). Cook (1981) has studied the effect of sodium nitrate solutions at different pH values on the permeability of the clay fraction of

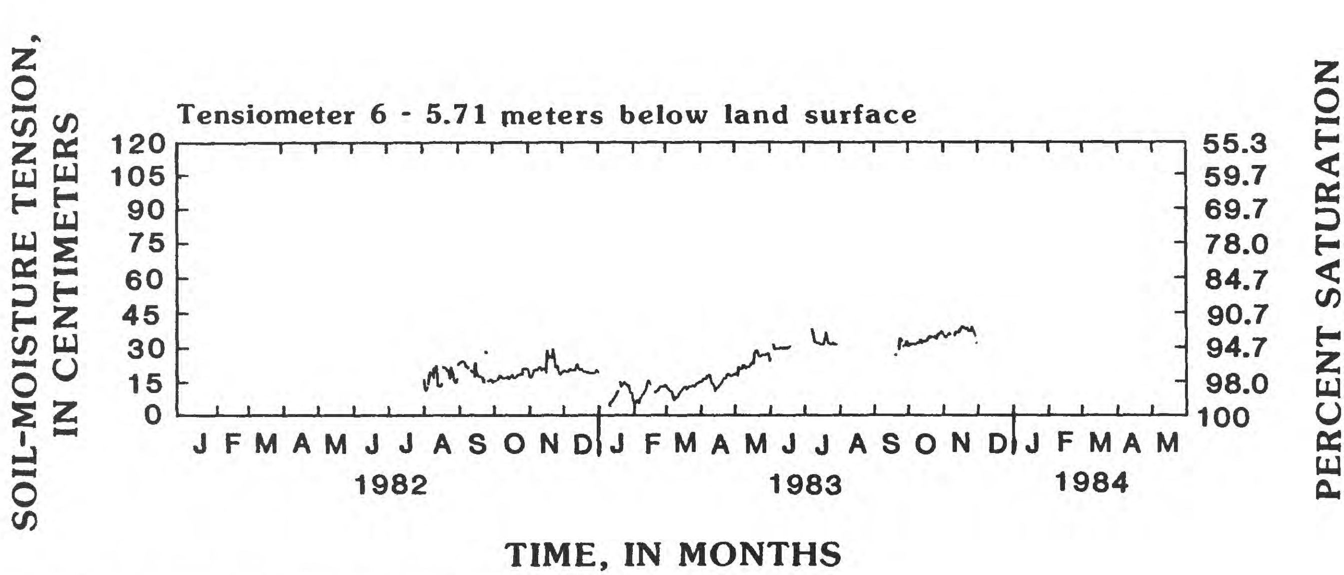


Figure 19. Soil-moisture tensions in backfill sand at monitoring site 3.

similar materials at the Savannah River Plant 10 km away. His results show that at pH values equal to those of the soil moisture at the study area (5.5–6.5), there is no reduction in hydraulic conductivity of the material caused by reactions of sodium with the clay.

With this in mind, results obtained from the tracer test provided insight into water movement in and around the trenches and a determination of the relative rates of water movement in the different materials.

Monitoring Site 1

Changes in soil-moisture conductance of soil water within the materials at experimental trench 1 are shown in figures 21, 22, and 23. These curves represent the conductances of soil water at various depths in compacted clayey sand (trench cap), undisturbed clayey sand, and backfill sand. The water to transport the tracer came from infiltrating precipitation.

Probes 3 and 6 (fig. 21) are located 0.49 and 1.08 m below land surface, respectively, in the trench cap, and probe 3 directly overlies probe 6. The salt buried in the trench cap in May 1983 was distributed in a circular pattern approximately 1 m from the perimeter of the shaft, just above probe 3 at a depth of about 0.45 m. The soil-moisture conductance measured by probe 3 increased sharply about 1 month later, indicating the arrival of the salt tracer. A combination of factors contributed to the sharp increase in soil-moisture conductance during June. Precipitation was above normal for the first 4 months of the year prior to introduction of the tracer on May 20. Thus, the antecedent soil-moisture content of the compacted clayey sand was high. During May, precipitation fell below normal, but for a 3-day period at the beginning of June, 5.6 cm of precipitation fell. This combination of events provided water to infiltrate, dissolve the salt, and percolate to the depth of probe 3 in a month's time. The highest soil-moisture conductances were recorded over a 45-day period from mid-July through August. The soil-moisture conductances then gradually decreased over a period of 6 months owing to decreased infiltration during summer and downward drainage of soil water. Precipitation was below normal the rest of the year, except for 3 months. During those months (September, November, and December), precipitation exceeded evapotranspiration (fig. 10).

These periods of infiltrating soil water are visible as small increases on an otherwise declining soil-moisture conductance curve (fig. 21). Probe 6, 0.59 m below probe 3, registered the presence of the tracer at the end of December 1983 (fig. 21). As at probe 3, the arrival of the tracer was indicated by a sharp increase in soil-moisture conductance; this was followed by a gradual decrease over time. From the differences between tracer arrival times (fig. 21), the velocity at which the tracer moved between these two probes at this time can be calculated. It took approximately 200 days for the tracer to move a distance of 0.59 m. Therefore, the tracer moved between these probes in the cap at a rate of 3×10^{-6} cm/s (centimeter per second).

Data from probes 19 and 20, located in backfill sand 5.22 and 6.33 m below land surface, respectively, show an offset, with respect to time, of the tracer front as it moved downward through the backfill (fig. 22). These probes have approximately the same orientation. Because the same tracer was applied in 1981 as in 1983, it cannot be said with certainty which salt application this tracer is from. However, based on tensiometer data, water-table well data, meteorologic data, and the fact

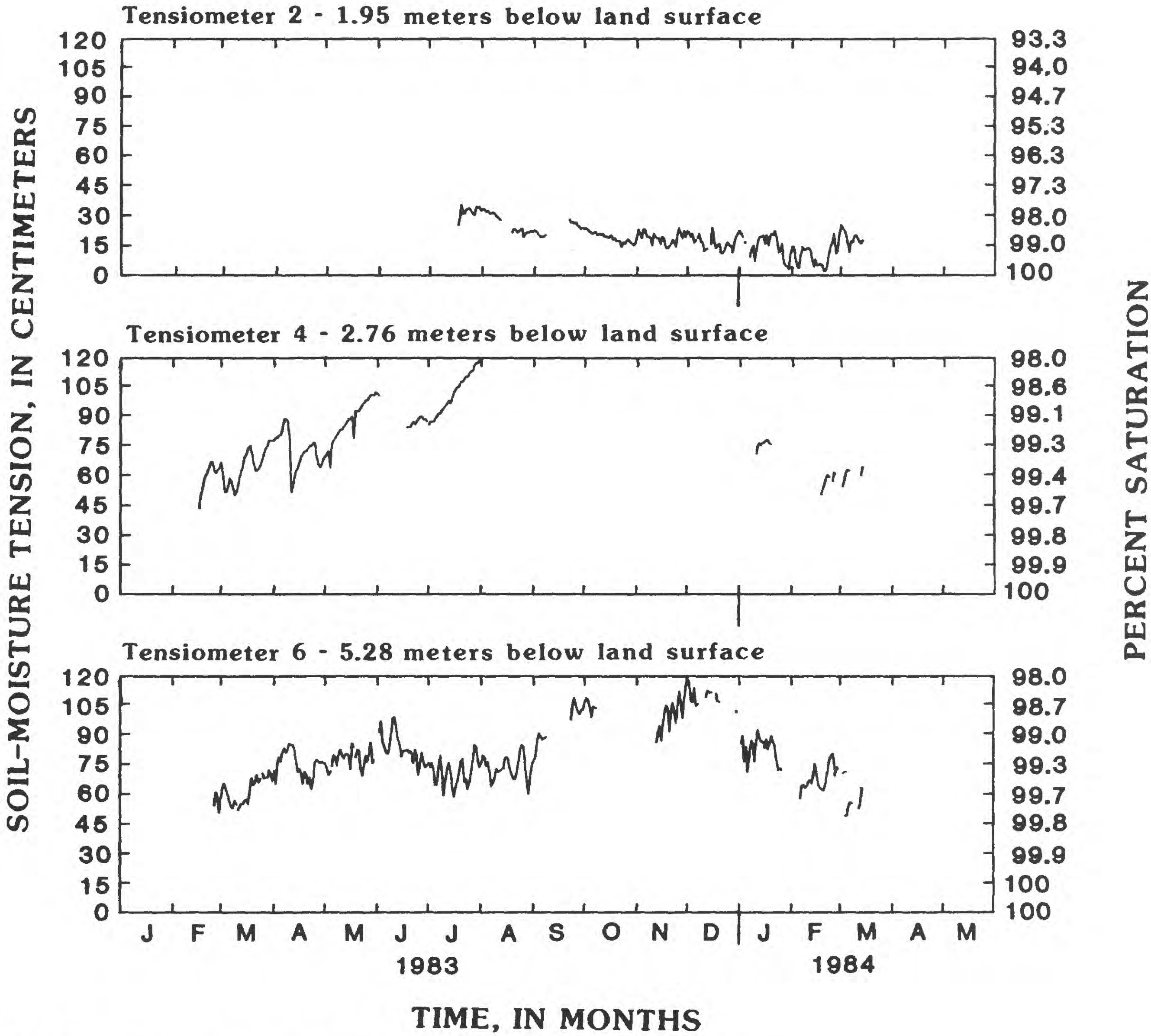


Figure 20. Soil-moisture tensions in undisturbed clayey sand at monitoring site 4.

that water ponded on the bottom of trench 1 in 1984, it is possible that this tracer moved from land surface to these probes during the recharge period in late winter and early spring of 1984.

The tracer was first detected at probe 19 about March 1, 1984, and at probe 20 on about March 20, 1984. Based on these data, the tracer moved between these two probes in sand at a rate of 6×10^{-5} cm/s. The tracer rate calculated here is considerably slower than the material's saturated hydraulic conductivity. Two reasons for this are that the rate is for unsaturated conditions where K_{unsat} is less than K_{sat} and the gradients in the backfill sand probably were relatively small.

It must be emphasized that the rates of tracer movement calculated above apply only between these probes for the period of time indicated. For example, the tracer rate of 3×10^{-6} cm/s in the trench cap applies only between probes 3 and 6 during June through December 1983. The rates of water movement at different locations and different times of year are contingent on various factors—the percent saturation of the materials, the duration and magnitude of evapotranspiration and precipitation, the depth of material below land surface, material type, and the degree of homogeneity of the material. For example, the duration of the soil-moisture conductance peak observed at probe 6 is shorter than that observed at probe 3. This would indicate more rapid movement of the tracer past the lower probe (probe 6). Therefore, the tracer rate calculated between probes 3 and 6 is not a constant rate through that material, but rather an average rate. Using tracer rates calculated between specific probes to deter-

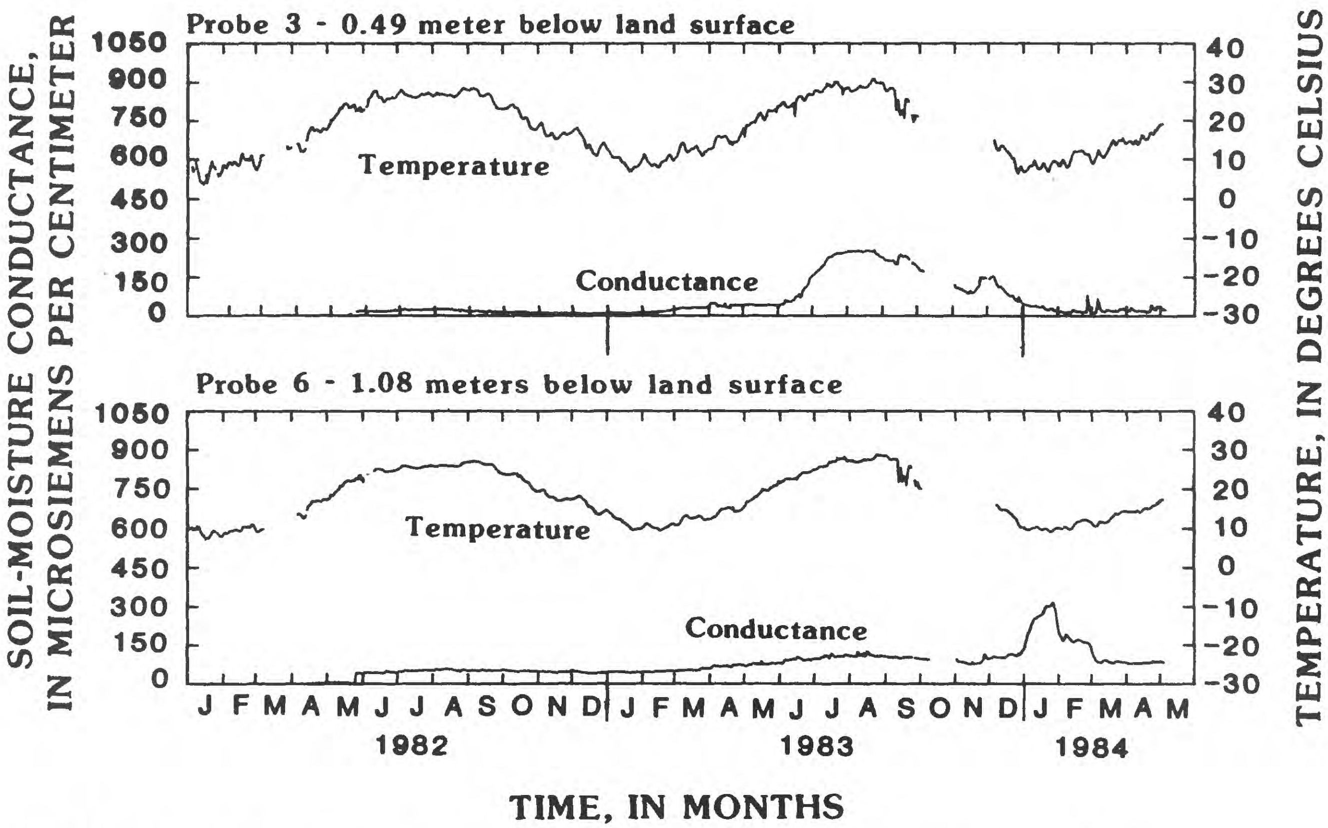


Figure 21. Soil-moisture conductances and temperatures in compacted clayey-sand cap at monitoring site 1.

mine the rate of tracer movement elsewhere would not be justified.

Data presented so far indicate tracer movement in the cap and backfill. The soil-moisture conductance probes located in undisturbed clayey sand (fig. 23) show no indication of tracer arrival from either the 1981 or 1983 salt application, except at probe 7, located about 0.1 m below the compacted clayey-sand barrier/undisturbed clayey sand contact. The leading edge of the tracer front is not as sharp as the edges in the cap and the backfill (figs. 21, 22), suggesting that the tracer was dispersed. Probe 10, located at a slightly greater depth (2.70 m below land surface), and probes 13 and 21, located 3.59 and 6.40 m below land surface, respectively, all show no indication of the tracer. Probe 20 (fig. 22) is located at approximately the same depth as probe 21, but in backfill sand. Data for these probes show that the salt tracer moved from the trench cap, downward through the backfill sand, to at least probe 20, located 6.33 m below land surface, but never reached the same depth in the undisturbed clayey sand. In the "Modeling Results" section, the direction of tracer movement through the undisturbed clayey sand is explained in detail. It appears that the tracer moved preferentially through the backfill sand rather than through the undisturbed clayey sand.

Monitoring Site 2

Experimental trench 2 was constructed in the same manner as trench 1 except the surface sand around trench 2 was left intact. The trench was instrumented with soil-moisture conductance probes and thermocouples in order to define moisture movement both inside and outside the trench. Of the 21 soil-moisture conductance probes installed at monitoring site 2, 14 were located in the upper half of the trench and 7 were positioned in the lower half. Six of the probes in the upper half of the trench were installed in the trench cap, and the remaining eight were distributed equally between backfill sand and undisturbed clayey sand. Many of these probes failed during the monitoring period. In fact, none of the four probes situated in the backfill sand in the upper half of the trench recorded usable data. The seven probes in the bottom half of the trench did record usable data.

Figure 24 illustrates soil-moisture conductance and temperature data for probes 12 and 19, located 4.34 and 6.47 m below land surface, respectively, in undisturbed clayey sand. Probe 12 is one of four probes representing the upper half of the trench, and probe 19 is one of five probes representing the lower half of the trench. The probes installed in the undisturbed clayey

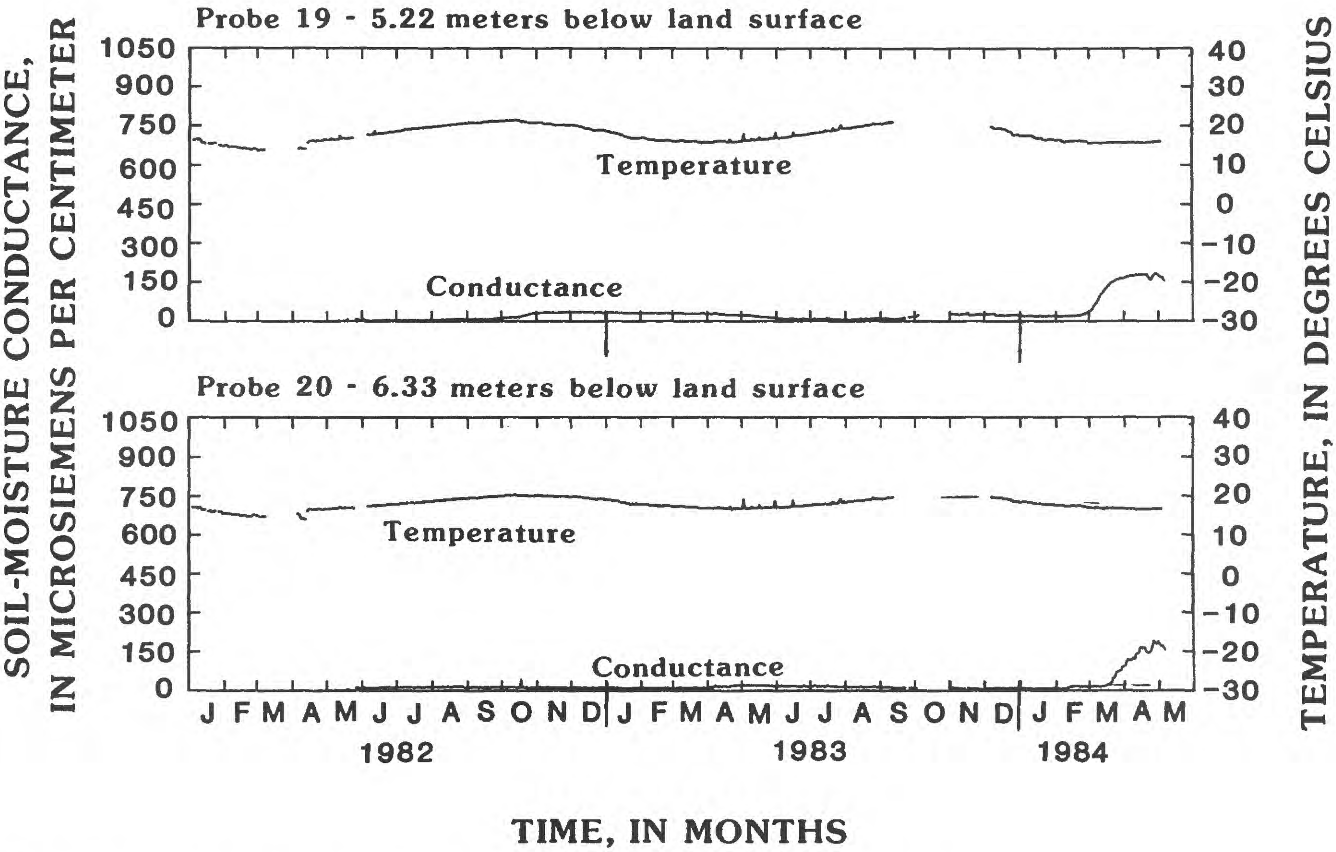


Figure 22. Soil-moisture conductances and temperatures in backfill sand at monitoring site 1.

sand showed no sign of the tracer, except probe 19, which showed a rise in soil-moisture conductance during April and May 1983 (fig. 24).

Figure 24 also shows data for probe 21, located 6.76 m below land surface in backfill sand. The tracer arrived at probe 21 in March 1983. This probe detected the tracer 1 month before probe 19 in undisturbed clayey sand, which was shallower than probe 21. An obvious question arises as to why the tracer was detected first by probe 21 and later by 19.

Probe 19 was situated 0.65 m above the trench bottom, and probe 21 was 0.36 m above the bottom. Figure 25 shows the water levels measured in monitoring sites 1 and 2 and at a nearby water-table well during 1984. Although water levels in monitoring site 2 were not recorded in 1983, observations indicate that they were similar to those measured in 1984. In March 1984 the water in monitoring site 2 was almost 0.27 m deep, while at the end of April 1984 the water was approximately 1 m deep. The soil-moisture conductance kick observed at probe 19 was probably due to salt-enriched water, which was ponding on the trench bottom and moving laterally into the undisturbed clayey sand. This interpretation is supported by the data from probe 12 (fig. 24). Probe 12 is 2.13 m above probe 19 in the undisturbed clayey sand and is similarly oriented. Soil-moisture conductance readings from probe 12 and other probes in undisturbed clayey sand above probe 19 showed no evidence of the tracer. The deep probes at monitoring site 1 did not detect any tracer either.

The salt in the water that ponded on the bottom of trench 2 could have been left over from the 1981 application at land surface or from the salt placed on the trench bottom. Regardless of the source, the data from the probes in the undisturbed clayey sand and the relative times of tracer arrival at probes 19 and 21 all indicate that the response of probe 19 was due to ponded water in the trench moving laterally into the undisturbed sediments.

Monitoring Site 3

Monitoring site 3 was located in a radioactive-waste burial trench approximately 355 m northwest of monitoring sites 1 and 2 (fig. 2). The waste-burial trench in which the monitoring site was located has only recently been completed (winter 1984). This final work

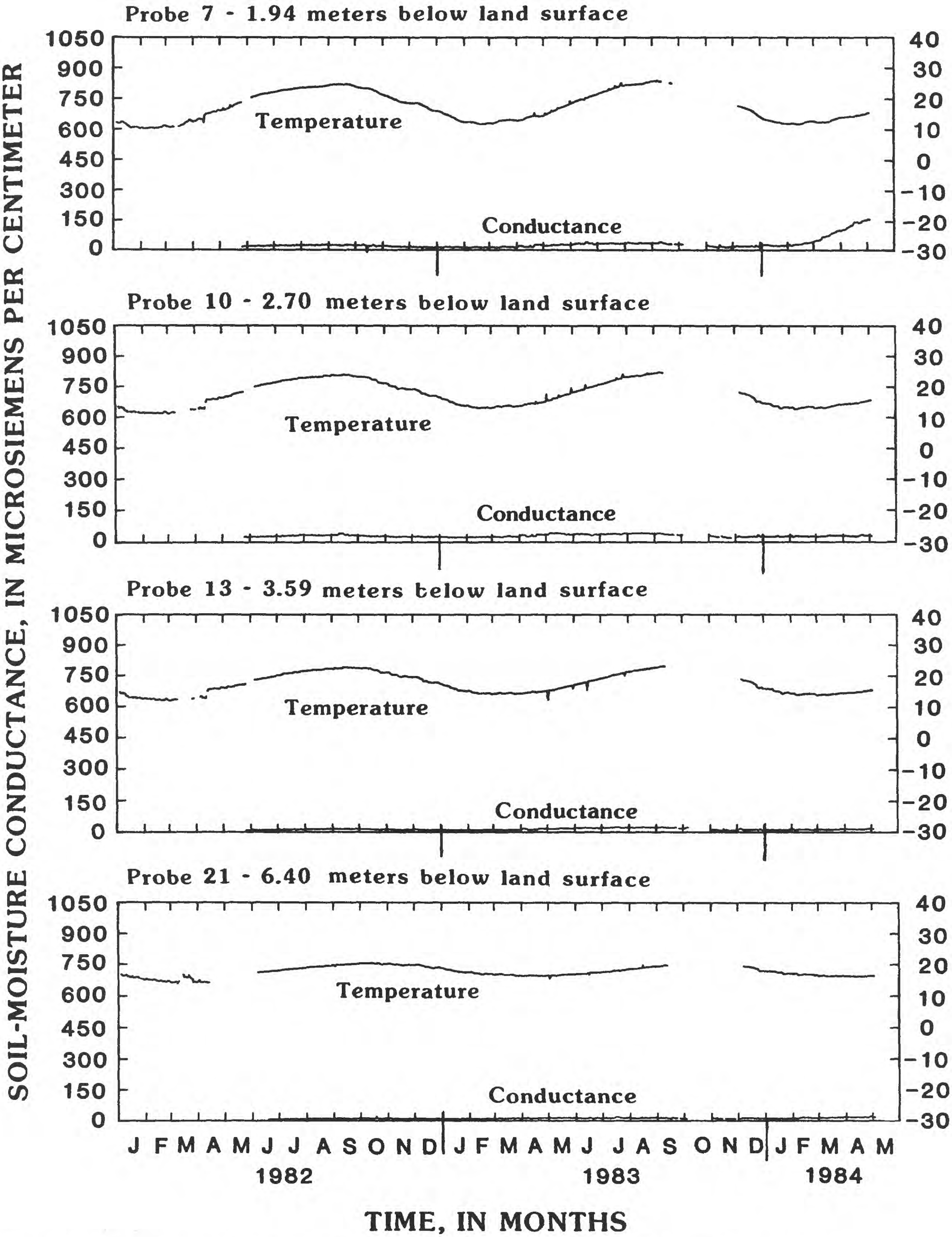


Figure 23. Soil-moisture conductances and temperatures in undisturbed clayey sand at monitoring site 1.

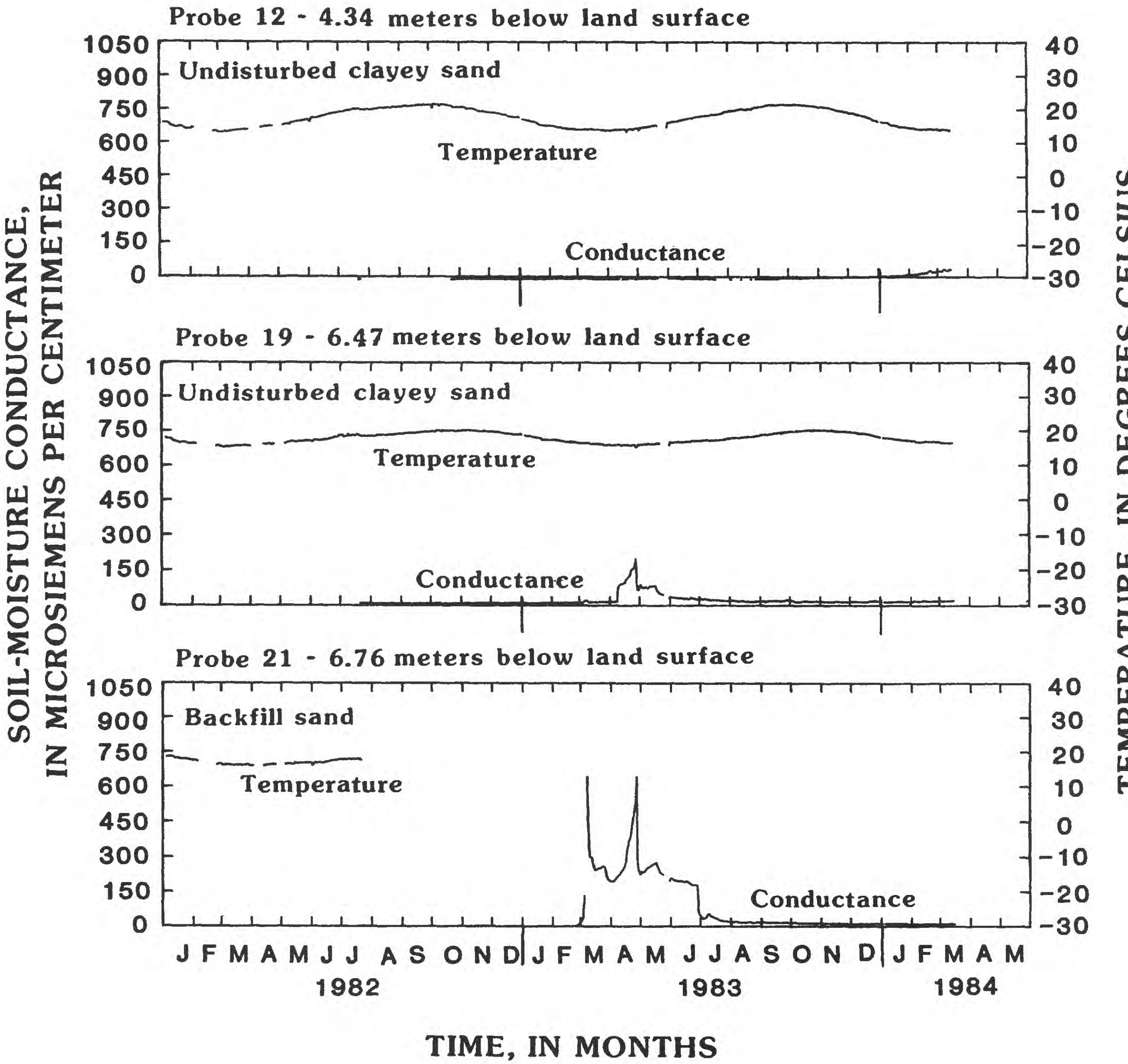


Figure 24. Soil-moisture conductances and temperatures in undisturbed clayey sand and backfill sand at monitoring site 2.

consisted of contouring the trench cap for drainage by sloping the adjacent ground away from the structure and establishing a uniform gradient in the longitudinal direction. Additionally, a sand layer was deposited over the cap, on which a grass cover was cultivated.

Twenty-one soil-moisture conductance probes were installed at site 3. Many of the probes below the trench cap provided little or no data owing to both insufficient maintenance and probe failure. Because of this it was decided not to use these data in the analysis of moisture movement. However, soil-moisture conductance and temperature probes located in the compacted clayey-sand barrier provided useful data. Figure 26 displays soil-moisture conductance values from probes 2 and 6, located 0.83 and 1.72 m below land surface, respectively.

Probe 2 is nearer present land surface and first indicates tracer movement at the beginning of October 1983. The main front did not pass the probe until sometime between November and December of the same year. The curve shape is similar (sharp rise and gradual decline) to that for the compacted clayey-sand cap at monitoring site 1. Probe 6 is 0.89 m deeper than probe 2. The first sign of tracer movement appeared on December 3, 1983 (fig. 26). There is no sign of an initial increase in soil-moisture conductance, as there was in probe 2. The tracer in the compacted clayey-sand barrier

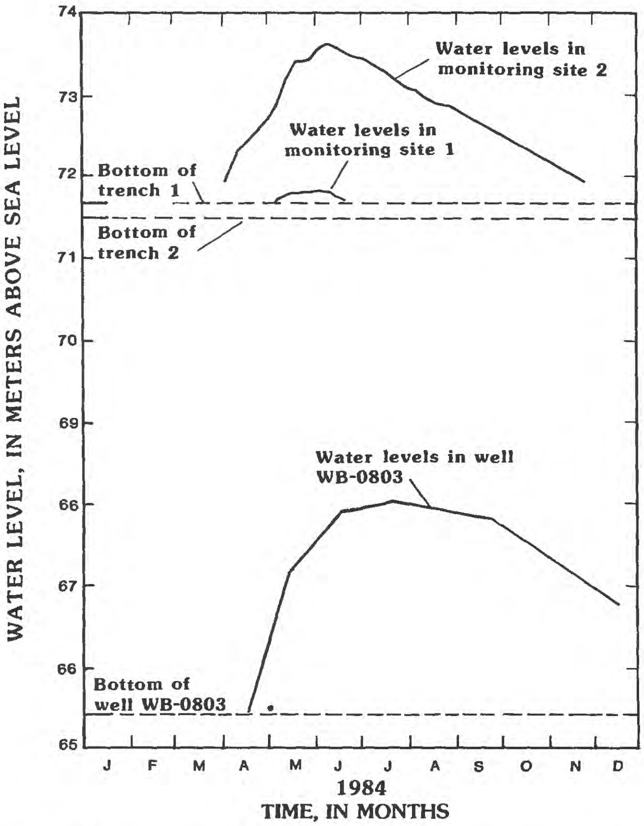


Figure 25. Water levels at monitoring sites 1 and 2, and at water-table well WB-0803.

had to be from the surface application in May 1983 because the first application of the tracer (November 1981) was on top of the backfill sand prior to installation of the trench cap.

Based on the offset between probes 2 and 6 (fig. 26) in 1983, the velocity of the tracer was 2×10^{-5} cm/s. The composition of the compacted clayey-sand barrier is identical to that of the compacted clayey-sand cap; therefore, velocities calculated in each can be compared. The velocity of tracer movement through the trench cap material at monitoring site 1 was 3×10^{-6} cm/s. Note that the velocity calculated in the trench cap material at monitoring site 1 took place within approximately 1 m of land surface, while the velocity at monitoring site 3 was calculated over a deeper section of compacted clayey sand. At this slightly greater depth, perhaps evapotranspiration effects were not as influential on the fate of available soil moisture, thus resulting in a faster velocity in the deeper part of the compacted clayey sand barrier. Evidently, an assumption of constant velocity near land surface is not valid.

The tracer movement at probes 2 and 6 coincided with the period of the year (late fall to early spring) when the soil-moisture content of the materials was at its highest.

Ponded water was not observed at the bottom of monitoring site 3. The waste trench at site 3 is in an area completely covered with compacted clayey sand (cap). The surface sand between trenches has been removed. This factor probably prevented much of the precipitation from reaching the trench bottoms.

Monitoring Site 4

Reliable soil-moisture conductance data were never collected from monitoring site 4 because all the soil-moisture conductance probes failed to function properly during the monitoring phase of this study. Therefore, soil-moisture conductance data for the period of record at this site is not discussed.

Concentrations of Tritium at Monitoring Sites 1 and 2

There are two reasons for determining the concentrations of tritium in soil samples: to provide background data on tritium levels with depth and to provide insight into soil-moisture movement through the different materials.

Table 3 lists the concentrations of tritium found in soil moisture from materials collected at monitoring sites 1 and 2. Figures 27 and 28 are plots of concentrations of tritium with depth at the two sites. The sources of the samples and the analyzing laboratories are indicated. Trenches 1 and 2 contain no radioactive material, so it is presumed that any tritium detected in the unsaturated materials at these sites came from infiltrating precipitation. Samples were not taken at monitoring sites 3 or 4, which are located in radioactive-waste burial trenches, because the site operator would not grant permission for soil sampling at either site.

The general trend for undisturbed clayey-sand, sandy-clay, and backfill-sand samples is toward increasing concentrations of tritium with depth (figs. 27, 28). As stated previously, no likely source of tritium below land surface exists at these sites. Therefore, the concentration in the source (i.e., precipitation) could not have been constant. If it were, tritium would decrease in concentration with increasing depth owing to radioactive decay. Based on the distribution of tritium at monitoring sites 1 and 2, the concentrations of tritium in the unsaturated materials sampled at depths greater than 5.54 m ranged from 2,700 to 6,390 pCi/L (picocuries per liter). The concentrations of tritium in the unsaturated materials at depths less than 5.54 m ranged from 1,410 to 5,510 pCi/L. The concentrations of tritium in precipitation collected from a nearby meteorologic station ranged from 500 to 6,700 pCi/L in 1982–83 (South Carolina Department of Health and Environmental Control, 1984). In contrast, Cahill (1982) reported concentrations of tritium in radioactive waste trench water greater than 1×10^{7} pCi/L. For comparison purposes, the maximum permissible concentration of tritium in drinking water, based on U.S. Environmental

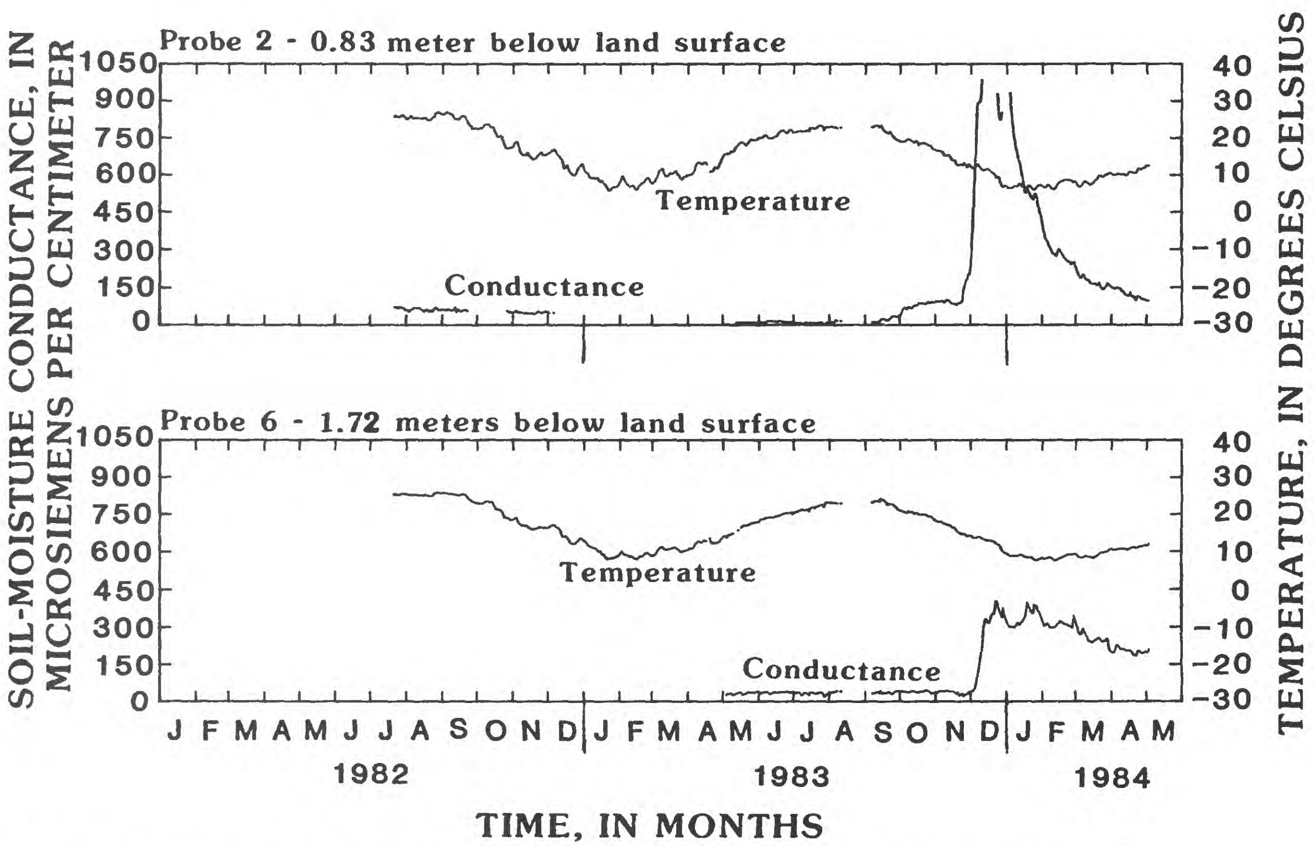


Figure 26. Soil-moisture conductances and temperatures in compacted clayey-sand barrier at monitoring site 3.

Protection Agency (EPA) standards, is 20,000 pCi/L (EPA, National Interim Primary Drinking Water Regulations, 1976, p. 154). One reason for the fluctuation in atmospheric tritium could be occasional releases of tritium from the Savannah River Plant.

Generally, at both monitoring sites the concentrations of tritium in clayey sand and backfill sand within 2 m of land surface are closely grouped. With depth, the concentrations of tritium measured in the clayey sand and backfill sand begin to separate. The moisture in the shallow materials at both sites contained similar concentrations of tritium, probably because the moisture was from precipitation events that occurred at about the same time. However, owing to different rates of water movement in the two materials, the moisture in the deeper clayey sand was probably from different precipitation events than the moisture in the backfill sand at the same depth. Therefore, since the concentration of tritium in precipitation was not constant, the deep backfill sand had different concentrations of tritium than the deep undisturbed clayey sand.

If the concentration of tritium for a given precipitation event were known, the movement of this water through the unsaturated zone might be monitored by using the tritium as a tracer. However, the lack of data on the timing and concentration of tritium in precipitation precludes this effort.

Site-Specific Hydrologic Budget and Trench Leakage Rates

The hydrologic budget presented here is for the part of the radioactive-waste burial site where undisturbed surface sand is present, that is, the southeastern half of the site where burial trenches do not exist (fig. 2). It is necessary to clarify this because the characteristics of the surface layer change drastically over the site, thus substantially affecting the runoff component used in calculating recharge.

The hydrologic budget is given by the equation

$$R = P - ET - RO \pm dS/dt \qquad (7)$$

where

R = recharge to the saturated zone;
P = precipitation;
ET = evapotranspiration;
RO = runoff; and
dS/dt = storage changes in the unsaturated zone.

From July 1983 through June 1984, total measured precipitation was 144 cm and evapotranspiration calculated by the energy budget/Bowen ratio method was 101 cm (fig. 10). Zero runoff was assumed to have occurred during this period. The net change of storage in the unsaturated zone was negligible. Mass-balance estimates using equation 7 indicate a residual of 43 cm

Table 3. Concentrations of tritium in soil moisture from materials collected at monitoring sites 1 and 2

Monitoring Site 1

Sample depth in meters below land surface	Collection date	Concentrations of tritium in picocuries per liter	Material
0.08	11/16/84	[1]2,180±47/[2]2,790±100	Compacted clayey-sand cap
0.66	11/16/84	2,680±52/ -	Compacted clayey-sand cap
0.62	11/16/84	2,110±45/2,090±80	Undisturbed clayey sand
0.62	11/16/84	- /2,050±80	Undisturbed clayey sand
0.58	11/16/84	2,130±46/1,520±60	Backfill sand
0.93	11/16/84	2,000±45/2,390±30	Undisturbed clayey sand
1.35	11/16/84	1,980±45/1,970±70	Undisturbed clayey sand
3.12	11/16/84	1,410±38/ -	Undisturbed clayey sand
2.97	11/16/84	2,630±51/2,270±80	Backfill sand
4.14	11/16/84	1,830±43/1,610±30	Undisturbed sandy clay
5.83	11/16/84	2,700±52/2,780±90	Undisturbed sandy clay
5.83	11/16/84	4,650±60/6,390±160	Backfill sand
7.08	11/16/84	5,090±71/5,540±150	Undisturbed clayey sand

Monitoring Site 2

Sample depth in meters below land surface	Collection date	Concentrations of tritium in picocuries per liter	Material
0.59	11/16/84	[2]3,440±110	Backfill sand
0.59	11/14/84	4,740±160	Backfill sand
0.67	11/16/84	2,370±80	Undisturbed clayey sand
0.67	11/14/84	2,420±80	Undisturbed clayey sand
1.06	11/16/84	2,320±80	Undisturbed clayey sand
1.37	11/16/84	2,560±90	Backfill sand
1.37	11/15/84	3,490±110	Backfill sand
1.95	11/16/84	3,010±100	Backfill sand
1.95	11/15/84	2,580±90	Backfill sand
3.14	11/16/84	3,120±100	Undisturbed sandy clay
3.14	11/16/84	2,740±90	Undisturbed sandy clay
3.20	11/16/84	3,080±100	Backfill sand
3.78	11/16/84	4,720±140	Undisturbed sandy clay
3.78	11/16/84	5,510±150	Undisturbed sandy clay
5.54	11/30/84	6,290±160	Undisturbed clayey sand
5.97	11/30/84	4,430±130	Backfill sand
7.45	11/30/84	4,580±130	Undisturbed clayey sand
	11/29/84	4,570±130	Trench water

1. Analysis performed by South Carolina Department of Health and Environmental Control.
2. Analysis performed by Chem-Nuclear Systems, Inc.

of recharge water to the saturated zone between July 1983 and June 1984.

Winter (1981) evaluates the hydrologic methodology used in a number of water budget studies and makes the point that by not evaluating or mentioning measurement errors, a water budget estimated by imprecise methods looks as good as one determined by using the best available theory, instruments, and analysis techniques. Therefore, the measurement errors associated with calculation of the water budget are discussed in the following paragraphs.

Factors that contribute to errors in the weighing bucket rain gage used to measure precipitation include inadequate calibration of the instrument, height of the gage orifice above the ground, and improper servicing. Manufacturer specifications claim a recording accuracy of ±0.25 cm and a range of 0 to 49.5 cm. In this study, recorded values were checked at randomly chosen times with calibrated weights to verify the accuracy of the measurements. Neff (1977) compared rain gage catch for daily and single rainfall events and found that for all rainfall events, gages having orifices 1 m above the ground (as ours was) caught 5 to 15 percent less rain than those having orifices at ground level. Nevertheless, errors in estimates on an annual basis are generally 5 percent or less (Winter, 1981).

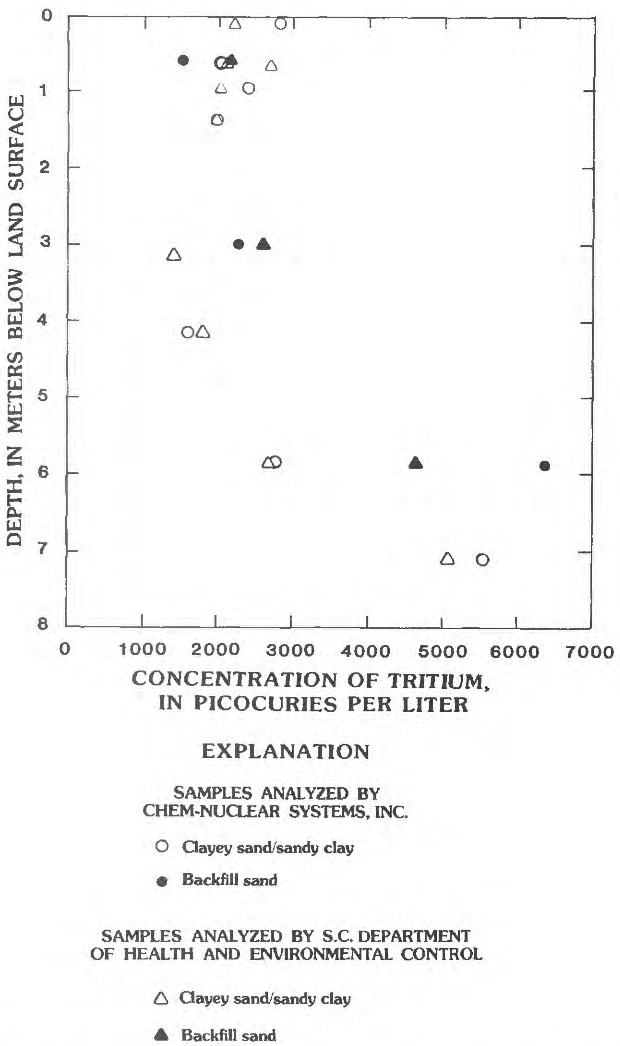


Figure 27. Concentrations of tritium in soil moisture from clayey sand/sandy clay and backfill sand at monitoring site 1.

The validity of the energy balance/Bowen ratio method is dependent on the accuracy with which each variable used in the method can be measured. The accuracy of the equipment, the competence of those servicing and calibrating it, and the completeness of the record all have a bearing on the errors associated with estimating evapotranspiration. The sensitivity of the Bowen ratio method to instrument measurement errors was analyzed in order to estimate the accuracy of the evapotranspiration results. Based on this sensitivity analysis, the evapotranspiration results are probably accurate to within 12 percent of the recorded values (Dennehy and McMahon, 1987).

The errors associated with assuming zero runoff are difficult to quantify. The hydrologic budget is determined for a specific area, where surface sand is present. In this area, no overland runoff was observed. In fact, on an hourly basis, a rainfall rate of 22.6 cm/h (centimeters per hour) would be required to exceed the average saturated hydraulic conductivity of the surface sand in order to produce surface runoff (Freeze and Cherry, 1979, p. 212). A rainfall intensity equaling or exceeding this magnitude was not recorded during the data collection period.

The errors associated with determining the change in storage in the unsaturated zone also depends on instrument error and proper instrument servicing. A detailed discussion of the errors involved in measuring soil tensions with a tensiometer is presented in Dennehy and McMahon (1985). The transducers recording the tensions have an accuracy of ±0.5 percent for repeatability of measurements. The cyclic nature of soil tensions shown by tensiometer data indicate that over the period of a year the net change in water content of the materials (i.e., changes in water storage in the unsaturated zone) was negligible (figs. 15, 18).

Lastly, if one assumes that errors for all the components of the hydrologic budget discussed are random, the greater the number of measurements considered, the more the errors will compensate; thus, long-term averages generally have smaller errors of

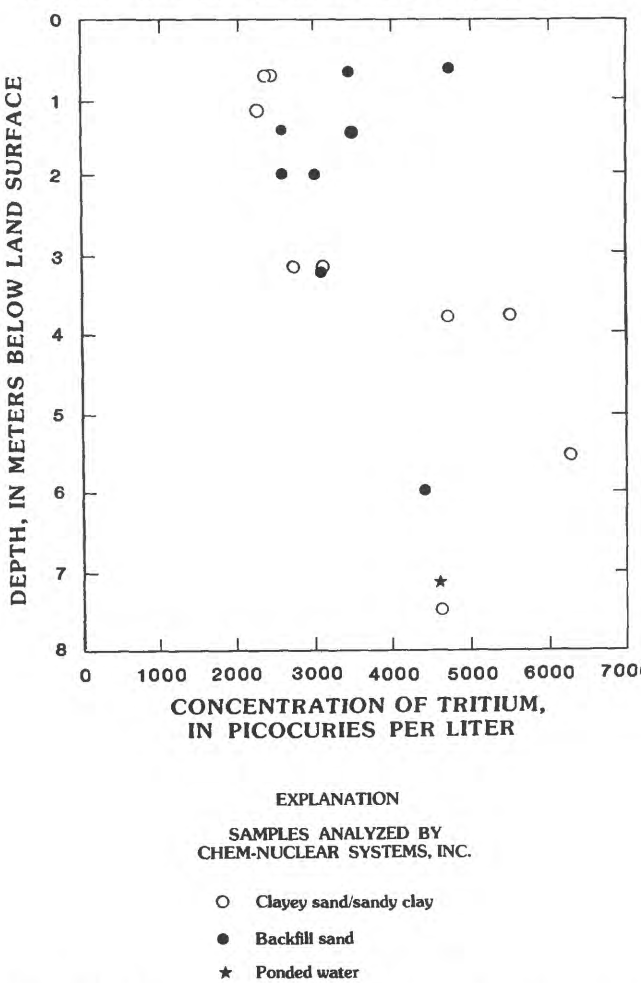


Figure 28. Concentrations of tritium in soil moisture from clayey sand/sandy clay and backfill sand at monitoring site 2.

estimation than short-term averages. Based on the preceding discussion, if one sums the error associated with each component of equation 7, the error in the calculation of annual recharge is ±17 percent. This does not include unknown errors in assuming zero overland runoff.

The water budget developed above assumes the presence of surface sand and the absence of runoff over that surface sand. However, over the site area, various conditions exist that produced quantities of recharge different from the 43 cm determined above. For example, figure 25 shows hydrographs of water levels measured in 1984 inside monitoring sites 1 and 2 and at nearby water-table well WB–0803 (fig. 2). The hydrographs show that the water in the trenches is perched above the water table and is not due to a rising water table. At experimental trench 2 (designed without the clayey-sand barrier), 2.3 m of water ponded on the trench bottom during the period for which the water budget was developed. Only 0.3 m of water ponded on the bottom of experimental trench 1 (designed with the clayey-sand barrier). It is assumed that all of the ponded water recharged the saturated zone. With these trenches only 3.4 m apart, the disparity in the quantity of water in the trench clearly represents a substantial difference in fluxes of water through trenches 1 and 2. The clayey-sand barrier is the only design variation between the two trenches. Therefore, trench design has a significant effect on the flux of water through the trench.

In areas of the burial site where a thin layer of surface sand overlies the trench cap and, to a greater extent, where the surface sand has been removed to expose the underlying undisturbed clayey sand, lateral flow and overland runoff can be significant. It is postulated that precipitation in these areas moves relatively rapidly through the vegetation cover (sand material) placed on top of the cap to the sand/trench-cap interface. Here some water percolates downward. However, most of the water probably moves along the interface and accumulates in low-lying areas, as is evident on the western edge of the site. Where clayey sand is present at land surface, overland runoff occurs, with the flow accumulating in the same low-lying areas. In this case recharge was probably less than 43 cm.

An opportunity existed at monitoring sites 1 and 2 to measure the combined vertical and horizontal leakage rate of water from the trench into the surrounding undisturbed clayey sand. Leakage rates were calculated by determining the slope of the falling limb for the monitoring site 1 and 2 hydrographs (fig. 25). The well-defined limb for site 2 gives a rate of 1×10^{-5} cm/s, and the few points available on the falling limb for site 1 give a rate of 2×10^{-5} cm/s. Note that these leakage rates are the combined rates of water moving into the undisturbed clayey sand beneath the trench as well as into the sides of the trench. These calculated leakage rates are discussed further in the "Modeling Results" section.

MODEL SIMULATIONS

Modeling Approach

Water movement in and around the experimental trenches was examined using a cross-sectional finite-element model of variably saturated ground-water flow in two dimensions (Davis and Neuman, 1983). Simulations were conducted to illustrate the effects of trench design and precipitation/evapotranspiration fluxes on water movement and to verify the conceptual model of water movement developed from the monitoring results. In this respect the simulations are similar in purpose to the theoretical analysis by Freeze and Witherspoon (1967), wherein the effects of topography and permeability variations on ground-water flow were studied. The present simulations are qualitative in that the model was adjusted only to provide a best fit with the levels of ponded water measured at trenches 1 and 2 (fig. 25), and the geometry of the trench and material boundaries has been simplified. The locations of the model cross sections (B-B′ and C-C′) are shown in figure 5.

Simulations for the months of March and July are presented because they demonstrate many aspects critical to the understanding of water movement in the unsaturated zone at the experimental trenches. Simulating both trench designs required a single grid for each month (fig. 29). Because the water table, represented by the lower grid boundary, was higher in July than March, the lower boundary on the July grid is higher than on the March grid. Otherwise, the grids are identical. The stippled pattern in figure 29 (see Explanation) represents the design difference between trenches 1 and 2. For trench 1, that area was assigned the properties of the compacted clayey sand. For trench 2, it was assigned the properties of the surface sand.

The cross-sectional model area represented by the March grid measured 1,070 and 1,270 cm in the horizontal and vertical dimensions, respectively. This grid contains 198 nodes and 174 elements, and has a maximum band width of 17. The grid used in the July simulations measured 1,070 and 1,000 cm in the horizontal and vertical dimensions, respectively. It contains 186 nodes and 163 elements, and has a maximum band width of 16. Small element dimensions, both horizontally and vertically, were used near the material boundaries because of expected large changes in hydraulic gradients over short distances. Larger horizontal and vertical node spacings were used near the left boundary because smaller changes in hydraulic gradients were expected in this region.

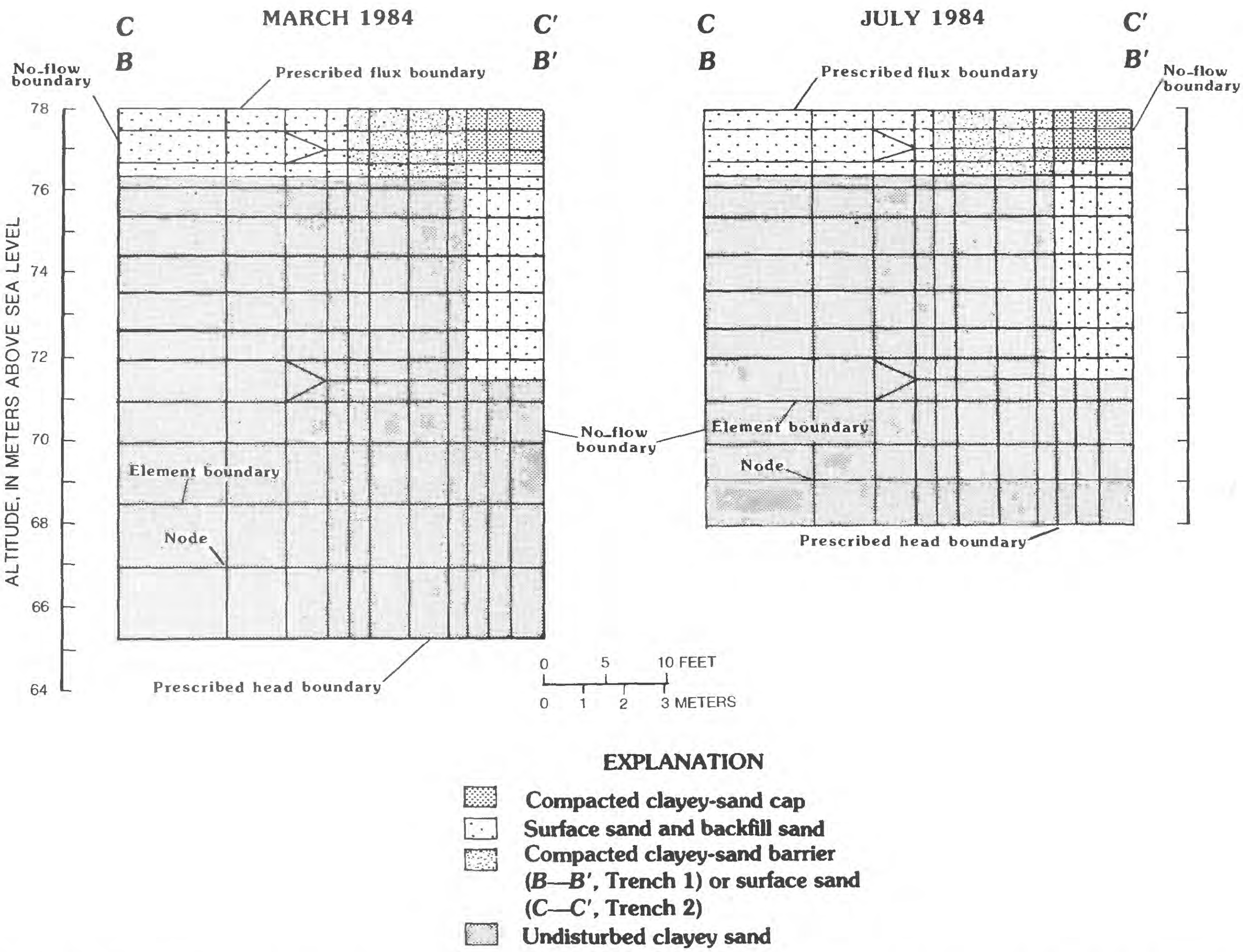


Figure 29. Finite-element grids used in model simulations for March and July 1984. (Lines of sections C–C′ and B–B′ shown in fig. 5.)

The contact between the surface sand and the undisturbed clayey sand was represented as a horizontal surface although it has a slope (less than 1°) to the east at the experimental trenches. Both the flat and the slightly inclined surfaces were used in trial simulations to determine their effect. The difference in simulated total hydraulic head in the trenches using a flat and an inclined interface was less than 3 percent. Therefore, in the final simulations the interface was represented as a horizontal surface for simplicity.

During the monitoring phase of the study, core samples were taken throughout the vertical extent of the trenches. Samples were taken in the surface sand, the compacted clayey-sand cap, the trench backfill sand, and the undisturbed clayey sand. Samples were then analyzed for various soil properties—saturated hydraulic conductivity, porosity, and grain-size distribution. The soil properties used in the model are as follows:

Material	*Saturated hydraulic conductivity (centimeters per second)*	*Porosity*
Surface sand and backfill sand	4.0×10^{-3}	0.36
Compacted clayey-sand cap	1.5×10^{-6}	0.30
Undisturbed clayey sand	1.4×10^{-7}	0.30

Soil samples were also used to determine a soil-moisture retention curve for each material. Application of the Brooks and Corey relationship (1964) to these data provided values of relative hydraulic conductivity versus percent saturation for each material.

Homogeneous and isotropic conditions within each material type were assumed. Specific storage in the unsaturated materials was assumed to be zero.

To simulate transient conditions, initial conditions must be specified over the entire flow system. The initial conditions are fully described by defining the pressure head at each node. The pore pressures in the materials at the beginning of each month were measured by soil-moisture tensiometers. An initial condition of static equilibrium was used in the surface sand, backfill sand, and compacted clayey sand. Static equilibrium implies that the total heads everywhere within a given material are equal. This is probably reasonable for the sand, in which gradients are relatively small. It is not as reasonable for the compacted clayey sand, in which gradients are probably steeper, but there were few measured data to support other initial conditions. In any event, the effect of these initial conditions did not extend beyond the first few days of the simulations.

The initial conditions in the undisturbed clayey sand were estimated by varying the pore pressure linearly from the water table (pressure equal to zero) to a point (pressure less than zero) near the top of the undisturbed clayey sand where the pressure was measured. The pressures used as initial conditions are a fair approximation of the distribution of the degree of saturation in each material at the beginning of each simulation period.

In addition to initial conditions, boundary conditions must be specified. The locations of the vertical cross sections (B-B′ and C-C′) selected for simulation are shown in figure 5. Flow was assumed symmetrical about the north-south center line of the trench, implying that flow at the center of the trench is predominantly downward (an assumption that is reasonable in the center of a column of homogeneous, unsaturated sand). Therefore, the right-hand boundary of the cross sections (fig. 29) was simulated as a no-flow boundary. The left boundary (fig. 29) was also a no-flow boundary. This boundary was some distance from the trench and had no effect on computations of hydraulic head near the trench. A prescribed hydraulic head boundary at the bottom (fig. 29) was used to represent the water-table elevation throughout the simulation. A water-table well some 13.7 m from the experimental trenches provided the water-table elevation for this boundary condition. The final model boundary consisted of a prescribed flux at the ground surface (fig. 29). The measured precipitation rates and daily evapotranspiration based on Bowen ratio calculations were used for the prescribed fluxes (fig. 30). The simulation time was 31 days.

Modeling Results

The simulations for March show that in the unsaturated zone at trench 1 water moved downward from the compacted clayey-sand cap to the backfill sand (fig. 31). In the surface sand adjacent to the compacted clayey-sand barrier, water primarily moved vertically from the surface sand downward into the undisturbed clayey sand. Lateral flow along the interface between the surface sand and the undisturbed clayey sand was inhibited from entering the trench by the compacted clayey-sand barrier. Water moved toward the trench in the undisturbed clayey sand near the trench side and downward at the bottom of the trench. A gradient divide occurred about 1 m below land surface in the compacted clayey sand and surface sand. Above the divide water moved upward toward the surface, and below the divide water moved downward. The gradient divide was created when the surface flux was changed from downward (precipitation) to upward (evapotranspiration) at the end of March. The model correctly calculated no ponding on the bottom of trench 1 at the end of March.

Owing to the absence of the compacted clayey sand barrier, the gradient divide affected the direction of flow through the cap to a greater extent in trench 2 than in trench 1 (fig. 31). During the period of evapotranspiration at the end of March, the direction of flow in the cap was predominantly upward. During periods of precipitation, however, the direction of flow in the cap was mainly downward toward the trench. The depth of the divide at both trenches is a net result of the magnitude and extent of the downward and upward fluxes during the simulation. The divide never moved below the surface-sand/undisturbed clayey-sand interface in March.

Water in the surface sand at trench 2 moved vertically downward into the undisturbed clayey sand and also laterally into the trench because of the absence of a compacted clayey-sand barrier around the trench. Soil-moisture movement at the side of the trench was generally downward and slightly away from the trench. The water depth in trench 2 at the end of March calculated by the model was 0.26 m. This compares favorably with the water depth of 0.27 m measured at monitoring site 2 (fig. 25). Water moved downward from the trench bottom. Notice that a saturated zone developed at the bottom of trench 2. This was a result of water ponding on the trench bottom, followed by infiltration of the water into the undisturbed clayey sand below and to the side of the trench.

The simulations for July show soil-moisture movement in the unsaturated zone at trench 1 similar to that in March; however, two gradient divides occurred in July while only one occurred in March (fig. 32). One divide is within 1 m of land surface, and the other is well within the undisturbed clayey sand beneath the surface sand. The deep divide is attributed to the 16-day period of evapotranspiration that occurred at the beginning of July (fig. 30). The shallow divide is due to evapotranspiration at the end of the month.

The irregular head distribution seen in the results of the July simulations was not observed at trench 1 in the results of the March simulations. The distribution was caused by the combined effects of the 16-day evapotranspiration period and the differences in hydraulic conductivity between the compacted clayey sand, the undisturbed clayey sand, and the backfill sand. The

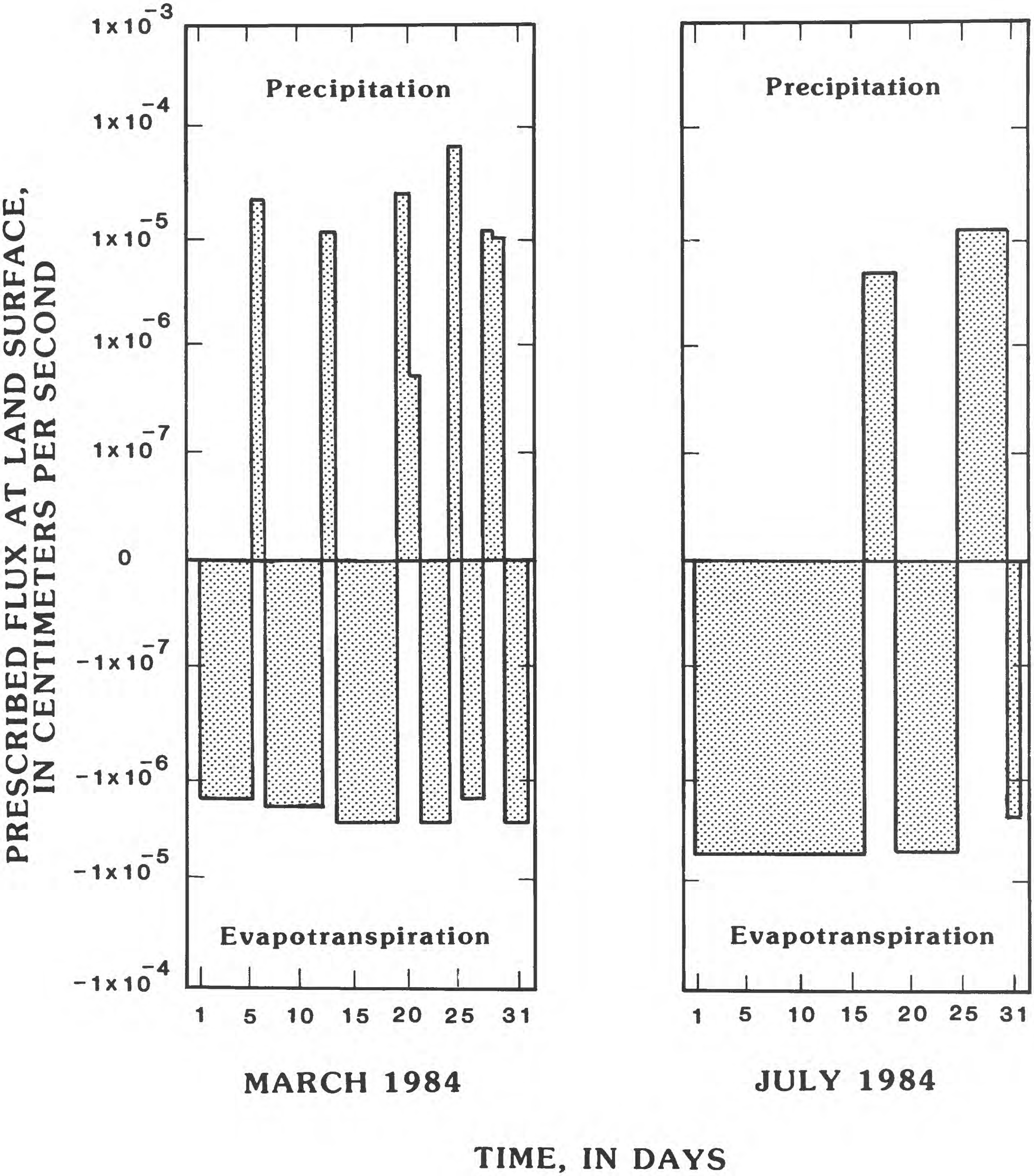


Figure 30. Prescribed fluxes at land surface used in model simulations for March and July 1984.

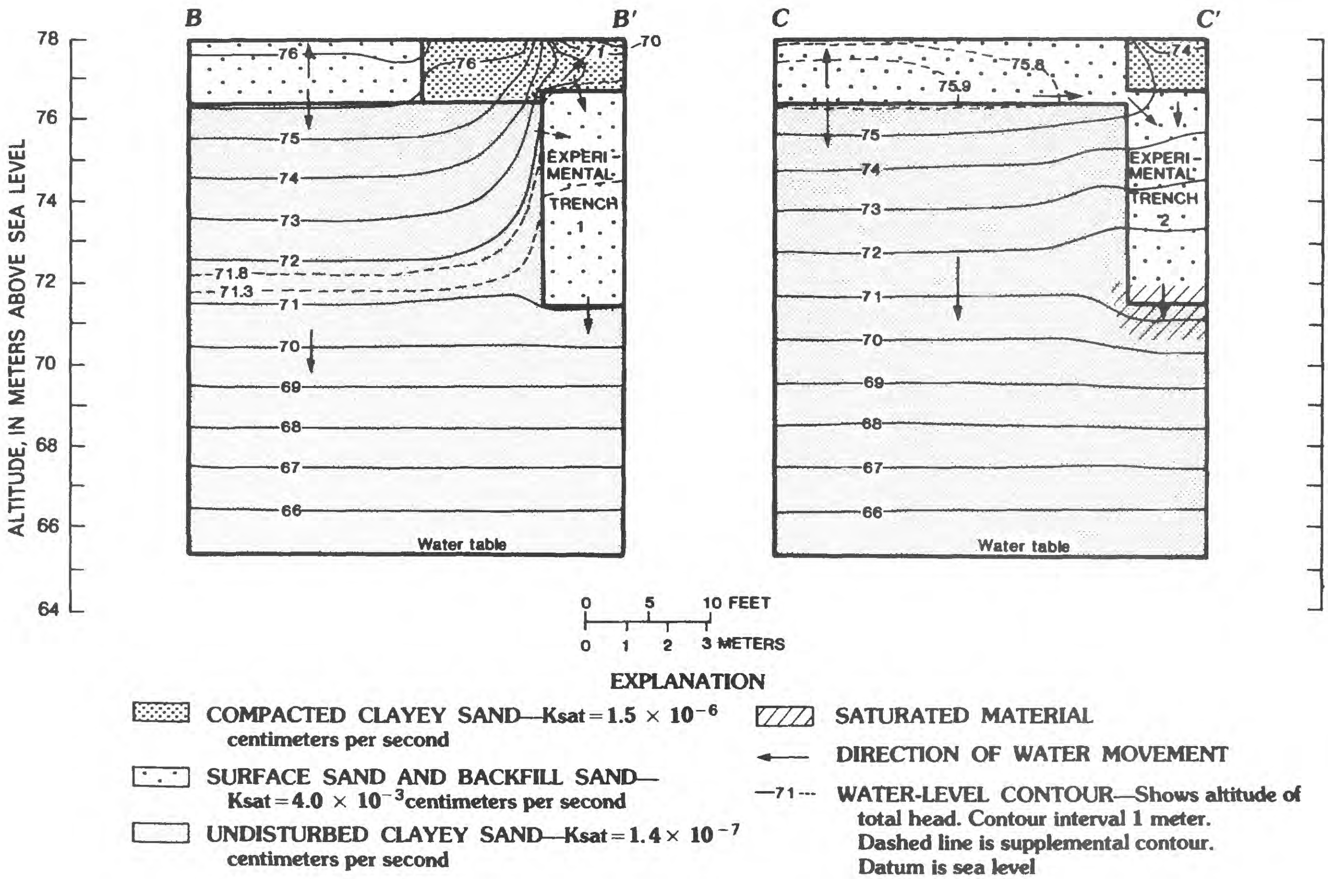


Figure 31. Simulated head distributions and flow directions at experimental trenches 1 and 2 for March 31, 1984.

gradient divides and the irregular head distribution caused significant upward and lateral flow, so that very little water actually moved downward from land surface to the saturated zone at trench 1 in July.

Two gradient divides are also present in the July results for trench 2 (fig. 32). They are at approximately the same depths as those at trench 1. The hydraulic head depression between the divides in the undisturbed clayey sand near trench 2 is larger than the one near trench 1. This can be explained by the presence of surface sand (rather than a compacted clayey-sand barrier) around trench 2, which allowed the influence of evapotranspiration to penetrate deeper into the undisturbed clayey sand. Also, without a clayey-sand barrier, much of the water in the surface sand flowed laterally into the trench backfill instead of downward into the undisturbed clayey sand.

The water level in trench 2 at the end of July, as calculated by the model, was 1 cm higher than the measured water level of 151 cm (figs. 25, 32). The measured water level in trench 2 fell about 33 cm from July 1 to July 31. That water flowed from the trench bottom and sides, and eventually it recharged the saturated zone. However, as at trench 1 in July, very little water actually moved downward from the land surface to the saturated zone. The model results support the conclusions about leakage from trench 2. Ponded water in the trench does move both downward and laterally from the trench. The model calculated a 33-cm decline in water level during July, which gives a leakage rate of 1.2×10^{-5}cm/s; the measured rate was 1×10^{-5}cm/s.

The zone of saturated material at the bottom of trench 2 expanded significantly from March to July. In fact, it developed into a mound of recharge at the water table. This result indicates two things. First, it supports the conclusion drawn from the tracer test data from probes 19 and 21 at trench 2 (fig. 24). Flow is directed horizontally from the saturated backfill sand toward the undisturbed clayey sand. Second, the recharge beneath this trench was much greater than the 43 cm predicted for undisturbed conditions.

The model simulations support the explanation given previously for the slow tracer velocities measured in the compacted clayey sand (trench cap). Obviously, the extent and duration of upward and downward surface fluxes would directly affect the rate of tracer movement in the shallow material. The model simulations also help explain why no evidence of the tracer was detected in the undisturbed clayey sand adjacent to the trenches. Water movement in the surface sand and in the

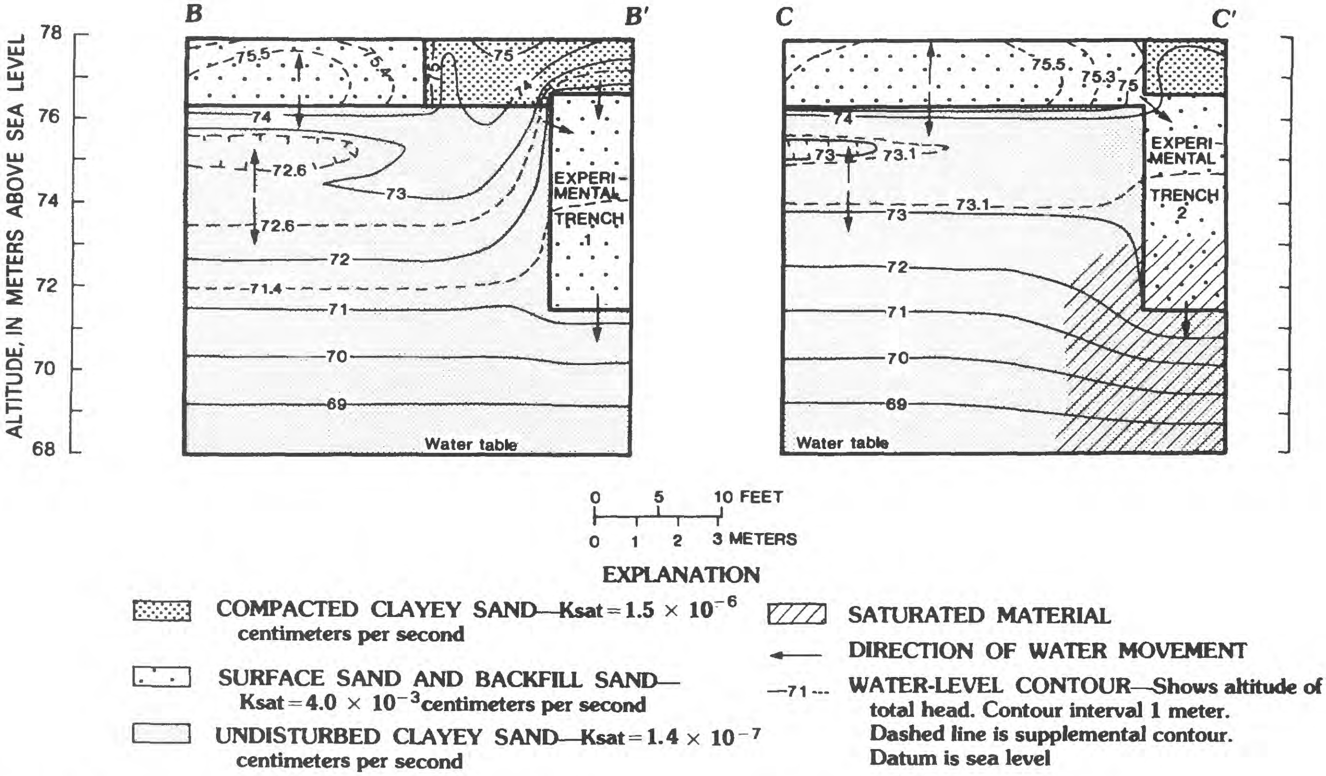


Figure 32. Simulated head distributions and flow directions at experimental trenches 1 and 2 for July 31, 1984.

undisturbed clayey sand adjacent to the top of the backfill sand was directed into the trenches; therefore, the tracer was transported into the backfill sand rather than down through the undisturbed clayey sand.

CONSIDERATIONS FOR FUTURE STUDIES

Experience obtained in this investigation is transferable to future studies. The following paragraphs detail some of the problems encountered in this study and offer alternatives to improve future studies of the unsaturated zone.

The approach used in this study to monitor moisture movement at depth within the unsaturated zone proved successful. However, the use of vertical shafts for the installation of horizontal monitoring probes at depth in experimental and actual waste trenches was not without difficulties. The major problems associated with this monitoring approach resulted from the effects of shifting of the vertical shafts initially during waste placement in the trenches and over time with the settling of trench backfill as well as the wastes themselves. Such movement was detected first in the radioactive waste trenches (monitoring sites 3 and 4) and later in the experimental trenches (monitoring sites 1 and 2). As a result, some soil tensiometers lost contact with the material. Separation of the porous cups from the material is critical because the separation renders the cups inactive. When separation did occur, the tensiometer probes were reset to ensure proper contact between the porous cups and the material. To avoid similar problems in the future and to maintain shaft stability, a separate hole could be excavated in the undisturbed sediment for placement of the vertical shafts rather than the shafts placed in an existing waste trench, where settling and shifting could occur.

Although the tracer-test experiment did contribute to the understanding of moisture migration in the unsaturated zone, it did not provide quantitative results of tracer movement. The use of nonreactive tracers, in conjunction with suction lysimeters, would eliminate the concern about the effect of changing moisture content on readings of soil-moisture conductance. Measurable concentrations of tracers in water samples obtained with the suction lysimeters would unequivocally verify the presence of the tracer at the lysimeter.

An additional unsaturated-zone monitoring technique not used in this study, neutron-moisture logging, could provide more exact definition of wetting-front movement in the near-surface part of the unsaturated zone. This, in combination with numerical modeling, would allow more precise delineation of moisture movement in the soil.

Sophisticated electronic monitoring equipment used in this study required frequent inspection to ensure valid data collection. The inability to access equipment in the field for servicing, calibration, and repair can result in loss of data. It is essential that the instruments be serviced regularly when conducting a study of this type.

SUMMARY AND CONCLUSIONS

Four unsaturated-zone monitoring sites and a meteorology station were installed at the low-level radioactive-waste burial site near Barnwell, S.C., to investigate water movement in the unsaturated zone at the site. Two monitoring sites (sites 1 and 2) were installed in experimental trenches, and two (sites 3 and 4) were installed in radioactive-waste trenches. Monitoring sites 1, 3, and 4 were in trenches constructed according to the design used at the site since 1976, whereby the surface sand around the trench perimeter is replaced by a 3-m-wide compacted clayey-sand barrier. Monitoring site 2 was in a trench constructed according to the pre-1976 design, whereby the surface sand around the trench perimeter was left intact.

Each monitoring site consisted of a 1.83-m-diameter vertical metal shaft placed in the trench. Soil-moisture tensiometers, soil-moisture conductance probes, and temperature sensors were placed horizontally at different depths through the shaft wall into compacted clayey sand, undisturbed clayey sand, and backfill sand. These instruments were used to monitor moisture movement in the unsaturated materials. Sodium chloride, used as a tracer, was buried near ground surface at each site so that it was above the undisturbed clayey sand and the backfill sand. The meteorology station was used to measure precipitation and to estimate actual evapotranspiration using the Bowen ratio method.

Core samples were used to measure variations in the hydrologic properties of the unsaturated-zone materials. Grain-size distributions, porosities, saturated hydraulic conductivities, and soil-moisture-characteristic curves were obtained for the various core samples. In addition, relative hydraulic conductivity-versus-percent saturation curves were determined.

Results of hydrologic testing of core samples produced the following average values of porosities and saturated hydraulic conductivities for the three materials, respectively: (1) undisturbed clayey sand, 0.30 and 1.4×10^{-7} cm/s; (2) compacted clayey sand, 0.30 and 1.5×10^{-6} cm/s; (3) backfill sand, 0.36 and 4.0×10^{-3} cm/s.

Evapotranspiration, using the Bowen ratio method, was less than precipitation in winter and spring of each year. At these times excess precipitation was available to infiltrate the unsaturated zone. Mass-balance calculations show that there were 43 cm of recharge from July 1983 through June 1984 at an undisturbed part of the site. Recharge rates change drastically over the site, decreasing significantly where the undisturbed surface sand has been replaced by compacted clayey sand.

Tensiometer data show that the unsaturated materials had their highest percent saturations in winter and spring, supporting the conclusion drawn from the meteorologic data that recharge occurred at this time. Percent saturations decreased in late spring and summer, reaching their lowest values in late summer before increasing again in fall. Saturations varied from 36 to 100 percent in the backfill sand and from about 75 to 100 percent in the undisturbed and compacted clayey sand. At a given depth the undisturbed clayey sand had higher percent saturations than the backfill sand. Within each, the deeper material had a higher percent saturation than the shallow material. The same general pattern was observed at all four monitoring sites. However, site 2 had much more ponded water in the backfill sand than any of the other three sites. More than 2.3 m of water ponded at site 2 in 1984, less than 0.3 m ponded at site 1, and none was measured at sites 3 and 4. The post-1976 trench construction practice of placing a compacted clayey-sand barrier around the trenches apparently significantly limits ponding in the bottom of those trenches.

During 1984, the rise and fall of ponded water in trench 2 was continuously monitored with a digital recorder. Using these data, a value of 1×10^{-5} cm/s was computed as the rate of leakage of ponded water from the trench at experimental site 2.

The tracer test data indicate that water movement occurred mainly during the recharge period, winter and spring, supporting the meteorologic and tensiometer data. The results further indicate that water that percolated through the compacted clayey sand at each site, dissolving the buried tracer, moved preferentially down through the backfill sand, rather than in the undisturbed clayey sand. However, data at site 2 do show that water in trench 2 (constructed according to the pre-1976 design) did migrate horizontally into the undisturbed clayey sand after ponding on the trench bottom. The tracer test results also provided rates of water movement in the unsaturated materials. The rates of unsaturated flow in the compacted clayey-sand cap (site 1) and barrier (site 3), and in backfill sand (site 1), were determined to be 3×10^{-6}, 2×10^{-5}, and 6×10^{-5} cm/s, respectively. It should be kept in mind that these rates of unsaturated flow were determined at specific locations during specific times of the year. Such rates are dependent on many factors, including percent saturation of the material, duration and magnitude of evapotranspiration and precipitation, depth of material below land surface, material type, and degree of homogeneity of the material. These factors should be considered before applying these specific flow rates elsewhere in the unsaturated zone.

Concentrations of tritium in core samples were determined to provide background data on concentrations with depth and to provide insight into soil-moisture movement through the different materials. The general trend for undisturbed clayey-sand, sandy-clay, and backfill-sand samples is toward increasing concentrations of tritium with depth. At monitoring sites 1 and 2, the concentrations of tritium in the unsaturated materials sampled at depths greater than 5.54 m ranged from 2,700 to 6,390 pCi/L and concentrations at depths less than 5.54 m ranged from 1,410 to 5,510 pCi/L.

A cross-sectional finite-element model of variably saturated flow was used to qualitatively illustrate the effects of precipitation/evapotranspiration rates and trench design on water movement at the experimental trenches. The model results support the meteorologic, tensiometer, and tracer-test data. They show that precipitation on trenches infiltrated the trench cap and moved vertically into the trench backfill material. Precipitation on the undisturbed material adjacent to the trenches moved vertically through the surface sand and either continued downward into undisturbed clayey sand or laterally along the sand/clayey-sand interface into the backfill sand, depending on trench design. The compacted clayey-sand barrier at trench 1 greatly inhibited water moving along the interface from entering the trench, whereas the absence of the barrier at trench 2 allowed water to enter the trench. The simulations also show that periods of evapotranspiration between periods of precipitation caused gradient divides to develop in the unsaturated materials. The depth of the divide was dependent on the material and on the magnitude and duration of the evapotranspiration/precipitation periods.

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METRIC CONVERSION FACTORS

The following factors may be used to convert metric (International System) units published herein to the inch-pound units.

Multiply metric units	By	To obtain inch-pound units
centimerer (cm)	0.3937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square hectometer (hm^2)	2.471	acre
centimeter per second (cm/s)	0.3937	inch per second (in/s)
becquerel per liter (Bq/L)	27.027	picocurie per liter (pCi/L)
gram (g)	0.03527	ounce (oz)

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F=9/5\ °C+32$$

Specific electrical conductance of water is expressed in microsiemens per centimeter at 25 °C (μS/cm). This unit is identical to micromhos per centimeter at 25 °C, formerly used by the U.S. Geological Survey.

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)–a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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