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HYDROLOGIC CHARACTERISTICS OF BENCHMARK SOILS OF HAWAII'S FOREST WATERSHEDS

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I. INTRODUCTION

The project was initiated in May, 1972. The initial effort involved mapping of forest soils on the islands of Oahu and Hawaii, and collection of relevant literature for preparing the study plan. The detailed study plan (El-Swaify, 1972) was prepared after cooperative discussions with staff of the Institute of Pacific Islands Forestry, Honolulu, Hawaii, and set forth the following three objectives:

1. Evaluate alternative methods for measuring water infiltration and its contribution to deep percolation in selected tropical soils for the purpose of developing a simple technique for field infiltration measurement.

2. Study mechanisms of water retention and movement in these soils for the purpose of modifying retention and infiltration properties of soils if necessary.

3. Study the interrelationships between the prevailing vegetative cover, dominant soil, and chemical composition of the water yielded by the watershed.

For field experimental work under Objectives 1 and 3, sites were selected on the forest watershed of the University of Hawaii Arboretum (section II). A constant temperature room was set up for laboratory work under all the objectives. After staffing and procuring the necessary equipment and supplies, the field work was started in January, 1973 on sites selected at the University of Hawaii Lyon's Arboretum. Section II includes further information on these sites. Sections III, IV, and V include results of investigations carried out to meet objectives 1, 2, and 3, respectively.

Reference

1. El-Swaify, S.A. 1972. Hydrologic characteristics of benchmark soils of Hawaii's forest watersheds. Study plan for U.S. Forest Service - University of Hawaii Cooperative Agreement No. 21-190.

II. EXPERIMENTAL FOREST WATERSHED AND SOILS

The field studies under objectives 1 and 3 were conducted on the forest watershed of the University of Hawaii Lyon's Arboretum. Fig. 1 shows a map of the watershed area with the location of two sites (Lower and Upper Plots) where hydrologic measurements for objective 1 were conducted and three sites where water quality samples for objective 3 were collected. The detailed land and soil description of Lower and Upper plots is given below.

<u>Lower Plot</u>

Location:	Island of Oahu, Manoa Valley, Lyon Arboretum. "Lower Plot" located about 300 feet northwest of the greenhouse.
Date:	March 20, 1974
Description by:	S. Nakamura, Soil Conservation Service
Soil:	Tantalus silty clay loam Typic Dystrandepts; medial over cindery, isothermic family
Topography:	Sloping upland, 12 percent slope
Parent Material:	Volcanic ash over cinders
Elevation:	640 feet
Rainfall:	160 inches
Drainage and Permeability:	Well drained, moderately rapid permeability
Erosion:	None
Vegetation:	California grass, honohono, creeping Chinese violet
Remarks:	This soil is representative of the silty clay loam type of Tantalus series

Soil Description:

A1 0-23 cm(0-9") - Dark brown (10 YR 3/3) silty clay loam; moderate fine and very fine subangular blocky structure; friable, sticky and plastic; many roots; many very fine to medium pores and common coarse pores; common worm holes and cast; occasional pebble up to ¼ inch in size; clear smooth boundary.

B21 23-41 cm(9-k6") - Dark yellowish brown (10 YR 3/4) silty clay loam;

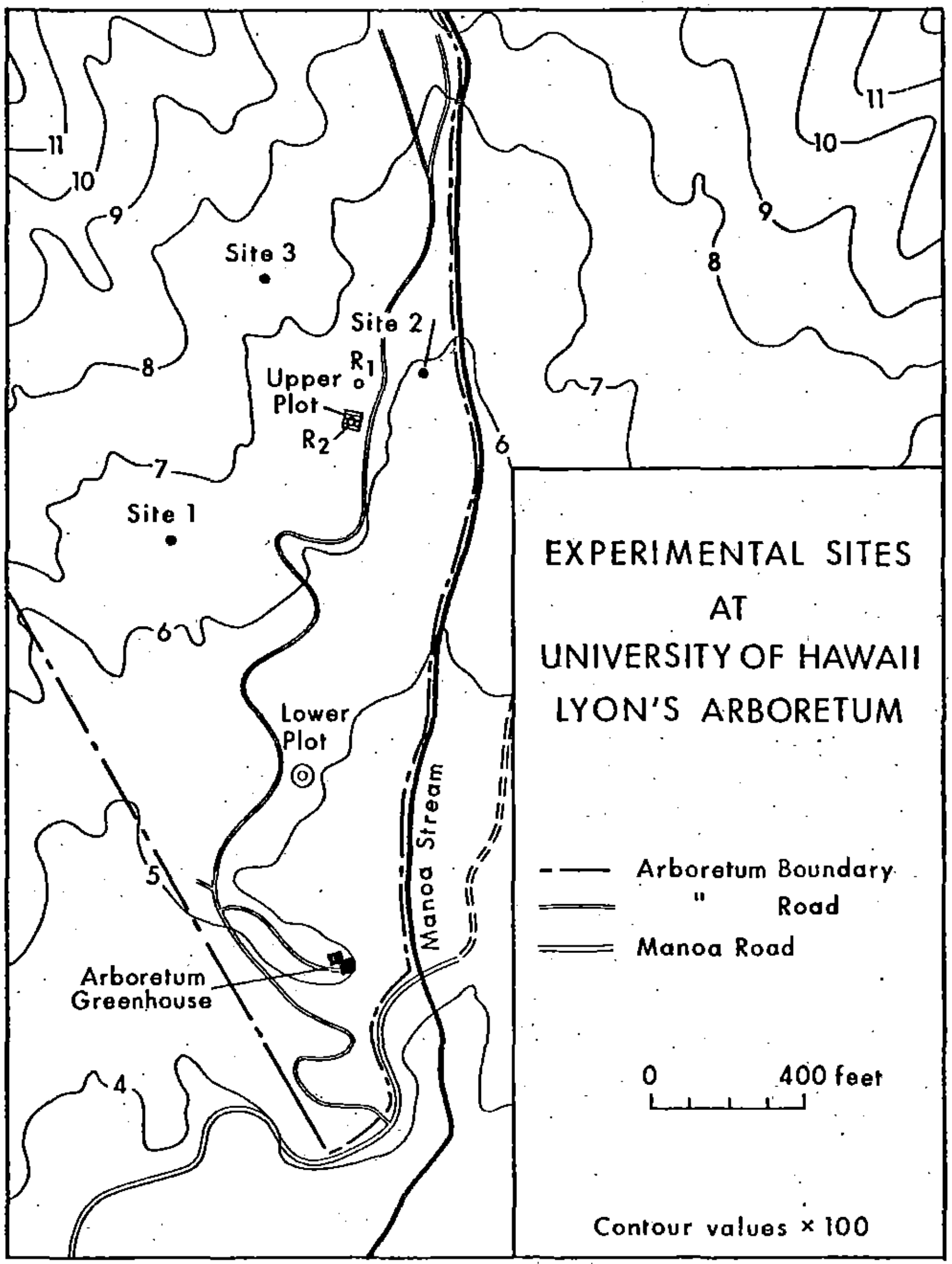

Fig. 1--Map showing experimental sites at the University Arboretum. Upper and lower plots were used for rainfall, runoff, and infiltration studies. R_1 represents the site for rainfall collection, R_1 for throughfall collection and sites 1, 2, and 3 for soil solution collection for water quality analysis.

moderate fine and very fine subangular blocky structure; friable, sticky and plastic; few roots; many very fine and fine pores; occasional partly weathered pebble up to 1 inch in size; gradual smooth boundary.

B22 41-89 cm(16-35") - Dark yellowish brown (10 YR 3/4) silty clay loam; moderate fine and very fine subangular blocky structure; friable sticky and plastic; few roots; many very fine and fine and few medium pores; larger pores have yellowish brown sugary coatings; weathered pebbles up to 2 inches occupy about 1 percent of the horizon; weathered cinders occupy up to 5 percent of lower half of horizon; abrupt smooth boundary.

C1 89-97 cm(35-38") - Very dark grayish brown (10 YR 3/2) weathered cinders that have very fine sandy loam texture and weak medium subangular blocky structure; friable, sticky, slightly plastic and smeary; many very fine pores; appear to hold high amount of moisture; a ¼-inch ironstone sheet with root matting occurs on top of this layer; abrupt smooth boundary.

C2 97-107 cm(38-43") - Variegated dark brown, dark reddish brown and black weathered cinders; smeary when crushed; appear to hold high anount of water; a ¼-inch ironstone sheet occurs on top of this layer; abrupt smooth boundary.

C3 107-178 cm(43-70") - Black partly weathered cinders; smeary when crushed; topped by ironstone sheet ¼-inch thick.

Upper Plot

Location:	Island of Oahu, Manoa Valley, Lyon Arboretum. "Upper Plot" located about ¼ mile northwest of the greenhouse.
Date:	March 20, 1974
Description by:	S. Nakamura, Soil Conservation Service
Soil:	Fluventic Humitropepts: fine loamy, mixed, isothermic family. (This classification is tentative)
Topography:	Moderately steep alluvial fan, 17 percent slope
Parent material:	Recent alluvium
Elevation:	620 feet
Rainfall:	160 inches
Drainage and Permeability:	Well drained; moderately rapid permeability

Erosion: None

Stoniness: Stony

Vegetation: Basketgrass, honohono, ti, kukui, octopus tree

Remarks: This is a well drained soil formed from recent alluvium under high rainfall. It is a variant and was not mapped out.

Soil Description:

A1 0-28 cm(0 -11") - Very dark grayish brown (10 YR 3/2) clay loam; moderate fine and very fine subangular blocky structure; friable, sticky and plastic; many roots; many pores; 10 to 20 percent gravel; few stones; clear wavy boundary.

C1 28-66 cm(11-26") - Dark brown (10 YR 3/3) clay loam; weak fine and medium subangular blocky structure; friable, sticky and plastic; many roots; many fine to medium and few coarse pores; 10 to 20 percent partly weathered gravel; clear smooth boundary.

C2 66-102 cm(26-40") - Dark brown (7.5 YR 3/2) clay loam; weak fine and medium subangular blocky structure; friable sticky and plastic; common roots; many very fine to medium pores, few coarse pores; 10 to 20 percent partly weathered gravel; few stones gradual wavy boundary.

C3 102-132 cm(40-52") - Same as above except 30 to 50 percent gravel and stones.

Worth noting for Lower Plot is the presence of three hard-pan ironstone layers between 90 and 107 cm depths, forming an interface between soil and cinder.

Selected properties of surface soil in Lower and Upper plots are given in Table 1. The table shows that surface horizons at both sites are high in organic matter content. Depending on the dispersion medium, different clay contents are recovered during particle size distribution analysis. Nevertheless, both are texturally classified as clays when ultimate dispersion is achieved. The high organic matter and clay contents are responsible for some of the observed swelling-shrinkage characteristics noted and discussed in the following sections.

Table 1 - Selected Properties of Surface Horizons of Study Sites

Sample	Particle Sized Distribution				Readily* Oxid. O.Matter %	pH**
	Dispersion medium	%sand >50μ	%silt 2-50μ	%clay <2μ		H_2O
Lower (0-23cm)	H_2O	4.3	94.2	1.5	5.6	5.0
	NaOH	5.8	41.9	52.3		
	$NaPO_3$	4.4	33.6	62.0		
Upper (0-28cm)	H_2O	10.5	50.9	38.6	8.4	6.2
	NaOH	16.2	45.0	38.8		
	$NaPO_3$	15.8	35.8	48.4		

* by Walkley-Black Method
** in 1:10 suspension

III. ALTERNATIVE METHODS FOR MEASURING INFILTRATION AND DEEP PERCOLATION

Most of the effort of this project was devoted towards Objective 1. Many results are included in this section, which inadvertently becomes voluminous. For the benefit of the reader, therefore, a statement of general principles and experimental approaches used for research under this objective are summarized below. Subsequent subsections will provide the details.

General Conceptual and Experimental Approaches

Infiltration of rain water or applied water into a soil profile, and subsequent drainage, is a process involving both unsaturated and saturated soil-water movement. During first stage of infiltration when the infiltration rate varies with time and during drainage, the water moves through the profile not completely saturated with water. During the second stage of infiltration when an apparent steady rate is established, an appreciable part of the soil profile is more or less saturated with water. The water conducting and water storage properties of soil are very significantly influenced by the degree of saturation. These properties, very often, also vary strongly from one soil horizon to another. According to the current soil water flow theory, the processes of infiltration and drainage can be mathematically described in terms of two basic properties of soil profile horizons, hydraulic conductivity as a function of soil water content (water conductivity function) and soil water content as a function of soil-water potential or tension (water storage function). At any given point in the soil profile, the infiltration rate at any time is equal to the product of the prevalent potential gradient and conductivity (by Darcy's Law). Characterization of a soil profile for infiltration and drainage, therefore, requires a determination of its water conductivity and water storage functions.

Many hydrologists in the past have overlooked the transient stage of infiltration, and have just used the apparent overall steady rate of infiltration as a characteristic of the soil profile, as a whole. While this characterization may not cause too much error in predicting infiltration of a very prolonged and heavy rainstorm, it may be totally misleading when infiltration of many commonly occuring rainstorms is considered. During medium-intensity and intermittently-heavy rainstorms, the soil profile may be largely unsaturated, with entirely different infiltration characteristics. Moreover, the transient stage of infiltration may not always be short and neglegible. Recent measurements with a rainulator on several important soils of Hawaii indicate that the apparent steady rate was not established, in many cases, up to two hours of a 2.5 in/hr rainstorm. Even when established, the apparent steady rate is affected by factors such as the layering and moisture distribution in deeper horizons of soil profile, condition of the soil surface, the head of applied water, the length of water application, depth to ground-water table, and the type of equipment or method used. A specific infiltration rate for a particular type of soil profile is, therefore, virtually non-existent.

It is with the above principles that the following studies were planned. Infiltration and deep percolation were measured under natural undisturbed field conditions. Due attention was given to determining the basic soil-water properties characterizing these processes.

A. Measuring hydrologic properties of soil profile using a double-ring infiltrometer with multiple-depth tensiometers

This experiment had three specific purposes:

1) Evaluation of lateral flow effects on infiltration rates measured inside a 30 cm diameter ring as a function of diameter of the outer buffer ring
2) Determination of the extent of lateral flow in different soil horizons, final infiltration rates corrected for lateral flow, and saturated hydraulic conductivities of the different horizons from measurements of vertical and lateral hydraulic gradients during infiltration
3) Investigation of determining deep percolation rates and unsaturated water conductivities (as a function of soil water contents) from measurements of soil-water tensions at vertical axis of the infiltrometer's axi-symmetric flow system during the process of drainage following infiltration

The experiment was conducted on Tantalus silty clay loam soil, whose complete profile description is given in Section II of this report. All details and results of the experiment have been written up in two manuscripts, which appear later in this section.

B. Measuring soil hydrologic properties on a forest watershed using a field-plot tensiometric technique

The experiment was designed to measure water conductivities and rainfall-runoff-soil water status relations on a fairly large-size plot under natural conditions of a forest watershed. Soil-profile tension measurements were provided at three different locations along the slope, in order to determine the effect of slope and to represent a good average for the heterogeneous soil and vegetation conditions. The experiment consisted of two phases:

1) In the first phase, soil-water tension changes were measured in profile while the soil was undergoing the process of drainage and redistribution, as the plot was completely covered with a plastic sheet to prevent evaporation and rainfall from entering the soil. A 3.5 ft deep steel siding was provided to prevent lateral flow from outside. Undisturbed soil cores were taken from the field sites to measure the water storage functions of different horizons. The field data were then analyzed to determine water conductivity functions for different soil horizons at each of the locations along the slope.

2) In the second phase, the plot was uncovered and a stand of natural grass re-established. Measurements were then made of the natural rainfall, runoff and soil-water tensions in the profile over a long period of time, by a combination of continuously-recording and manually-reading gauges. The data provide a needed picture of the nature of tropical rainstorms and rainfall-infiltration-soil water status relationships, which could be practically used in various ways. The data would serve as a nucleus for future development and testing of some rainfall-infiltration models.

The field plot was located on an alluvial soil patch of the UH Arboretum watershed. Complete profile description of this soil is given in Section II. The study has been written up into two manuscripts which are presented in this section following the first two noted under A above.

C. A system for continuously monitoring soil-water status on forest watersheds

Approach here was to provide an automatic means of continuously recording soil-water tensions in the profile, which could then be used to calculate infiltration, drainage water yield, evapotranspiration, and, by a careful analysis, water conductivity functions of the soil profile. Specific objectives in the present work were (1) to assemble a pressure transducer-scanner-recorder system that would run on battery power, for use on remote forest watersheds where regular power line may not be accessible, and (2) to test its use to monitor soil-water status on a Hawaii's forest watershed.

The monitoring system was assembled and tested in the laboratory before installing it on the forest-watershed plot described above under B. Details of the design, as well as examples of monitored data and applications are presented in a manuscript.

D. Simplified techniques for measuring water conductivity and water storage functions on soil cores

It may be economical and more convenient for remote forest locations to measure hydrologic properties of a field soil on undistrubed soil cores carefully taken from the field sites. Unfortunately, the techniques of measurement available so far have been, by and large, time consuming and tedious. With this motivation, some simplified techniques were searched and investigated. As a result, three very promising new methods have been developed. The methods were tested on the experimental data available in the literature and compared with more sophisticated methods on determination of the water conductivity and storage functions. One of the methods was applied to packed cores of soil from one of our experimental sites at the Arboretum (Tantalus silty clay loam). The manuscript for this method is also included in this section, while the other two methods have just recently been published (Ahuja, 1974; Ahuja, 1975).

References

1. Ahuja, L.R. 1974. Unsaturated hydraulic conductivity from cumulative inflow data. Soil Sci. Soc. Amer. Proc. 38:695-699.

2. Ahuja, L.R. 1975. A one-step wetting procedure for determining both water characteristic and hydraulic conductivity of a soil core. Soil Sci. Soc. Amer. Proc. 39(3):May-June (in press).

Measuring Hydrologic Properties of Soil Profile Using a Double-Ring Infiltrometer with Multiple-Depth Tensiometers: 1. Infiltration, Lateral Flow, and Saturated Hydraulic Conductivity

Water is becoming an increasingly critical resource in several parts of the world. The complexity of problems confronting the water-resources investigator has caused an increasing need for more quantitative data for all phases of the hydrologic cycle. Infiltration and drainage of water into and through the soil are very important phases of this cycle. Under certain conditions, such as in Hawaii, infiltration represents, almost exclusively, the net water contribution of a rainstorm to the water resources. Quantitative description of the processes of infiltration and drainage in terms of hydrologic characteristics of the watershed soils has, therefore, currently assumed greater interest and importance.

The hydrologic properties of field soil are best measured <u>in situ</u>, although for remote locations it may be more convenient to measure these properties on undisturbed soil cores brought from the field site to the laboratory. A generally recommended method is to measure the rate of water entry into the soil and soil-water suction changes as indicated by tensiometers installed at different depths in the profile while water is ponded at a constant level in a large basin (Nielsen et al., 1973). After an apparent steady rate is attained, water application is discontinued, the soil surface is covered with a plastic sheet to prevent evaporation, and changes in soil-water suction are recorded with time as the process of drainage occurs. Simultaneously, soil samples may be collected from different depths to determine the suction-water content relationship and bulk density of each horizon in the profile.

For detailed studies on watersheds such as in Hawaii, large basins are not practical because of steep terrain or difficulty in obtaining the large supply of water required. Small-size ring infiltrometers have been commonly used to measure the overall infiltration rate of the soil, with some error caused by lateral flow which can be reduced by use of an appropriate-size buffer ring (Olson and Swartzendruber, 1960; Johnson, 1963). The purpose of the present study was to test the use of a double-ring infiltrometer with variable buffer zones combined with the use of multiple-depth tensiometers to determine both saturated and unsaturated hydrologic properties of a forest soil profile. Corrections for any lateral flow effects are made by measuring both vertical and lateral hydraulic gradients. The use of multiple-depth tensiometers (having the tensiometer cups for all desired depths on one stem) eliminates the necessity of boring many more holes in a small area that the use of single-depth tensiometers requires. The present paper deals with measurements of infiltration rates, vertical and lateral hydraulic gradients, and calculations of lateral flow and saturated hydraulic conductivities. The second paper of the series will deal with unsaturated hydrologic properties.

Theory

Consider a double-ring infiltrometer with two concentric rings of radii r_1 and r_2 respectively, and with two multiple-depth tensiometers (MDTs) assembled as shown in Fig. 1. One MDT is located at the center of the rings, and the other outside the inner rings at a radius of r_3 cm. The MDTs have porous cups located at the desired depths in the soil. Water is ponded and maintained at a certain level in the inner ring as well as in the buffer area surrounded by the outer ring, as the water infiltrates down into the soil. The rate of infiltration is measured either in the inner ring alone or in the inner ring and the buffer area.

The flow system of Fig. 1 is symmetrical about the vertical axis. Water from the circular ponded area would move vertically downward as well as radially. The radial or lateral flow would be maximum from the outer boundary, and would decrease inwardly to approach zero value at the vertical axis. Assuming the soil directly beneath the inner ring and above the wetting-front is more or less saturated with water (except for entrapped air), as often occurs under ponded conditions, the flow from the inner ring may be apportioned into vertical and lateral components at any given depth L as:

$$\pi r_1^2 \, v_0 = -\pi r_1^2 \, K_s \, (L) \, \frac{\partial H}{\partial z} - 2\pi r_1 \int_0^L K_s \, (z) \left. \frac{\partial H}{\partial r} \right|_{r_1} dz$$

or

$$v_0 = -K_s \, (L) \, \frac{\partial H}{\partial z} - \frac{2}{r_1} \int_0^L K_s(z) \left. \frac{\partial H}{\partial r} \right|_{r_1} dz \qquad [1]$$

where v_0 is the rate of water entry per unit area measured in the inner ring, z is the soil depth variable, K_s (L) is the saturated hydraulic conductivity of the soil at depth z = L, H is the total hydraulic head, $\partial H/\partial z$ is the average vertical hydraulic gradient, r_1 is radius of the inner ring, and $\partial H/\partial r$ is the radial hydraulic gradient at r_1. Hydraulic conductivity at any given depth is assumed to be isotropic. The ratio of lateral flow component in any given soil layer of unit length to

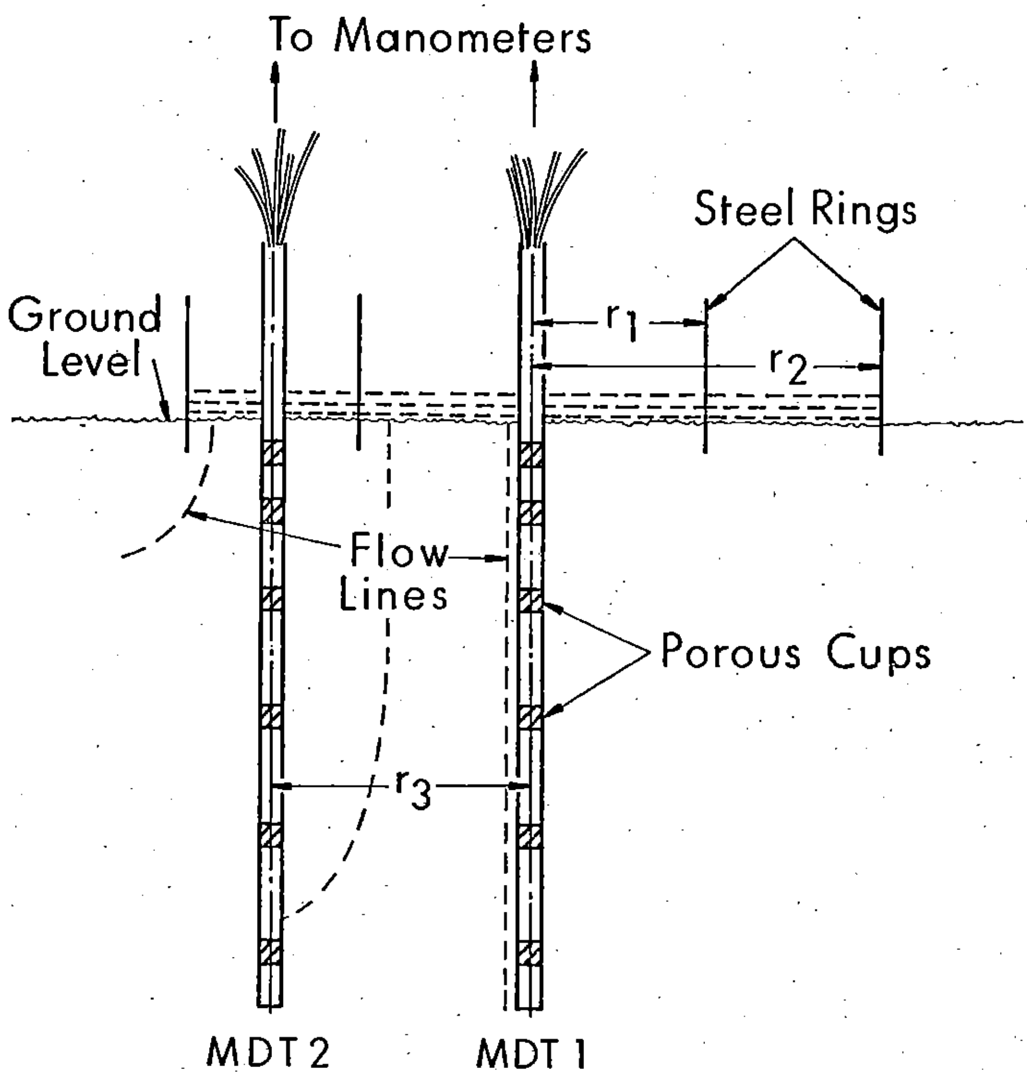

Fig. 1--Schematic diagram of ring infiltrometer and multiple-depth tensiometer experimental design with depth.

vertical flow at given depth beneath the inner ring can be derived to be

$$\frac{\text{Lateral Flow}}{\text{Vertical Flow}} = \frac{2\ \partial H/\partial r}{r_1 \partial H/\partial z} . \qquad [2]$$

The vertical and lateral gradients can be estimated from tensiometric measurements for different soil depths of the two (or more) MDTs as shown in Fig. 1. When the ratio of lateral to vertical flow as given by Eq. [2] is appreciable, saturated hydraulic conductivities of different soil horizons can then be derived by solving Eq. [1], starting from the top layer (where lateral flow is prevented by ring walls) and proceeding downward progressively.

Experimental

The Soil:

Field measurements were conducted on Tantalus silty clay loam, a member of Typic Dystrandepts, medial over cindery, isothermic family. This soil is developed from volcanic ash overlying cinders. A characteristic feature of the profile is the existence of three 1-cm thick ironstone layers at depths of about 90, 97, and 107 cm, forming an interface between the volcanic ash and weathered and partly weathered cinder.

Procedure for Infiltrometer-Tensiometer Experiments:

Infiltration and drainage measurements were made in the field using a multiple-ring infiltrometer equipped with four multiple-depth tensiometers installed as shown in Fig. 2. The smallest ring of 30-cm (12-inch) diameter was always used as the inner ring. The outer ring was either 60, 90, or 120 cm (24, 36, or 48 inches) in diameter depending on the desired extent of the buffer zone. The buffer zone in any given run was one continuous area, the ponded water in which was interconnected through four to six 1-cm holes made in the intervening rings at the ground level. These holes could be plugged with rubber stoppers when desired. Multiple-depth tensiometer no. 1 (MDT 1), which formed the central vertical axis, had porous cups located at 7.6, 22.9, 45.7, 76.2, 106.7 and 137.2 cm (3, 9, 18, 30, 42, and 54 inches) from the soil surface. The other three MDTs were equally spaced at a radius of 38 cm (15 inches) from the central unit. MDT 2 had the same number and location of porous cups as MDT 1. MDTs 3 and 4 were shallower units, each with five cups centered at 10, 20, 30, 40, and 50 cm from the soil surface.

Installation of infiltrometer rings and the MDTs was done with care so as to cause minimum disturbance to the soil. The rings, all 46 cm high and made of 1/3-cm galvanized steel, were bevelled from outside to inside at the lower edge. They were driven 15 cm deep into the ground one by one starting with the smallest ring. For this purpose, a driving plate (1.3 cm thick steel) was centered on the ring and on it was placed a heavy wood block (5 x 10 cm, 1 m long) upon which mod-

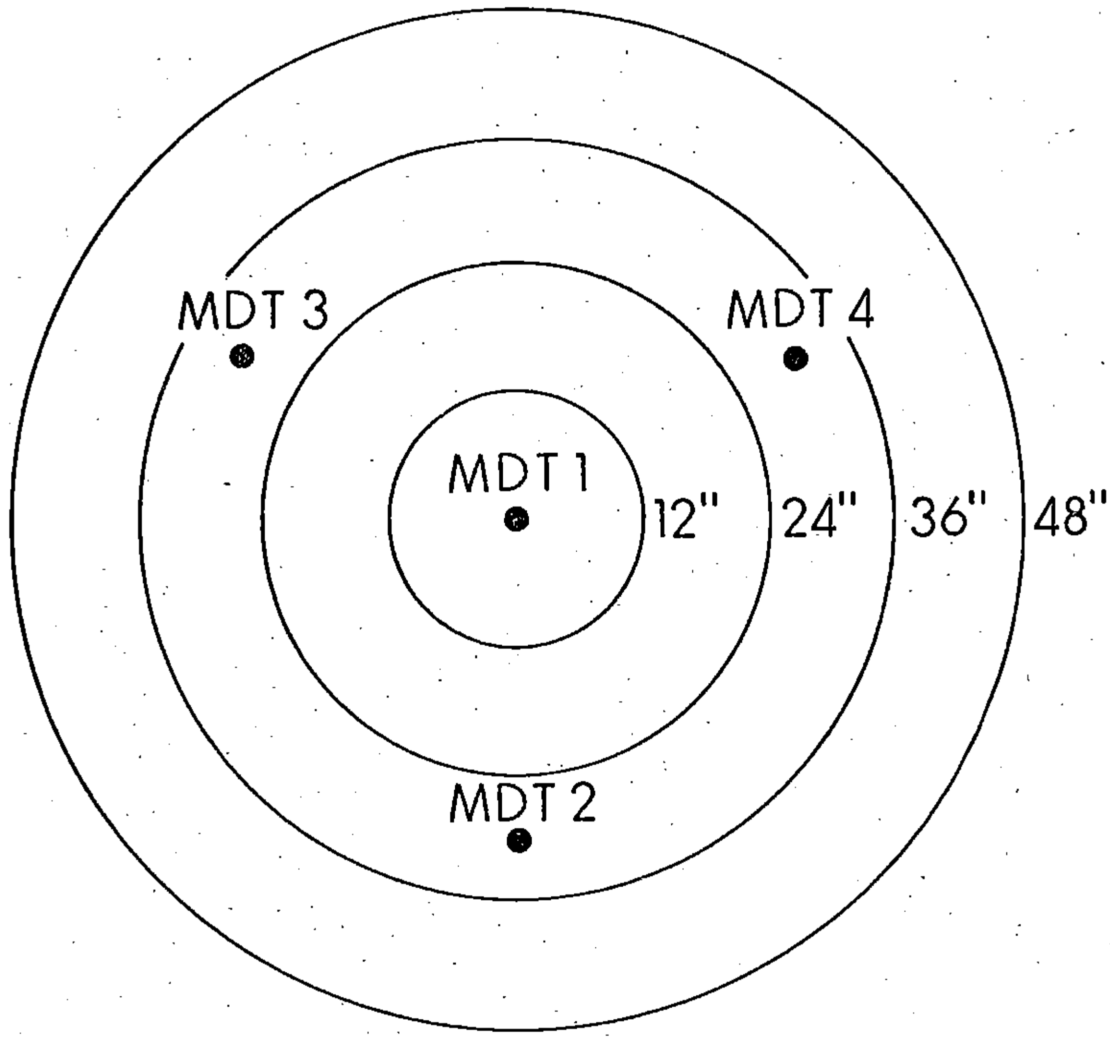

Fig. 2--Perspective view of ring infiltrometer and tensiometer combination employed in this study.

erate blows of a heavy sledge were applied. The driving plate was recentered and the wood block moved around after every 2 to 3 blows, so that the ring could penetrate the soil uniformly. After the driving was completed, the disturbed soil adjacent to the rings was tamped firm with a hand tool.

For installing the tensiometers, which were of 3.2 cm outer diameter, holes were very carefully made with a 2.5-cm-diameter screw auger. The auger stem moved through a guide tube fixed on a leveled stand so that the hole was vertically straight and excessive widening of the hole by random movement of the auger was prevented. The auger was operated very gently and the soil was removed from it at each 5-cm depth interval. The hole was dug about 15 cm deeper than actually required for the tensiometer stem. After all the holes were ready, a 2-cm steel tube was inserted in each hole, water was gently poured into the tube to fill it, and then the tube was slowly pulled out leaving the hole full of water. The tensiometer stem was then slowly slipped into the hole.

The process of infiltration was initiated by ponding water in the inner ring and in the buffer zone to a level above the soil surface of 7 cm, which was maintained throughout the duration of the run by means of float valves. The soil within the rings was covered with pieces of burlap to prevent direct water impact and subsequent disturbance of soil surface. The water was supplied from two different supply tanks (each of 30-gal capacity and 30 cm diameter) fitted with 0.6-cm glass tubes to show the water level inside. The water level was read at very frequent time intervals in each tank, as a measure of cumulative infiltration in both the inner ring and the buffer zone.

Some infiltration runs were made even before the tensiometers were installed. After the tensiometers were set up, they were read visually at short time intervals, beginning with 15 seconds and up to 20 minutes near the end of the runs. During early stages of infiltration, at least two persons were required to read the four manometer sets, while one additional person was reading the water levels in the supply tanks. Infiltration was allowed to continue for 6 to 8 hours in most cases, except in one case when it was allowed to run for 48 hours to see the long-term effects on infiltration rates. After each infiltration run, the soil surface inside the rings was covered with a sheet of plastic and a sheet of 2-cm thick styrofoam, cut to size, in order to prevent evaporation and reduce condensation and temperature fluctuations beneath the plastic. Frequent readings of tension at different soil depths were continued for 11 to 23 days as the soil profile drained following infiltration. During this phase of study, it was necessary to keep natural rain water from entering the draining plot. For this purpose, a 6 x 6 m umbrella was erected over the experimental area, and diversionary drains were dug upslope. The drainage phase of the studies will be reported in the following subsection.

Altogether 26 infiltration runs were made, 13 before and 13 after the tensiometers were installed. The runs in the first set were made at 3-day intervals, and consisted of 2 to 4 replications for each of the cases under study. They involved no outer buffer ring, and buffer rings of 60-, 90-, or 120-cm diameter. The runs in the second set, made at an interval of 11-23 days, consisted of a similar combination of buffer rings. The initial three runs and run No. 14 were meant to establish soil stability after the disturbance incurred during installation of rings and tensiometers, and therefore data from these runs have been excluded from this report.

After the field measurements were completed, a trench was dug beneath the rings, and 4 to 7 undisturbed soil cores were collected from each tensiometric depth. A San Dimas core sampler (Andrews and Broadfoot, 1958), which consists of an auger rotating around a stationary collection tube, was specially constructed to take 11-cm diameter, 7.5-cm-long cores. The trench served an additional purpose during direct measurements of lateral flow as described below.

Direct Measurement of Lateral Flow:

In order to confirm the tensiometric estimates of lateral flow, at least approximately and qualitatively, a direct measurement of lateral flow was undertaken. The field set-up for this measurement is shown in Fig. 12. Advantage was taken of the general slope (nearly 12%) of hardpan layers and the soil profile. In the trench dug previously just downslope from the infiltrometer rings, four 120 x 30 cm steel trays were pounded horizontally into the profile at 25, 60, 90, and 110 cm depths. Their location in the trench was so chosen that they were parallel to the surface in the direction perpendicular to the slope. About 90 cm away from the edge of the trench and directly upslope, a 30-cm-diameter infiltrometer ring was installed in the same manner as described in section B. The line joining the central axis of the ring with the center of each tray was parallel to the slope at that plane. The trays were slightly tipped on one side where an outlet was provided so that the water that was collecting on the trays would flow into a measuring cylinder or bottle.

Results and Discussion

The infiltration rates (as a function of time) measured in the inner ring for two of the runs made at 3-day intervals of drainage are presented in Fig. 3. The outer buffer ring used in these runs was the largest, i.e., 120-cm diameter. The data points were calculated from cumulative inflow readings as taken in the field at short time-intervals using a finite difference method. The inflow readings were not smoothed for this purpose. Hence, the scatter in the data is probably a result of imperfections in the float valve (to maintain a constant head) and errors in reading the water level in the supply tanks. The scatter decreases with time as the rates were averaged progressively for larger time-intervals. The moisture content of the soil profile before the above (3-day interval) runs would be fairly close to the "field capacity", as the experimental area was protected from rain and evaporation. However, some subsurface lateral flow of water from the surroundings could have taken place.

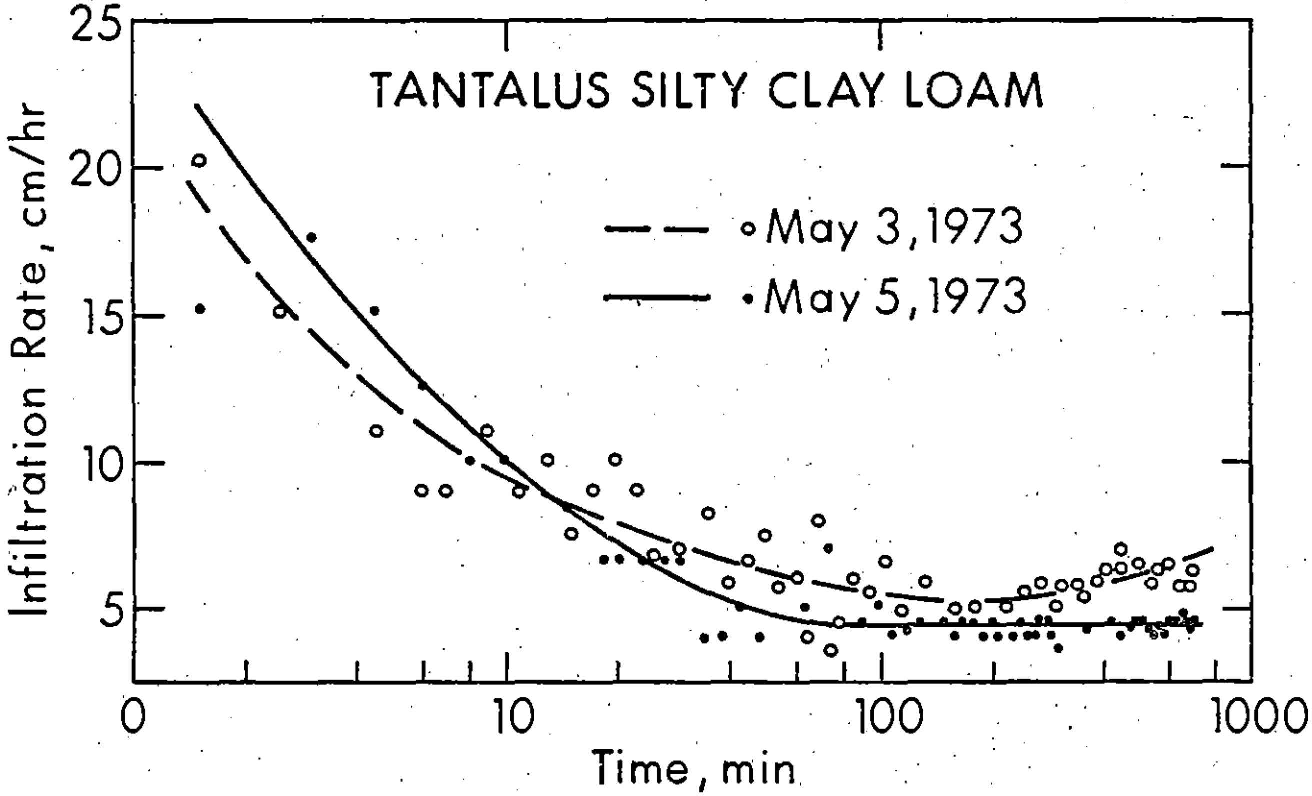

Fig. 3--Changes of infiltration rate with time during two runs preceded by a 3-day interval of drainage.

The curves in Fig. 3 show a fair degree of agreement; however, an important difference should be noted. The infiltration rate in one of the runs reaches a steady state after nearly 100 min and remains steady till the end at 700 min. The rate in the other run does not; on the contrary, it starts to increase after the normal decrease with time up to 200 min. The data thus indicate that a value of final steady infiltration rate assigned to the soil under investigation would be affected by the initial conditions in the profile as well as the deeper layers and duration of the infiltration experiment.

Fig. 4 shows the infiltration rates as a function of time for two runs made when the soil was initially drier than the field capacity. The run made on July 13 followed a drainage period of 11 days, while the run made on August 17 followed a drainage period of 13 days. The soil-water suction value varied from 6 cm at 137 cm depth to 82 cm at 7.6 cm depth before the first run, whereas it varied from 8 cm to 94 cm before the second run. The infiltration rates measured in the first run were somewhat higher than those measured in the second run for all time periods. The data show an increase in the rates with time after nearly 100 min in the first run, as noted earlier for a case in Fig. 3. In order to investigate longer term behavior of infiltration rates, an infiltration runs made on October 26 was continued for 2880 min. The data are presented in Fig. 5. The rates remained steady between 100 and 200 min, but afterwards underwent large time-fluctuations. The data of this run further supports the comments made above in discussion of Fig. 3. To interpret overall infiltration-rate data properly, the investigator must know the hydrology of (deep) underlying strata as well as that of the soil profile.

In order to assess the variability in field infiltration data and to verify the effect of size of the buffer ring, the final infiltration rates measured in the inner ring are plotted as a function of radial length of the buffer zone in Fig. 6. Data points are from all the different runs made at 3-day intervals (wet runs) or 11-23 day intervals (dry runs). The final infiltration rates show considerable scatter, varying from nearly 3 to 9.5 cm/hr. One reason for the variability could be the differences in initial wetness of deeper ground layers and in duration of the infiltration runs as discussed above. Another reason may be the soil's incomplete reversibility as regards swelling and shrinkage upon wetting and drying. Cracks, indicating shrinkage, were visible on the surface soil outside the rings which dried much beyond 200 cm suction.

In Fig. 6, mean infiltration rates for a given buffer-zone size are shown separately for wet and dry runs. The mean values for wet runs indicate practically no effect of the length of the buffer zone on the final infiltration rate; this does not necessarily mean however, that there was no effect on early infiltration rates. The mean final values for dry runs show some decrease in rate with increasing length of the buffer zone. The mean rate in the inner ring with no buffer is nearly 27% higher than that with the 45-cm radial buffer (120-cm-diameter buffer ring). This difference between wet and dry runs would, of course, be expected on the basis of Eq. [1], as the lateral gradient $\partial H/\partial r$ would be larger in the drier soil. However, the difference would also depend

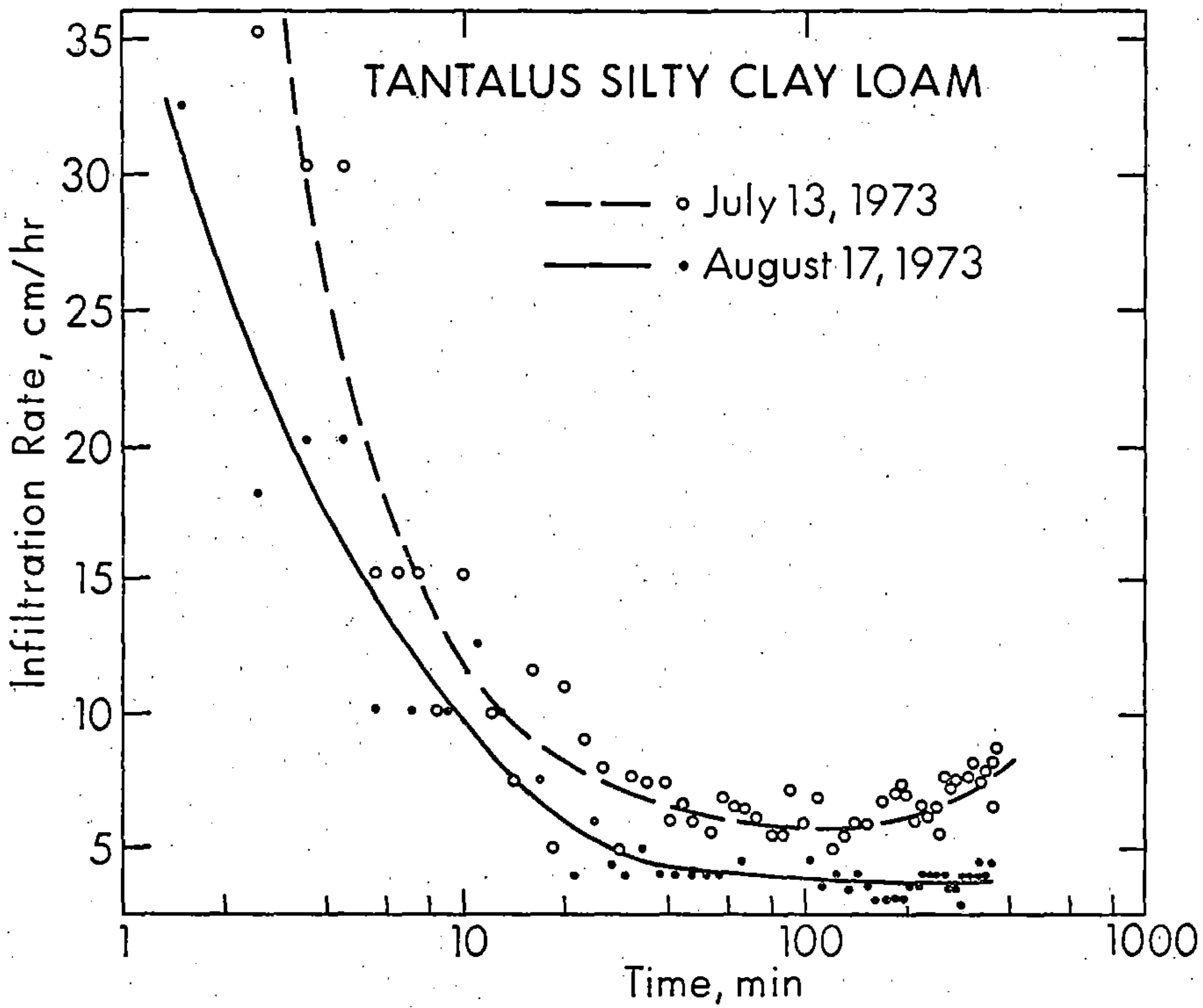

Fig. 4--Changes of infiltration rate with time during two runs, one preceded by an 11-day interval of drainage (o) and the second preceded by a 13-day interval (•).

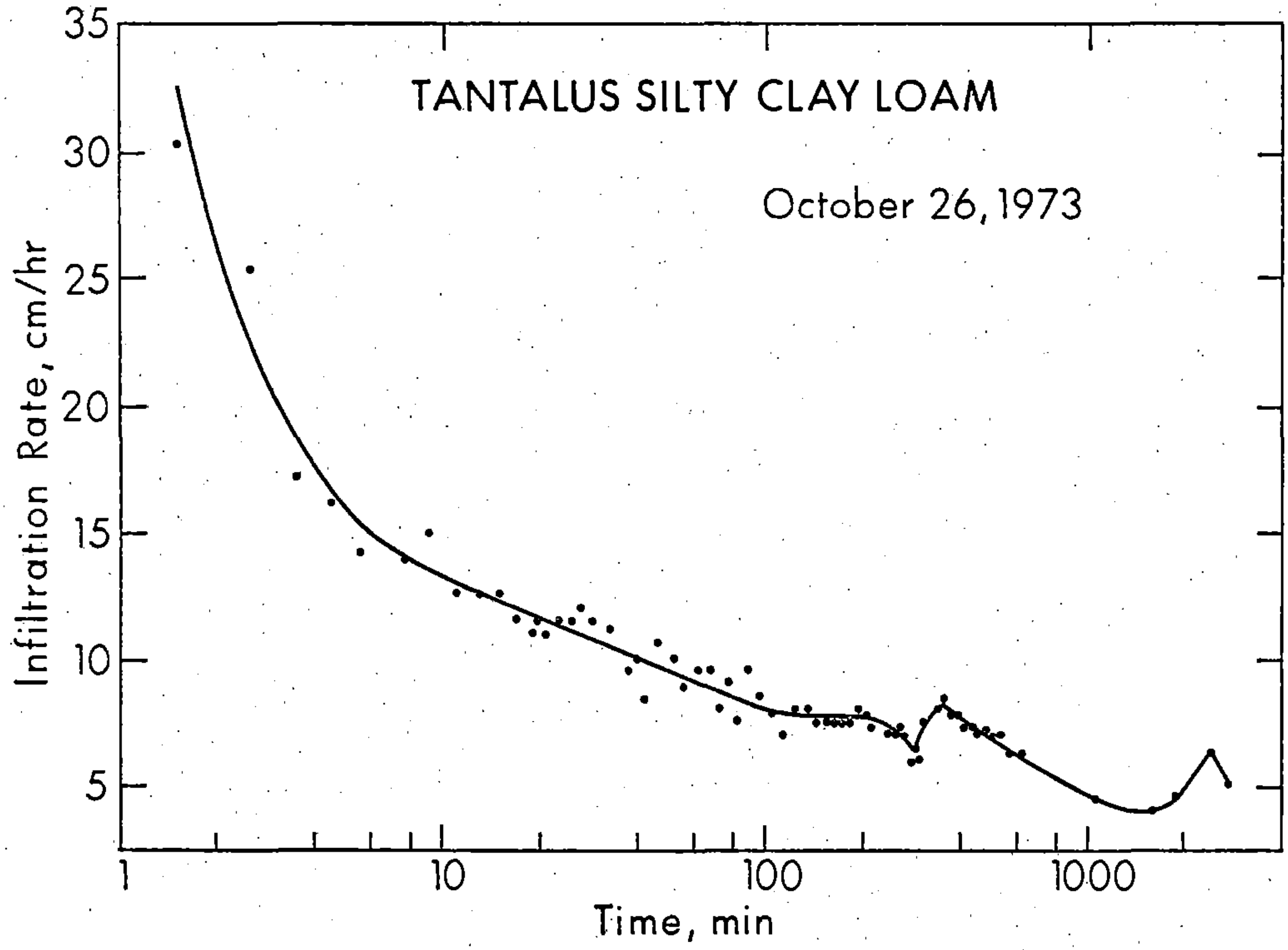

Fig. 5--Changes of infiltration rate in Tantalus silty clay loam over an extended period of water application.

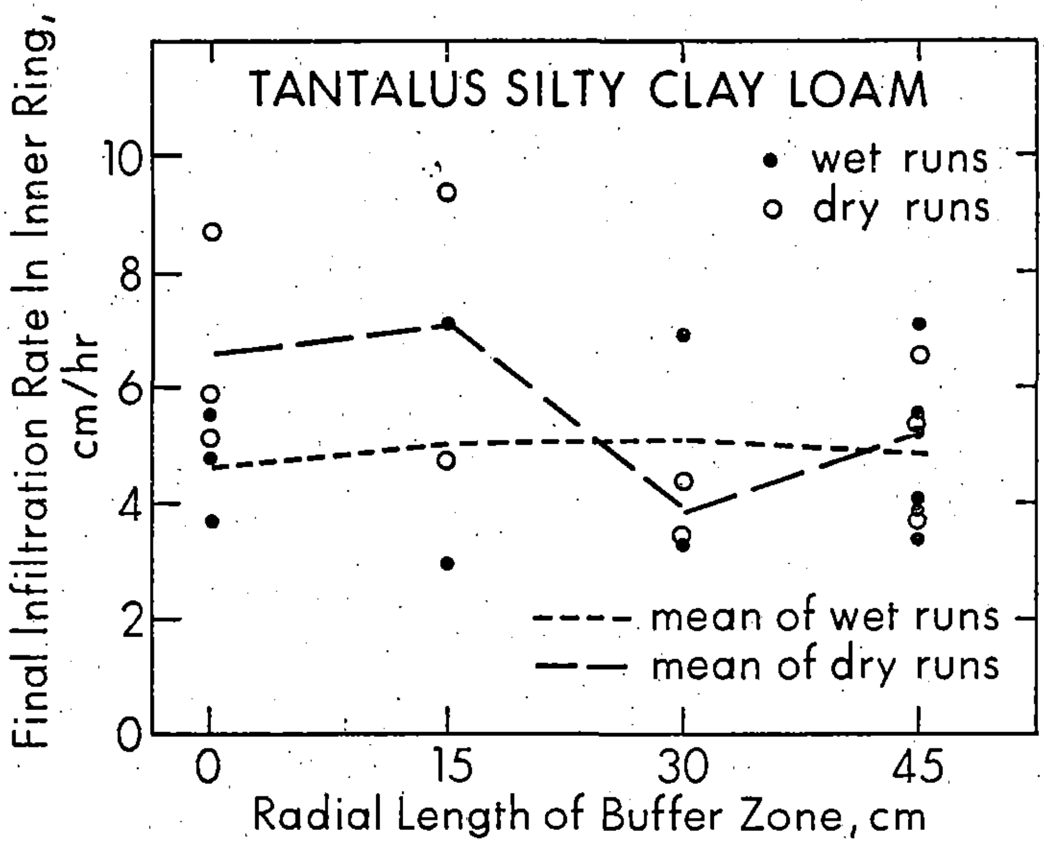

Fig. 6--Effect of the extent of buffer zone on final infiltration rates measured in the inner ring of a double ring infiltrometer.

upon the duration of infiltration, as the lateral gradients would decrease with time. Nevertheless, the effect of a buffer zone even in the dry runs is not substantial as compared to the 200 to 250% differences reported by Olson and Swartzendruber (1960) for sand-silt-sand profile. One reason is that the soil profile in the so-called dry runs was really moist (suction less than 200 cm H_2O) as compared with air-dry packed material used by Olson and Swartzendurber. Another reason may be that the Tantalus soil used in this study is very highly aggregated, with high hydraulic conductivity at saturation but very sharply declining conductivity upon desaturation. Both of these reasons would make the vertical hydraulic gradient due to gravity and hence the vertical component of flow in Eq. [1] much more important than the horizontal gradients and the lateral component of flow.

The change of hydraulic heads in the soil profile during infiltration as indicated by the multi-depth tensiometer located in the inner ring (MDT 1) are presented in Fig. 7 for two of the runs. The data in Fig. 7B are for a run in which no buffer zone was provided. No attempt was made to smooth the trends as the data points are simply joined by straight lines. The data show that water under ponded conditions moves very rapidly down the profile. In 10 min, the wetting front was nearly a meter deep. In 30 min, the hydraulic heads are fairly close to the final steady values. Soil-water pressures at the depth of 137 cm, comprising the loose cinder layer, change very slightly. A small suction prevails in this layer even after steady state is achieved, indicating that the permeability of this layer is much higher than in the layers above it. The soil-water pressure changes at a slower rate during infiltration without a buffer zone than that with a 45-cm-buffer zone (Fig. 7A), indicating the effect of lateral flow on vertical water movement.

In order to show that lateral flow does in fact occur, and its relative distribution with depth, the hydraulic heads measured outside the rings of ponded water are presented in Fig. 8 for two of the runs. The data points are averages of the values indicated by the three multiple-depth tensiometers (MDTs 2, 3, and 4 in Fig. 2) located at the radius of 38 cm (15 inches) from the vertical axis. Data in Fig. 8A are from a run involving no buffer zone, where the water was ponded only in the inner ring with radius of 15 cm, (6 inches). Thus, the hydraulic head readings are for points radially located 23 cm away from the ponded area. This is the same run for which the hydraulic heads inside the ponded area were presented in Fig. 7B. The data in Fig. 8B are from a run where the water was ponded to a radius of 30 cm (15-cm inner ring and 15-cm buffer zone), so that the readings are for points radially located 8 cm away from the ponded area. The figure shows that lateral flow occurs most in the driest soil horizons at the top. Comparison of Figs. 8A and 8B shows, as expected, that wetting of the soil 8 cm away from the ponded radius (Fig. 8B) is much faster and more complete than that of soil 23 cm away (Fig. 8A). This is evidenced by faster diminution of hydraulic gradients in the first than in the second case. It should be noted that the change in hydraulic heads at 7.6 cm depth in the top layer outside the ponded area was due to upward flow of water from the lower layers, since the lateral flow at this depth was shut out by the walls of infiltrometer rings installed to a depth of 15 cm.

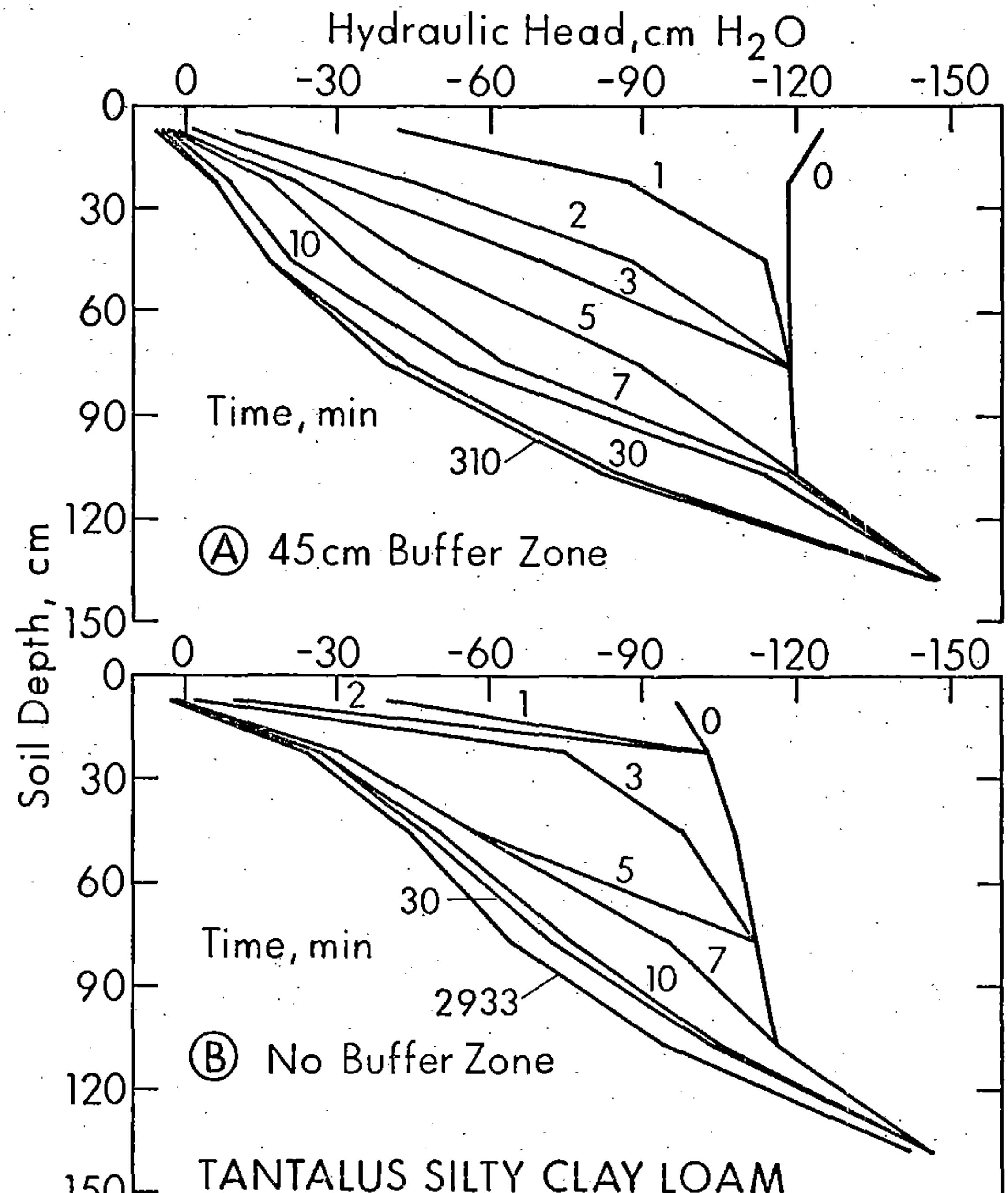

Fig. 7--Changes in hydraulic head with depth and with time as indicated by multiple-depth tensiometers in the center of the inner ring both in the presence of a buffer zone (A) and in its absence (B).

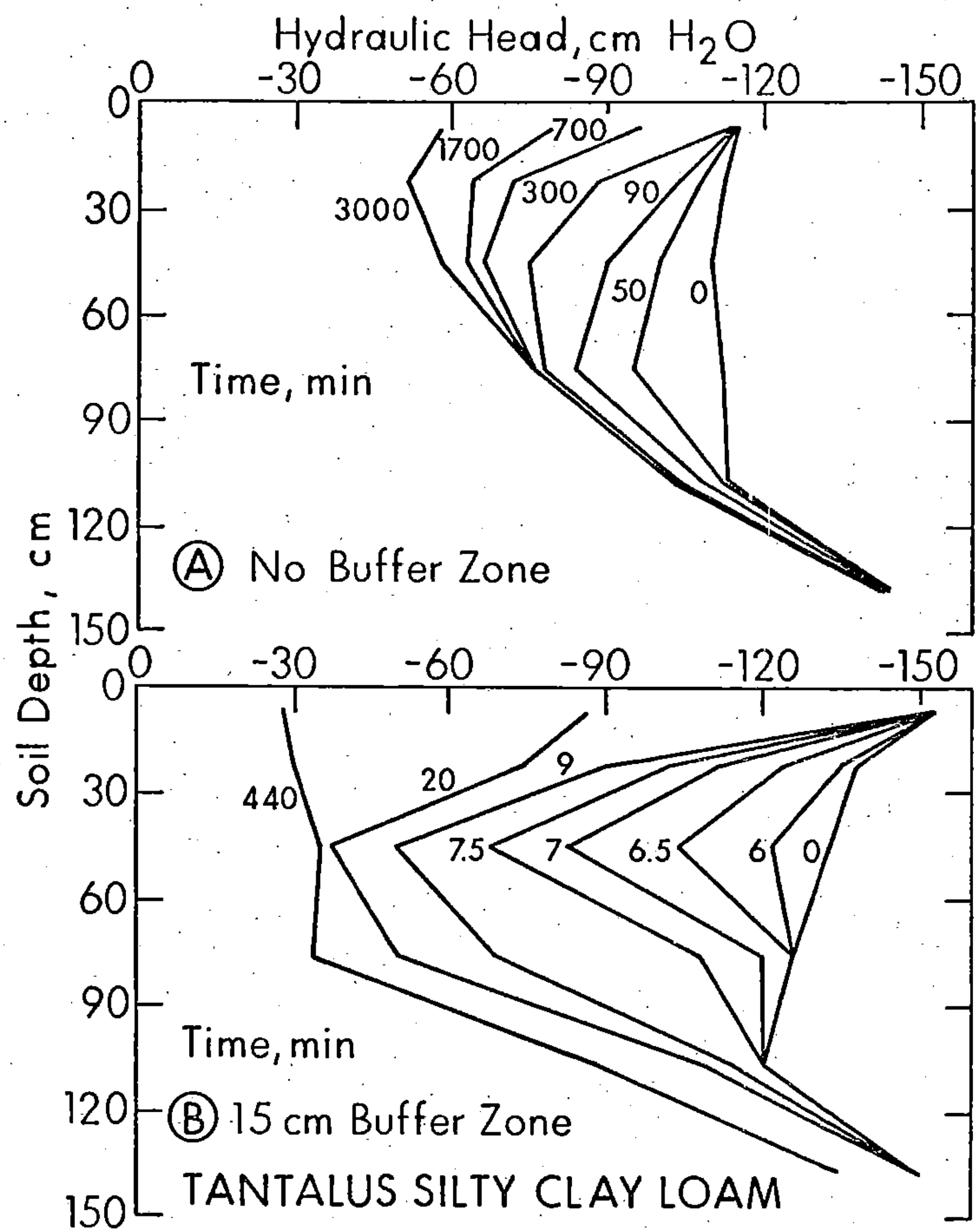

Fig. 8--Changes in hydraulic head with depth and with time as indicated by multiple-depth tensiometers located laterally 23 cm away from ponded zone (A) and 8 cm away (B).

Ratios of lateral to vertical flow of water at different depths beneath the inner ring as calculated by Eq. [2] for the two cases of Fig. 8 are presented in Fig. 9. The radial hydraulic gradients $\partial H/\partial r$ at radius (of the inner ring) r_1 for various depths were estimated from the two available readings of hydraulic head at the center (vertical axis) and 38 cm from the center. Assuming a symmetry around the vertical axis, a parabolic equation was fitted to pass through the two given points, which was then differentiated to obtain slope at $r = r_1$. The data in Fig. 9 indicate that lateral flow was as much as 20% of the vertical flow in some soil horizons in early stages of infiltration. The proportion of lateral flow decreased with time. This decrease was slower in the absence of a buffer zone (Fig. 9A) and in the upper soil region between 20 and 50 cm depths. With a 15-cm buffer zone (Fig. 9B), the lateral flow near the end of the infiltration run (440 min) decreased to within 4% of the vertical flow in the surface layer and to zero in the lower layers. In the absence of a buffer zone, the values vaired from 6% in the surface layer to almost zero at 1 m depth at the end of the run which lasted for 3000 min. In all cases, no significant lateral contribution was observed in flow below 1 m depth.

Ratios of lateral to vertical flow of water from the inner ring at the end of 12 infiltration runs (made after installation of the tensiometers) are calculated in Table 1. For runs where the radial tensiometers were within the buffer ponded-water zone (90-and 120-cm outer rings), values are also given for the first depth of 7.6 cm. These values do not represent the lateral/vertical flow ratios (as the lateral flow was shut out at this depth by the ring walls), but do serve as estimates of error due to soil heterogeneity, experimental measurements, and calculations. Data in Table 1 for some of the runs show negative values of lateral/vertical flow ratio at certain depths. These negative values would indicate either a flow of water from outside toward the central (vertical) axis, or perhaps the result of various errors. Examination of these and the values at 7.6 cm depth reveals that the uncertainty in the calculated lateral/vertical flow may be as much as 10% or more. It would appear then that near the end of infiltration runs, the lateral flow was not significant in any of the runs under the moist field conditions prevailing during the experiments. Only in one out of three cases without a buffer zone (run No. 24) was a high ratio (29%) calculated, and that was in the surface layer (22.9 cm depth).

Average hydraulic conductivities for the different soil layers falling between the tensiometric locations were calculated for each of the runs using the hydraulic head data of Table 1 and final infiltration rates of Fig. 6. The calculated values for the runs with maximum buffer zone of 45 cm (outer ring of 120-cm diameter) are shown in Fig. 10. The drainage period preceding each run is also shown. A wide variability is noted in data for the upper 30 to 40 cm of soil. For the first two runs (no. 15 and 16) made under wetter conditions following a relatively short drainage period, the conductivity values are relatively low but agree fairly well. Values for the next run (no. 17) following a drainage period of 11 days are much higher. For the subsequent runs (no. 18 and 19), the values are closer to those for the first two runs. Variability in calculated conductivity values may be due to different states of saturation under various experiments. Another explanation for this variability in

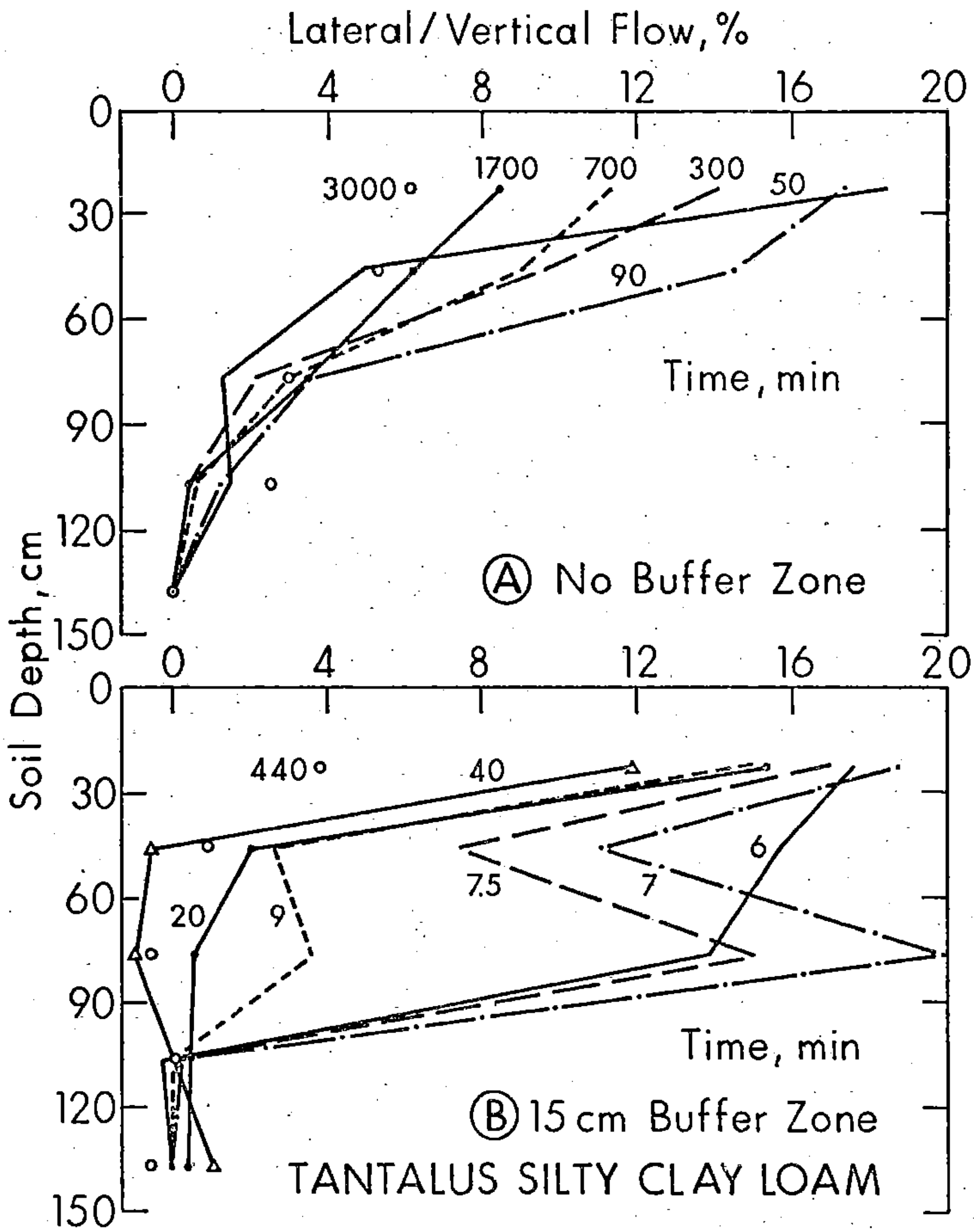

Fig. 9--The percentage of lateral to vertical flow at various depths of the soil profile in the absence of a buffer zone (A) and in the presence of one (B).

Table 1--CALCULATIONS OF THE RATIOS OF LATERAL/VERTICAL FLOW OF WATER FROM THE INNER RING AT END OF INFILTRATION RUNS

Run No.	Buffer Ring Diam. cm	Duration min	Soil Depth cm	-Hydraulic Head, H, at Vertical Axis cm H_2O	-Hydraulic Head, H, at 38-cm Radius cm H_2O	$-\frac{\partial H}{\partial z}$	$-\partial H/\partial r$ At r_1 = 15.2 cm	$\frac{2}{r_1}\frac{\partial H/\partial r}{\partial H/\partial z}$
15	120	232	7.6	- 4	3.5	1.33	0.16	0.015
			22.9	8	8	0.87	0	0
			45.7	26	20	0.67	-0.13	-0.024
			76.2	40	22.5	0.53	-0.37	-0.088
			106.7	85	85	8.67	0	0
			137.16	141	140.5	7.33	-0.01	-0.001
16	120	245	7.6	- 3	3	1.27	0.13	0.013
			22.9	8	8	0.60	0	0
			45.7	19	14	0.93	-0.06	-0.008
			76.2	28	14	0.93	-0.19	-0.026
			106.7	86	18	6.00	0.11	0.002
			137.16	142	141	1.00	-0.02	-0.003
17	120	375	7.6	- 8	2	0.33	0.20	0.078
			22.9	5	4	0.40	-0.02	-0.007
			45.7	16	10	0.53	-0.13	-0.030
			76.2	36	12	1.20	-0.50	-0.054
			106.7	78	76	8.33	-0.42	-0.001
			137.16	142	142	0.87	0	0
18	120	310	7.6	- 5	7	1.20	0.25	0.027
			22.9	6	9	0.60	0.06	0.013
			45.7	17	10	0.60	-0.15	-0.031
			76.2	40	17	1.20	-0.48	-0.052
			106.7	82	78	5.0	-0.08	-0.002
			137.16	145	141	1.07	-0.08	-0.010
19	120	350	7.6	- 4	- 4	0.60	0	0
			22.9	8.5	0	0.67	0.18	0.034
			45.7	20	13	0.53	-0.15	-0.035
			76.2	38.5	14	0.67	-0.51	-0.099
			106.7	79	74	9.67	-0.11	-0.001
			137.16	142	135	1.50	-0.15	-0.013
20	60	425	7.6	- 5	37	0.87	0.88	---
			22.9	15	41	0.93	0.55	0.075
			45.7	30	46	0.67	0.34	0.065
			76.2	51	61	0.80	0.20	0.034
			106.7	87	90	2.56	0.06	0.003
			137.16	139	140	1.11	0.02	0.000

Table 1 (CONT.)

Run No.	Buffer Ring Diam. cm	Duration min	Soil Depth cm	-Hydraulic Head, H, at Vertical Axiz cm H_2O	38-cm Radius cm H_2O	$\frac{\partial H}{\partial z}$	$-\partial H/\partial r$ At r_1 = 15.2 cm	$\frac{2}{r_1}\frac{\partial H/\partial r}{\partial H/\partial z}$
21	60	440	7.6	- 6	28	1.00	0.71	------
			22.9	15	30	1.07	0.31	0.038
			45.7	33	35	0.60	0.04	0.008
			76.2	47	34	0.60	-0.27	-0.058
			106.7	86	87.5	4.33	0.03	0.007
			137.16	136	134	1.00	-0.04	-0.005
22	0	450	7.6	- 2	106	1.40	2.27	-----
			22.9	25	85	1.33	1.26	0.121
			45.7	47.5	78	0.73	0.64	0.119
			76.2	67	81	0.73	0.29	0.051
			106.7	105	102	1.87	-0.06	-0.004
			137.16	139.5	147	0.87	0.16	0.023
23	0	3000	7.6	- 2	58	1.40	1.26	-----
			22.9	24.5	52	1.20	0.58	0.062
			45.7	44	58	0.80	0.29	0.047
			76.2	63.5	76.5	1.20	0.27	0.029
			106.7	94.5	104	1.00	0.20	0.026
			137.16	142	144.5	4.00	0.05	0.002
24	0	450	7.6	- 2	121	1.13	2.58	-----
			22.9	20	78	0.53	1.22	0.293
			45.7	44.5	70	0.47	0.54	0.147
			76.2	64.5	73	0.60	0.18	0.038
			106.7	98	100.5	5.33	0.03	0.001
			137.16	145	141	3.33	-0.08	-0.003
25	90	370	7.6	- 6	- 15	0.40	-0.19	-0.061
			22.9	5.5	4	1.07	-0.03	-0.004
			45.7	18	18	0.47	0	0
			76.2	29	38.5	0.60	0.19	0.043
			106.7	69.5	76	7.00	0.14	0.003
			137.16	142	136.5	1.50	-0.09	-0.008
25	90	330	7.6	- 3	1	0.60	0.08	0.018
			22.9	7	5	0.53	-0.04	-0.010
			45.7	17	18	0.47	0.02	0.006
			76.2	32	36	0.60	0.08	0.018
			106.7	71	74.5	3.00	0.07	0.003
			137.16	144	135.5	2.17	-0.09	-0.006

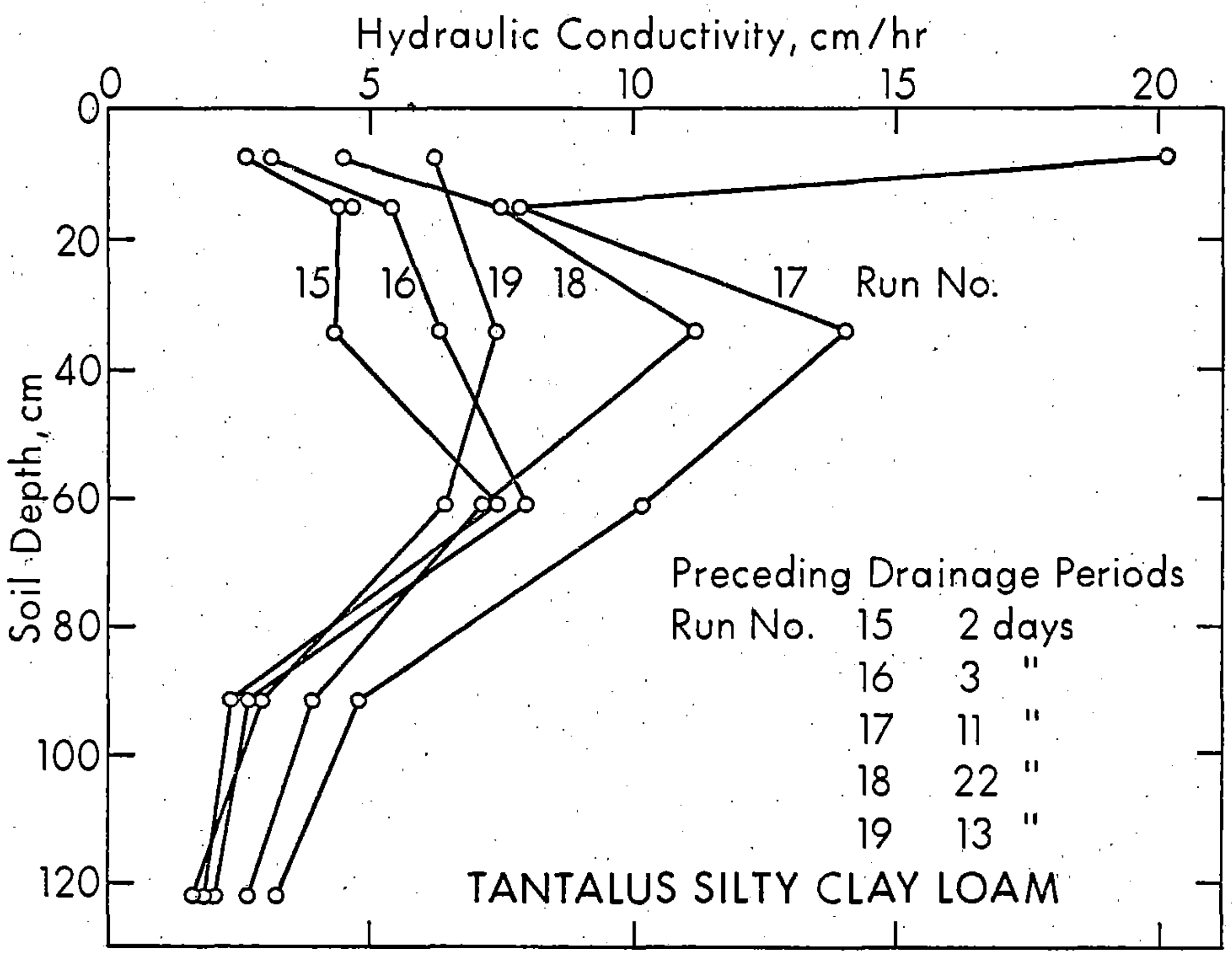

Fig. 10--Average hydraulic conductivities for the different soil layers lying between the various tensiometer depths. Values are calculated for infiltration runs with a buffer ring of 120-cm diameter.

conductivities (noted mostly) in upper portions of the profile may lie, as stated earlier, in the shrinking and swelling of Tantalus soil upon drying and wetting, which may not be completely reversible. Under natural conditions, this soil is known to remain near saturation under the high rainfall conditions prevailing in this forest location.

Values for hydraulic conductivities of different soil layers averaged over all the runs for a given buffer zone are presented in Fig. 11. A correction was made for lateral flow in run no. 24 which showed a high ratio of lateral/vertical flow at one depth. The values for different buffer-zones show a variability of ±2.2 cm/hr. There is no consistent indication of the effect of buffer-zone size on the conductivities. The average of all conductivities shows an increase from 7.1 cm/hr at the soil surface to 9.3 cm/hr at 60 cm depth, but this trend reverses at 60 to 120 cm depth where the average value is 2.98 cm/hr. This may reflect the contribution of indurated layers noted at depths of 90-107 cm as stated in experimental methods.

The conclusion reached above, that there was no appreciable lateral flow in the soil profile at the end of 5-7 hours of water infiltration, was somewhat contrary to expectation. This is because the ironstone hardpan did not seem to appreciably impede the vertical downward movement of water. Intact samples of the three layers of hardpan were collected and their saturated hydraulic conductivities measured in the laboratory. These were found to be 0.135, 0.368 and 1.03 cm/hr, from top to bottom, respectively. The values for the upper two ironstone layers are very low compared with the values (between 7 and 9 cm/hr) for the top part of the soil profile. However, the average conductivity for the part of the soil profile between 90 and 120 cm depth (containing the hardpans), as determined by the tensiometric and flow rate measurements, was between 3 to 5 cm/hr. These differences can be explained by the fact that the hardpan is not a continuous uniformly developed mass. Approximate estimates using means of the above values show that intact indurated sections of the hardpan impede vertical water movement through only 53% of the effective area.

Direct vertification of the magnitude of lateral flow was attempted during two infiltration runs by measuring overall infiltration rates in the 30-cm ring as well as the lateral outflow rates on the specially installed trays (Fig. 12). The runs were continued for more than 40 hours. Lateral flow of water was received only on one tray located at 90 cm depth directly above the ironstone hardpan. The lateral flow rates measured at this depth expressed as a percentage of total flow rates in the ring are shown in Fig. 13, as a function of time. Run no. 2 was made when the soil was "drier" than that for run no. 1, which explains the higher percentage of lateral flow encountered in run no. 2. In both cases, the lateral flow increased with time from the movement the water first appeared on the tray (50-80 min) until nearly 300 min had elapsed. Subsequently, lateral flow decreased with time up to 2,500 minutes. At the peak, lateral flow was 3.5% of the total flow from the ring in one run and 10.2% in the other. The initial increase of lateral flow with time as measured in the second experiment may be contradictory to the tensiometer estimates, above, which indicate that lateral flow is maximum at the beginning and decreases with time. It may indicate, however, that in

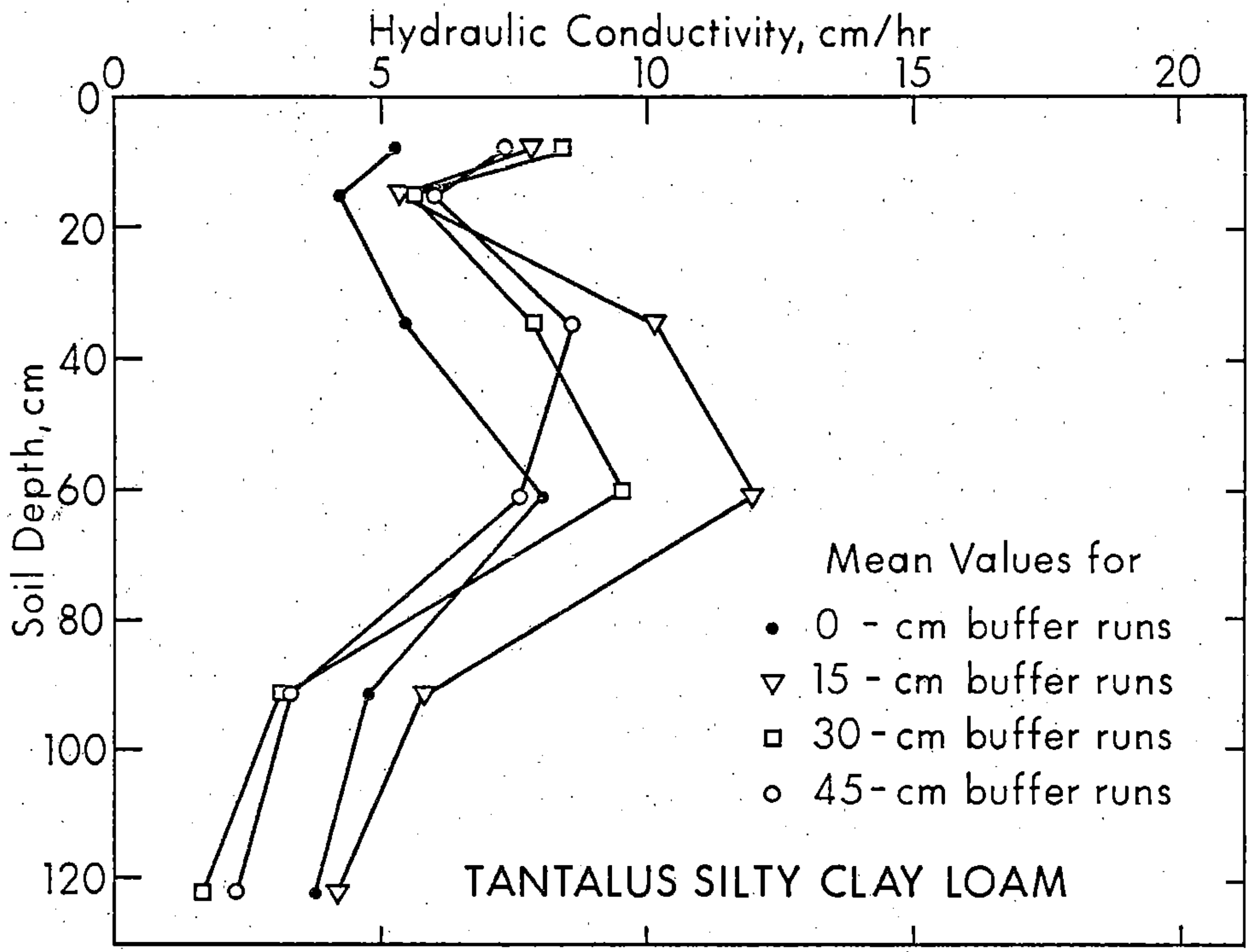

Fig. 11-Average hydraulic conductivities for the different soil layers as calculated for infiltration runs with different buffer aones.

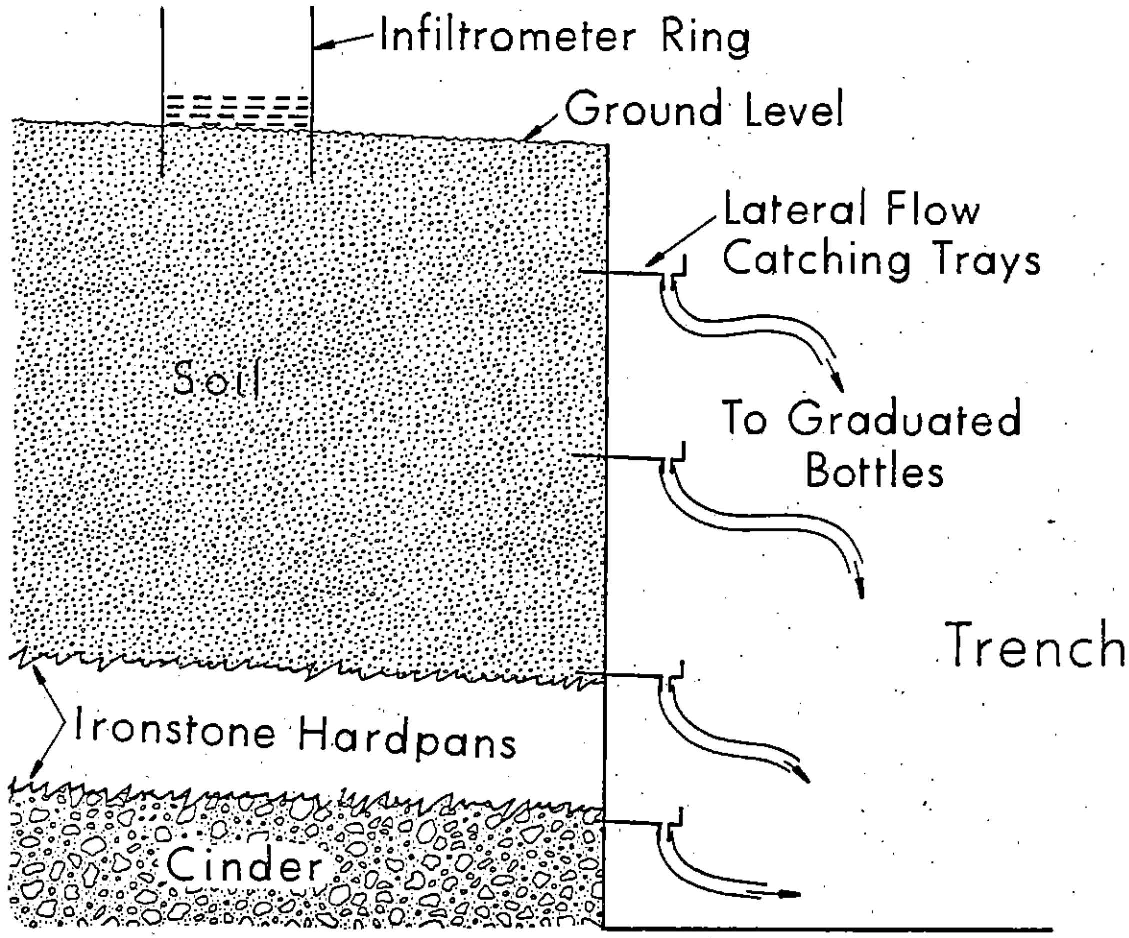

Fig. 12-- Experimental set-up for direct measurement of lateral flow, with catching trays at 25, 60, 90, and 110 cm depths.

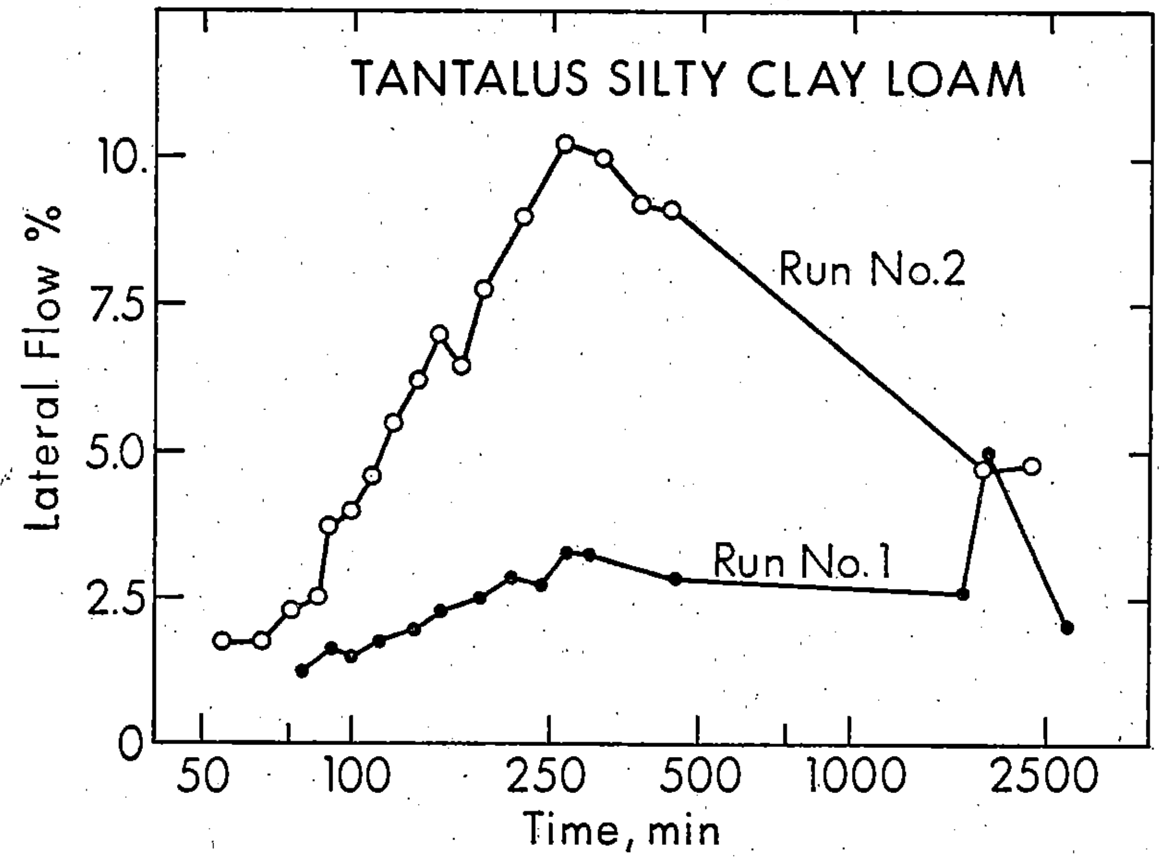

Fig. 13--Lateral flow received on the catching tray at 90 cm, expressed as percent of the total flow from the infiltrometer ring, as a function of time for two different runs.

direct measurement, a thorough wetting of the 90 cm of soil between the ring and the trays is needed in the early stages of infiltration before total lateral flow is to be realized. Thus the lateral flow appearing at the tray at early stages is only a fraction of the possible total lateral flow which is achieved with time as the wetting of the soil progresses to near-saturation. Beyond this point, a steady state of water flow is approached with almost equal proportions of lateral flow for the two runs, as expected. The percentages of lateral flow shown in Fig. 13 are very much within the estimates based on tensiometeric data for a no-buffer zone case. It is recognized however that some water could have flowed laterally against the (12%) slope of the ironstone layers, and thus was not included in measurements of flow on the trays.

Conclusions

It may be concluded from the results presented above that the combined use of multi-depth tensiometers with ring infiltrometers provides a good means to study the hydraulic properties of a soil profile. The extent of lateral flow can be estimated and corrected for. For the Tantalus soil at the prevailing initial moisture conditions (moist to wet) of the present experiments, the lateral flow from an inner ring of 30-cm diameter was practically eliminated when a buffer ring of 90-cm diameter was employed. The lateral flow generally decreased with time during each run so that infiltration rates were not significantly affected by lateral flow after longer times (5-7 hrs) even when a buffer ring of only 60-cm diameter was used.

Findings based on use of ring infiltrometers alone may not always apply to a different soil or to the same soil at different initial moisture conditions. In general, therefore, it would be desirable to use the multi-depth tensiometers with the ring infiltrometers and obtain hydraulic characteristics of the soil profile.

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Measuring Hydrologic Properties of Soil Profile Using a Double-Ring Infiltrometer with Multiple-Depth Tensiometers: 2. Drainage Flow Rates and Unsaturated Conductivities

In first paper of this series, it was shown how infiltration rates and saturated hydraulic conductivities could be measured in a small-size ring infiltrometer by using multi-depth tensiometers (having porous cups for all the desired depths on one stem) to measure vertical and lateral hydraulic gradients, and to correct for lateral flow effects if necessary. For this paper, the objective is to determine hydraulic gradients, soil-water flow rates and unsaturated hydraulic conductivities of the soil profile during the drainage phase. These calculations are made from transient tensiometric readings at different depths of the soil profile. The soil's suction-water content relationships required for the calculations are measured on undisturbed soil cores.

Methods and Materials

The experimental methods and materials for infiltration and drainage measurements in a double ring infiltrometer equipped with multiple-depth tensiometers have been fully described in the first paper of this series. The soil was Tantalus silty clay loam, located on the island of Oahu, Hawaii. The infiltrometer consisted of an inner ring of 30 cm diameter, and a concentric outer (buffer) ring of either 60, 90, or 120 cm diameter. A multi-depth tensiometer installed at the center of the rings, forming the central vertical axis, had porous cups located at 7.6, 22.9, 45.7, 76.2, 106.7, and 137.2 cm depths from the soil surface. Following 11 of the ponded-water infiltration runs, each lasting for 5 to 7 hours, frequent tension measurements were made for the drainage periods of 11 to 23 days. The 11 infiltration runs consisted of 2 to 4 replications for each of the cases involving different width of buffer zone. During drainage, the soil surface inside the rings was covered with a sheet of plastic and a sheet of 2 cm thick styrofoam, cut to size, in order to prevent evaporation, as well as reduce condensation and temperature fluctuations beneath the plastic. To keep out the natural rain water, a 6 x 6 meter umbrella was erected over the experimental area. To eliminate interference of runoff from adjacent areas, a diversion drain was dug upslope.

After the field measurements were completed, a trench was dug beneath the rings, and 3 to 7 undisturbed soil cores were collected from each tensiometric depth. A San Dimas core sampler, which consists of an auger rotating around a stationery collection tube (Andrews and

Broadfoot, 1958), was specially constructed to take 11 cm diameter, 7.5 cm long cores. Suction-water content relationships of these soil cores were measured by hanging water columns during drying and wetting cycles between 0 and 200 cm H_2O suctions.

The transient soil-water tension measurements (obtained from the multiple-depth tensiometer at the vertical axis) during the above drainage and wetting periods were analyzed to determine the unsaturated hydraulic conductivity for different layers of the soil profile. The suction-water content relationships measured on undisturbed soil cores were used in these determinations. The technique of analysis was essentially the same as given by Nielsen et al. (1973). The difference was that a least-square cubic spline fitting (de Boor and Rice, 1968) was employed to evaluate the hydraulic gradients, given by slopes of the field tensiometric hydraulic head data. A sliding least-square parabolic fit was used to evaluate the time derivative for determination of flow rates.

Results and Discussion

Hydraulic head changes in the soil profile during the drainage following two of the infiltration runs are shown in Fig. 1. The data in Fig. 1A are for a case involving the maximum buffer-zone radial width of 45 cm (outer ring of 120 cm diameter) used during infiltration, while those in Fig. 1B are for a case involving no buffer zone. The curves drawn through the points for the few selected times given in Fig. 1 are the cubic spline functions fitted to the data of hydraulic head vs. soil depth on the least-squares basis, using one internal knot as indicated by a solid dot on each curve. The end knots of the spline were located at zero and 150 cm depths. The time values noted against the curves are relative to the zero time when water supply to the rings was stopped. The water ponded in the rings was still infiltrating at zero time.

The two-piece cubic spline curves show generally good fit to the data as indicated by Fig. 1. At large times, the hydraulic head values measured near the soil surface, at 7.6 cm depth, fluctuated with time, indicating the plastic and styrofoam sheets were not completely effective in eliminating evaporation and condensation. The curve for the highest time in Fig. 1B also shows a reversal of gradients between 60 and 90 cm depths, due to some unknown reasons.

The suction-water content relationships (the soil-water characteristics) measured on the undisturbed soil cores for different soil depths are presented in Figs. 2 to 4. For each depth, the data are for a drying and wetting cycle between 0 and 200 cm H_2O suctions. Each data point is a mean of 3 to 7 individual values. The smooth solid curves are the least-squares fits of the power-form equations given in the Figs. The fits were made to the data points between 10 and 200 cm suctions, separately for drying and wetting cases. The equations describe the water characteristic data quite well, the results being better for the drying data than for the wetting data. The water characteristics of the top soil at 7.6 and 22.9 cm depths are essentially similar. The subsoil from 45.7 to 76.2 cm depths retains more water at 200 cm suction than

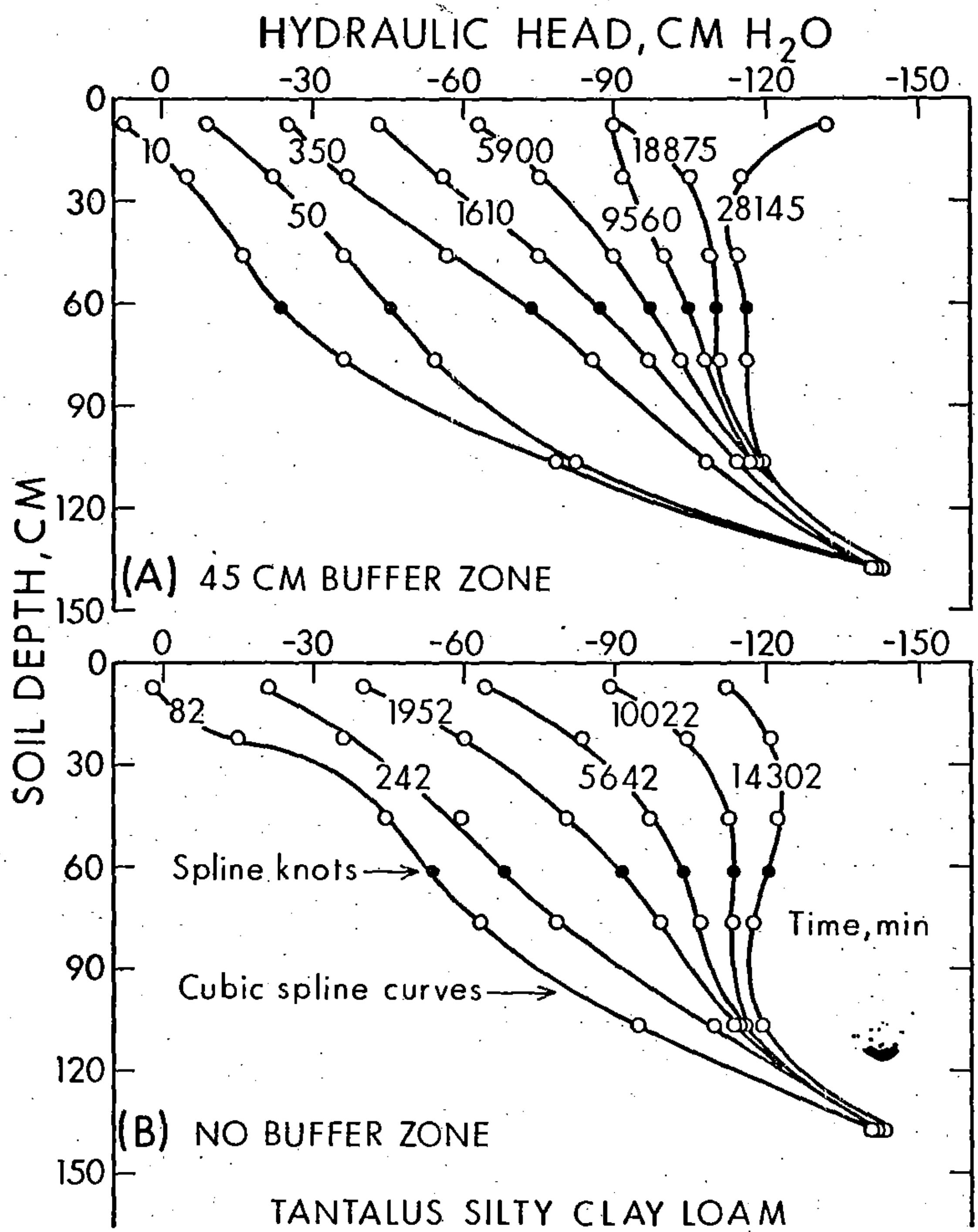

Fig. 1--Hydraulic head changes in the soil profile during the drainage following infiltration involving two different buffer zones. The curves are cubic spline functions fitted to the data points.

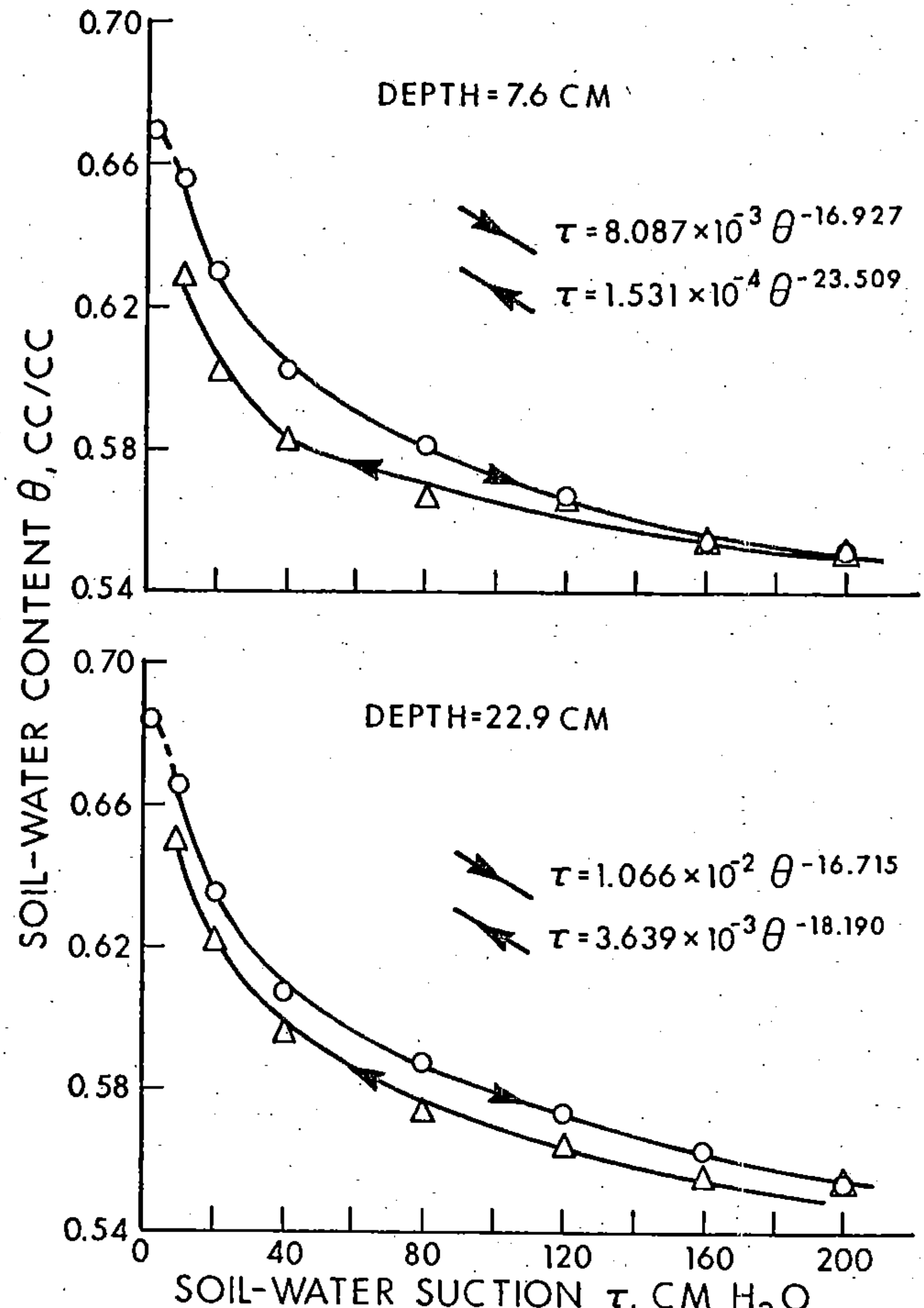

Fig. 2--Soil-water content-suction relationships for undisturbed soil cores taken at 7.6 and 22.9 cm depths. The curves represent the given equations fitted to the data for wetting and drying cycles.

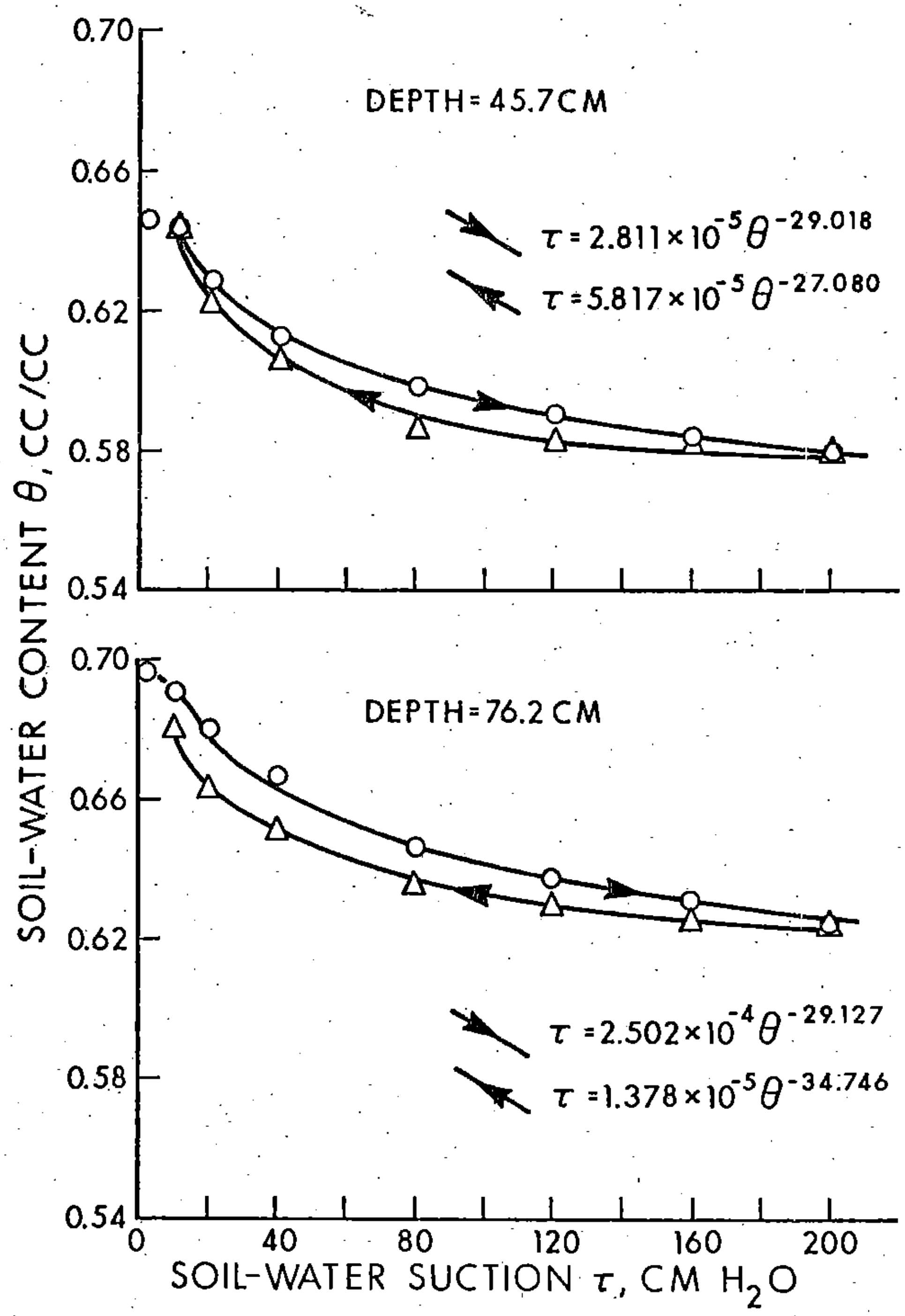

Fig. 3--Soil-water content-suction relationships for undisturbed soil cores taken at 45.7 and 76.2 cm depths.

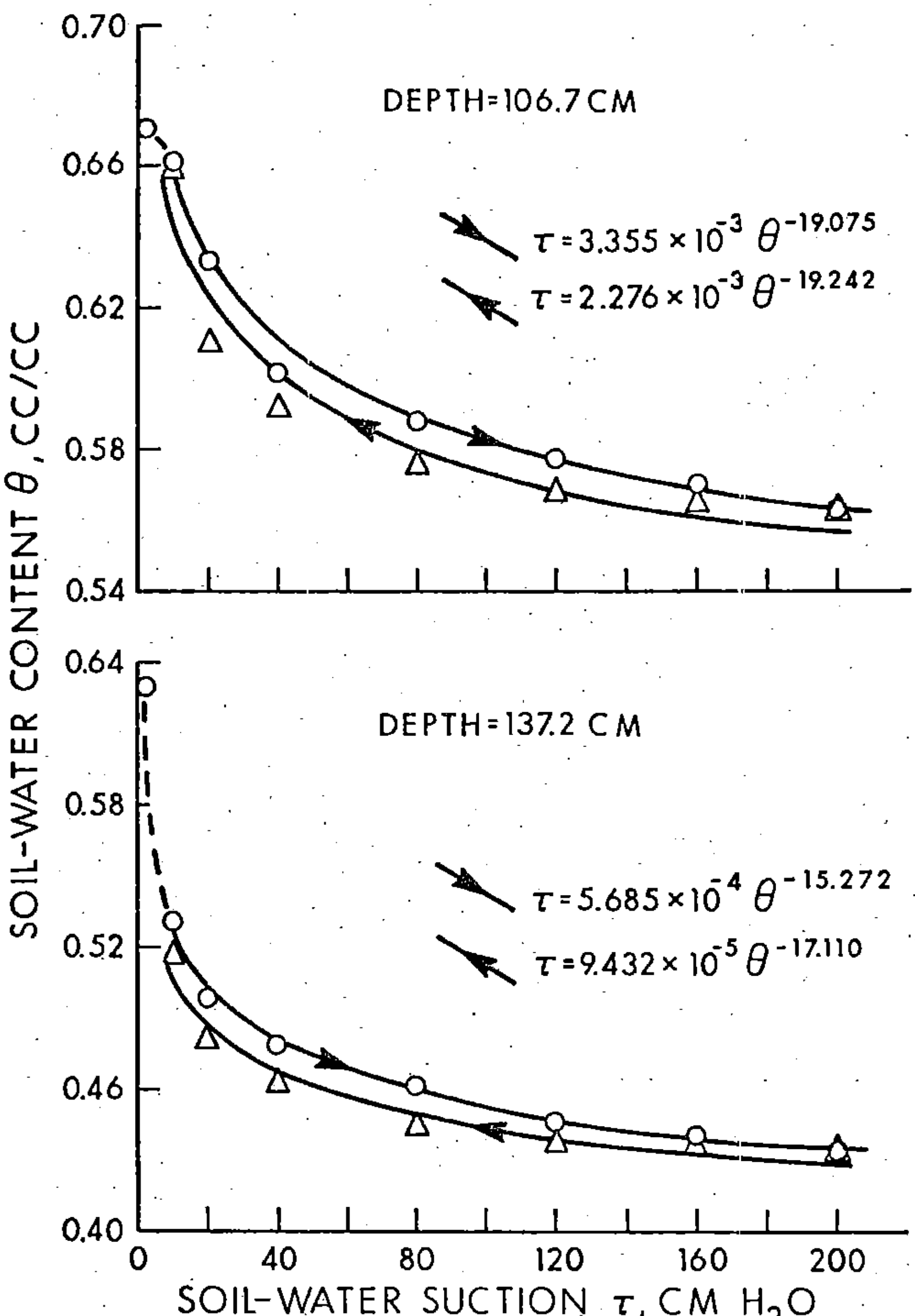

Fig. 4--Soil-water content-suction relationships for undisturbed cores taken at 106.7 and 137.2 cm depths.

does the top soil, indicating a larger proportion of fine pores. The soil layer at 106.7 cm depth is again very similar to the top soil in water retention properties. However, the partly-weathered cinder layer at 137.2 cm depth is drastically different from the upper layers in retaining much less water.

It is interesting to note the hysteresis effect existing between the drying and wetting curves for all the soil depths. However, the hysteresis between 0 and 200 cm suction causes a maximum difference of only about 0.01 in the volumetric water content.

From the tensiometric measurements such as presented in Fig. 1, and the soil-water characteristic curves of Fig. 2 to 4, water stored in the soil profile and deep percolation below a given depth were calculated as a function of time during the drainage process. Fig. 5 shows the changes in cm of water stored in upper 60 cm and upper 120 cm of soil profile during two of drainage runs, one involving the maximum buffer zone and the other no buffer zone. The cumulative amount of deep percolation can be easily calculated from these data. The results indicate practically no effect due to the absence of a buffer zone on the calculations of the water stored at different times. The data further show that after two weeks of drainage, the deep percolation below 120 cm depth is only about 7 cm of water, nearly 8.5 percent of the total initial storage. The storage and, hence, deep percolation can, for the most part, be described for this soil by a simple logarithmic equation as indicated by the data in Fig. 5. The data seem to follow a straight line between times of 10 and 20,000 min.

The hydraulic conductivity-water content relationships calculated from the above tensiometric data and water characteristics are presented as semilog plots in Fig. 6 to 9 for four different soil profile depths. In each plot, the data points stemming from different buffer zone used during infiltration are distinguished by different symbols. The results indicate good determinations of the hydraulic conductivity functions by the techniques employed here, as compared to the field determinations by other methods. There is practically no difference due to the size of buffer zone used during infiltration preceeding the drainage process for which the calculations are made. It is noted that the effect of water content on hydraulic conductivity follows almost an identical pattern for the upper two soil layers. In both layers the hydraulic conductivity decreased approximately to one-half the initial value by a 2.5% reduction in volumetric water content. However, the hydraulic conductivity of the soil at the two lower depths appeared to exhibit more drastic reduction (15 to 20 fold) over the same reduction in water content.

It may be concluded from the results presented above that the tensiometric measurements in a ring infiltrometer can give very satisfactory determination of water storage, deep percolation, and unsaturated hydraulic conductivities during the drainage process. It is clearly illustrated, in contrast to the saturated cases discussed in the first paper, that in the absence of replenishment by rainfall, drainage of water from the profile results in only limited contribution to ground water recharge.

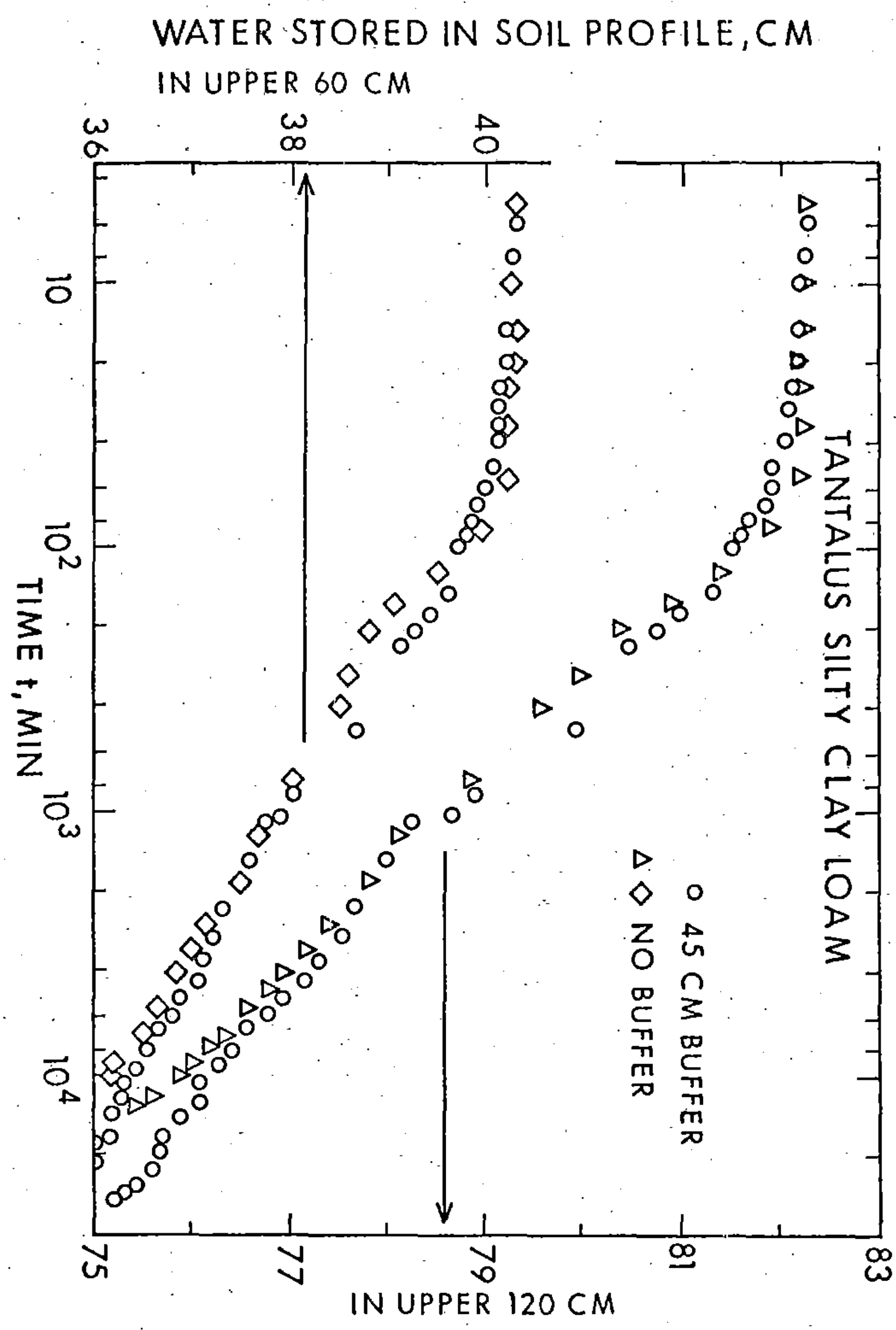

Fig. 5--Water stored in soil profile up to 60 and 120 cm depths as a function of time during drainage following infiltration with the maximum buffer and no buffer zone.

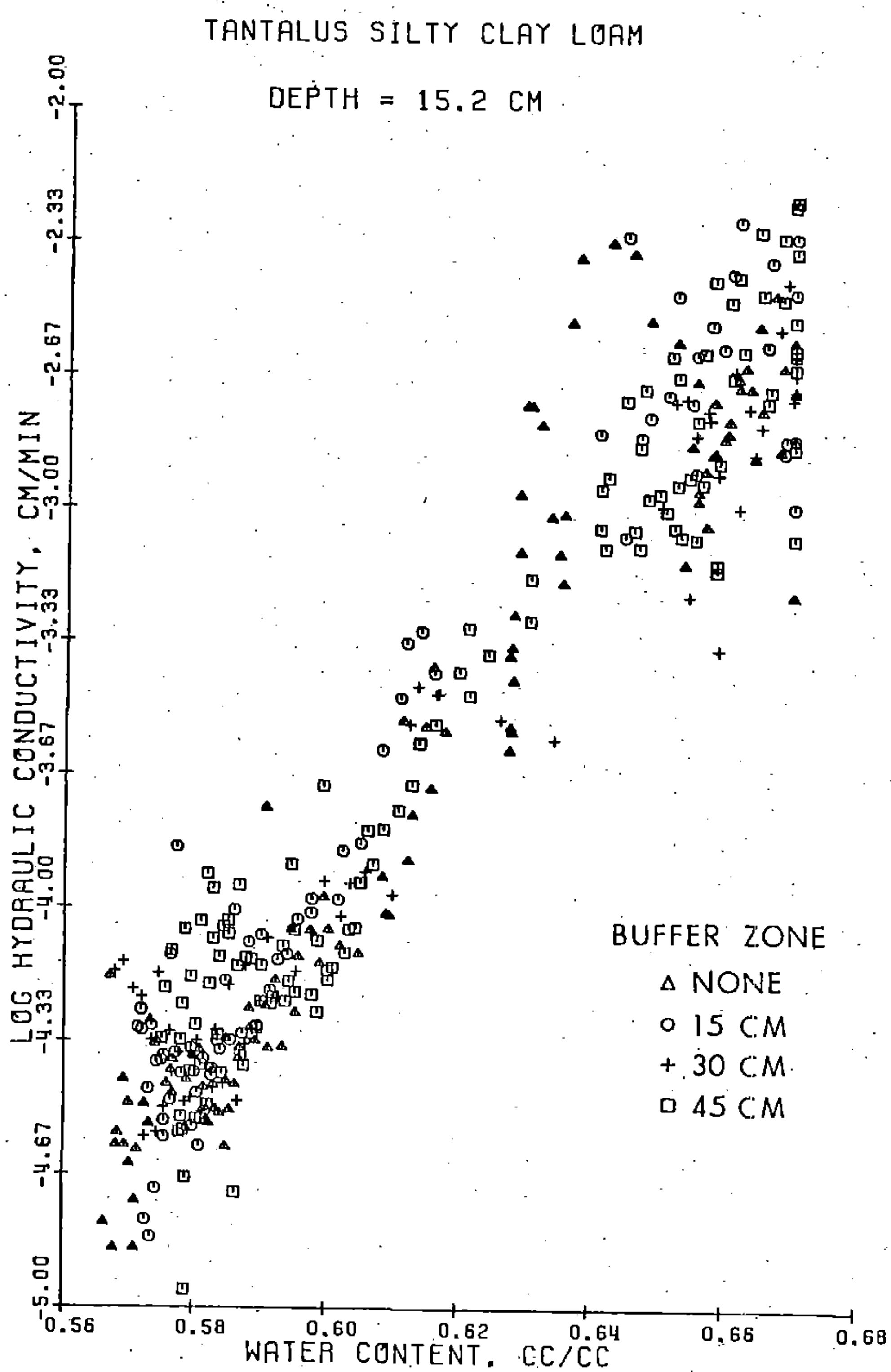

Fig. 6--Hydraulic conductivity as a function of water content for 15.2 cm soil depth, as determined during drainage following infiltration involving buffer zone of different radial widths.

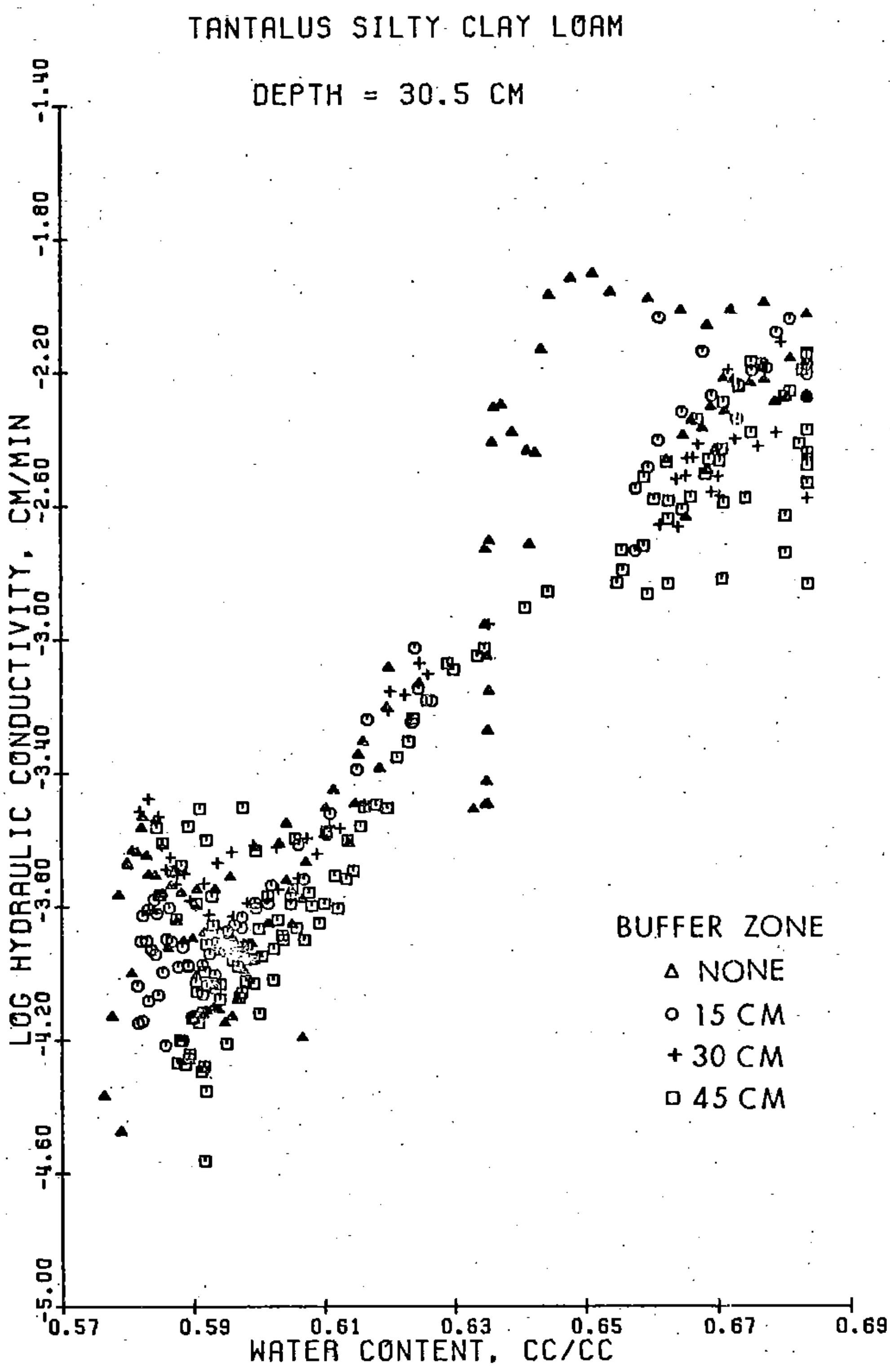

Fig. 7--Hydraulic conductivity as a function of water content for 30.5 cm soil depth. The different symbols indicate different buffer zones.

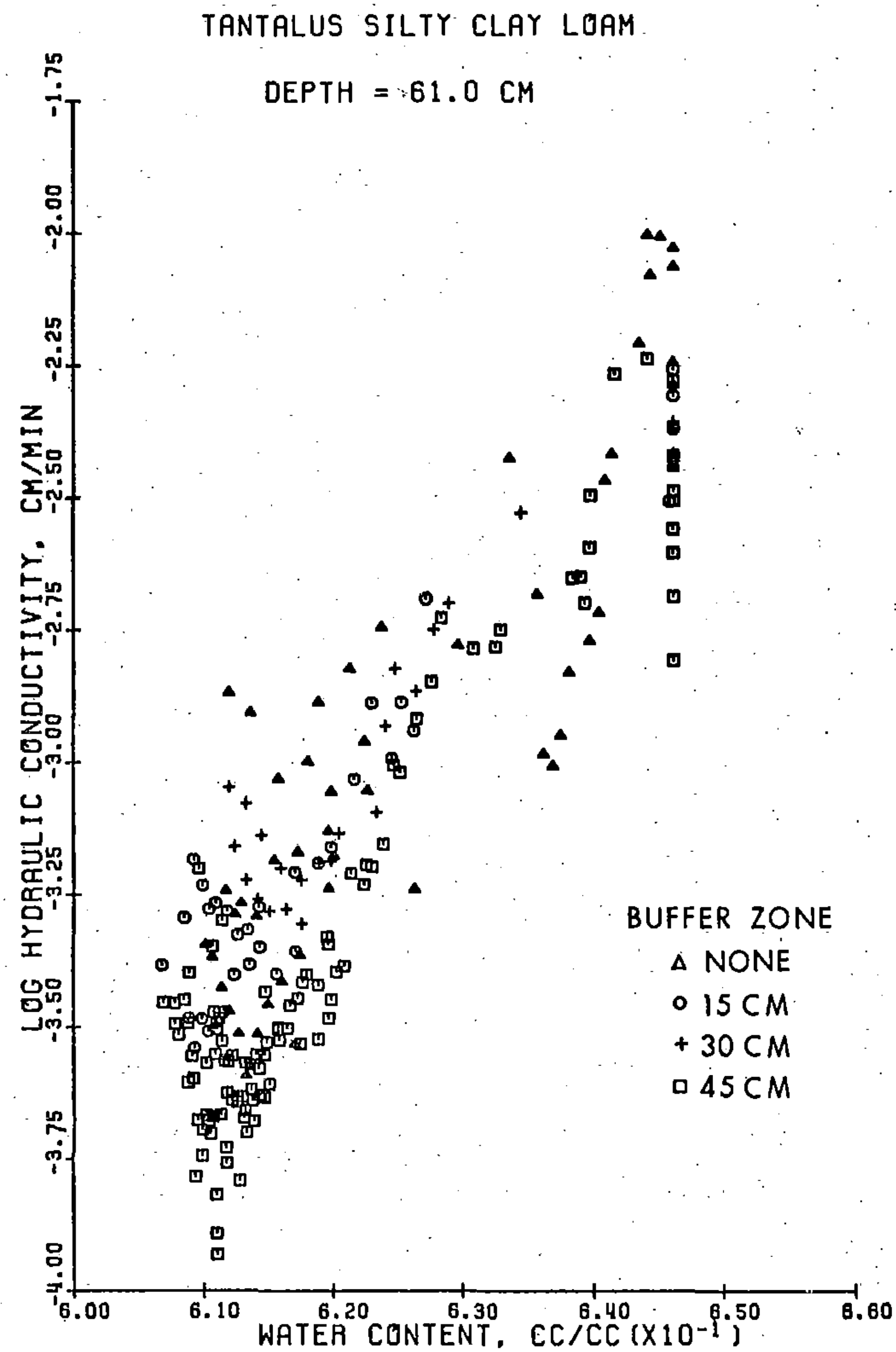

Fig. 8--Hydraulic conductivity as a function of water content for 61.0 cm soil depth. The different symbols indicate different buffer zones.

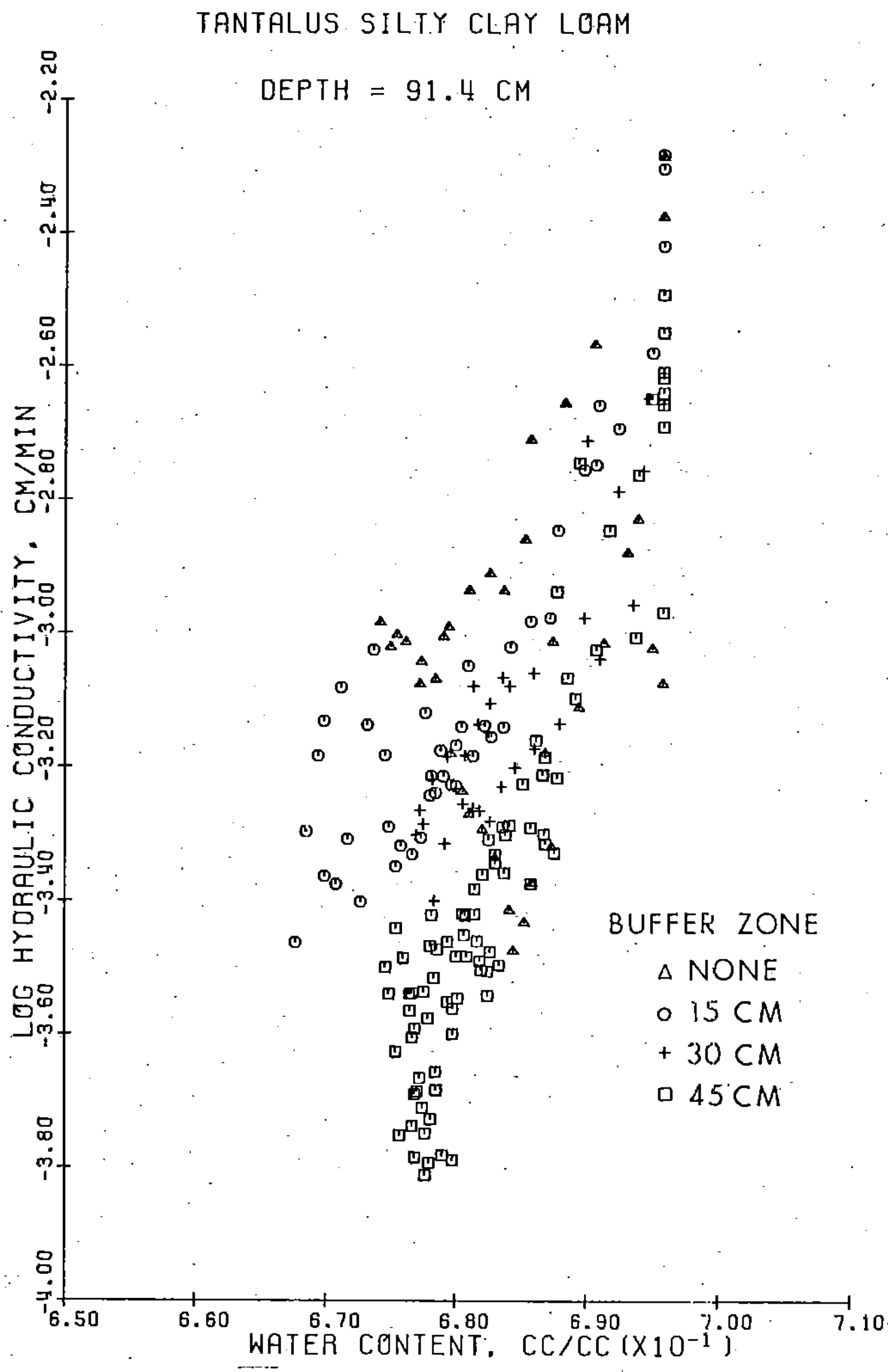

Fig. 9--Hydraulic conductivity as a function of water content for 91.4 cm soil depth. The different symbols indicate different buffer zones.

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1. Andrews, L. A., and W. M. Broadfoot. 1958. The San Dimas Core Sampler. Soil Sci. 85:297-301.

2. de Boor, C. and J. R. Rice. 1968. Least Squares Cubic Spline Approximation: 1. Fixed Knots. CSD TR 20, Purdue University Computer Sciences Department.

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Measuring Soil Hydrologic Properties on a Forest Watershed Using Field-Plot Tensiometric Technique: 1. Water Conductivities and Drainage Water Yield

Under natural conditions of a forest watershed, where the rainfall intensities may range from very low to very high and the frequency of rainstorms may vary widely, the proportion of rainfall entering the ground water resources may be very significantly influenced by unsaturated-flow properties of the soil profile. Since both the soil-water conductivities and the soil-water potentials governing the water flow (during either infiltration or drainage) change very drastically with the change in degree of soil's saturation (with water), a knowledge of hydraulic conductivity and potential as a function of soil-water content is an essential pre-requisite to prediction of water catching, water yield, and storage capabilities of a watershed.

The hydraulic conductivities of a field soil are best measured in situ. A generally recommended method (Nielsen et al., 1973) is to choose a large-size representative plot, near the center of which tensiometers going to several selected soil depths are installed. The soil profile is first saturated with water by allowing a large quantity of ponded water to infiltrate, which also yields the saturated hydraulic conductivities. During the subsequent process of drainage, soil-water tension changes at different depths are recorded with time while the soil surface is protected (with a plastic sheet) from evaporation and rain. The tension data are analyzed according to the Richard's Equation of unsaturated flow (Nielsen et al., 1973) to determine the water conductivities as a function of soil-water content for each soil horizon, assuming a prior knowledge of soil-water potential (or suction, since the potentials are negative) as a function of water content. The latter relationship is measured separately either by field sampling or neutron meter measurements during drainage or by laboratory measurements on undisturbed soil cores.

The forest watersheds have certain unique characteristics that need to be considered in using the above field-plot tensiometric technique. The terrain is generally hilly, so that a representative plot may have an appreciable slope, thus requiring an alternative to the ponding technique for initial saturation of soil and obtaining saturated hydraulic

conductivities. The effect of slope and slope-soil depth interactions on soil-water tension measurements may be important. The steepness of land may also enhance subsurface lateral flow from outside surroundings to the plot, and thus interrupt the drainage cycle. This would be specially so in case of a rainfall during the period of drainage cycle measurements. A watershed in tropics, such as in Hawaii, may receive some rainfall at any time of the year. The present studies indicated another complication; a rainfall during the drainage cycle caused cooling of the plastic sheet covering the plot, enhanced condensation under the sheet and, as a result, fluctuation of soil-water tensions near the soil surface.

The present study sought to evaluate the field-plot tensiometric technique for determining unsaturated water conductivities and water yield (drainage) characteristics of a forest watershed in Hawaii, and to assess the effect of slope on the measured properties. Adequate precautions were taken to prevent the subsurface lateral flow.

Material and Methods

In watershed of the University of Hawaii Lyon's Arboretum, a nearly 45 sq m (11 x 4.2 m) plot was demarcated in a relatively-undisturbed forest area. Tall trees covered the plot from all around, but the plot itself contained only the undergrowth of grass and some short plants. The plot surface was uneven, but generally sloping in one direction, along the length, with an average slope of nearly 18 per cent.

In order to prevent the subsurface lateral flow from outside the plot, a water-impermeable siding, made from 3 m x 1.2 m x 1.6 mm galvanized iron sheets, was installed 1 m deep and 20 cm above the surface all around the plot. For placing the siding, a 60 cm wide trench was dug around the plot and then back-filled with the original soil. An outlet was provided in the siding for runoff from the plot. Three sets of tensiometers were installed in the plot along the middle line running parallel to the slope and length, as shown by a diagram in Fig. 1. The middle set of tensiometers was located around the center of the plot, and the other two sets were about 12 ft away from the center, one upslope and the other downslope. Each set had five tensiometers, one for each of the soil depths of nearly 7.5, 30, 60, 90, and 120 cm below the surface at the individual locations. For installation of a tensiometer, the hole carefully made with a screw auger was slightly bigger than required in dimensions. It was filled with a medium-thick soil slurry and then the tensiometer stem was gently slided into it to the required depth. This slurry hopefully plugged the gaps between the tensiometer stem and the surrounding soil. The five tensiometers of a set were connected by 3 mm nylon tubing to a corresponding set of mercury manometers located outside the plot, adjacent to the nearest boundary. The tensiometer-manometer assemblies were locally constructed.

Performance of tensiometers was satisfactorily observed for nearly a month. Following a heavy rainstorm, the entire plot was covered with double-layer black polyethylene sheet. Holes were made in the plastic sheet at appropriate locations to allow the tensiometer tubes to come

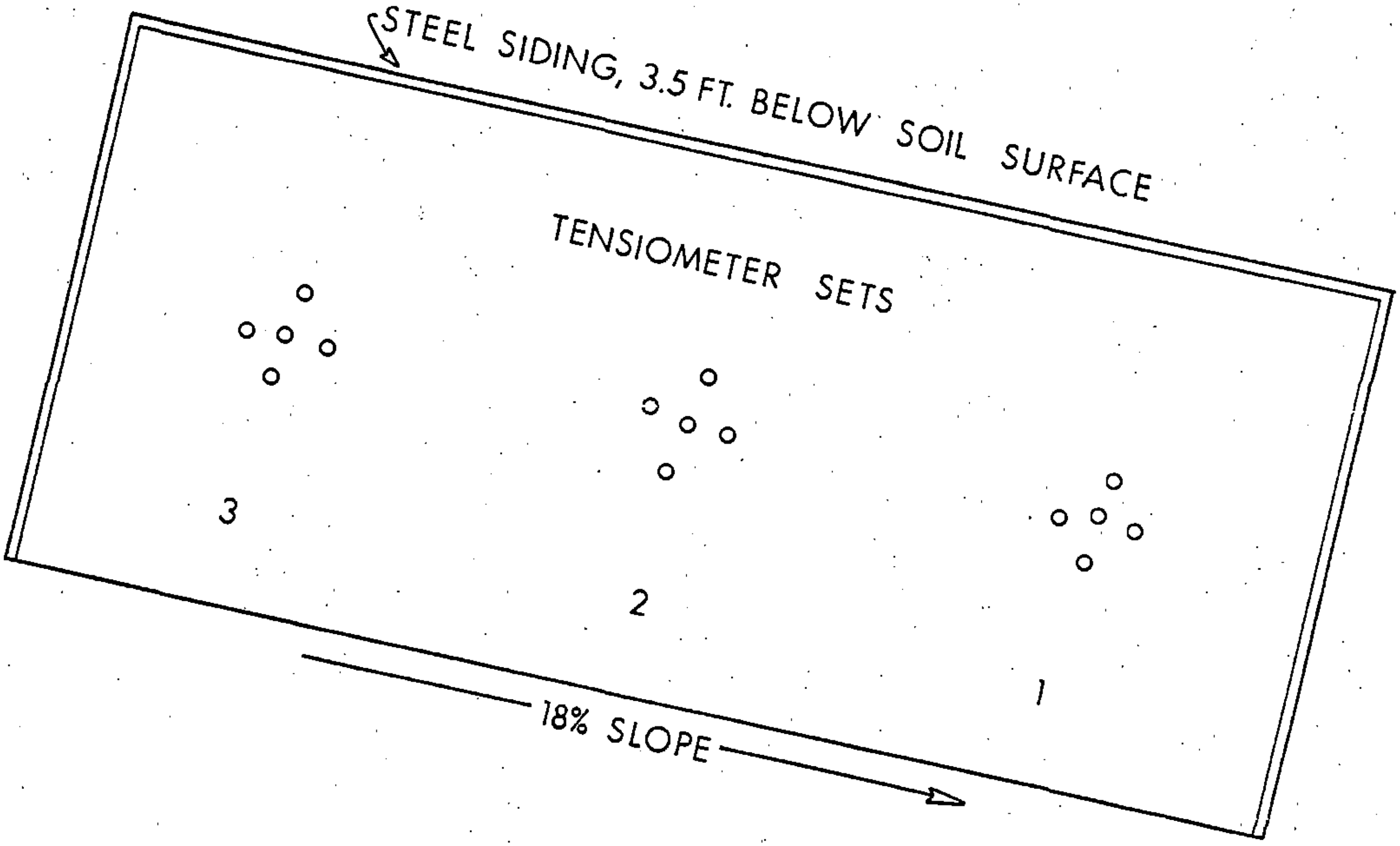

Fig. 1--A schematic drawing of the forest-watershed plot showing location of the three tensiometer sets along the slope.

through. The openings around the tubes were sealed with water-repellent tapes to prevent rain-water seeping through them. Soil-water tensions were recorded at short time intervals on the first day after covering the plot, then twice a day for a while and tapered down to once a day or longer interval later. Initially, the tensions for 7.5 cm depth showed appreciable fluctuation with time, due possibly to temperature changes and condensation beneath the plastic sheet. The area around the tensiometers was painted white to reduce temperature variations. The seals around the tensiometer stems were reinforced to check some suspected rain-water seepage through the tapes. The drying of the plot progressed very slowly and the measurements were continued for 5 months.

After the field measurements were completed, a trench was dug near the plot and 3 to 4 undisturbed soil cores were collected from each tensiometric depth. A San Dimas core sampler, which consists of an auger rotating around a stationery collection tube (Andrews and Broadfoot, 1958), was specially constructed to take 11 cm diameter, 7.5 cm long cores. Suction-water content relationships of the field soil were assumed to be given by laboratory measurements on these cores by hanging water columns during drainage and wetting cycles between 0 and 200 cm H_2O water suctions. For some of the cores, measurements were also made between 0 and 860 cm suctions.

The soil-water tension data and the suction-water content data were analyzed to determine the unsaturated hydraulic conductivity for different layers of the soil profile. The technique of analysis was essentially the same as given by Nielsen et al (1973). The difference was that a least-squares cubic spline fitting (de Boor and Rice, 1968) was employed to evaluate the hydraulic gradients. Furthermore, a sliding least-squares parabolic fit was used to evaluate the time derivative for the determination of flux.

Results and Discussion

The suction-water content relationships (the soil-water characteristics) measured on undisturbed soil cores for four different soil depths of the watershed are presented in Fig. 2 and 3. For each depth, the data are given for a drying and wetting cycle between 0 and 200 cm H_2O suctions. For first two depths of 15 and 30 cm, the data are also given for a cycle between 0 and 860 cm. There is appreciable hysteresis between wetting and drying curves for these latter two cases in Fig. 2. Between 0 and 200 cm suction, the hysteresis is less, as expected. The data also indicate that the amount of water retained at higher suctions increases with depth, showing greater proportion of smaller pores.

The hydraulic head changes with time at different depths in the soil profile as measured by individual units in one of the tensiometer-sets (set no. 1) are presented in Fig. 4. The data indicate that the soil-water tension (negative of hydraulic head minus soil depth) are very slow. In five months of drainage, the tensions in the surface soil did not exceed 50 cm H_2O. This suggests that the water conductivities are very low at even small soil-water tensions. Fig. 2 indicates that at these small tensions, the soil-water content decreases very sharply.

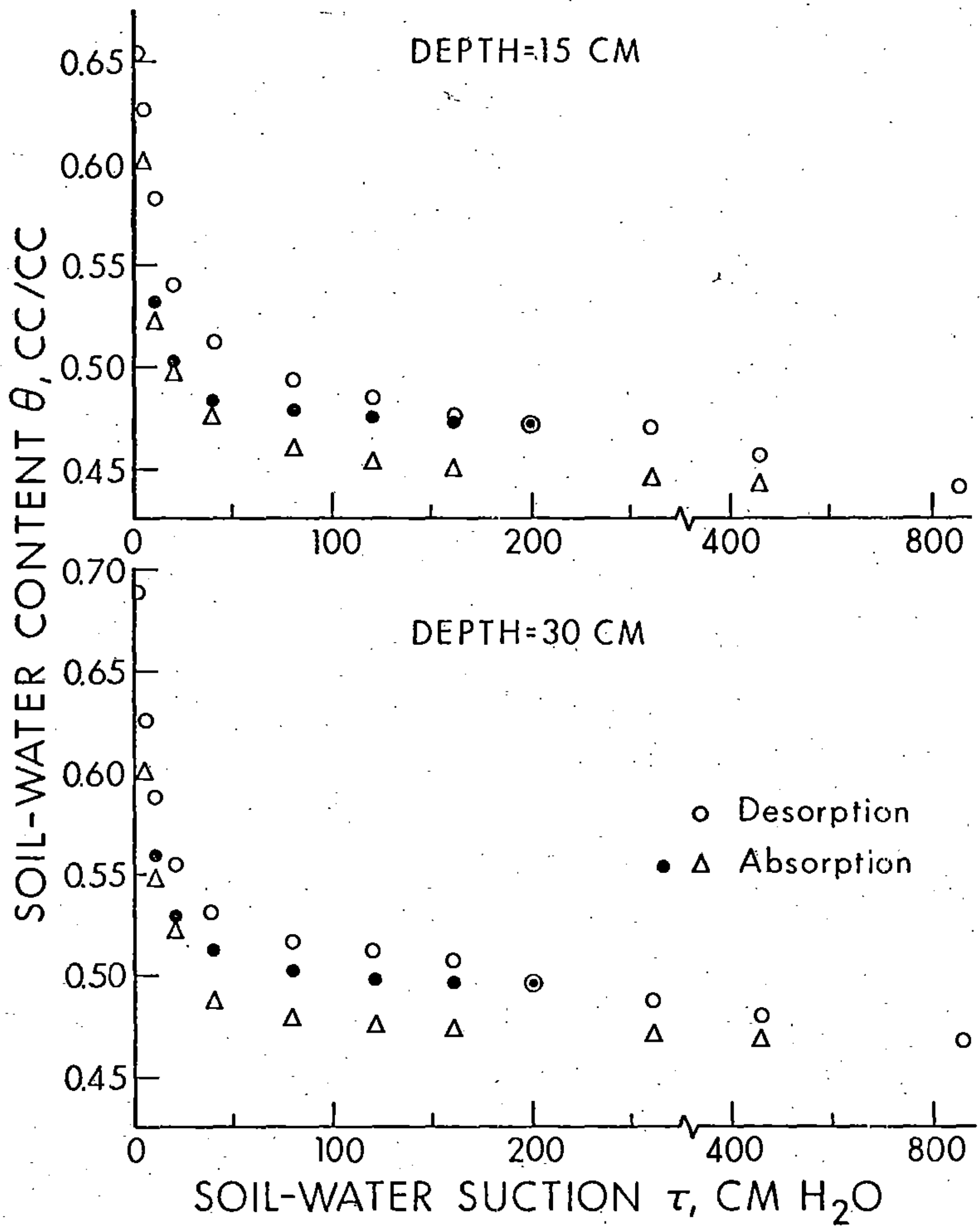

Fig. 2--Soil water content-suction relationships of the undisturbed soil cores from 15 and 30 cm depths. Each point is a mean of 3 to 4 measurements.

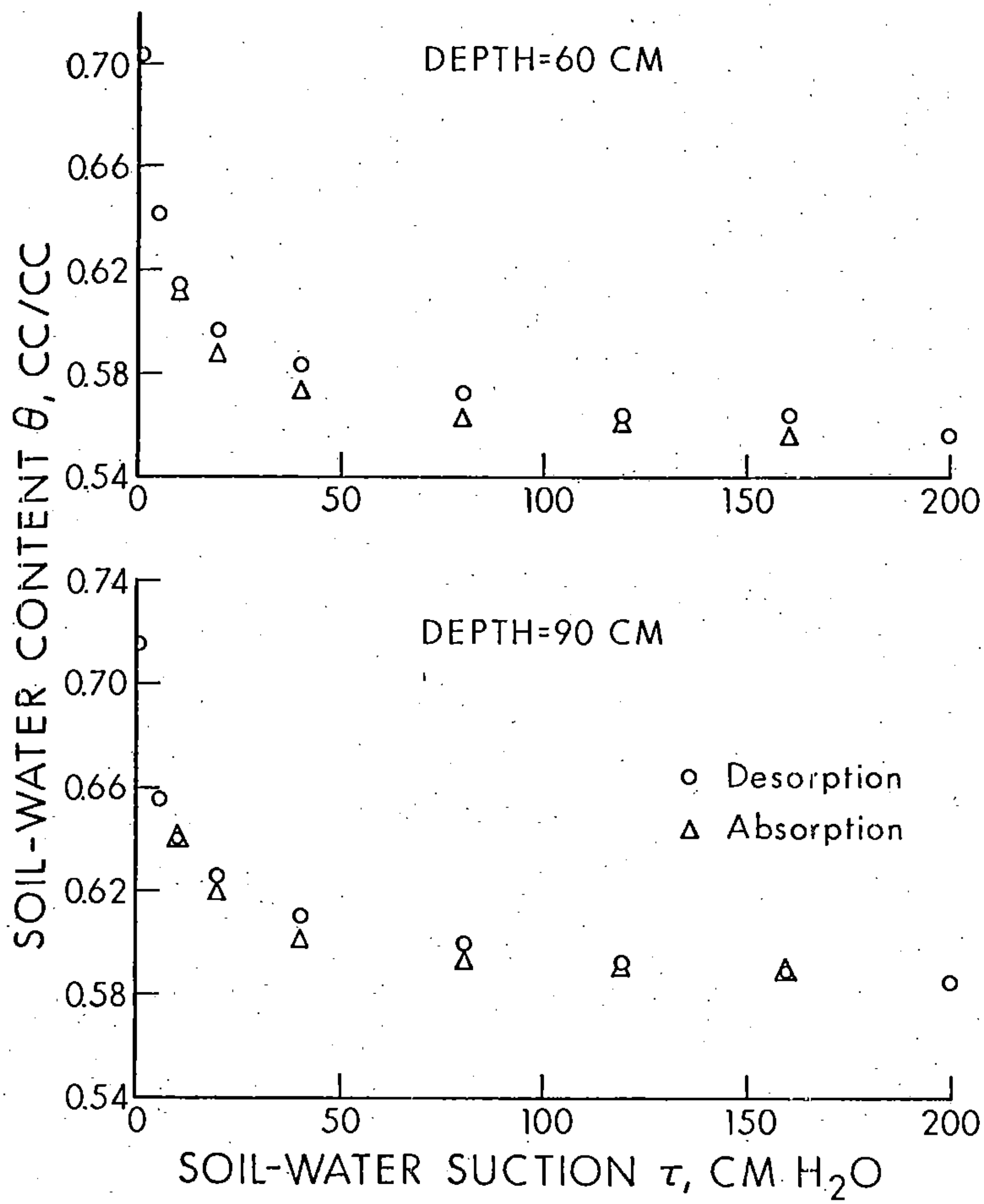

Fig.3--Soil water content-suction relationships of the undisturbed soil cores from 60 and 90 cm depths.

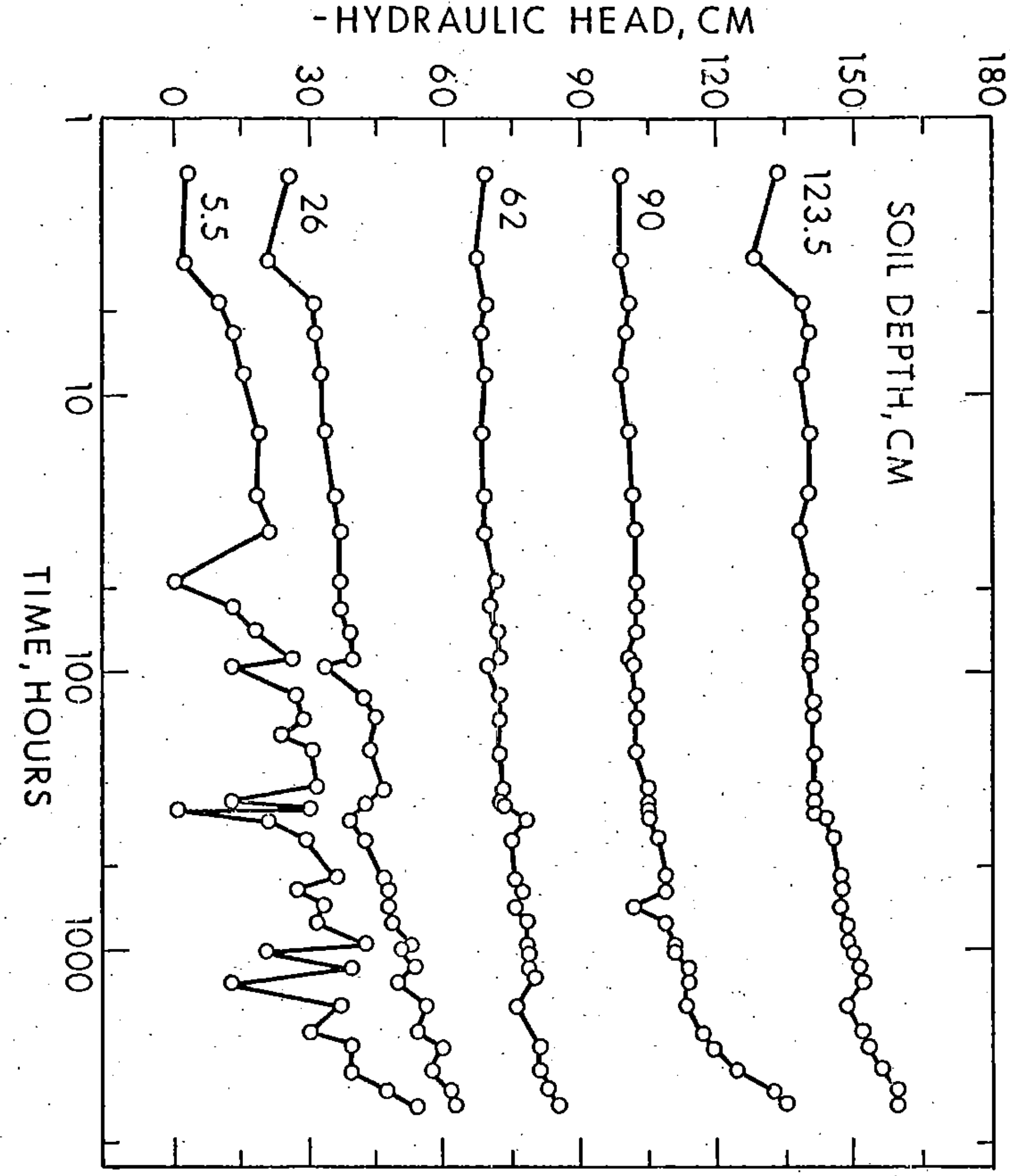

Fig. 4--Hydraulic head changes with time at different depths in the soil profile measured at the tensiometer-set location no. 1.

Fig. 4 further shows some appreciable fluctuations in soil-water tensions measured at 5.5 cm from the soil surface. The larger fluctuations coincided with occurrence of heavy rainstorms of 3 to 5 cm. They may, thus, be a result of increased condensation of water beneath the plastic cover and some likely leakage of water through the sealing tapes around the tensiometer stems. Some influence of these factors can be seen on the tension readings of 26 cm soil depth, but the effect is not nearly as significant as at the soil surface.

Fig. 5 shows the transient water yield during drainage, the amount of water draining downwards, from top 105 cm of soil profile as calculated from the curves of Fig. 2 and 3 and the soil-water tension measurements at three positions along the slope. There are fluctuations in the data points, more or less corresponding to the fluctuations in hydraulic heads as shown in Fig. 4. There is also an appreciable difference between the water yield calculated at the position of tensiometer set no. 1 and 2 and that of set no. 3 for the first two weeks. The drainage from position of set no. 3, the highest location on the slope, is less than that from the two lower locations. This difference, thus, would not be expectedly due to direct effect of slope on the water movement. It may be due to natural variations in soil at the different locations and experimental errors. It is interesting to observe that the water yield data in Fig. 5 fall along a straight line on the semi-log plot. A simple exponential equation, such as in the model of Nielsen et al. (1973), would describe them fairly well.

The unsaturated hydraulic conductivity as a function of water content for four different profile layers, determined from the tensiometric measurements and soil-water characteristics (Fig. 2, 3) are presented in Fig. 6 to 9. The data obtained from different locations along the slope are shown by different symbols. There is an appreciable scatter in the data and some apparent differences in conductivity values between different slope positions, but there are no consistent differences that could be attributed to the effect of slope. The slope effect would have resulted in apparently higher conductivity values at a higher location.

The results presented above would lead to a conclusion that the field tensiometric technique can be satisfactorily used on a forest watershed for measuring the water conductivities and drainage water yield if the field plot is protected from subsurface lateral flow and leakage of rain water. Interestingly, the effect of slope, an average of 18 per cent in the present study, on soil-water movement during drainage was not appreciable.

References

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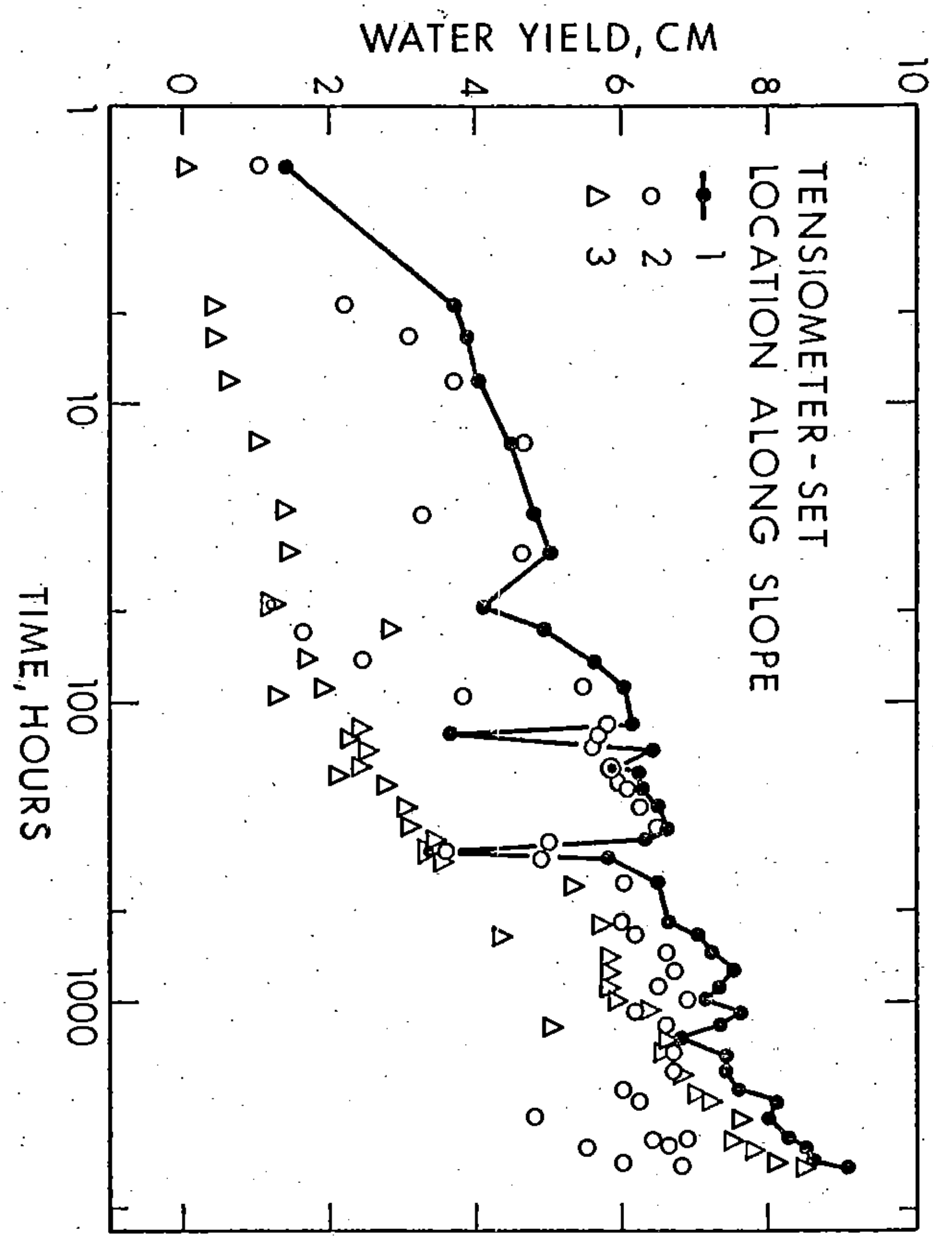

Fig. 5--Drainage water yield as a function of time from upper 105 cm of soil profile, as measured at three different locations along the slope.

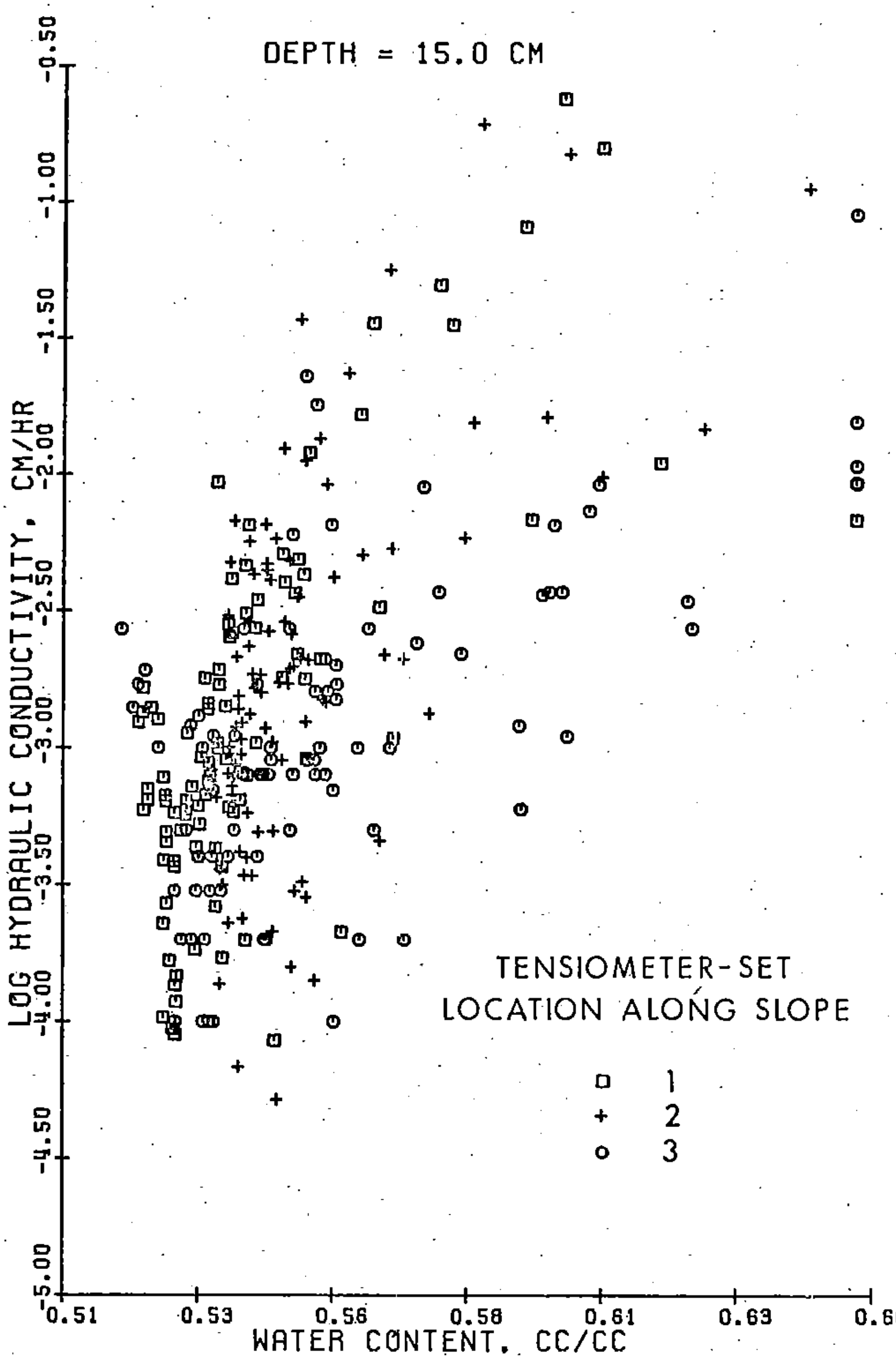

Fig. 6--Hydraulic conductivity as a function of water content for 15 cm soil depth, as determined at three different locations along the slope.

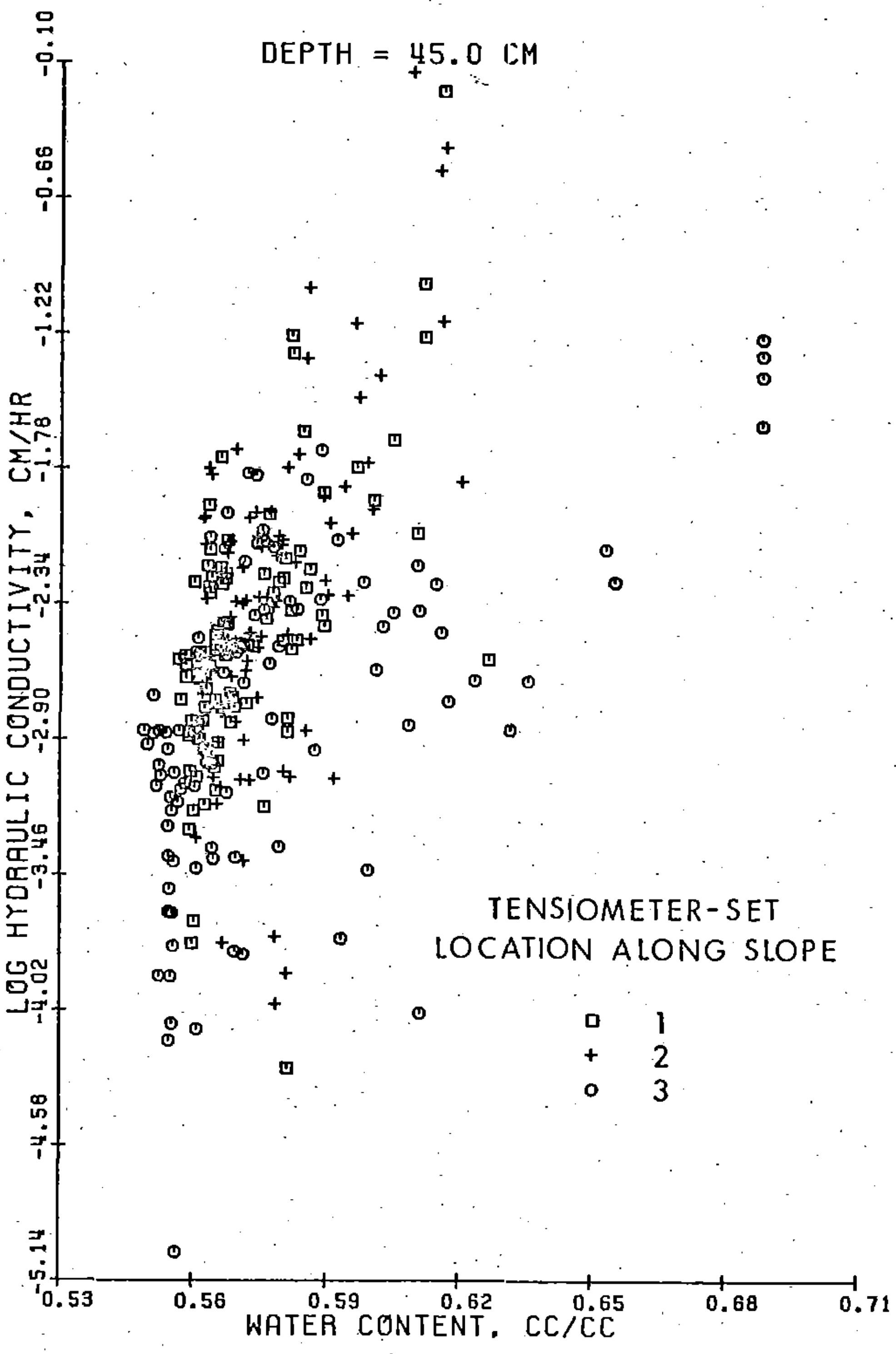

Fig. 7--Hydraulic conductivity as a function of water content for 45 cm depth, as determined at three different locations along the slope.

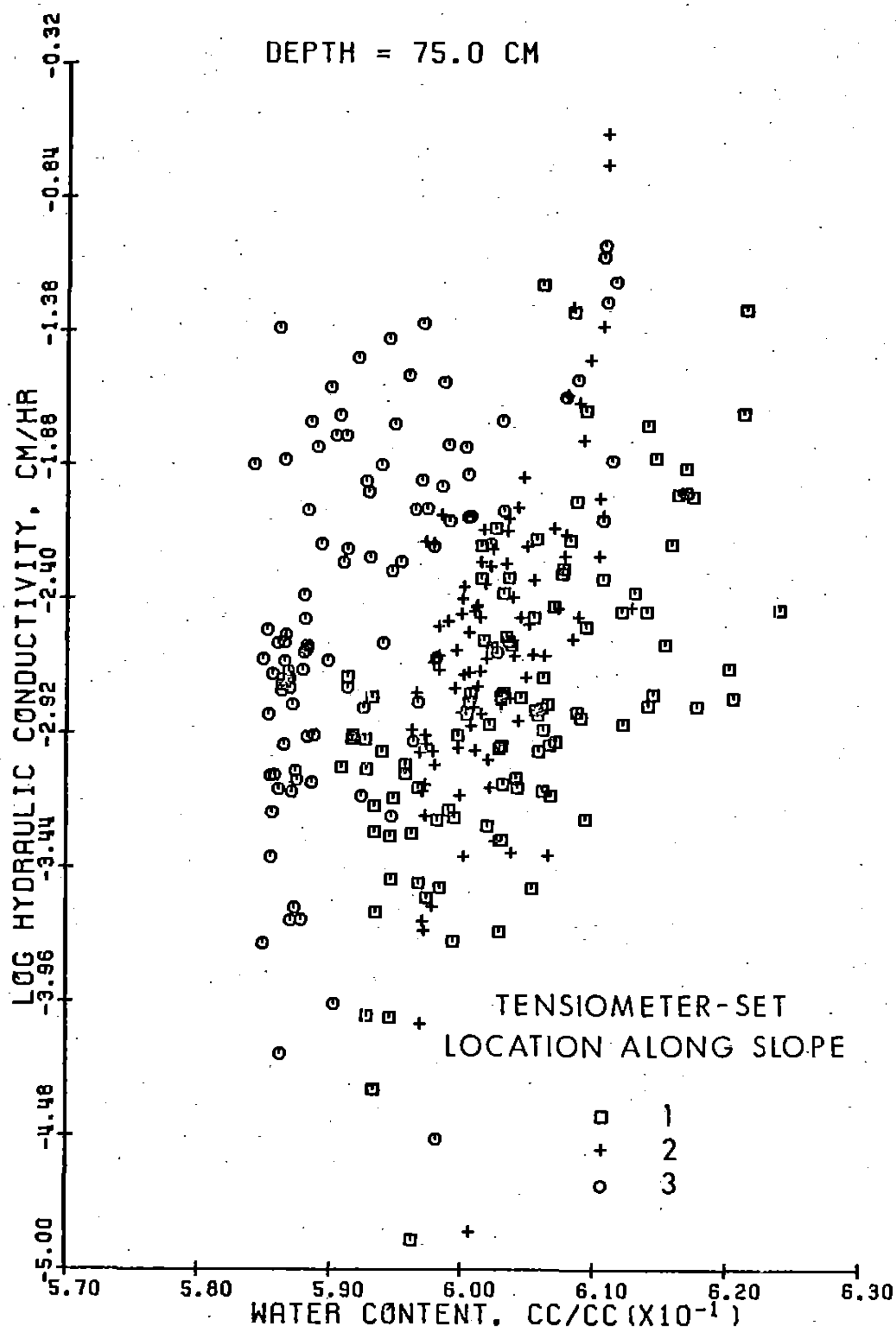

Fig. 8--Hydraulic conductivity as a function of water content for 75 cm depth, as determined at three different locations along the slope.

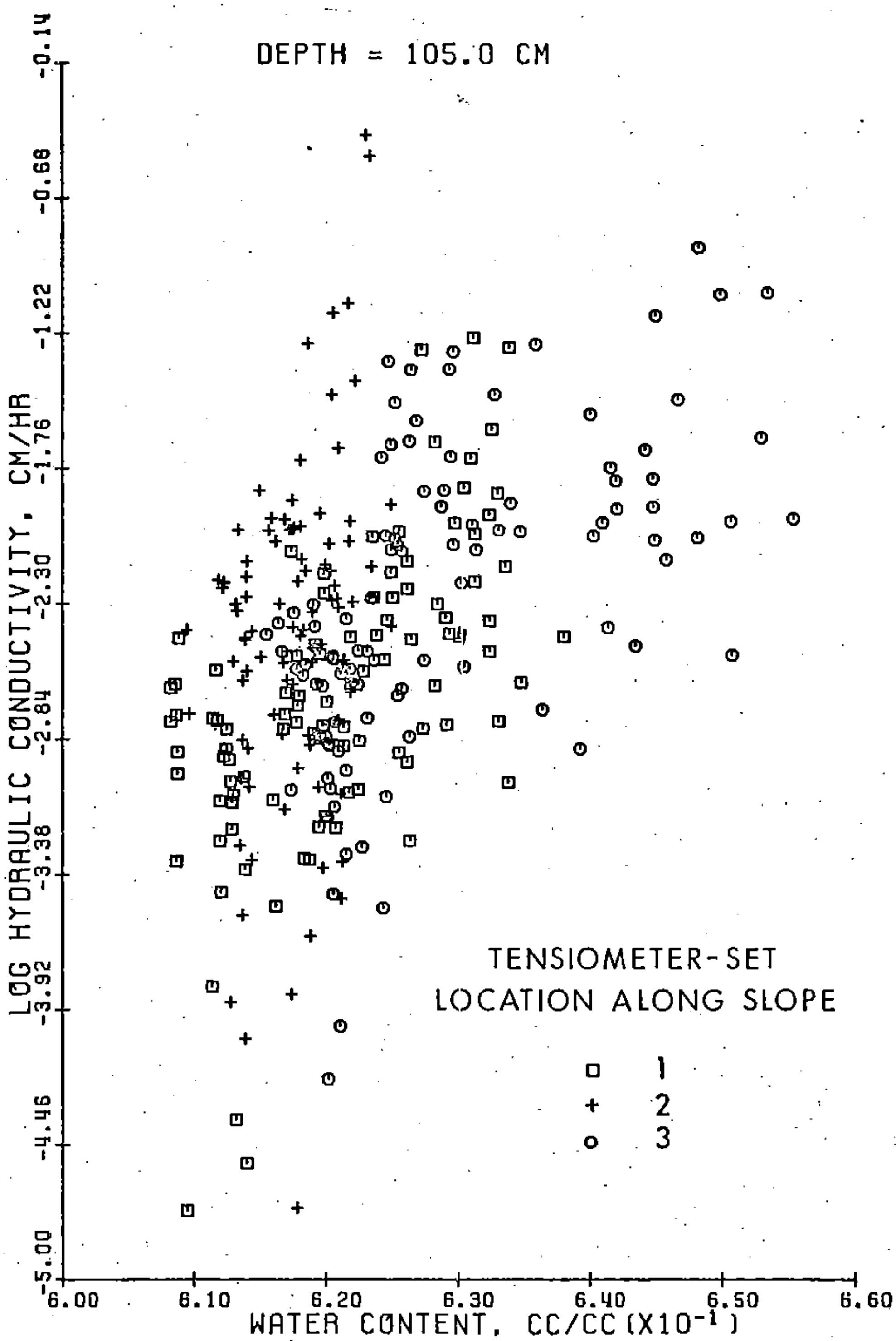

Fig. 9--Hydraulic conductivity as a function of water content for 105 cm depth, as determined at three different locations along the slope.

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Measuring Soil Hydrologic Properties on a Forest Watershed Using Field-Plot Tensiometric Technique: 2. Rainfall-Infiltration and Soil-Water Relations Under Natural Conditions

The natural rainfall on a watershed is generally characterized by widely varying intensities and frequencies both within a storm and between storms. The infiltration of such a rainfall into soils would be determined by highly dynamic soil-water conditions existing prior to and during the rainstorm. The rainfall-infiltration relationships or the infiltration-time relationships measured under natural conditions would be much different than those measured under idealized conditions, such as in a ponded-water infiltrometer or with a constant-intensity rain simulator. In order to devise some simple methods of field infiltration measurements and to relate the highly complex infiltration behavior in nature to soil characteristics measured by the simple idealized methods, it is necessary to conduct actual measurements on a forest watershed for a variety of natural rainstorms.

Specific purposes of this study were: (1) to measure natural rainfall-infiltration and soil-water relations for a variety of rainstorms on a forest-watershed plot, (2) attempt to determine the saturated hydraulic conductivities of the soil profile from measurements during selected heavy rainstorms, and (3) to prepare a nucleus for future development of simple physical-based models relating infiltration to soil-water properties.

Materials and Methods

The measurements were made on the forest-watershed plot (at the University of Hawaii Lyon's Arboretum) as described in the subsection dealing with water conductivities and water yield. Rainfall on the 11 x 4.2 m plot was measured by three recording raingages and four manual plastic gages. It was desirable to use this number of raingages in order to arrive at a reliable average value of rainfall, since the spatial variability under the intercepting tree canopies was appreciable. Runoff from the plot was collected at one point and lead into several interconnected 50 gal. barrels. In the initial stages of study, only two barrels were used and the water level in the barrels was read visually from a glass tube connected to the barrels. Later, four barrels were provided and a Steven's water level recorder was installed for monitoring the amount of runoff with time on a weekly or daily chart. The rainfall and runoff recordings were checked daily. The barrels were emptied manually whenever they were nearly full.

The daily rainfall and runoff records were read at 5 min intervals. The data were processed using the appropriate calibrations, and analyzed to obtain rainfall-runoff-infiltration relationships for various rainstorms.

Soil-water suctions at different depths of the profile were measured with fifteen tensiometers installed in the plot as described in the preceding subsection. Initially, these tensiometers were connected to mercury manometers and read manually, generally once a day. Later on, the tensions were read with the help of an automatic monitoring system as described in the next subsection. In addition to these fifteen tensiometers, three more tensiometers going to 30 cm soil depth were installed at three random locations in the plot in order to measure the spatial variability. These three units were equipped with mercury manometers which were read manually.

Results and Discussion

1. Natural Rainfall-Runoff-Infiltration Relationships:

The detailed measurements of rainfall and runoff over the period of several months were examined for typical patterns of natural rain occurring in the Arboretum watershed. These typical patterns are illustrated by computer plots of the data for seven selected days in Fig. 1 to 7. The cumulative rainfall is indicated by square symbols and straight lines joining them, while the measured cumulative runoff is shown by circles and lines. The triangles represent predicted runoff based on an assumption of constantly water-saturated soil profile as discussed later separately. The difference between rainfall and runoff at any given time is the cumulative infiltration.

Fig. 1 shows a common pattern in which there is a small rainfall to start with, followed by a period of little rain, and then a heavy rain of variable intensity. Fig. 2 shows a similar pattern, but in which the initial phase consists of two small steps. Fig. 3 shows another pattern of more or less continuous rainfall with brief periods of no rain. The rain intensity varies with time in a way that appears like a sequence of steps. Fig. 4 shows a case of continuous rainfall of approximately constant intensity. Fig. 5, 6 and 7 show, in an order of transition, rain patterns in which there are fairly large amounts of high-intensity rainfall occurring relatively early in the storm. The intensity tends to decrease later in the storm.

The measured runoff data of the seven selected days presented above indicate that more than 93 per cent of the rainfall infiltrated into the ground. The runoff represented only 4 to 7 per cent of the rainfall and most of this occurred during the most intense storm periods.

2. Saturated Hydraulic Conductivities of Soil Profile from Selected Heavy Rainstorms:

When the soil profile is completely saturated with water during a rainstorm, subsequent infiltration of rain water occurs at a steady

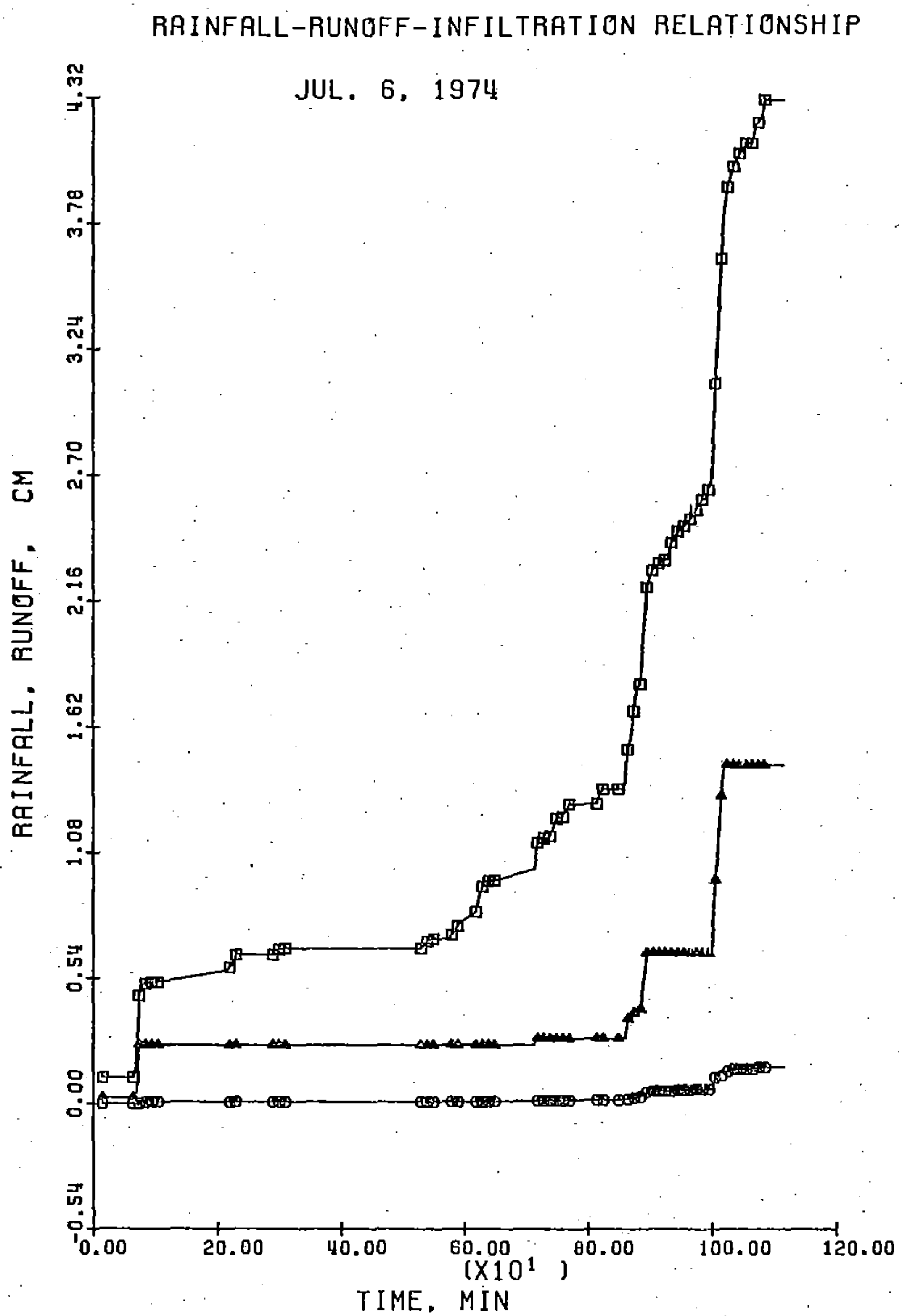

Fig. 1--Cumulative rainfall (squares) and runoff (circles) for a day showing a common pattern of small rainfall, followed by a period of little rain, and then a heavy rain of variable intensity. The triangles represent predicted runoff based on assumption of constantly-saturated soil profile.

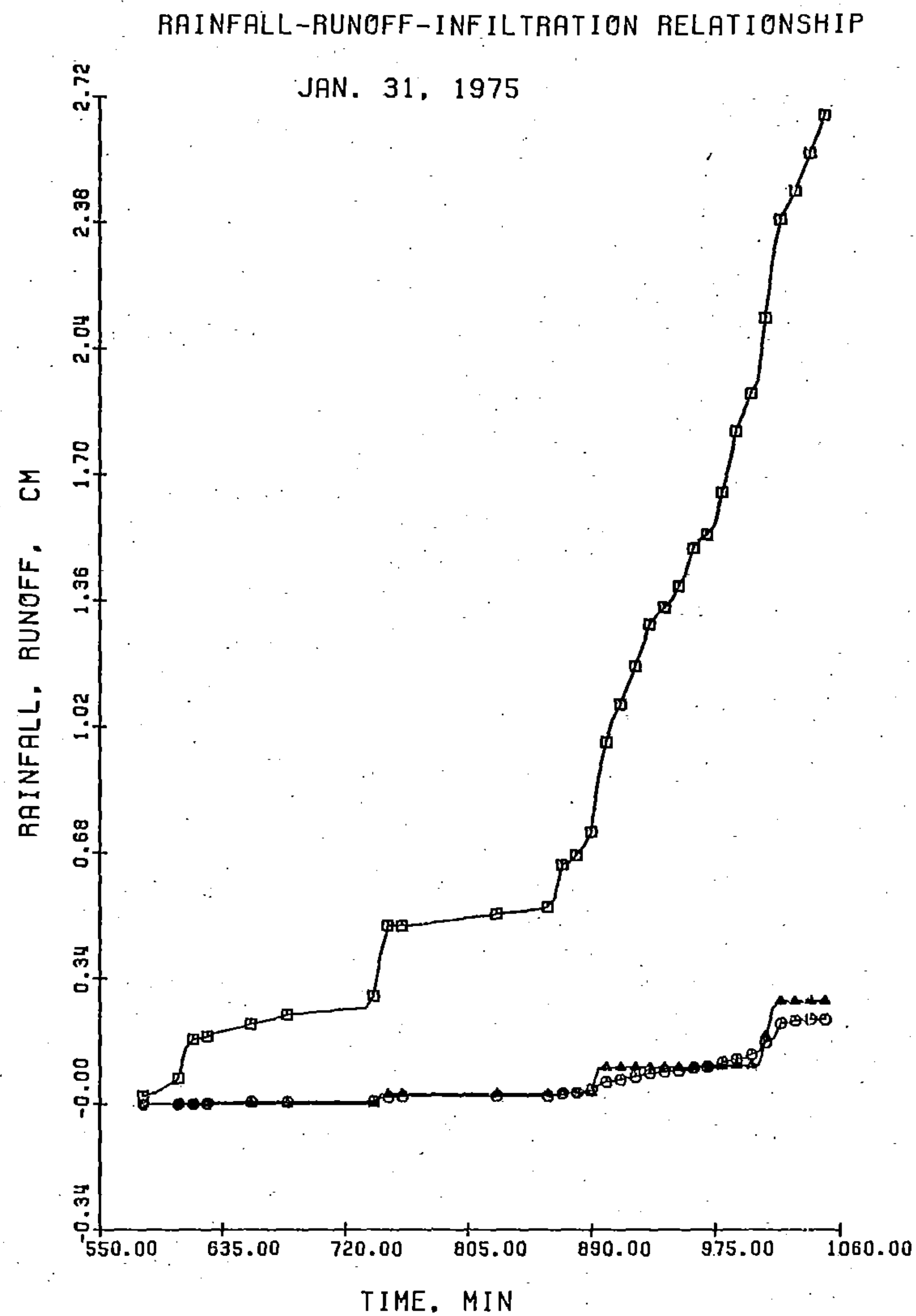

Fig. 2--Cumulative rainfall (squares) and runoff (circles) for a day showing a pattern similar to that of Fig. 1, but in which the initial phase consists of two steps. The triangles represent predicted runoff based on assumption of constantly-saturated soil profile.

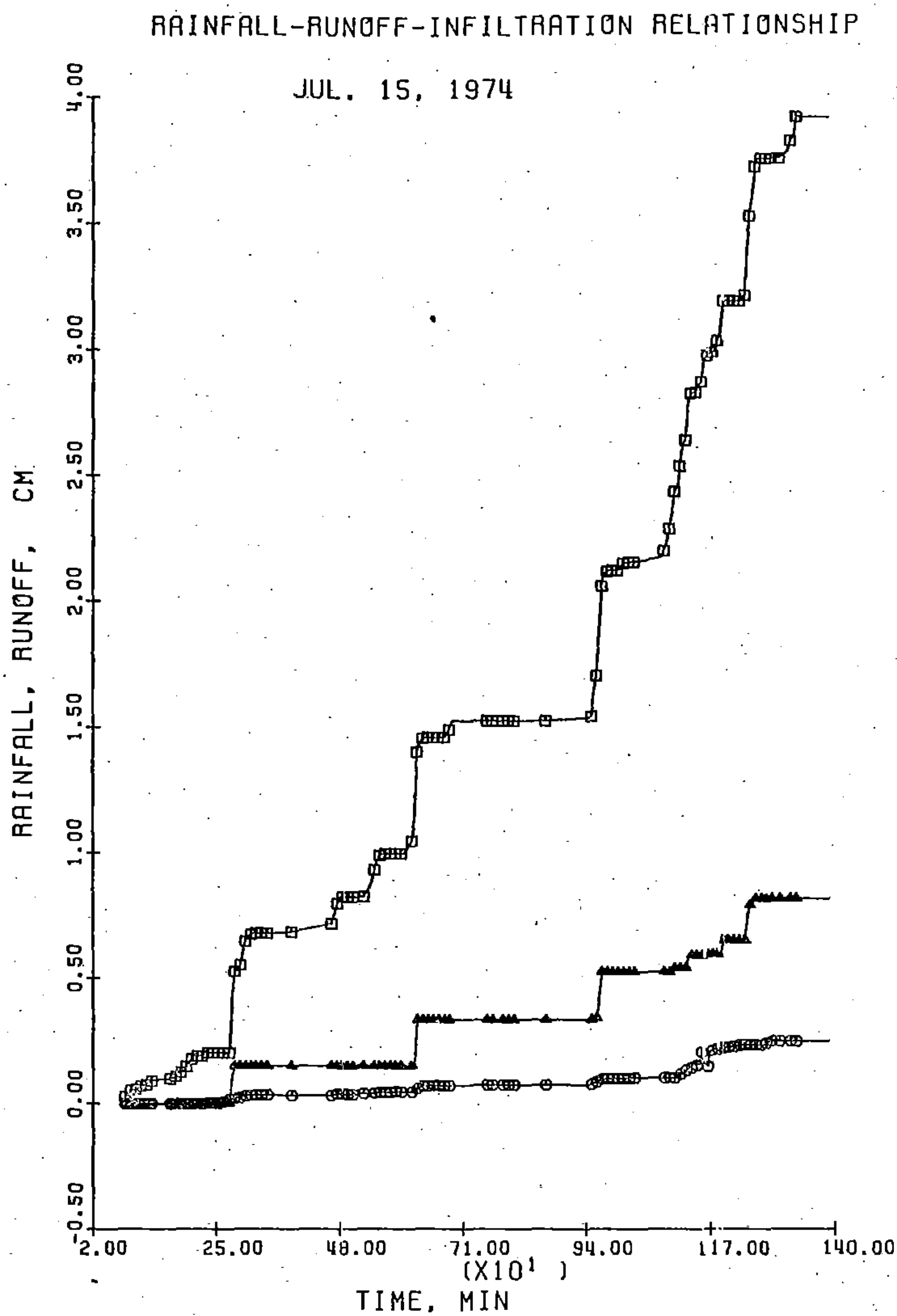

Fig. 3--Cumulative rainfall (squares) and runoff (circles) for a day showing more or less continuous rainfall with brief periods of no rain. The triangles represent predicted runoff based on assumption of constantly-saturated soil profile.

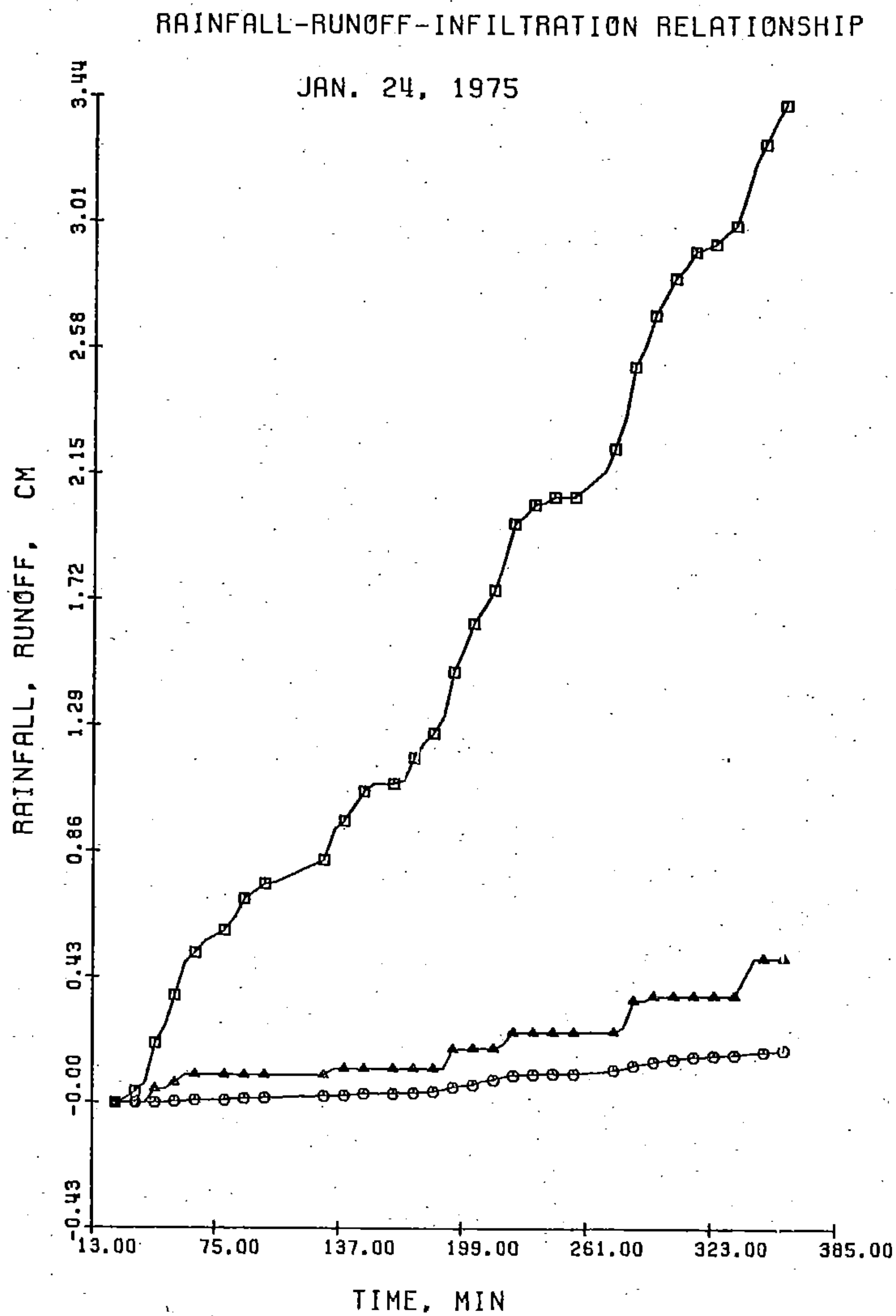

Fig. 4--Cumulative rainfall (squares) and runoff (circles) for a case of continuous rainfall of approximately constant intensity. The triangles represent predicted runoff based on assumption of constantly-saturated soil profile.

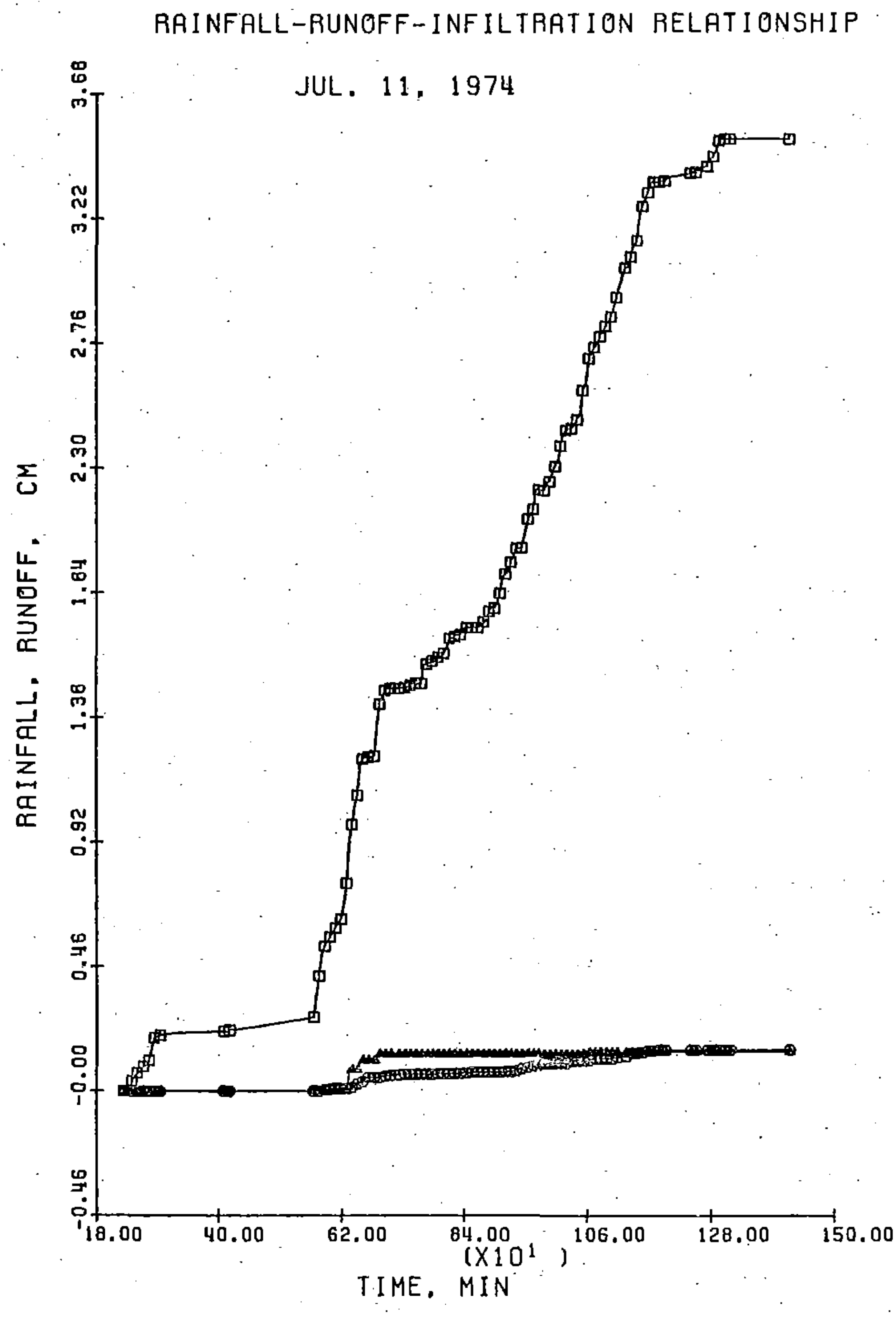

Fig. 5--Cumulative rainfall (squares) and runoff (circles) for a day when an appreciable amount of high-intensity rain occurred early in the storm. The triangles represent predicted runoff based on assumption of constantly-saturated soil profile.

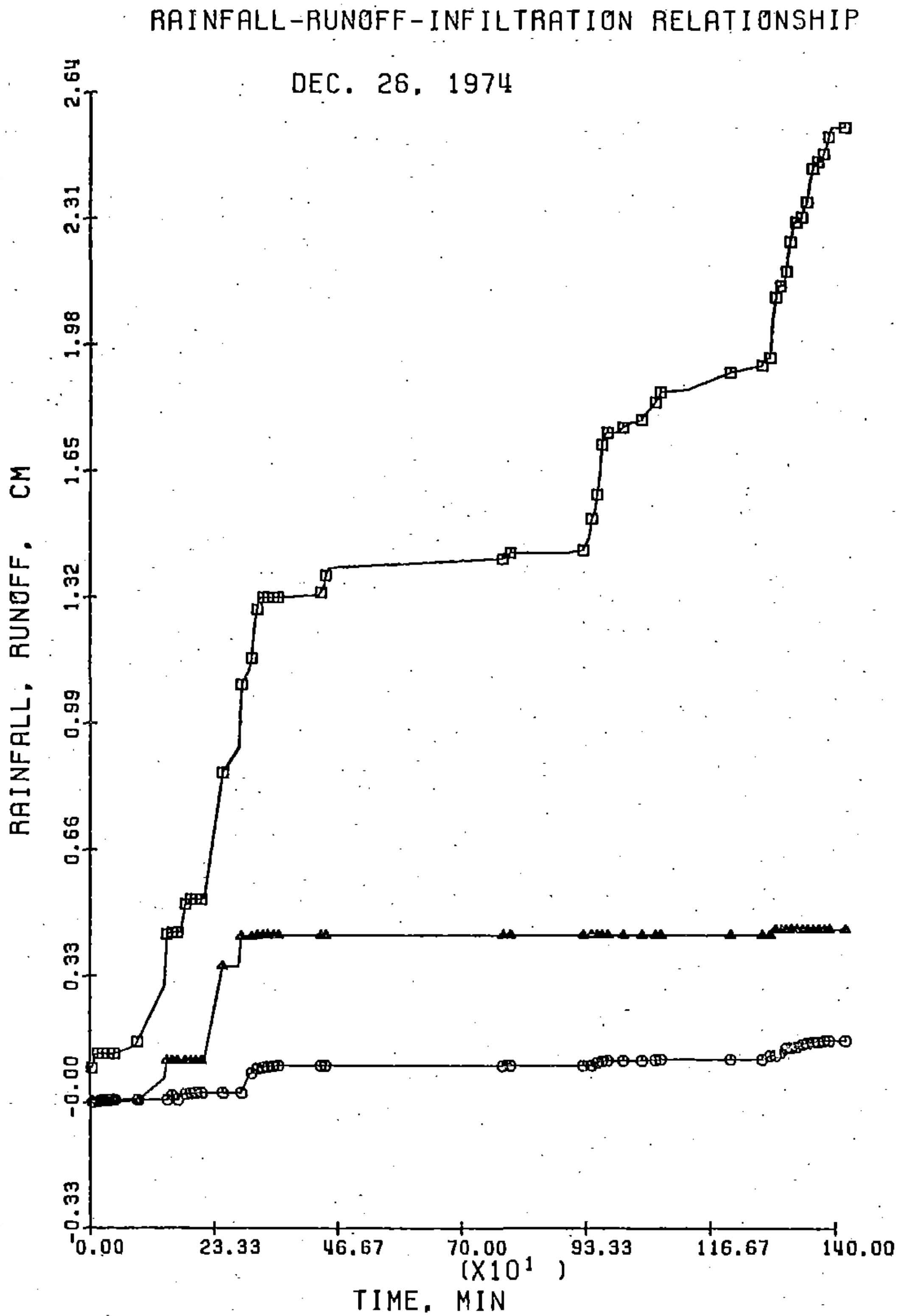

Fig. 6--Cumulative rainfall (squares) and runoff (circles) for another day receiving a fairly large amount of high-intensity rain early in the storm. The triangles represent predicted runoff based on assumption of constantly-saturated soil-profile.

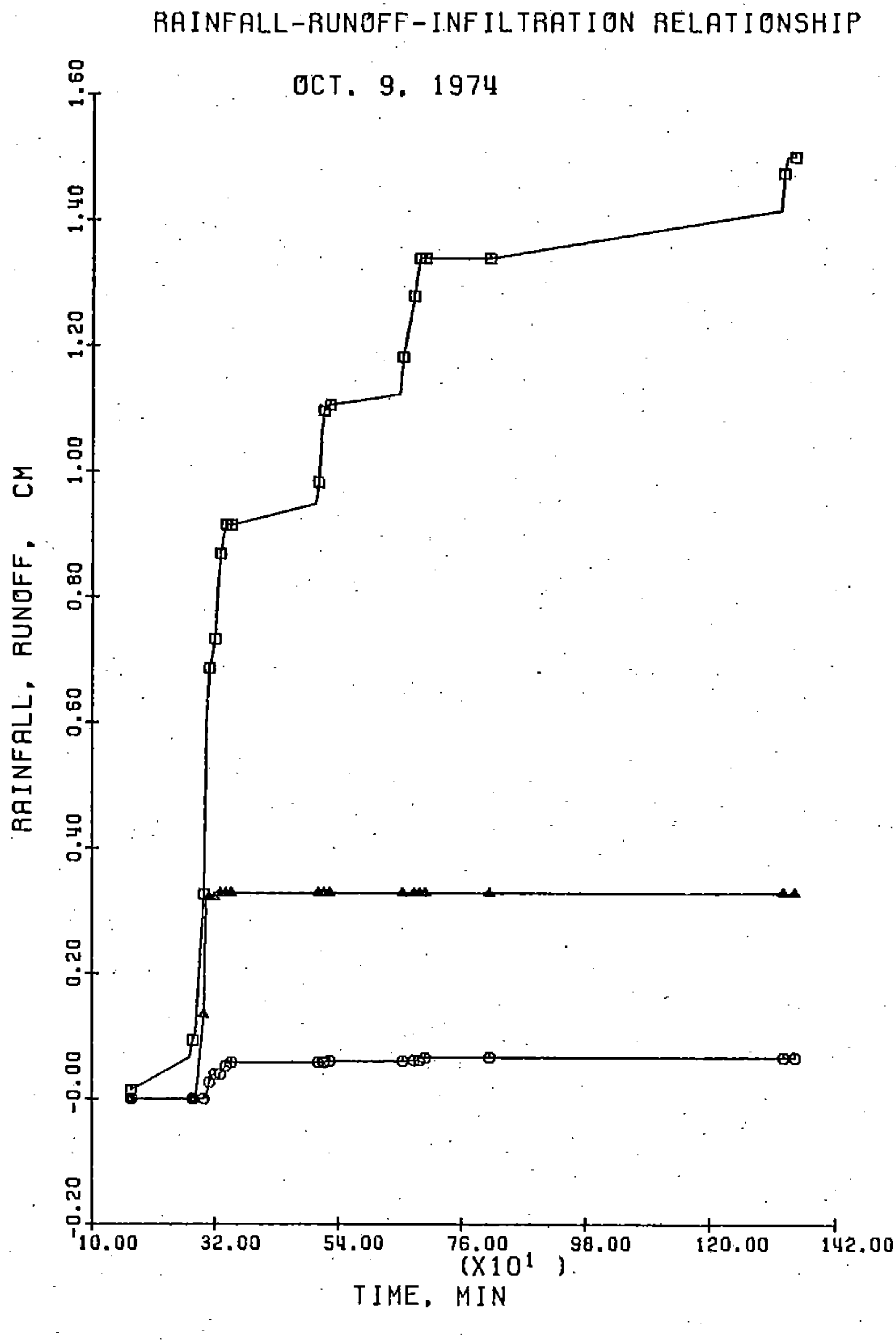

Fig. 7--Cumulative rainfall (squares) and runoff (circles) for another day receiving a large amount of high-intensity rain early in the storm. The triangles represent predicted runoff based on assumption of constantly-saturated soil profile.

rate equal to average saturated hydraulic conductivity of the profile. The excess of rainfall runs off. From the daily measured rainfall-runoff data of many heavy rainstorms, the cases which incorporated a period of steady infiltration rate were chosen. The dates, day-time intervals during which the infiltration was steady, and the steady infiltration rates calculated for those intervals for ten selected rainstorms are given in Table 1. The steady rate or the average saturated hydraulic conductivity of the profile thus calculated varied between 0.79 and 1.52 cm/hr, with mean of 1.036 cm/hr. This mean value for the profile compares excellently with an average figure of 1.117 cm/hr for 1-meter profile calculated from laboratory measurements on undisturbed soil cores. The cores were taken from four different soil depths at a location just outside the experimental plot, as described in the preceding subsection.

Table 1--Steady Infiltration Rates Recorded During Heavy Rainstorms on Certain Days

Date	Day-Time Interval	Steady Infiltration Rate, cm/hr
6-13-74	2:30-3:00	1.13
6-21-74	3:50-4:40	0.94
6-27-74	8:30-9:10	0.93
7- 6-74	6:20-7:00	1.10
7- 6-74	8:35-9:35	1.52
7-16-74	2:50-4:30	0.91
11-20-74	12:45-13:55	1.07
11-21-74	13:45-14:30	1.07
1-24-75	13:45-15:00	0.79
1-31-75	4:25-4:55	0.91

Mean = 1.036 cm/hr

The steady infiltration rate was used in combination with hydraulic gradients measured with tensiometers during two of the above rainstorms to determine hydraulic conductivities for different layers of the soil profile. Darcy's Law, which equates flow rate to the product of conductivity and hydraulic gradient, was applied for each soil layer. The results of calculation are presented in Fig. 8. The soil-core data for the different soil depths are also shown in the figure for comparison. Each core-data point is a mean of measurements on three different soil cores. The <u>in-situ</u> field and soil-core data agree fairly well except at 15 cm (6 in) depth. The discrepancy for 15 cm depth is well within the normal high natural variability known to occur in the surface soil horizons. As indicated above, the average hydraulic conductivities calculated for the profile from the above two measurements were very close (1.036 and 1.117 cm/hr, respectively). These results give confidence in the soil-core technique as used in the present studies.

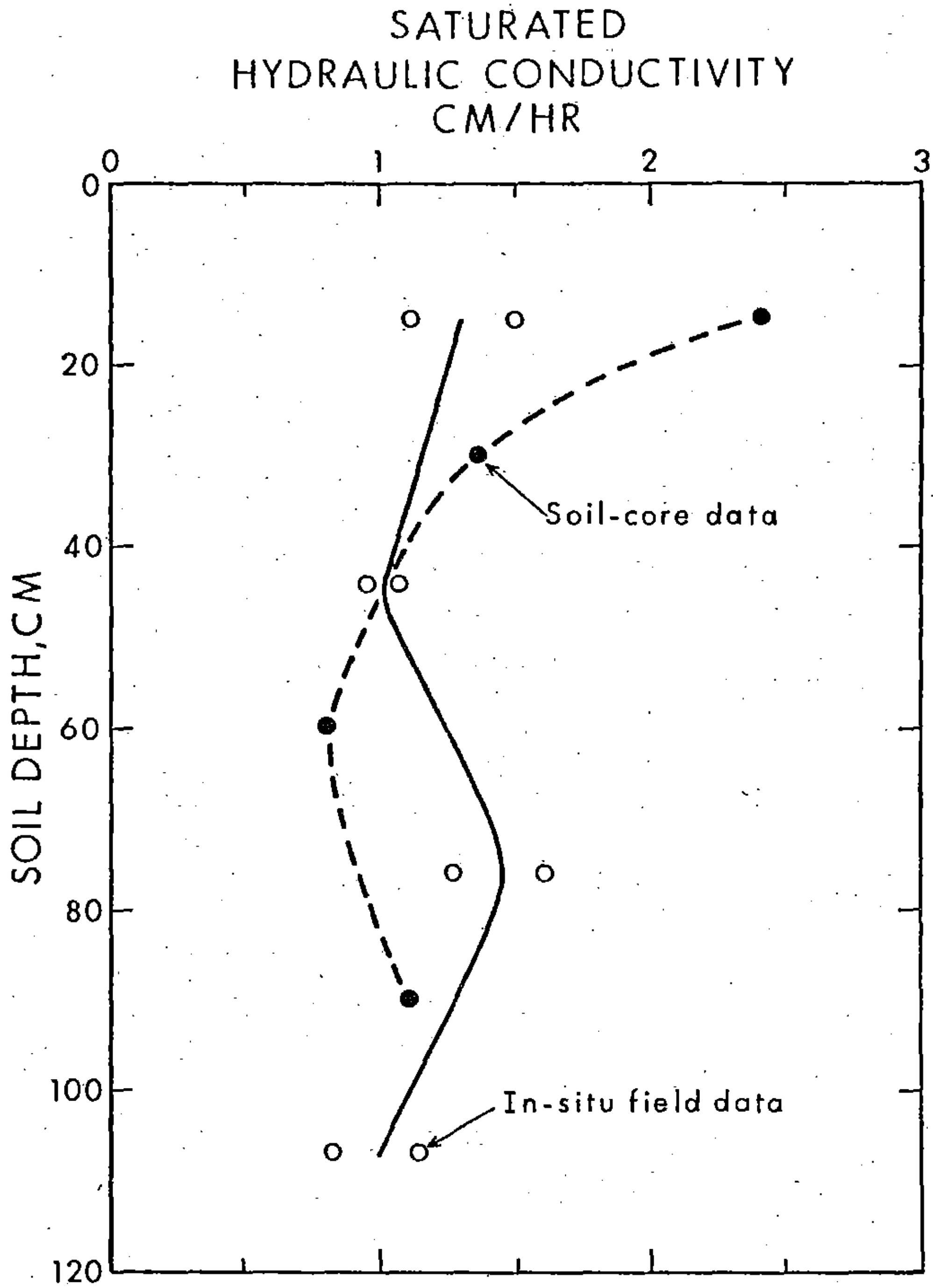

Fig. 8--Saturated hydraulic conductivities determined from field measurements of steady infiltration rate and soil hydraulic gradients compared with the determinations on soil cores.

3. Predicted Runoff Based on Assumption of Constantly Water-Saturated Soil Profile:

The tensiometric measurements indicated that the soil profile of the Arboretum watershed remained quite wet most of the time. Soil-water suctions at 30 cm depth never exceeded 70 cm (water) under natural conditions. At greater depths, the suctions encountered were much lower than 70 cm. The annual rainfall in this watershed is nearly 400 cm, with not so much variation between seasons. Under such conditions, it may be thought that the soil profile gets completely saturated with water very early in the rainstorm. Subsequent infiltration would then occur at a rate not exceeding the average saturated hydraulic conductivity of the profile. In other words, once the profile is saturated, a rainfall of intensity less than the saturated conductivity of the profile would all infiltrate. A rainfall of intensity higher than the conductivity would infiltrate at a steady rate equal to the conductivity, and the excess would run off.

Based on the assumption of a constantly saturated soil profile of average measured conductivity of 1.036 cm/hr, the runoff predicted for the seven selected rainy days were shown in Fig. 1 to 7, respectively. The predicted values are integrated from values calculated for 5 min intervals of rainfall. The results indicate that good predictions were obtained only in two out of the seven cases presented. In the other five cases, the runoff was over-predicted whenever a very high-intensity rain spell occurred either early in the storm or after a period of small or no rainfall. It thus appears that the assumption of constantly saturated profile is not acceptable. The soil gets unsaturated during brief periods of small or no rainfall, which makes it possible for infiltration rates to exceed saturated conductivity. There is, thus, a necessity for measuring unsaturated water conductivity and storage functions of soil, and then to develop a simple model incorporating these soil properties for predicting infiltration of natural rainfalls.

4. Daily and Monthly Data of Rainfall, Runoff and Soil-Water Suctions:

The recorded daily data for rainfall, runoff and soil-water suction at 30 cm soil depth are summarized monthwise in Tables 2 to 17. The data cover a period from September, 1973 to middle of February, 1975, except for two months (March and April, 1974) when adequate data were not recorded due to repair of some gages, and installation and testing of new instruments. Rainfall is given for all the gages located inside the plot (under the canopy) and for one gage located in the open which was recorded for some selected period. The symbols * indicate missing data, which generally occurs for some week-ends and holidays or when the manual data were not collected daily. The rainfall and runoff values given for the day following such missed days are therefore cumulated values, incorporating the rainfall and runoff over these days. There are some other values missing due to malfunctioning of some particular gages. In such cases, the data values on the following days are not cumulated. As indicated earlier, the runoff from the experimental plot was collected and measured in two coupled 55-gal barrels in early stages of study, and in four coupled barrels later on. For some days of heavy

TABLE 2

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF SEPTEMBER, 1973

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER, GAGE NO., CM: 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESPONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM: 1	2	3	MEAN	AIR TEMP. C
1	13:00	0.00	0.00	0.00	0.03	0.03	0.00	0.00	0.007	****	0.000	0.007	0.000	15	15	22	17.33	24
2	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
3	12:00	0.38	0.41	0.58	0.48	0.69	0.43	0.25	0.461	****	0.001	0.461	0.003	16	15	20	17.00	24
4	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
5	14:00	1.37	1.12	1.37	2.08	1.57	1.42	1.14	1.441	****	0.006	1.441	0.004	16	9	20	15.00	24
6	14:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
7	09:00	1.02	1.02	1.30	1.32	1.47	1.07	0.76	1.136	****	0.004	1.136	0.003	12	8	20	13.33	24
8	12:00	0.00	0.05	0.00	0.05	0.05	0.08	0.00	0.033	****	0.000	0.033	0.000	14	14	20	16.00	24
9	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
10	13:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	17	19	21	19.00	25
11	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
12	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
13	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
14	13:00	1.47	1.42	1.65	2.29	2.29	1.83	1.14	1.727	****	0.006	1.727	0.003	16	9	17	14.00	24
15	09:00	0.00	0.00	0.00	0.03	0.03	0.00	0.00	0.007	****	0.000	0.007	0.003	16	11	22	16.33	23
16	09:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
17	13:00	0.48	0.48	0.69	0.79	0.81	0.66	0.38	0.613	****	0.003	0.613	0.004	17	17	21	18.33	23
18	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
19	14:00	0.08	0.08	0.15	0.23	0.18	0.15	0.13	0.142	****	0.000	0.142	0.000	18	17	24	19.67	24
20	14:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
21	14:00	1.02	1.02	1.02	1.96	1.42	1.22	1.07	1.245	****	0.010	1.245	0.008	13	9	18	13.33	24
22	14:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
23	14:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
24	14:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
25	12:00	0.03	0.05	0.05	0.08	0.08	0.05	0.00	0.047	****	0.000	0.047	0.000	5	10	21	12.00	25
26	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
27	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
28	16:00	1.14	1.40	1.80	1.88	2.13	1.73	1.65	1.676	****	0.007	1.676	0.004	15	7	19	13.67	24
29	12:00	2.69	2.16	2.67	3.56	3.30	2.79	2.41	2.798	****	0.010	1.575	0.006	14	8	17	13.00	22
30	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
TOTAL	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	11.332	*****	0.046	10.109	0.005	MEAN	. . .	. . .	15.571	23.9

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 3

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF OCTOBER, 1973

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER, GAGE NO., CM: 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESP-ONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM: 1	2	3	MEAN	AIR TEMP. C
1	15:00	0.99	1.04	1.52	1.35	1.63	1.32	1.09	1.277	****	0.004	1.277	0.003	14	4	8	8.67	23
2	15:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
3	17:00	0.05	0.03	0.05	0.10	0.08	0.05	0.00	0.051	****	0.000	0.051	0.000	15	14	28	19.00	23
4	17:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
5	18:00	0.08	0.05	0.08	0.15	0.10	0.08	0.00	0.076	****	0.000	0.076	0.000	17	17	25	19.67	23
6	18:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
7	18:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
8	10:00	1.93	2.03	2.34	3.38	3.05	2.31	2.03	2.438	****	0.010	1.448	0.007	16	4	23	14.33	21
9	10:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
10	13:00	0.03	0.03	0.03	0.05	0.08	0.08	0.05	0.047	****	0.000	0.047	0.000	18	14	29	20.33	23
11	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
12	09:00	0.94	1.02	****	1.27	1.37	1.22	0.51	1.054	****	0.007	1.054	0.007	15	12	22	16.33	22
13	12:00	0.71	0.69	****	0.94	1.02	0.84	0.76	0.825	****	*****	*****	*****	14	6	23	14.33	22
14	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
15	14:00	9.75	8.00	6.86	****	****	****	7.62	9.231	****	*****	*****	*****	10	10	17	12.33	24
16	14:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
17	13:00	1.22	2.34	2.79	2.67	2.79	2.92	2.54	2.467	****	0.010	0.533	0.019	12	11	23	15.33	25
18	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
19	13:00	6.63	6.98	6.35	9.78	9.78	9.65	7.62	8.113	****	0.010	0.686	0.015	12	5	23	13.33	21
20	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
21	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
22	13:00	2.16	2.41	****	3.94	3.94	3.05	2.67	3.027	****	0.010	1.219	0.008	10	9	15	11.33	21
23	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
24	13:00	0.13	0.13	0.13	0.20	0.25	0.20	0.13	0.167	****	0.000	0.167	0.000	13	16	27	18.67	22
25	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
26	14:00	0.00	0.05	0.00	0.05	0.08	0.05	0.05	0.040	****	0.000	0.040	0.000	17	20	36	24.33	23
27	12:00	0.08	0.10	0.08	0.13	0.18	0.10	0.13	0.112	****	0.000	0.112	0.000	17	20	42	26.33	22
28	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
29	15:00	0.41	0.66	0.76	1.17	0.71	0.81	0.51	0.718	****	0.002	0.718	0.003	18	23	60	33.67	21
30	15:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
31	13:00	4.34	3.81	4.01	4.19	4.57	4.32	3.81	4.151	****	0.010	3.302	0.003	13	15	31	19.67	25
TOTAL	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	33.797	*****	0.063	10.731	0.006	MEAN	. . .	. . .	17.979	22.6

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 4

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF NOVEMBER, 1973

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER GAGE NO., CM 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESP-ONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM 1	2	3	MEAN	AIR TEMP. C
1	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
2	14:00	1.42	2.18	2.29	1.63	2.13	2.18	1.78	1.945	****	0.010	0.762	0.013	13	14	43	23.33	23
3	10:00	0.03	0.08	0.08	0.08	0.13	0.08	0.00	0.065	****	0.000	0.065	0.000	15	16	43	24.67	23
4	10:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
5	10:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	17	21	77	38.33	24
6	13:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	20	21	80	40.33	23
7	13:00	0.03	0.08	0.08	0.08	0.08	0.08	0.08	0.069	****	0.000	0.069	0.000	27	24	93	48.00	24
8	15:00	0.15	0.20	0.25	0.18	0.25	0.18	0.13	0.192	****	0.000	0.192	0.001	25	14	107	48.67	24
9	14:00	0.61	1.07	0.89	0.91	0.97	0.97	0.89	0.900	****	0.004	0.900	0.004	29	24	87	46.67	24
10	11:00	0.03	0.03	0.00	0.03	0.03	0.00	0.03	0.018	****	0.000	0.018	0.000	25	22	85	44.00	24
11	11:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
12	15:00	****	****	9.14	****	****	3.81	****	*****	****	0.010	1.092	0.009	13	3	23	13.00	20
13	15:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
14	14:00	0.23	0.18	0.36	0.46	0.28	0.20	0.25	0.279	****	0.001	0.279	0.002	16	14	29	19.67	24
15	14:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
16	12:00	0.20	0.38	0.36	0.28	0.41	0.25	0.25	0.305	****	0.001	0.305	0.004	14	16	37	22.33	23
17	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
18	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
19	14:00	0.46	0.71	0.97	0.66	1.12	0.81	0.76	0.784	****	0.002	0.784	0.002	17	16	55	29.33	23
20	17:00	0.33	0.48	0.51	0.46	0.56	0.38	0.38	0.443	****	0.003	0.443	0.007	***	16	48	32.00	25
21	14:00	0.00	0.05	0.00	0.05	0.05	0.03	0.00	0.025	****	0.000	0.025	0.000	18	17	63	32.67	23
22	14:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
23	14:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	18	21	98	45.67	22
24	10:00	4.06	3.30	3.25	4.44	4.32	4.06	3.81	3.893	****	0.007	3.893	0.002	15	5	25	15.00	21
25	10:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
26	14:00	3.94	4.06	3.73	4.44	5.71	4.95	3.81	4.380	****	0.010	0.610	0.016	15	1	27	14.33	20
27	14:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
28	15:00	2.03	2.29	2.46	2.67	3.43	2.41	3.05	2.620	****	0.010	1.702	0.006	10	9	23	14.00	22
29	15:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
30	09:00	6.10	6.98	7.11	7.11	8.38	7.62	7.62	7.275	****	0.010	1.854	0.005	12	4	20	12.00	22
TOTAL									33.481	*****	0.067	12.994	0.005	MEAN			29.684	22.8

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 5

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF DECEMBER, 1973

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER GAGE NO., CM 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESP-ONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM 1	2	3	MEAN	AIR TEMP. C
1	12:00	0.69	0.81	0.91	1.22	1.02	0.86	****	0.919	****	0.004	0.919	0.004	13	***	23	18.00	21
2	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
3	14:00	2.84	2.79	2.95	3.56	3.56	3.81	****	3.251	****	0.010	0.508	0.020	12	***	24	18.00	24
4	14:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
5	16:00	0.03	0.08	0.05	0.10	0.08	0.08	0.00	0.058	****	0.000	0.058	0.000	15	***	***	15.00	22
6	16:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	15	***	***	15.00	23
7	16:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	22	***	***	22.00	22
8	11:00	****	3.30	****	3.43	3.81	3.43	3.81	3.556	****	0.010	1.905	0.005	14	***	***	14.00	21
9	11:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
10	16:00	2.03	1.55	****	2.29	2.39	1.88	1.65	1.964	****	0.009	1.964	0.004	13	***	***	13.00	20
11	16:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
12	14:00	3.05	3.81	3.05	5.08	5.08	3.56	4.06	3.955	****	0.010	0.610	0.016	13	***	***	13.00	23
13	14:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
14	08:30	0.00	0.08	0.00	0.08	0.08	0.05	0.00	0.040	****	0.000	0.040	0.000	15	***	***	15.00	20
15	13:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	17	***	***	17.00	22
16	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
17	13:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	18	***	***	18.00	23
18	12:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	19	***	***	19.00	24
19	12:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	25	***	***	25.00	22
20	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
21	11:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	27	***	***	27.00	21
22	11:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
23	11:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
24	12:00	1.07	1.32	1.60	1.57	1.83	1.52	1.78	1.528	****	0.006	1.528	0.004	24	***	***	24.00	22
25	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
26	15:00	0.25	0.41	0.46	0.51	0.56	0.43	0.25	0.410	****	0.000	0.410	0.000	20	***	***	20.00	21
27	15:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
28	15:00	0.69	0.86	1.04	1.12	1.17	0.97	0.89	0.962	****	0.003	0.962	0.003	17	***	***	17.00	21
29	15:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
30	15:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
31	12:00	6.10	7.11	8.13	8.13	9.65	****	8.89	8.400	****	*****	*****	*****	13	***	***	13.00	21
TOTAL . . .									25.043	*****	0.052	8.903	0.006	MEAN . . .			17.944	21.8

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 6

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF JANUARY, 1974

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER, GAGE NO., CM: 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESP-ONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM: 1	2	3	MEAN	AIR TEMP. C
1	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
2	10:00	1.32	1.32	1.37	1.47	1.83	2.18	1.52	1.575	****	0.004	1.575	0.003	10	***	***	10.00	21
3	10:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
4	12:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	13	***	***	13.00	23
5	10:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	17	***	***	17.00	22
6	10:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
7	12:00	6.10	6.98	8.08	7.11	8.89	8.51	8.89	7.794	****	0.010	0.737	0.014	13	***	***	13.00	20
8	14:00	0.48	0.56	0.61	0.61	0.86	0.58	0.51	0.602	****	0.003	0.602	0.005	11	***	***	11.00	22
9	13:00	1.52	1.57	1.52	1.42	1.98	1.52	1.65	1.600	****	0.010	1.422	0.007	13	7	13	11.00	22
10	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
11	13:00	0.00	0.03	0.00	0.03	0.03	0.03	0.00	0.015	****	0.000	0.015	0.000	17	18	20	18.33	21
12	12:00	2.18	1.93	2.03	2.08	2.67	3.17	2.03	2.301	****	0.010	1.397	0.007	15	13	29	19.00	23
13	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
14	12:00	1.22	1.27	1.32	1.27	1.78	1.42	1.27	1.364	****	*****	*****	*****	15	13	25	17.67	21
15	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
16	12:00	0.81	1.17	1.07	0.97	1.37	0.91	1.40	1.099	****	0.010	1.092	0.009	14	13	23	16.67	23
17	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
18	09:00	0.00	0.05	0.05	0.05	0.08	0.03	0.00	0.036	****	0.000	0.036	0.000	17	18	27	20.67	21
19	09:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
20	09:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
21	11:00	0.05	0.08	0.05	0.08	0.10	0.05	0.00	0.058	****	0.000	0.058	0.000	21	20	62	34.33	23
22	14:00	0.25	0.38	0.38	0.46	0.48	0.33	0.38	0.381	****	*****	*****	*****	15	23	49	29.00	22
23	14:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
24	13:00	2.95	3.43	3.25	4.57	3.81	3.43	3.05	3.498	****	0.010	1.067	0.009	15	11	21	15.67	20
25	14:00	0.71	0.66	1.02	0.81	0.81	0.61	0.51	0.733	****	0.004	0.733	0.006	17	12	21	16.67	21
26	14:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
27	11:00	2.84	3.94	3.81	4.70	4.57	4.44	4.32	4.089	****	0.010	1.067	0.009	17	9	20	15.33	20
28	11:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
29	13:00	0.41	0.46	0.51	0.51	0.53	0.41	0.25	0.439	****	0.003	0.439	0.007	17	15	24	18.67	21
30	13:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
31	14:00	6.10	5.84	5.99	7.11	6.22	7.62	6.35	6.462	****	*****	*****	*****	17	10	17	14.67	20
TOTAL									32.047	*****	0.074	10.240	0.007	MEAN			17.315	21.4

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 7

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF FEBRUARY, 1974

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER, GAGE NO., CM: 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESP-ONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM: 1	2	3	MEAN	AIR TEMP. C
1	14:00	4.06	5.21	4.44	4.95	6.35	4.83	3.81	4.808	****	*****	*****	*****	15	11	19	15.00	20
2	10:00	0.56	0.51	0.51	0.48	0.46	0.43	****	0.491	****	0.002	0.491	0.005	16	12	19	15.67	21
3	10:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
4	10:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
5	10:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	19	21	31	23.67	20
6	10:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
7	14:00	1.47	0.91	1.07	1.73	1.32	1.09	1.40	1.285	****	0.005	1.285	0.004	23	15	36	24.67	20
8	15:00	2.34	2.67	2.67	4.44	3.30	3.17	****	3.099	****	*****	*****	*****	17	11	22	16.67	20
9	15:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
10	15:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
11	12:00	3.05	2.92	3.05	4.83	3.94	3.43	3.17	3.483	****	0.010	0.686	0.015	15	10	21	15.33	19
12	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
13	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
14	14:00	3.81	4.06	4.06	5.21	5.08	4.83	3.94	4.427	****	0.010	2.286	0.004	17	12	21	16.67	23
15	10:00	0.13	0.33	0.25	0.38	0.38	0.25	0.25	0.283	****	0.002	0.283	0.007	15	13	22	16.67	21
16	10:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
17	10:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
18	10:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
19	17:00	1.22	1.40	1.42	1.55	1.65	1.32	1.40	1.422	****	*****	*****	*****	20	19	30	23.00	21
20	17:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
21	14:00	0.05	0.10	0.15	0.08	0.15	0.08	0.05	0.094	****	0.000	0.094	0.000	27	25	38	30.00	23
22	16:00	0.05	0.10	0.15	0.15	0.13	0.10	0.05	0.105	****	0.000	0.105	0.000	34	28	42	34.67	22
23	12:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	****	0.000	0.000	-----	38	30	45	37.67	21
24	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
25	12:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
26	14:00	0.36	0.61	0.63	0.56	0.66	0.51	0.51	0.548	****	0.002	0.548	0.004	62	43	65	56.67	23
27	14:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
28	14:00	1.02	1.07	1.37	1.42	1.47	1.17	1.17	1.241	****	0.007	1.241	0.006	35	29	29	31.00	20
TOTAL									21.286	*****	0.039	7.019	0.006	MEAN			25.524	21.0

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 8

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF MAY, 1974

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER GAGE NO., CM 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESP-ONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM 1	2	3	MEAN	AIR TEMP. C
1	10:00	1.22	1.57	1.88	1.37	1.35	1.27	****	1.444	****	0.008	1.444	0.005	10	13	20	14.33	***
2	10:00	1.14	1.78	2.08	1.57	1.50	1.24	1.45	1.539	2.29	0.020	1.539	0.013	7	6	17	10.00	***
3	09:00	0.61	0.71	0.61	0.76	0.41	0.56	****	0.610	0.66	0.015	0.610	0.025	9	11	19	13.00	***
4	09:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
5	09:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
6	08:00	0.91	0.76	0.86	0.76	1.12	0.86	****	0.881	1.35	0.066	0.881	0.076	16	24	23	21.00	***
7	09:15	0.38	0.48	0.41	0.43	0.00	0.00	****	0.284	0.56	0.000	0.284	0.000	17	19	37	24.33	***
8	09:00	1.22	1.32	1.32	1.27	0.05	0.08	0.08	0.762	1.52	0.000	0.762	0.000	12	15	23	16.67	***
9	09:45	1.07	1.12	1.50	1.14	1.09	0.69	0.81	1.060	1.57	0.004	1.060	0.003	11	9	19	13.00	***
10	09:00	0.13	0.05	0.10	0.05	0.13	****	0.08	0.089	0.10	0.000	0.089	0.000	12	15	21	16.00	***
11	09:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
12	09:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
13	08:30	1.30	1.32	1.85	1.85	1.57	****	****	1.580	****	0.005	1.580	0.003	15	19	19	17.67	***
14	09:45	3.35	4.32	3.94	4.06	****	****	****	3.918	4.50	0.190	3.918	0.048	11	6	47	21.33	***
15	08:55	3.43	3.30	3.66	3.73	2.57	2.01	****	3.116	4.04	*****	*****	*****	11	9	17	12.33	***
16	09:06	1.63	2.08	2.11	2.36	1.14	1.50	****	1.803	2.16	*****	*****	*****	11	15	19	15.00	***
17	09:15	0.91	0.84	0.91	1.02	0.36	****	1.02	0.842	1.45	*****	*****	*****	12	11	19	14.00	***
18	13:00	1.83	2.92	3.43	2.92	****	****	****	2.775	****	*****	*****	*****	12	11	18	13.67	***
19	13:30	1.22	1.57	1.88	1.63	****	****	****	1.575	****	*****	*****	*****	10	11	18	13.00	28
20	09:40	1.93	2.57	3.58	2.90	****	****	****	2.743	9.58	*****	*****	*****	9	11	21	13.67	***
21	08:30	1.88	2.21	2.16	2.54	1.55	****	1.83	2.028	2.67	0.047	2.028	0.023	7	10	20	12.33	***
22	08:50	0.86	1.17	1.02	1.22	1.85	****	1.80	1.321	1.24	0.009	1.321	0.007	8	11	21	13.33	***
23	08:50	0.97	1.37	1.68	1.63	0.30	****	0.41	1.058	1.65	0.042	1.058	0.040	8	11	21	13.33	***
24	09:30	0.08	0.05	0.10	0.05	0.00	****	0.00	0.047	0.03	0.000	0.047	0.000	11	18	21	16.67	***
25	10:45	0.33	0.38	0.41	0.38	0.58	****	0.33	0.402	****	*****	*****	*****	13	25	25	21.00	25
26	11:00	0.05	0.05	0.08	0.03	0.00	****	0.00	0.034	****	0.000	0.034	0.000	16	33	27	25.33	23
27	11:00	1.22	1.52	1.32	1.93	1.04	****	1.45	1.414	2.08	0.020	1.414	0.014	16	17	24	19.00	22
28	08:35	0.05	0.08	0.10	0.08	0.00	****	0.00	0.051	0.03	0.000	0.051	0.000	11	21	25	19.00	***
29	08:55	0.00	0.00	0.00	0.00	0.00	****	0.00	0.000	0.00	0.000	0.000	-----	15	39	27	27.00	***
30	09:23	3.05	4.06	2.92	4.57	2.84	****	2.79	3.374	3.86	0.132	3.374	0.039	13	23	25	20.33	***
31	09:45	0.51	0.66	0.66	0.76	0.56	****	0.69	0.639	1.57	0.009	0.639	0.013	13	31	25	23.00	***
TOTAL									35.386	42.90	0.566	22.129	0.026	MEAN			17.012	24.5

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 9

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF JUNE, 1974

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER, GAGE NO., CM 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESP-ONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM 1	2	3	MEAN	AIR TEMP, C
1	09:00	0.33	0.36	0.46	0.41	0.28	****	0.30	0.356	0.56	0.002	0.356	0.005	11	17	23	17.00	***
2	09:15	****	****	****	****	1.60	****	0.33	0.965	****	0.019	0.965	0.020	***	***	***	*****	***
3	10:00	1.27	1.52	1.52	1.78	1.75	****	0.36	1.367	2.29	0.000	1.367	0.000	11	15	21	15.67	***
4	09:10	2.79	3.17	3.17	3.43	2.84	****	0.76	2.697	3.89	0.092	2.697	0.034	9	11	21	13.67	***
5	09:40	2.44	2.67	2.46	3.15	3.96	****	0.46	2.523	2.97	0.098	2.523	0.039	11	11	21	14.33	***
6	09:00	0.13	0.10	0.15	0.13	0.00	****	0.03	0.089	0.08	0.000	0.089	0.000	11	17	21	16.33	***
7	09:35	0.18	0.20	0.15	0.13	0.15	****	0.30	0.186	0.33	0.000	0.186	0.000	13	15	23	17.00	***
8	09:45	0.61	0.81	0.81	0.86	0.84	****	0.86	0.800	1.14	0.008	0.800	0.009	15	31	25	23.67	***
9	10:45	****	****	****	****	1.09	****	0.84	0.965	****	0.021	0.965	0.022	***	***	***	*****	***
10	13:00	4.06	4.57	4.32	5.21	5.12	****	4.01	5.215	5.49	0.065	5.215	0.012	11	9	21	13.67	***
11	09:05	0.10	0.10	0.13	0.08	0.03	****	0.05	0.080	0.10	0.000	0.080	0.000	11	13	21	15.00	***
12	08:55	0.05	0.05	0.08	0.03	0.03	****	0.10	0.055	0.13	0.000	0.055	0.000	15	13	23	17.00	***
13	08:55	0.00	0.00	0.00	0.00	0.00	****	0.00	0.000	0.08	0.000	0.000	-----	17	43	27	29.00	***
14	08:45	2.08	2.79	2.79	3.05	2.57	****	2.11	2.565	3.25	0.053	2.565	0.021	11	59	23	31.00	***
15	10:00	0.51	0.61	0.66	0.71	0.71	****	0.66	0.643	0.89	0.008	0.643	0.013	11	37	21	23.00	***
16	09:00	0.13	0.10	0.15	0.13	0.00	****	0.13	0.106	0.08	0.000	0.106	0.000	11	17	21	16.33	***
17	08:45	0.05	0.05	0.08	0.03	0.00	****	0.03	0.038	0.08	0.000	0.038	0.000	15	33	25	24.33	***
18	08:50	0.33	0.25	0.25	0.30	0.38	****	0.56	0.347	0.48	0.003	0.347	0.008	15	109	27	50.33	***
19	08:35	1.27	1.17	1.22	1.47	1.30	****	3.33	1.626	1.40	0.035	1.626	0.021	13	131	27	57.00	***
20	08:40	0.05	0.05	0.08	0.05	0.00	****	0.05	0.047	0.05	0.000	0.047	0.000	13	151	27	63.67	***
22	09:40	2.39	2.54	2.92	3.12	3.38	****	2.36	2.786	3.45	0.108	2.786	0.039	9	13	22	14.67	***
23	09:40	****	****	****	****	0.99	****	0.97	0.978	****	0.028	0.978	0.029	***	***	***	*****	***
24	08:45	1.02	1.17	1.27	1.17	1.12	****	1.12	1.143	1.63	0.028	1.143	0.025	11	39	21	23.67	23
25	08:45	0.13	0.10	0.13	0.08	0.08	****	****	0.102	0.20	0.000	0.102	0.000	11	39	21	23.67	23
26	08:45	0.05	0.03	0.05	0.03	0.05	****	0.08	0.047	0.13	0.000	0.047	0.000	14	63	25	34.00	24
27	09:20	0.66	0.71	0.71	0.74	0.94	****	0.97	0.787	1.12	0.005	0.787	0.007	11	47	25	27.67	24
28	10:05	2.03	2.18	2.18	2.18	0.66	****	2.41	1.943	3.02	0.116	1.943	0.060	9	19	21	16.33	24
29	10:45	4.95	6.35	5.46	6.60	5.97	****	6.22	5.927	6.38	0.160	5.927	0.027	9	11	21	13.67	24
30	10:45	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
TOTAL									34.383	39.19	0.847	34.383	0.025	MEAN			24.467	23.7

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 10

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF JULY, 1974

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER, GAGE NO., CM: 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESP-ONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM: 1	2	3	MEAN	AIR TEMP. C
1	09:00	0.97	0.76	0.97	1.02	1.07	****	1.14	0.986	1.47	0.000	0.986	0.000	9	15	21	15.00	24
2	08:35	0.20	0.13	0.15	0.15	0.18	****	2.67	0.580	0.28	0.005	0.580	0.009	11	17	21	16.33	24
3	08:25	0.05	0.03	0.05	0.03	0.00	****	0.00	0.025	0.03	0.000	0.025	0.000	11	23	22	18.67	24
4	08:35	0.00	0.00	0.03	0.03	0.00	****	0.00	0.008	0.00	0.000	0.008	0.000	15	39	25	26.33	23
5	08:40	0.05	0.08	0.20	0.08	0.08	****	0.10	0.097	0.36	0.000	0.097	0.002	19	67	28	38.00	24
6	09:40	0.56	0.46	0.43	0.46	0.86	****	0.63	0.567	0.63	0.005	0.567	0.010	9	107	21	45.67	24
7	09:40	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
8	09:10	3.43	3.68	3.56	3.56	4.93	****	3.81	3.827	4.11	0.156	3.827	0.041	11	13	21	15.00	24
9	08:35	0.38	0.28	0.36	0.38	0.36	****	0.30	0.343	0.48	0.000	0.343	0.001	9	33	19	20.33	24
10	08:50	0.25	0.25	0.25	0.25	1.14	****	1.47	0.605	0.18	0.000	0.605	0.000	11	55	21	29.00	24
11	08:55	0.03	0.03	0.03	0.03	0.00	****	0.00	0.017	0.03	0.000	0.017	0.000	14	69	23	35.33	24
12	09:10	3.43	3.94	4.44	4.19	4.04	****	3.25	3.882	5.08	0.152	3.882	0.039	7	4	13	8.00	23
13	09:10	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
14	09:10	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
15	09:20	4.32	4.83	5.21	5.33	4.47	****	3.94	4.682	6.30	0.023	4.682	0.005	11	17	15	14.33	24
16	08:30	3.81	4.83	5.08	4.70	4.62	****	3.02	4.343	5.21	0.248	3.754	0.066	7	9	15	10.33	24
17	09:10	4.06	4.57	4.57	4.44	3.51	****	4.55	4.284	5.51	0.190	4.023	0.047	15	17	15	15.67	24
18	08:25	1.88	1.73	2.18	2.03	2.51	1.02	1.63	1.854	2.57	0.112	1.854	0.060	7	11	15	11.00	24
19	08:40	0.36	0.30	0.38	0.38	2.24	0.25	0.30	0.602	0.51	0.000	0.602	0.000	9	15	17	13.67	24
20	09:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	-----	18	15	21	18.00	***
21	09:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	-----	13	30	26	23.00	23
22	08:59	0.10	0.08	0.13	0.08	0.08	0.13	0.15	0.105	0.03	0.030	0.105	0.284	10	19	23	17.33	24
23	08:58	0.10	0.08	0.13	0.08	0.00	0.00	0.00	0.054	0.03	0.000	0.054	0.000	10	19	23	17.33	24
24	09:12	0.51	0.33	0.51	0.51	0.48	0.38	0.51	0.461	0.53	0.007	0.461	0.015	14	31	21	22.00	24
25	08:43	0.20	0.15	0.23	0.15	0.10	0.10	0.20	0.163	0.30	0.000	0.163	0.000	15	39	21	25.00	23
26	09:15	1.02	1.02	1.12	1.02	1.02	0.66	1.02	0.980	1.30	0.027	0.980	0.027	15	43	21	26.33	***
27	05:0	1.42	1.78	2.44	1.93	2.26	1.50	1.55	1.840	****	0.102	1.840	0.055	8	12	21	13.67	22
28	10:45	****	****	****	****	0.10	0.08	0.20	0.127	****	0.000	0.127	0.000	***	***	***	*****	***
29	08:40	0.20	0.20	0.36	0.18	0.00	0.00	0.00	0.134	2.59	0.000	0.134	0.000	11	23	21	18.33	24
30	08:30	0.03	0.03	0.08	0.03	0.00	0.00	0.00	0.022	0.03	0.000	0.022	0.000	15	39	25	26.33	24
31	08:40	0.23	0.15	0.23	0.15	0.18	0.15	0.28	0.196	0.23	0.000	0.196	0.000	17	57	27	33.67	24
TOTAL									30.787	37.77	1.058	29.937	0.035	MEAN			21.247	23.8

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 11

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF AUGUST, 1974

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER, GAGE NO., CM: 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESP-ONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM: 1	2	3	MEAN	AIR TEMP. C
1	08:55	0.03	0.03	0.08	0.03	0.00	0.00	0.03	0.025	0.08	0.000	0.025	0.000	19	106	29	51.33	23
2	11:00	0.66	0.66	0.91	0.66	0.58	0.71	0.46	0.664	****	0.001	0.664	0.001	7	43	23	24.33	22
3	10:10	****	****	****	****	****	0.28	0.51	0.394	****	0.013	0.394	0.032	***	***	***	*****	***
4	10:40	****	****	****	****	****	0.13	0.08	0.102	****	0.000	0.102	0.000	***	***	***	*****	***
5	09:05	0.46	0.46	0.48	0.51	****	0.28	0.41	0.432	1.17	0.000	0.432	0.000	11	83	25	39.67	24
6	08:45	0.61	0.81	0.86	0.66	0.66	0.63	0.56	0.686	0.91	0.011	0.686	0.016	7	63	17	29.00	23
7	09:15	0.15	0.10	0.13	0.10	0.08	0.10	0.15	0.116	0.20	0.000	0.116	0.004	9	73	21	34.33	23
8	09:20	0.25	0.25	0.23	0.15	0.28	0.13	0.15	0.207	0.23	0.000	0.207	0.000	9	80	19	36.00	23
9	09:00	0.05	0.03	0.03	0.03	0.00	0.00	0.00	0.018	0.10	0.000	0.018	0.000	13	129	25	55.67	23
10	11:30	0.46	0.46	0.56	0.41	0.41	0.39	0.46	0.454	****	0.006	0.454	0.013	12	159	25	65.33	24
11	10:30	****	****	****	****	0.33	0.25	0.38	0.322	****	0.002	0.322	0.007	***	***	***	*****	***
12	09:10	3.43	3.56	4.32	3.56	3.07	4.90	4.98	3.973	5.79	0.154	3.973	0.039	5	11	19	11.67	21
13	08:40	0.13	0.10	0.10	0.08	0.05	0.00	0.05	0.073	0.20	0.001	0.073	0.018	9	19	21	16.33	23
14	09:10	0.03	0.00	0.03	0.00	0.00	0.00	0.00	0.007	0.05	0.000	0.007	0.000	11	33	25	23.00	23
15	08:55	0.51	0.61	0.56	0.48	0.51	0.58	0.63	0.555	0.91	0.000	0.555	0.001	11	39	21	23.67	21
16	10:30	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
17	10:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	-----	17	99	30	48.67	25
18	10:30	****	****	****	****	0.41	****	0.58	0.495	****	0.000	0.495	0.000	***	***	***	*****	***
19	09:15	0.81	1.12	1.02	0.71	0.46	****	0.66	0.796	1.22	0.000	0.796	0.000	13	153	22	62.67	24
20	08:50	1.27	1.32	1.22	1.12	1.07	0.91	0.97	1.125	1.55	0.013	1.125	0.011	5	31	19	18.33	22
21	09:20	0.48	0.53	0.58	0.46	0.43	0.43	0.53	0.493	0.89	0.004	0.493	0.009	6	11	17	11.33	22
22	09:10	0.71	0.86	0.91	0.76	0.76	0.66	0.61	0.755	1.17	0.004	0.755	0.005	7	11	19	12.33	21
23	09:10	0.61	0.61	0.66	0.43	0.33	0.30	****	0.491	0.99	0.000	0.491	0.001	6	***	***	6.00	22
24	11:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	-----	12	***	24	18.00	26
25	11:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
26	09:15	0.03	0.05	0.05	0.00	0.00	0.00	0.00	0.018	0.08	0.000	0.018	0.000	7	***	19	13.00	25
27	09:15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	-----	19	***	23	21.00	25
29	09:10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.03	0.000	0.000	-----	25	148	53	75.33	22
30	08:50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.03	0.000	0.000	-----	29	53	49	43.67	23
31	10:30	****	****	****	****	****	****	0.05	0.051	****	0.000	0.051	0.000	***	***	***	*****	***
TOTAL									12.251	15.60	0.210	12.251	0.017	MEAN			32.203	23.0

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 12

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF SEPTEMBER, 1974

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER, GAGE NO., CM: 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESPONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM: 1	2	3	MEAN	AIR TEMP. C
1	10:30	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
2	10:30	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
3	08:55	2.79	2.79	2.54	2.44	****	****	3.00	2.713	3.45	0.021	2.713	0.008	7	15	15	12.33	23
4	09:55	0.05	0.05	0.05	0.03	0.00	0.00	0.05	0.033	0.05	0.000	0.033	0.000	11	29	21	20.33	25
5	09:00	0.61	0.71	0.76	0.71	0.46	0.63	0.79	0.668	0.81	0.002	0.668	0.002	9	13	17	13.00	23
6	08:50	0.13	0.08	0.13	0.08	0.05	0.05	0.03	0.076	0.15	0.000	0.076	0.000	11	25	21	19.00	23
7	10:30	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
8	15:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
9	09:50	0.61	0.66	0.71	0.61	0.46	0.48	0.23	0.537	1.04	0.000	0.537	0.000	13	39	27	26.33	22
10	09:00	1.07	1.02	1.07	0.91	0.43	0.71	1.14	0.907	1.24	0.014	0.907	0.015	5	15	17	12.33	22
11	08:55	0.08	0.08	0.08	0.05	0.00	0.00	0.05	0.047	0.08	0.000	0.047	0.000	9	17	19	15.00	22
12	09:00	0.28	0.30	0.20	0.23	0.15	****	0.33	0.250	0.38	0.000	0.250	0.000	11	27	21	19.67	23
13	09:10	0.56	0.38	0.38	0.36	0.33	****	0.41	0.402	0.58	0.000	0.402	0.000	9	15	19	14.33	25
14	09:10	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
15	09:10	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
16	09:30	0.15	0.15	0.18	0.15	0.13	****	0.18	0.157	0.28	0.000	0.157	0.000	13	61	27	33.67	24
17	08:50	0.20	0.13	0.15	0.10	0.08	0.10	0.15	0.131	0.25	0.000	0.131	0.000	17	89	29	45.00	24
18	09:10	0.28	0.15	0.23	0.10	0.10	0.20	0.25	0.185	0.28	0.000	0.185	0.000	17	105	29	50.33	24
19	09:05	3.81	3.96	3.86	3.68	2.77	2.74	3.17	3.429	4.04	0.124	1.638	0.076	11	13	21	15.00	23
20	09:05	2.08	2.29	2.34	1.52	1.30	1.40	1.52	1.778	2.03	0.013	1.778	0.007	9	15	21	15.00	23
21	09:35	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
22	09:05	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
23	09:40	0.46	0.41	0.56	0.36	0.00	0.00	0.00	0.254	0.48	0.000	0.254	0.000	13	33	25	23.67	24
24	08:40	0.97	1.12	1.12	1.12	0.69	****	0.97	0.995	1.17	0.081	0.995	0.081	15	23	29	22.33	24
25	09:05	0.18	0.15	0.18	0.15	0.08	****	0.15	0.148	0.25	0.000	0.148	0.000	15	33	29	25.67	23
26	09:15	0.86	0.91	0.76	0.71	0.43	****	0.71	0.732	1.14	0.000	0.732	0.001	7	13	19	13.00	21
27	08:55	0.08	0.08	0.10	0.08	0.05	****	0.08	0.076	0.10	0.000	0.076	0.000	9	11	19	13.00	23
28	09:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
29	09:30	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
30	09:00	0.18	0.13	0.10	0.08	0.10	****	0.20	0.131	0.28	0.000	0.131	0.000	15	59	27	33.67	23
TOTAL									13.649	18.11	0.254	11.858	0.021	MEAN			22.133	23.2

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 13

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF OCTOBER, 1974

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER GAGE NO., CM 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESP-ONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM 1	2	3	MEAN	AIR TEMP. C
1	14:00	0.97	0.91	0.81	0.66	0.43	0.63	0.76	0.740	0.99	0.064	0.740	0.087	17	43	23	27.67	25
2	09:30	0.05	0.03	0.05	0.03	0.00	0.00	0.00	0.022	0.03	0.000	0.022	0.000	17	53	23	31.00	23
3	08:55	0.38	0.46	0.51	0.36	0.61	0.38	0.63	0.475	0.51	0.014	0.475	0.029	17	39	23	26.33	22
4	09:00	0.56	0.66	0.66	0.51	0.46	0.46	0.58	0.555	0.66	0.013	0.555	0.023	11	13	23	15.67	22
5	09:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
6	09:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
7	09:00	0.61	0.46	0.46	0.46	****	0.25	1.27	0.584	0.63	0.004	0.584	0.007	17	33	25	25.00	22
8	08:45	1.37	1.63	1.88	1.42	1.14	1.19	1.42	1.437	1.90	0.050	1.437	0.035	7	11	17	11.67	22
9	09:00	0.48	0.61	0.66	0.51	0.36	0.33	0.38	0.475	0.71	0.012	0.475	0.025	9	11	17	12.33	21
10	09:00	1.52	1.83	1.78	1.27	1.70	1.27	1.52	1.557	1.75	0.066	1.557	0.042	7	11	17	11.67	21
11	09:10	0.28	0.25	0.28	0.20	0.10	0.08	0.15	0.192	0.30	0.000	0.192	0.000	9	13	19	13.67	21
12	09:10	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
13	09:10	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
14	09:10	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
15	09:20	1.07	1.07	1.27	0.97	****	0.86	1.07	1.050	1.75	0.019	1.050	0.018	15	25	25	21.67	21
16	08:35	7.37	9.40	6.98	7.75	9.83	****	8.43	8.293	8.53	0.161	5.095	0.032	7	11	19	12.33	21
17	09:10	0.30	0.30	0.36	0.23	0.18	0.25	0.25	0.269	0.23	0.000	0.269	0.000	7	11	19	12.33	22
18	09:25	0.76	0.91	0.97	0.86	0.61	0.13	0.76	0.715	0.84	0.000	0.715	0.000	7	9	19	11.67	24
19	09:25	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
20	09:25	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
21	09:00	2.51	2.92	3.05	2.67	2.11	2.08	2.59	2.562	3.76	0.137	2.562	0.053	9	17	21	15.67	22
22	09:40	0.13	0.13	0.15	0.10	0.08	0.10	0.13	0.116	0.20	0.000	0.116	0.000	11	19	23	17.67	24
23	08:45	0.15	0.08	0.10	0.18	0.10	0.13	0.13	0.123	0.23	0.000	0.123	0.000	15	23	25	21.00	22
24	08:35	0.25	0.33	0.36	0.28	0.13	0.18	0.20	0.247	0.38	0.000	0.247	0.000	13	25	25	21.00	21
25	08:45	0.08	0.05	0.05	0.03	0.00	0.00	0.00	0.029	0.03	0.000	0.029	0.000	13	15	25	17.67	22
26	13:20	0.56	0.69	0.66	0.56	0.38	0.46	0.69	0.570	****	0.000	0.570	0.000	11	25	25	20.33	23
27	08:45	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
28	13:30	****	****	****	****	8.64	8.38	8.13	8.382	****	0.081	2.565	0.032	***	***	***	*****	***
29	08:35	****	****	****	****	****	****	****	*****	****	0.188	*****	0.016	2	7	17	8.67	22
30	11:15	0.86	1.19	1.19	0.86	0.79	0.38	0.46	0.820	****	0.012	0.820	0.015	10	15	23	16.00	22
31	08:35	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
TOTAL									41.307	38.20	0.820	32.293	0.025	MEAN			17.667	22.1

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 14

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF NOVEMBER, 1974

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER, GAGE NO., CM: 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESP-ONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM: 1	2	3	MEAN	AIR TEMP. C
1	11:15	1.14	1.32	1.42	1.17	0.81	0.81	1.02	1.099	****	0.057	1.099	0.052	10	15	22	15.67	23
2	08:35	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
3	08:35	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
4	09:45	1.83	1.98	1.78	1.57	1.12	****	1.30	1.596	4.90	0.003	1.596	0.002	9	19	23	17.00	20
5	08:45	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
6	08:40	0.33	0.38	0.46	0.33	0.28	0.28	0.30	0.337	0.76	0.000	0.337	0.000	9	15	23	15.67	22
7	08:45	2.18	2.54	2.79	2.36	2.54	2.13	2.41	2.424	3.12	0.097	2.424	0.040	7	27	19	17.67	20
8	08:30	0.86	1.02	0.91	0.81	0.81	0.76	0.86	0.864	1.27	*****	*****	*****	7	9	19	11.67	20
9	08:30	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
10	08:30	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
11	08:35	5.08	5.21	6.10	5.18	****	4.88	4.83	5.211	6.96	*****	*****	*****	7	9	17	11.00	22
12	13:30	0.76	0.81	****	0.86	0.84	0.63	****	0.782	****	0.054	0.782	0.069	9	17	17	14.33	22
13	09:10	0.03	0.05	0.00	0.03	0.00	0.00	0.00	0.015	0.00	0.000	0.015	0.000	13	19	19	17.00	20
14	08:40	0.13	0.33	0.48	0.20	0.15	****	****	0.259	0.56	0.000	0.259	0.000	15	23	8	15.33	19
15	08:37	0.03	0.03	0.03	0.00	0.00	0.00	0.00	0.011	0.05	0.000	0.011	0.000	17	31	21	23.00	19
16	08:35	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
17	08:35	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
18	09:00	4.83	6.48	6.10	5.69	4.34	4.09	****	5.254	6.27	0.141	5.254	0.027	3	6	9	6.00	20
19	08:50	0.05	0.08	0.08	0.05	0.00	0.00	0.00	0.036	0.03	0.000	0.036	0.000	10	12	9	10.33	23
20	08:55	1.52	2.34	2.64	1.68	1.96	1.83	2.59	2.079	2.69	0.116	2.079	0.056	6	6	13	8.33	20
21	11:40	****	****	****	****	****	****	****	*****	****	0.176	2.997	0.059	***	***	***	*****	21
22	08:35	7.11	****	9.78	7.75	8.59	5.54	8.10	8.146	8.76	0.094	2.984	0.032	5	5	21	10.33	21
23	08:35	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
24	08:35	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
25	08:40	0.51	0.61	0.71	0.61	0.00	0.00	0.00	0.348	0.71	0.000	0.348	0.000	11	15	13	13.00	21
26	08:55	0.05	0.05	0.05	0.03	0.00	0.00	0.00	0.025	0.00	0.000	0.025	0.000	14	19	15	16.00	22
27	08:45	0.00	0.03	0.05	0.00	0.00	0.00	0.00	0.011	0.05	0.000	0.011	0.000	14	21	19	18.00	22
28	08:45	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
29	08:40	0.03	0.05	0.08	0.00	0.00	0.00	0.00	0.022	0.13	0.000	0.022	0.000	18	37	24	26.33	21
30	08:40	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
TOTAL									46.025	59.13	0.737	20.281	0.036	MEAN			14.815	20.9

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 15

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF DECEMBER, 1974

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER GAGE NO., CM 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESP-ONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM 1	2	3	MEAN	AIR TEMP. C
1	08:40	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
2	08:20	0.03	0.08	0.08	0.00	0.00	0.00	0.00	0.025	0.10	0.000	0.025	0.000	25	57	22	34.67	21
3	08:35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	-----	30	73	37	46.67	20
4	08:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	-----	33	71	40	48.00	20
5	08:50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	-----	36	91	43	56.67	22
6	08:45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	-----	41	117	49	69.00	21
7	08:45	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
8	08:45	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
9	08:35	1.83	2.92	3.30	1.83	2.01	1.96	2.95	2.398	3.07	0.000	2.398	0.000	6	5	9	6.67	21
10	08:35	0.13	0.13	0.13	0.08	0.05	****	0.13	0.106	0.15	0.000	0.106	0.000	9	13	11	11.00	22
11	08:35	0.03	0.03	0.05	0.00	0.00	0.00	0.00	0.015	0.03	0.000	0.015	0.000	11	21	15	15.67	22
12	08:35	1.17	1.63	1.83	1.12	1.04	1.14	1.55	1.353	1.65	0.057	1.353	0.042	5	5	11	7.00	21
13	08:35	0.03	0.03	0.05	0.03	0.00	0.00	0.00	0.018	0.03	0.000	0.018	0.000	9	13	13	11.67	21
14	08:35	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
15	08:35	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
16	08:45	3.05	3.94	3.81	2.67	2.49	3.91	5.33	3.600	3.68	0.000	3.600	0.000	9	11	13	11.00	19
17	08:50	0.10	0.13	0.13	0.08	0.03	0.05	0.05	0.080	0.05	0.000	0.080	0.000	9	15	13	12.33	20
18	08:35	0.03	0.03	0.05	0.03	0.00	0.00	0.00	0.018	0.03	0.000	0.018	0.000	11	17	17	15.00	22
19	08:25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	-----	13	15	19	15.67	20
20	08:30	1.27	1.93	1.98	1.22	1.22	1.40	1.88	1.557	1.90	0.054	1.557	0.035	5	7	15	9.00	19
21	08:30	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
22	08:30	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
23	08:45	7.24	****	9.96	7.11	6.96	6.68	8.53	8.146	6.96	0.114	8.146	0.014	5	3	10	6.00	20
24	08:55	1.27	1.93	1.93	1.27	0.99	1.27	1.70	1.480	1.73	0.056	1.480	0.038	6	7	10	7.67	20
25	08:55	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
26	08:45	3.05	4.70	4.44	3.17	3.05	****	3.89	3.717	4.34	0.051	3.717	0.014	5	7	11	7.67	19
27	08:30	2.08	3.33	3.66	2.13	2.18	2.54	2.92	2.692	3.07	0.161	2.522	0.064	5	6	11	7.33	19
28	08:30	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
29	08:30	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
30	08:50	0.38	0.53	0.61	0.28	0.28	0.38	0.58	0.435	0.63	0.000	0.435	0.000	11	15	15	13.67	***
31	10:40	0.15	0.28	0.25	0.08	0.08	0.20	0.20	0.178	0.25	0.000	0.178	0.000	13	19	15	15.67	***
TOTAL									25.819	27.69	0.494	25.649	0.019	MEAN			20.381	20.5

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 16

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF JANUARY, 1975

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER — GAGE NO., CM 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESP-ONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM 1	2	3	MEAN	AIR TEMP. C
1	08:30	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
2	09:55	1.83	2.67	2.67	1.78	1.60	2.01	2.36	2.130	2.41	0.159	2.130	0.074	9	13	12	11.33	20
3	08:45	1.12	1.63	1.63	1.07	1.40	1.09	0.94	1.266	1.55	0.077	1.266	0.061	5	15	15	11.67	18
4	08:45	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
5	08:45	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
6	08:50	1.96	3.17	3.17	1.98	2.01	2.46	2.59	2.478	3.17	0.451	2.478	0.182	5	7	10	7.33	19
7	09:50	2.54	3.81	3.68	2.74	2.49	2.54	3.40	3.030	3.48	0.185	2.324	0.080	5	7	10	7.33	19
8	08:45	1.52	2.54	2.79	1.83	1.90	1.78	****	2.062	2.34	0.135	2.062	0.066	5	7	11	7.67	18
9	09:15	0.74	0.91	0.86	0.61	0.46	0.56	****	0.690	0.81	0.048	0.690	0.070	6	7	12	8.33	20
10	09:25	0.18	0.25	0.23	0.13	0.08	0.13	****	0.165	0.20	0.001	0.165	0.006	7	13	15	11.67	21
11	09:25	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
12	09:25	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
13	09:30	****	****	****	****	****	****	****	*****	****	0.185	*****	0.014	7	11	11	9.67	20
14	09:50	2.18	3.56	3.61	2.54	2.11	2.39	****	2.730	3.38	0.191	1.753	0.109	5	9	12	8.67	19
15	09:30	0.13	0.25	0.25	0.13	0.08	0.23	****	0.178	0.38	0.000	0.178	0.000	8	9	12	9.67	20
16	09:30	0.03	0.05	0.05	0.03	0.00	0.00	0.00	0.022	0.03	0.000	0.022	0.000	11	15	15	13.67	20
17	09:00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.004	0.03	0.000	0.004	0.000	13	19	17	16.33	20
18	09:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
19	09:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
20	09:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	-----	19	36	25	26.67	19
21	09:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.03	0.000	0.000	-----	19	39	25	27.67	20
22	15:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	-----	21	57	29	35.67	23
23	09:40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.03	0.000	0.000	-----	24	61	31	38.67	21
24	09:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	-----	26	69	33	42.67	20
25	09:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
26	09:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
27	09:05	5.59	6.73	8.76	6.98	6.98	6.63	5.77	6.778	8.36	0.182	3.526	0.052	12	20	17	16.33	17
28	08:25	0.08	0.10	0.13	0.08	0.00	0.03	0.00	0.058	0.03	0.000	0.058	0.000	14	27	21	20.67	17
29	09:40	0.00	0.03	0.03	0.00	0.00	0.00	0.00	0.007	0.03	0.000	0.007	0.000	16	35	25	25.33	20
30	09:45	1.02	1.27	1.32	0.84	0.76	1.04	1.30	1.078	1.27	0.021	1.078	0.020	5	5	23	11.00	19
31	09:20	2.79	3.94	3.94	2.87	2.72	2.84	3.43	3.219	3.71	0.154	4.699	0.033	5	4	9	6.00	21
TOTAL									39.153	49.76	1.791	35.698	0.050	MEAN			17.000	19.6

NOTE : THE SYMBOLS * INDICATE MISSING DATA

TABLE 17

DAILY RAINFALL, RUNOFF AND SOIL-WATER SUCTION DATA

FOR THE MONTH OF FEBRUARY, 1975

DATE	STARTING CLOCK TIME	RAINFALL UNDER FOREST COVER GAGE NO., CM 1	2	3	4	5	6	7	MEAN	RAINFALL IN THE OPEN, CM	RUN-OFF, CM	RAINFALL CORRESPONDING TO RUNOFF, CM	RUNOFF RAINFALL RATIO	SOIL-WATER SUCTION AT 30 CM DEPTH, CM 1	2	3	MEAN	AIR TEMP. C
1	09:20	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
2	15:00	4.27	4.70	5.59	4.83	3.78	4.14	4.90	4.601	6.02	0.227	2.616	0.087	5	9	15	9.67	21
3	09:15	1.68	2.59	2.16	2.67	2.01	1.35	1.93	2.054	2.29	0.159	1.892	0.084	5	7	10	7.33	20
4	09:45	2.13	2.92	3.17	2.03	1.63	1.98	2.59	2.351	2.79	0.183	2.351	0.078	5	6	11	7.33	19
5	10:15	1.02	1.37	1.65	1.02	0.91	1.09	1.12	1.168	1.50	0.070	1.168	0.060	6	10	11	9.00	20
6	10:45	0.05	0.05	0.05	0.03	0.00	0.03	0.00	0.029	0.03	0.000	0.029	0.000	11	18	15	14.67	20
7	10:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	-----	13	23	19	18.33	19
8	10:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
9	10:00	****	****	****	****	****	****	****	*****	****	*****	*****	*****	***	***	***	*****	***
10	09:40	0.13	0.15	0.23	0.10	0.00	0.15	0.00	0.109	0.23	0.000	0.109	0.000	19	39	26	28.00	20
11	08:50	0.00	0.03	0.03	0.00	0.00	0.00	0.00	0.007	0.00	0.000	0.007	0.000	20	46	27	31.00	20
12	09:15	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.004	0.05	0.000	0.004	0.000	21	56	29	35.33	19
13	09:45	3.43	4.70	4.44	3.35	3.30	3.63	4.29	3.879	4.62	0.133	3.879	0.034	7	7	26	13.33	19
14	10:00	1.02	1.42	1.52	1.02	0.94	1.19	1.55	1.237	1.65	0.035	1.237	0.028	6	7	10	7.67	19
TOTAL									15.440	19.18	0.807	13.293	0.061	MEAN			16.515	19.6

NOTE : THE SYMBOLS * INDICATE MISSING DATA

rainstorms, even the capacity of four barrels was insufficient to collect all the runoff. For this reason, the rainfall received until the time of the measured amount of runoff is shown for each day in the Tables.

The daily rainfall varied widely during any given month. Among the months recorded, August and September were the driest, with 11 to 14 cm of rainfall under the canopy. November and January were the wettest with 46 and 39 cm, respectively. Rainfall recorded in the open was, on the average, 25% more than the amount recorded under the canopy.

Runoff from the plot also varied widely from day to day, depending upon the rainfall and soil-water status. In the duration of runoff measurements (until the time the barrels were full), 0.5 to 6% of the rainfall on the plot ran off. The runoff percentage was smaller in early part of the storms, as indicated particularly by data for the first few months when only two 55-gal barrels were used to collect runoff. This finding is explained by the fact that infiltration rates are high initially when the soil is not completely saturated with water. The soil profile was generally moist to wet all the time. The daily recorded soil-water suction at 30 cm depth varied between 6 and 69 cm water over the whole period of measurements. The monthly mean suction ranged from 15 to 32 cm water.

The results presented above indicate that the measurement of rainfall-runoff and soil-water relationships under natural watershed conditions is useful in characterizing the infiltration of natural rain. Saturated hydraulic conductivities of different soil horizons are determined in-situ. Analysis of results shows that characterization of infiltration also requires a determination of soil hydraulic properties when the soil is only partially saturated with water. For some practical uses, this study provides a rough guide for predicting infiltration of natural rain by way of runoff to rainfall ratios.

A System for Continuously Monitoring Soil-Water Status on Forest Watersheds

Soil-water status of a watershed determines to a great degree how much of a rainstorm would infiltrate into the ground and how much would runoff. This is so because the initial soil-water status determines the water potential gradients and conductivities which, in turn, govern the flow of water through soil. Knowledge of the dynamic soil-water status through the year would be essential for predicting the rainfall-runoff relationships during different rainstorms. Its continuous monitoring would provide a measure of drainage water yield and evapotranspiration between the rainstorms. By a careful analysis of such data, one could determine the soil's basic properties of water conductivity and water storage as a function of soil-water potential. The knowledge of soil-water status and basic hydrologic properties would make watershed management more objective.

Recent developments in the fast-response pressure transducers, automatic scanning and recording systems for field use (Watson, 1967; Rice, 1969) make it possible to continuously monitor the soil-water pressure or tensions in the profile at several locations. The soil water contents can then be derived from the tension measurements using the pre-determined tension-water content relationship for each soil horizon.

Rice (1969) described and tested a hydraulic scanning system in which twelve tensiometers were connected to a pressure transducer through a 12-port scanning valve. The valve was equipped with a solenoid switching motor that was energized with a timer. The signal from the transducer was recorded on a millivolt recorder. The power source for energizing the transducer, switching motor, timer and recorder was from a regular 110-volt line. Rice pointed out some limitations of the hydraulic scanning system, the important among them being (a) a response lag when switching from one tensiometer to another, (b) more connections involved, which increases the chance for air leaks, and (c) temperature effects when some of the temperature-sensitive water-leads are above ground. When these limitations are critical, it would be best to use an electric scanning system, in which each tensiometer has its own transducer, located close to the tensiometer cup, and the signals are electronically scanned. However, the electronic system is much more expensive because of the cost of several more pressure teansducers.

Objective of the present study was to assemble a transducer-hydraulic scanning valve-timer-recorder system that would run on battery power, for use on remote forest watersheds where regular power line may not be accessible, and test its use to monitor soil-water status on a Hawaii's forest watershed.

Design of the Monitoring System

Design of the completely battery-operated monitoring system devised for the watershed studies is shown by a schematic diagram in Fig. 1. Field tensiometers and reference-pressure channels were connected to a pressure transducer (Statham, Model PM131TC) through a 24-port hydraulic scanning valve (Scanivalve, W. Wafer). The valve was equipped with a solenoid stepping motor which responded to a 24-volt dc pulse emitted at controlled time intervals by a timer-pulser. With each step of the motor, the transducer is connected internally to a different tensiometer, with no volume changes in the system when switching from one port to another. In this manner, all the channels are sequentially scanned. The timer-pulser was powered by 24-volt dc current obtained from two 12-volt batteries connected in parallel. The pressure transducer required an energizing current of constant 5-volts dc voltage, which was obtained from a 7.5-volt battery connected to a 5-volt dc regulator. The regulator gave a very stable output over a long time period. The millivolt output of the transducer was fed to a strip-chart recorder (WeatherMeasure, EPR-2T), which was operated on a 12-volt automobile battery. The recorder had a regulated motor, which is not affected by normal changes of the battery's voltage. A 96-amp automobile battery

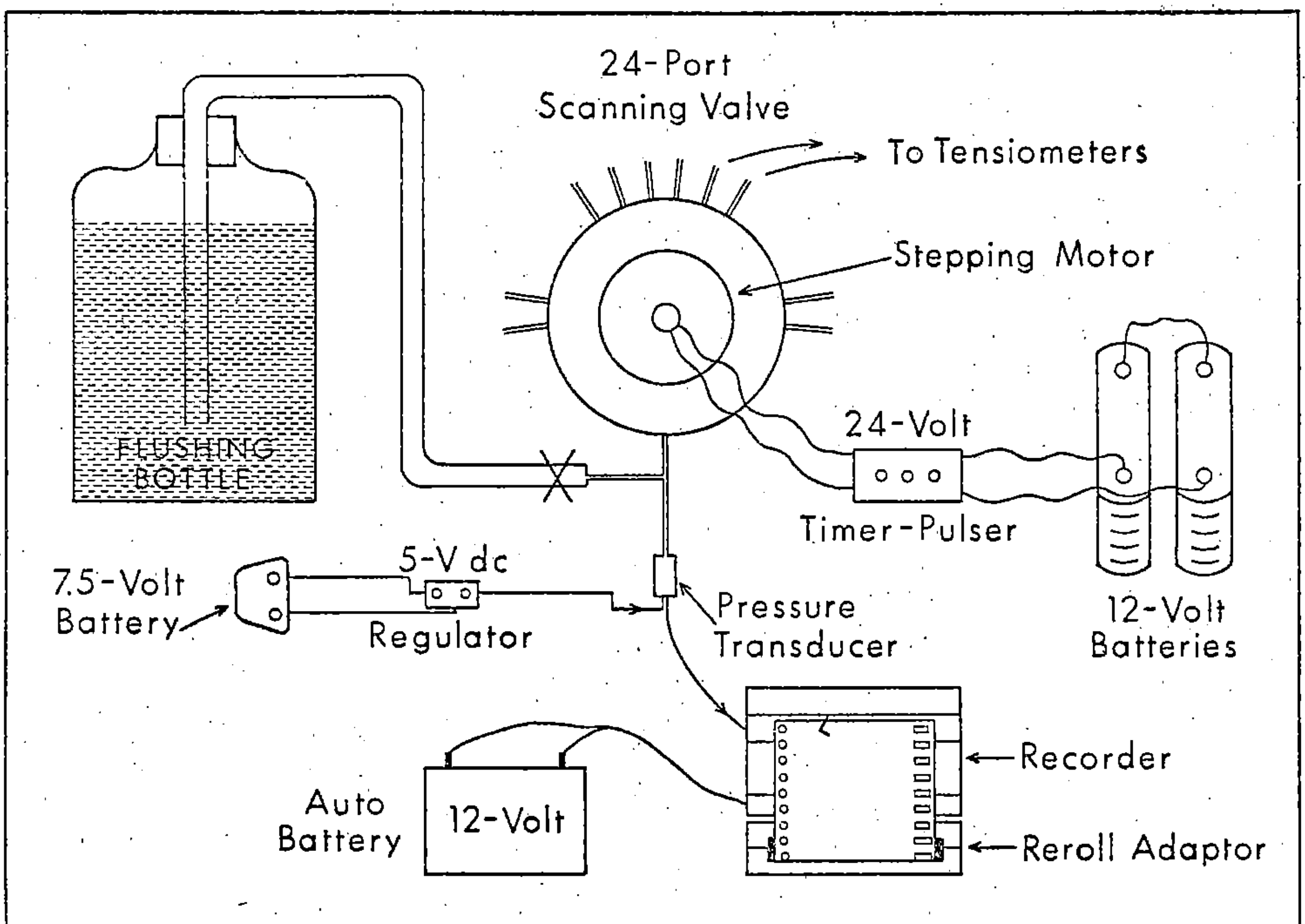

Fig. 1--A schematic diagram of the completely battery-operated monitoring system devised for watershed studies.

performed well for one week period, after which it was removed and recharged. Two batteries, used alternately, were convenient and satisfactory. The strip chart coming out of the recorder was automatically rolled on to a reroll adapter, powered by flash-light cells (3-v dc).

Each port of the scanning valve was connected to an individual tensiometer or reference-pressure channel by 3 mm O.D. nylon tubing. To remove air bubbles as they appeared in the valve and leads, a sideline was provided between the transducer and scanning valve for flushing individual channels. The whole monitoring system, shown in Fig. 1, was enclosed in a styrofoam-insulated box in order to reduce the effects of temperature fluctuations on the units. The nylon tubings connecting the tensiometers to the scanivalve were exposed to the environment. In order to account for the environmental effects on the water pressure readings, if any, three reference-pressure channels were provided in the scanning cycle (of 24 channels). A frequent record of air temperatures was maintained in order to correlate any such effects.

The monitoring was conducted on the forest-watershed plot at the U.S. Arboretum, described in the previous subsections. The plot had three sets of tensiometers installed along the slope. Each set had five tensiometers, one for each of the soil depths of nearly 7.5, 30, 60, 90, and 120 cm below the soil surface at the individual locations. At the site of each tensiometer set, a water bottle was placed to serve as the reference-pressure channel. Thus, there were a total of 15 individual tensiometers and 3 reference channels. Six additional channels were available on the 24-port scanning valve. So, the two shallower tensiometers in each of the three sets were connected to these six ports by T-connections. In this way, the shallower units were read twice in the scanning cycle of 24. This was advantageous in that the shallower soil depths underwent more frequent soil-water pressure changes. The box containing the sensing and recording units was located outside the plot, so as to avoid frequent entry into the plot and not to interfere with natural conditions of rainfall and runoff.

The response time of the scanning system depends on the transducer sensitivity, tensiometer-cup conductance, soil-water conductivity, and amount of air in the system. The cup conductance would be critical when the soil is wet, but the soil-water conductivity may limit the sensitivity when the soil dries up. Testing of the system <u>in-situ</u> for some time indicated that a switching interval of 2 min was satisfactory for all different channels. The problem of air bubbles was encountered frequently as the soil-water tensions increased, especially for the tensiometers located deep in the profile. Continuous vigilance, flushing of just the problem channels when necessary and a biweekly to monthly flushing of all the units was required.

Monitored Data and Applications

An example of monitored data is given in Fig. 2. The figure shows the changes in the recorder's reading with the changing of channels resulting from consecutive stepping of the motor. The chart speed was

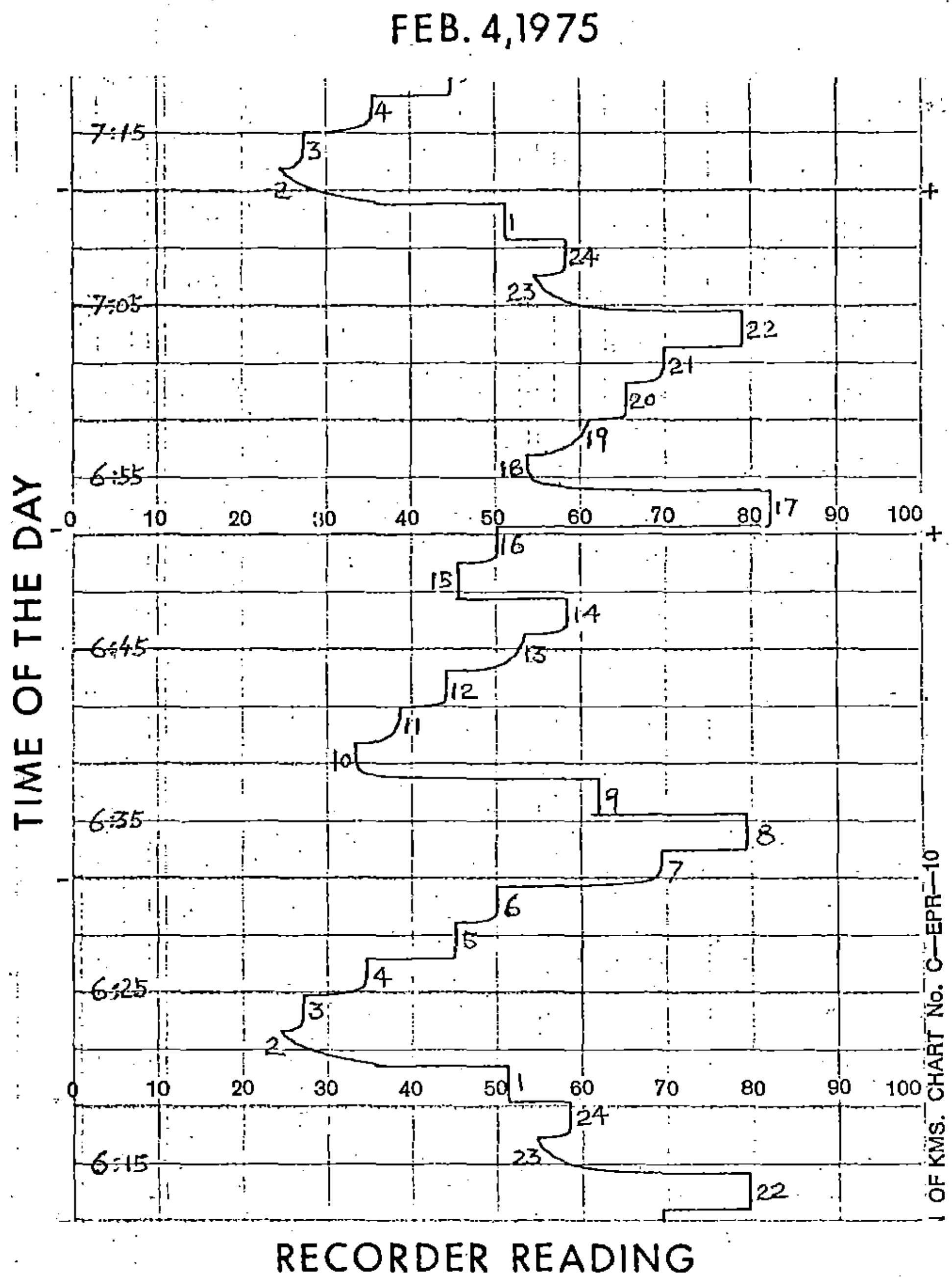

Fig. 2--An example of actually recorded data for all the 24 channels.

18 cm/hr. The stepping interval was a little over 2 min. The complete cycle of 24 channels was completed in 50 min. The numbers written next to each step are channel numbers. Channel Nos. 1, 9 and 17 were the reference-pressure channels. As the soil-water tensions increased, the recorder reading decreased. A pre-determined calibration of the system and the changes in calibration as indicated by the reference channels were used to decipher the recorded data in terms of soil-water tensions as cm of water. For this purpose, the ground level at the location of a given tensiometer and its depth below the soil surface were also required.

Fig. 3 shows the cumulative rainfall and soil-water suction changes at 5.5 cm and 26 cm soil depths at the location of tensiometer set no. 1 for 24 hours starting from the morning of August 20, 1974. The data indicate a general correspondence between the rainfall and soil-water suction changes. As expected, the suction at 26 cm soil depth shows a more delayed response than that at 5.5 cm depth. The suctions at 5.5 cm depth are lower than those at 26 cm depth through the 24 hour period, indicating the potential gradients and water flow were downwards. Fig. 4 shows the suction changes at these two depths for another day which received no rainfall at all. The soil-water suction increases at both the depths, more so at the surface (5.5 cm depth). The surface soil had higher suctions due to evapotranspiration and deep percolation of water. Fig. 5 shows rainfall and suction changes in the soil on a day in February, 1975 when the rainfall was higher than that shown in Fig. 3. The results are an example of more frequent changes of suctions with weather conditions.

Fig. 6, 7, and 8 illustrate the use of monitored data for calculating soil water storage gain or loss, infiltration minus evapotranspiration in the profile, evapotranspiration and deep percolation. The water storage in the profile at any given time was calculated by converting the measured soil-water suctions to water contents using the water characteristic curves of the watershed-plot presented in an earlier subsection. The deep percolation rate below any given soil depth was computed by Darcy's Law as a product of hydraulic gradient and appropriate unsaturated hydraulic conductivity as a function of soil-water content. The sum of deep percolation and water storage gain or loss at any time represented the amount of water infiltration minus the evapotranspiration. All the calculations shown in Fig. 6 to 8 were made for the upper 75 cm of soil profile from readings of the tensiometer set no. 1.

Fig. 6 has the calculations for a day in August, 1974 which received only 0.45 cm of rainfall and there was no runoff. The measured infilgration shown in the figure is, therefore, just all the rainfall. The figure indicates that the deep percolation below 75 cm depth was practically negligible on this day. There is a great deal of scatter in the calculations of infiltration minus evapotranspiration, although these values fairly well follow the trend of measured infiltration.

Fig. 7. shows calculations of evapotranspiration and deep percolation for a day which received no rainfall. Deep percolation was again very small. Evapotranspiration was nearly 1.8 cm of water for the day.

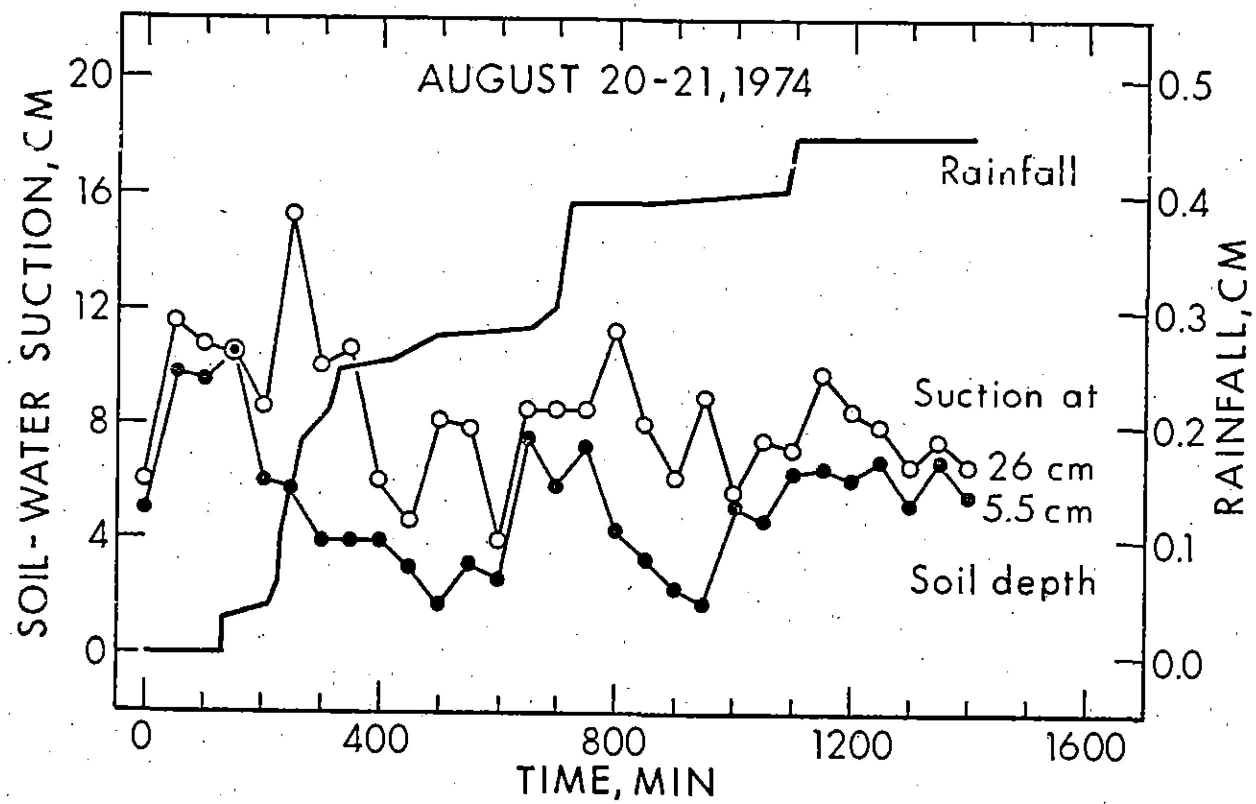

Fig. 3--Cumulative rainfall and soil-water suction changes at 5.5 and 26 cm soil depths for a 24-hr period.

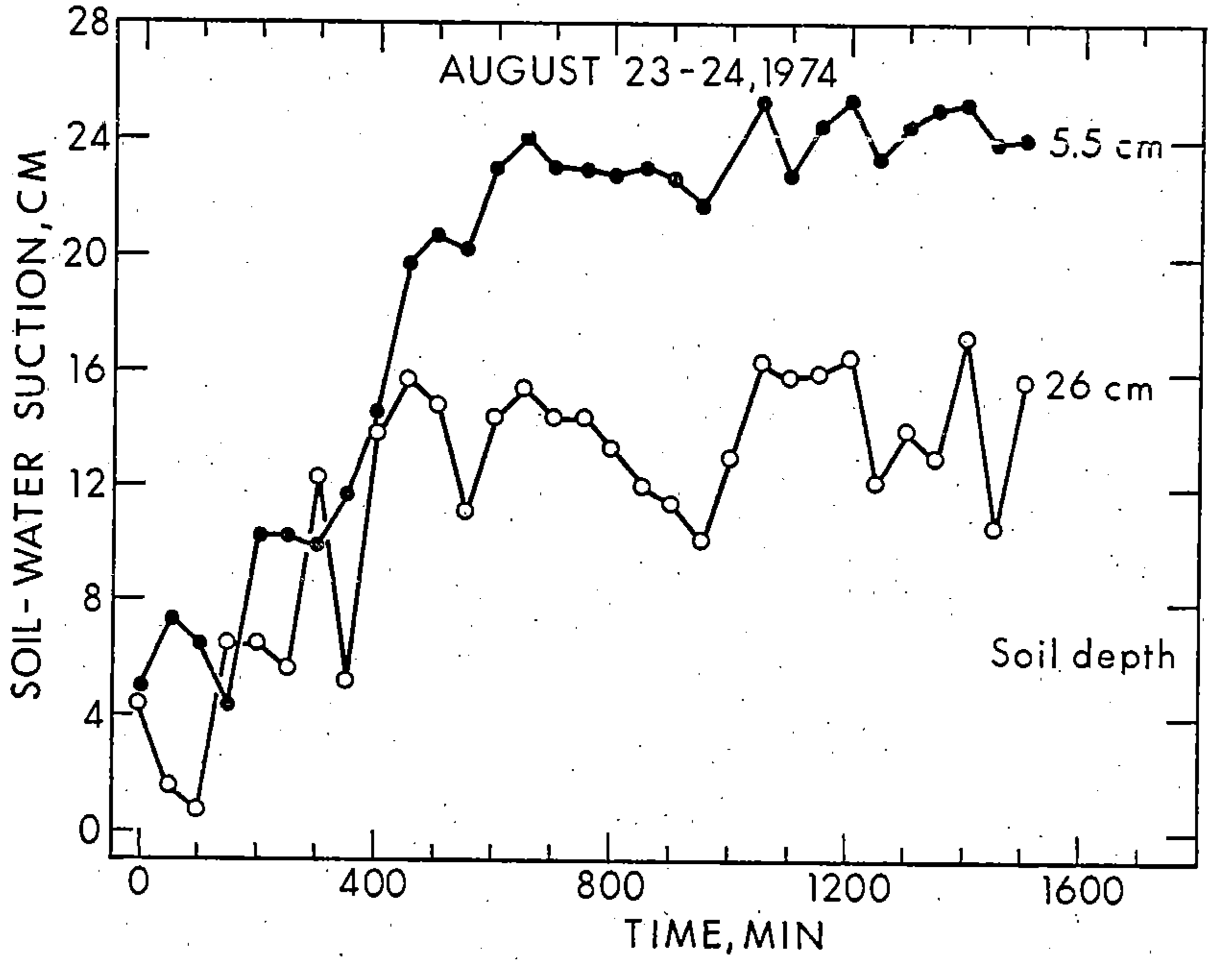

Fig. 4--Soil-water suction changes at 5.5 and 26 cm depths for a day which received no rainfall.

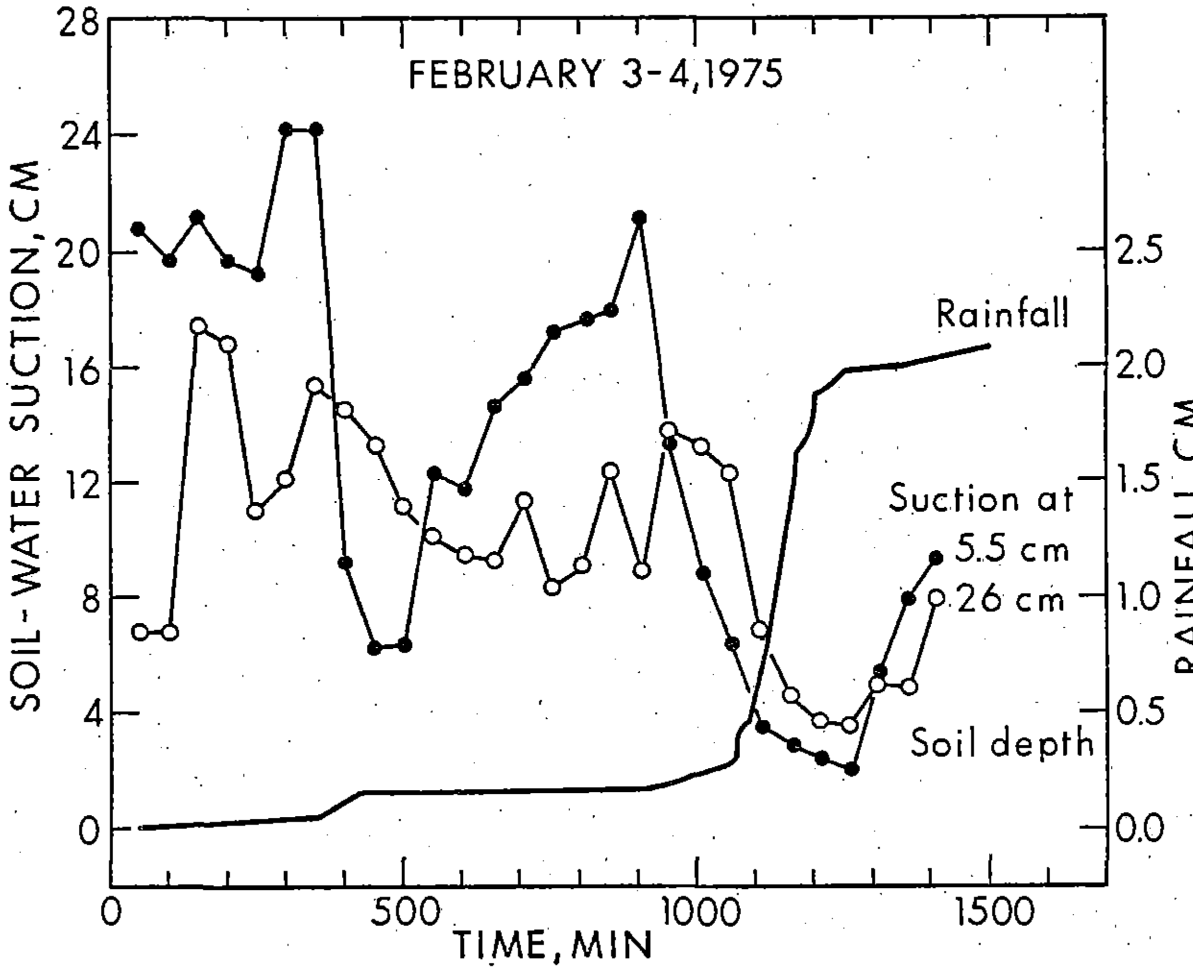

Fig. 5--Cumulative rainfall and soil-water suction changes at the two depths for a day showing more frequent changes.

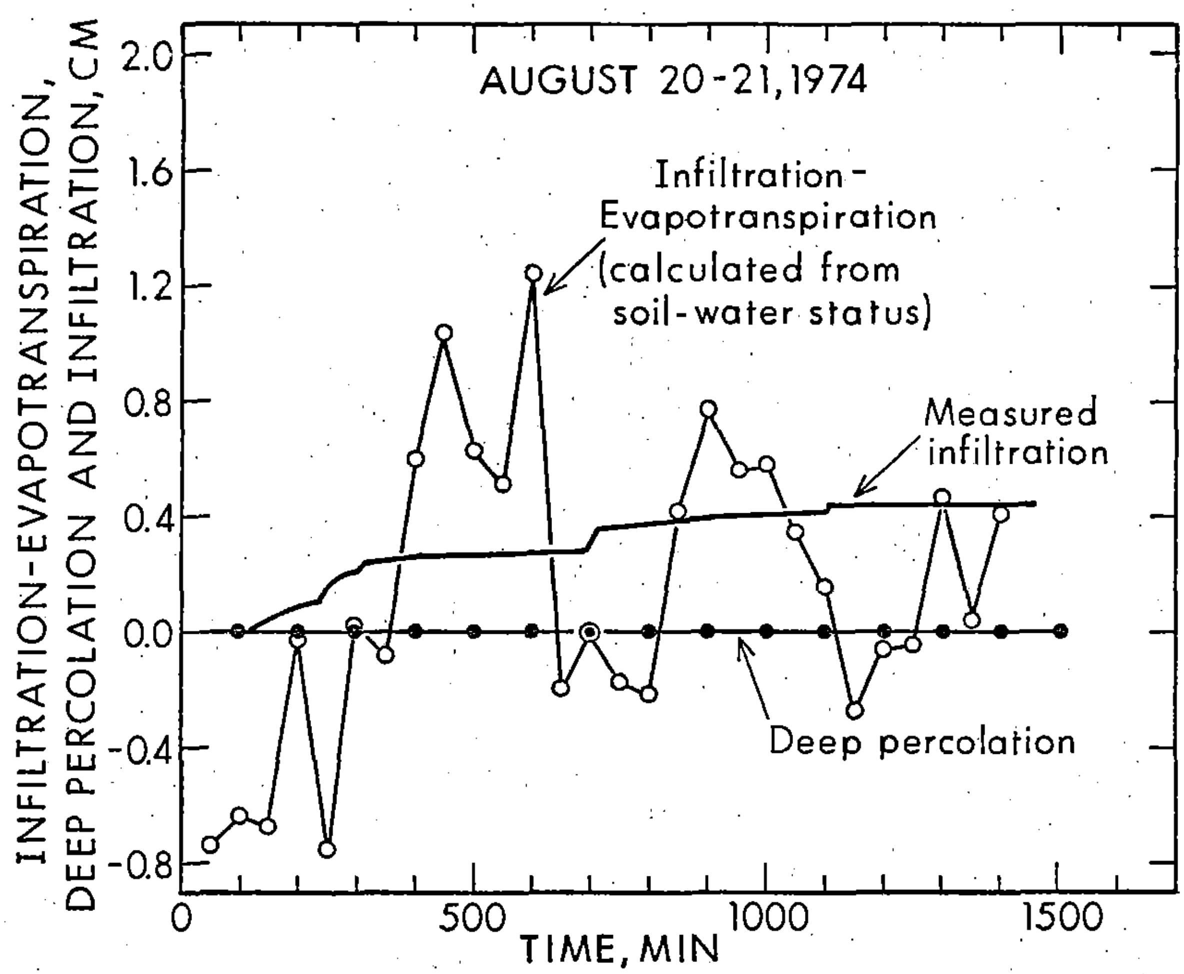

Fig. 6--Infiltration minus evapotranspiration and deep percolation calculated from the monitored data, and infiltration measured in the plot for a day which received a small amount of rainfall.

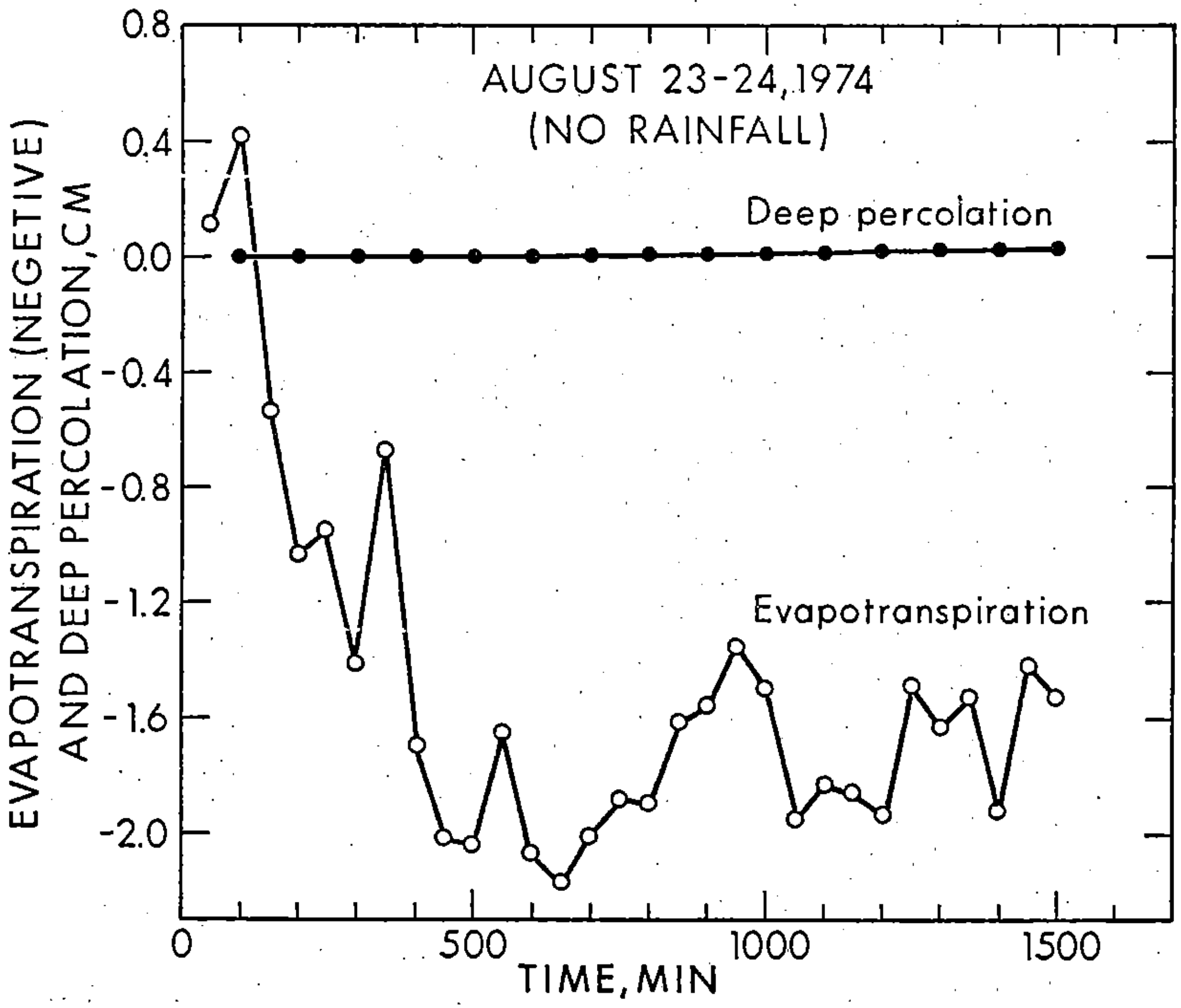

Fig. 7--Evapotranspiration and deep percolation calculated from the monitored data, and infiltration measured in the plot for a day which received no rainfall.

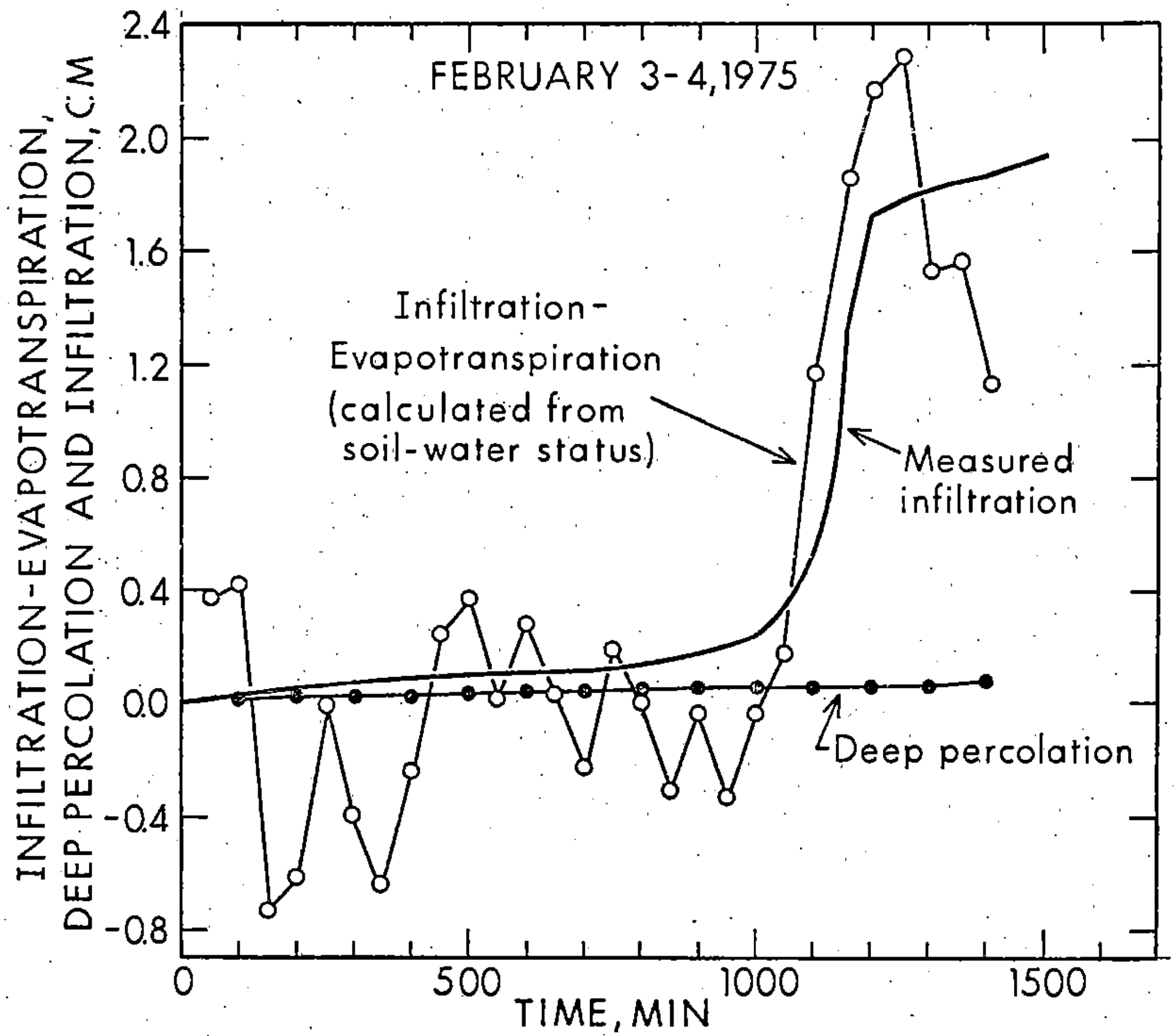

Fig. 8--Infiltration minus evapotranspiration and deep percolation calculated from the monitored data, and infiltration measured in the plot for a day receiving appreciable rainfall and runoff.

Fig. 8. shows the calculations for a day in February, 1975 which received an appreciable rainfall (2.2 cm), resulting in some runoff. The measured infiltration shown in the figure is the difference of measured rainfall and runoff in the watershed plot. There is a good correspondence between the measured infiltration and the calculated infiltration minus evapotranspiration data. The deep percolation on this day was much more than that on the other two days, but was still relatively small.

In conclusion, based on experience with a wide variety of rainfall conditions the results presented above indicate a great utility of the devised system for continuous monitoring of soil-water status of this forest watershed which undergoes relatively little (if any) intense drying. The precision of measurements could be further improved by choosing more sensitive tensiometers and minimizing the volume of water in the system. When monitoring of the rapid process of infiltration under heavier rainstorms is required, it would be desirable to have a separate pressure transducer for each tensiometer and an electronic scanner. On the other hand, for watersheds with more intense drying periods, this setup would be useful during only the wet season when the soil-water tensions do not exceed 1 bar. For monitoring the drier conditions, psychrometric measurement of soil-water potentials or direct soil moisture sampling would be required.

References

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Determining Both Water Characteristics and Hydraulic Conductivity of a Soil Core at High Water Contents from a Transient Flow Experiment

Application of the theory of unsaturated flow for describing water movement through a soil requires the determination of the soil's suction-water content (soil-water characteristics) and unsaturated hydraulic conductivity relationships. The suction-water content relationship is normally obtained by subjecting a soil core to a sequence of several pressure steps during either water absorption or desorption (wetting or drying). At each step, the sample is allowed to come to equilibrium with the applied pressure. Hydraulic conductivity of the soil core may be obtained by one of several techniques, such as described by Gardner (1956), Klute (1965), Green and Corey (1971), or Ahuja (1974). Each of these techniques has certain advantages and certain limitations. By and large, the methods commonly used for determining these two hydrologic properties of soil are time-consuming and tedious. More efficient and suitable methods are a subject for continuing research. Certain simplified approaches, even though somewhat approximate, are very useful for practical purposes.

In an earlier work, a wetting procedure was presented for simultaneously determining both the water characteristics and hydraulic conductivity of a soil core (Ahuja, 1975). In this procedure, the two relationships were determined by a similarity analysis of cumulative inflow and wetting-front position data for soil-water contents below the bubbling-pressure value. A supplementary technique proposed for determining the two hydrologic properties at high soil-water contents was briefly discussed. This technique involves measurement of cumulative water inflow or outflow from a short soil core as the water enters or leaves through a high-resistance porous plate on one end, and a monitoring of soil-water suction at the other end.

In this report, this proposed technique is examined in some detail to evaluate its utility in transient inflow as well as outflow experiments for two soils of widely differing properties. Transient measurement of the soil hydraulic properties may be superior to a steady state measurement in some cases, as was recently suggested by Corey and Brooks (1974) who reported an appreciable difference between the steady and transient measurements. It is recognized that the latter do not simulate well the continually fluctuating conditions experienced by soil water under field situations.

Principle of the Method

When water absorption by or desorption from a short soil core occurs through a porous plate of high hydraulic resistance (considerably reducing the rate of water flow), the hydraulic gradients in the soil are generally small. Furthermore, the change in water content with time at different positions varies, but only to a small degree. Under these conditions, an average value of the soil-water suction, corresponding to the known average water content in the core at any given time, may be approximated by a simple mean or a weighted mean of the two suction values at the two ends of the core. Soil water suction at the inlet or outlet end for any given time can be derived from the measurement of flux (obtained from cumulative flow) at that end, knowing the hydraulic resistance of the porous plate and the suction or water pressure maintained on one-soil side of the porous plate (Ahuja, 1973). For a horizontal core, the equation is

$$\tau_0 = rv(t) + \tau_w \qquad [1]$$

where τ_0 is the suction at the plate-soil interface, $v(t)$ is the water flux as a function of time t, taken positive for absorption and negative for desorption, τ_w is the constant suction maintained in the water on the other side of the porous plate, and r is the hydraulic resistance of the plate. Hence, only one additional measurement of suction is needed at the other end of the core. For calculation of hydraulic conductivity, the suction gradient across the soil core gives an estimate of the average gradient in the core. An arithmatic mean of the fluxes at two ends of the core, which would be one-half of the value of flux measured at the inlet or outlet end, gives an estimate of average flux in the core corresponding to the above gradient.

Methods and Materials

The method of calculation stated above was first illustrated and tested by applying it to several sets of generated numerical-solution data for Yolo light clay soil. Numerical solutions were obtained for a 7.5 cm long soil core, for cases of water absorption or desorption in the suction range of 0 to 150 cm H_2O and through porous plates of two different hydraulic resistances. The techniques and the functional representations used in obtaining the numerical solutions for suction-water content and hydraulic conductivity of Yolo soil were as given in an earlier paper (Ahuja, 1973). The flux condition of Eq. [1] was imposed on the plate-soil boundary, and the condition of no flow applied at position $x = 7.5$ cm.

The method was then applied to experimental data for Tantalus silty clay loam soil, a volcanic ash soil from the island of Oahu, Hawaii. This soil was formerly classified within the Kapoho family of the Humic Latosols. In the new comprehensive system it is classified in the medial over cindery isothermic family, Typic Dystrandepts subgroup, of the order Inceptisols. It exhibits some swelling and shrinkage as visually observed upon wetting and drying and was chosen because of its practical importance in representing soils of Hawaii's forest watersheds. The soil sample was air-dried, passed through a 1.0 mm sieve, and packed to a bulk density of 1.0 g/cc in a plexiglass tube, 7.0 cm in diameter and 7.5 cm long, with temporary extensions on each end. The extensions were carefully removed and replaced by perforated plastic disc taped on the ends. The core was then wetted (after removing the plastic disc) by applying water through a high resistance porous plate attached on one end. Water on the outer side of the plate was maintained at zero pressure with a constant-head burette and the inflow of water was recorded with time. After the wetting front arrived at the other end of the core, a sensitive tensiometer plate, of the same diameter as the soil core, was attached at that end and the soil-water suction continuously recorded with a pressure transducer-recorder system. After wetting, the core was subjected to a sequence of desorption and absorption steps under suctions of nearly 100 or 150 cm H_2O. The cumulative outflow or inflow at one end and soil-water suction at the other end were recorded with time during each step. The hydraulic resistance of the porous plate was measured before and after the experiment. The plexiglass soil container was provided with holes near the middle to allow flow of air. All experiments were conducted in a constant temperature room at $21 \pm 1°C$.

Results and Discussion

Transient soil-water suction and water content distribution curves are shown in Fig. 1, A and B, respectively, for a wetting of Yolo soil

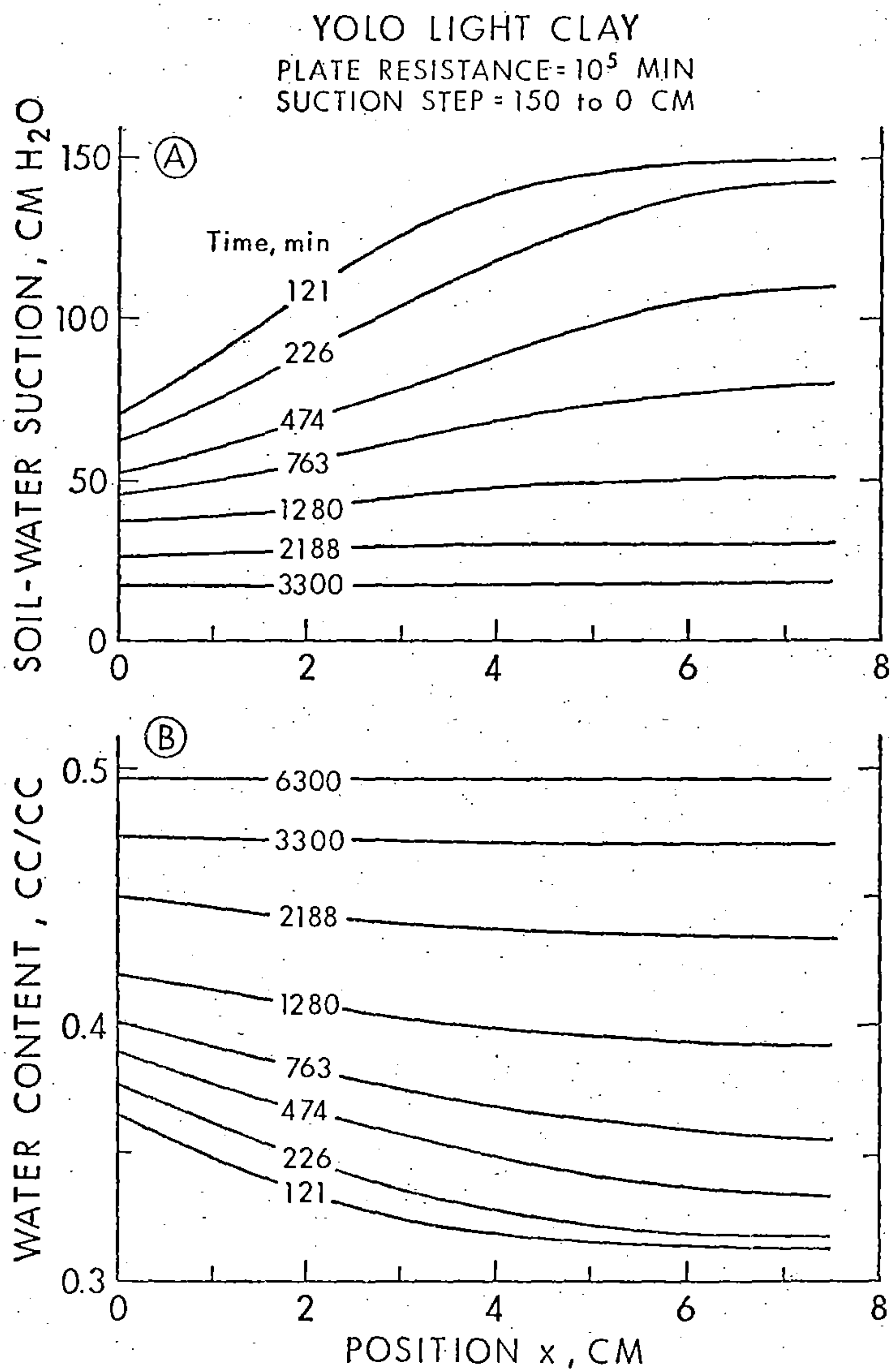

Fig. 1--Transitent soil-water suction and water content distributions during water adsorption into a Yolo soil core initially at a water content of 0.314 cc/cc (suction of 150 cm) through a porous plate with 10^5 min hydraulic resistance. Stated times are based on the start of wetting.

initially at a water content of 0.314 cc/cc (suction of 150 cm H_2O) through a porous plate with a hydraulic resistance of 10^5 min. The curves are for several times after the wetting-front has reached the other end. They indicate that suction and water content change rapidly near the inlet end (x = 0) initially, but later level out and become more even throughout the core. To some degree, the curves show an S-shaped character. It may be mentioned here that the hydraulic conductivity at the initial water content of soil (0.314 cc/cc) was nearly 8.0×10^{-6} cm/min. The average hydraulic resistance of soil at this water content as estimated by using the middle of the core as the average distance of flow was nearly 5.0×10^5 min. This value is about five times the hydraulic resistance of the porous plate. Fig. 2, A and B, present similar data as Fig. 1 for the case of desorption of soil initially saturated with water, with the water on the outer side of the porous plate maintained at a suction of 150 cm. The pattern of suction and water content changes at different times and positions generally resemble those for the absorption case in Fig. 1. However, the curves do not show the S-shaped character observed above.

Fig. 3, A and B, show the soil-water suction and hydraulic conductivity as a function of water content for Yolo soil. These were calculated as described above for a porous plate resistance of 10^5 min from the data of Fig. 1 and 2, and are compared with the actual functions used in generating the numerical solutions for both absorption and desorption cases. For the desorption data, the suction value, τ, corresponding to a given average water content in the core was calculated as a weighted mean of the two values τ_0 at x = 0 and $\tau_{7.5}$ at x = 7.5 cm as given by the expression $(\tau_0 + 2\,\tau_{7.5})/3$. This latter expression is derived assuming that the suction-position curve is best fitted by a parabola passing through the two end points and having a slope of zero at x = 7.5 cm. Better results were obtained by this method than by using the simple arithmetic mean of suction values at the two ends, as would be expected from the shape of curves in Fig. 2A. In contrast, and as expected from Fig. 1A, the parabolas did not give a good fit to the suction-position curves for the absorption data as they have an S-shaped character. The average values of suction shown in Fig. 3A for this case are simple arithmetic means of the two end values.

Fig. 3 indicates that both the absorption and desorption data give a fairly good calculation of the suction-water content relationship. The hydraulic conductivity values calculated from the absorption data agree closely with the true values except for the two points corresponding to the early times when the wetting front had just barely reached the other end. Those calculated from the desorption data are fairly good for water contents above 0.45 cc/cc, but are 20 to 30% below the actual values at lower water contents. Overall, the absorption data seem to give better results. However, because reliable data during absorption are only obtained after the water content at the other end of the core starts to increase, the range of water contents for which the determinations are made is reduced.

To show the effect of a reduction in hydraulic resistance of the porous plate, the suction- and hydraulic conductivity-water content re-

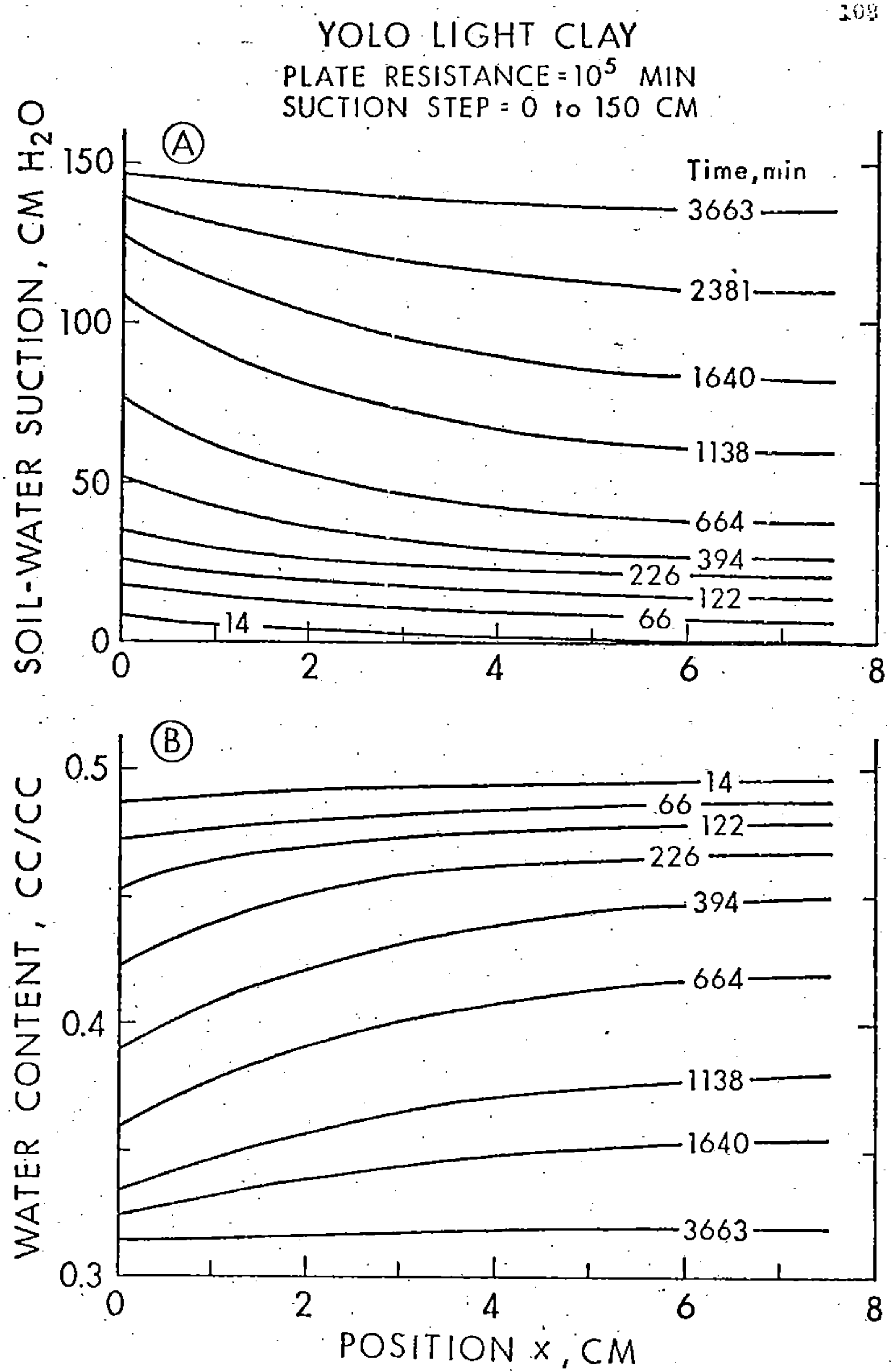

Fig. 2--Transient soil-water suction and water content distributions during desorption of an initially saturated Yolo soil core through a porous plate of 10^5 min hydraulic resistance to a final suction of 150 cm. Stated times are based on the start of desorption.

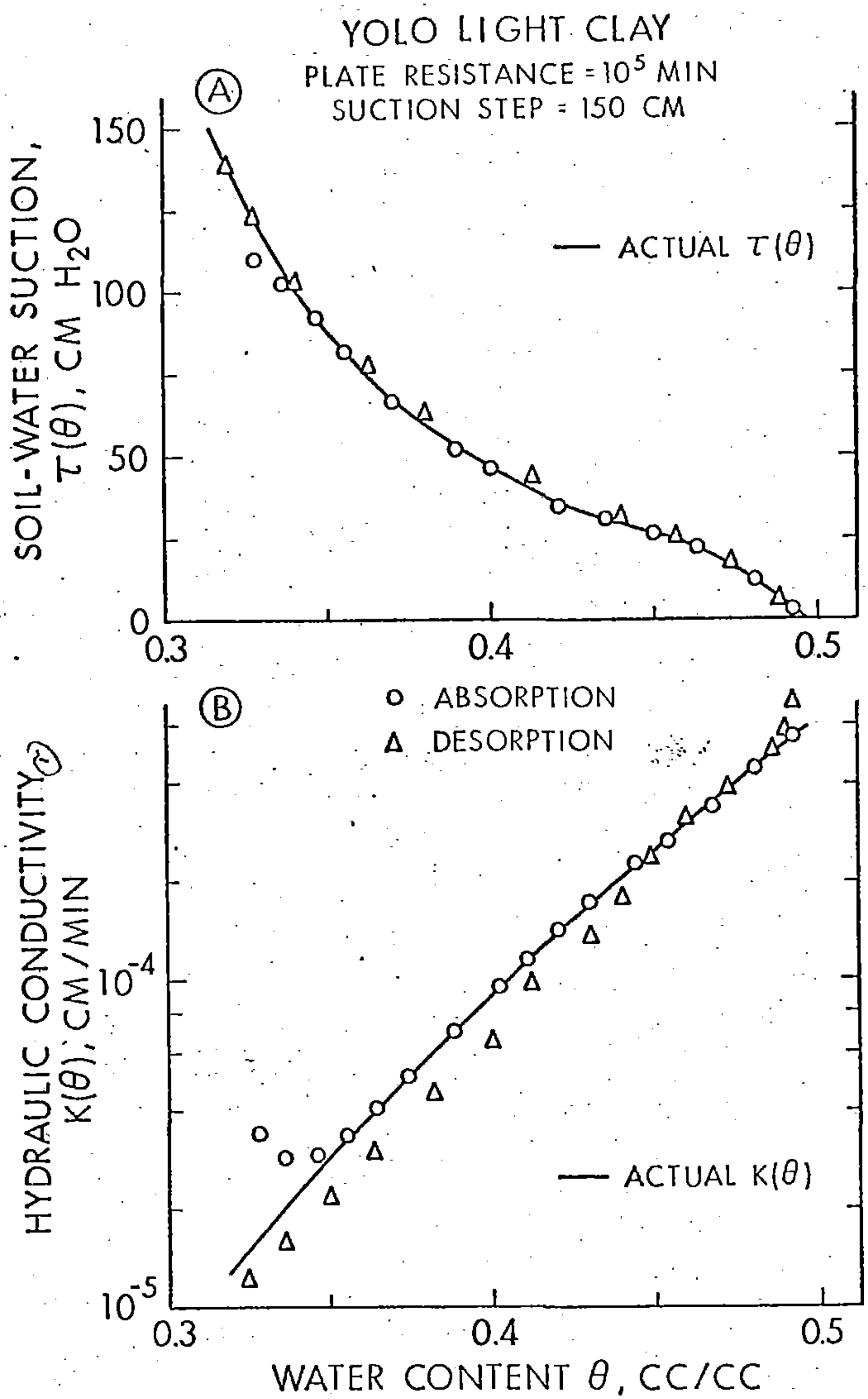

Fig. 3--Suction-water content and hydraulic conductivity relationships of Yolo soil calculated by the proposed method from adsorption and desorption data for a plate resistance of 10^5 min and a suction step of 150 cm.

lationships were calculated for the Yolo soil from numerical-solution data generated with a plate resistance of 1.727×10^4 min and are presented in Fig. 4, A and B. The calculations are for two wetting cases, one in which the initial soil water content was 0.314 cc/cc as in the case of the higher resistance discussed above, and the other in which the initial water content was 0.34 cc/cc (corresponding to a suction of 100 cm H_2O). The suction data calculated with the step of 150 cm are satisfactory only for suctions less than 50 cm, while those calculated with the step of 100 cm are satisfactory up to the maximum mean suction value of 65 cm. Not much difference between hydraulic conductivity values was calculated for the two suction steps. However, these were not as close to actual K values as were those calculated with the higher plate resistance (shown in Fig. 3B), although they still seem satisfactory. Therefore, it appears for a given suction step, the higher plate resistance gives better calculations, and is good over a wider range of water contents than is the low plate resistance. A smaller plate resistance requires a smaller suction step. These tests seem to indicate that a plate resistance equal to nearly one-fifth of the average hydraulic resistance of soil at the lowest water content in the suction step would be a good choice. The specific values of plate resistances used here were chosen for a 7.5 cm long soil core. The required value of plate resistance, as well as the duration of the experiment would decrease as the length of the core decreases.

Table 1 summarizes experimental data obtained for Tantalus silty clay loam and used for calculation of required functions. Fig. 5 shows the suction-water content data calculated from these experimental measurements during two desorption-absorption sequences. The solid lines in the figure represent the main hysteresis loop between 0 and 200 cm suctions as experimentally determined by small equilibrium steps on two similarly-packed but different soil cores. Hydraulic resistance of the porous plate was nearly constant during the experiment at 1.008×10^4 min. The data indicate that the desorption step of 18 to 100 cm suction and the absorption step of 100 to 4 cm give fairly satisfactory estimates of the suction-water content relationship. While the absorption step of 150 to 4 seems to give good agreement with the experimental equilibrium absorption data, the desorption step of 4 to 150 cm suction overestimates them. The final water content in the soil core at 150 cm suction is higher for direct desorption from 4 to 150 cm than for the incremental equilibrium value. This may indicate a lack of equilibrium in the first case, although the desorption step was terminated when a suction of nearly 150 cm was recorded on the far end of the core. This descrepancy may be just a transient effect caused by very slow diffusion of air to some pore sequences (Corey and Brooks, 1975). In general, with the plate resistance used, a suction step of 100 cm seems more appropriate for this soil.

Fig. 6 shows the corresponding hydraulic conductivity-water content relationship data calculated for Tantalus soil. The data from different suction steps agree fairly well, although there is appreciable scatter. There is no apparent consistent hysteresis in the data from desorption and absorption steps, in contrast to the effect noticed in suction-water content data of Fig. 5.

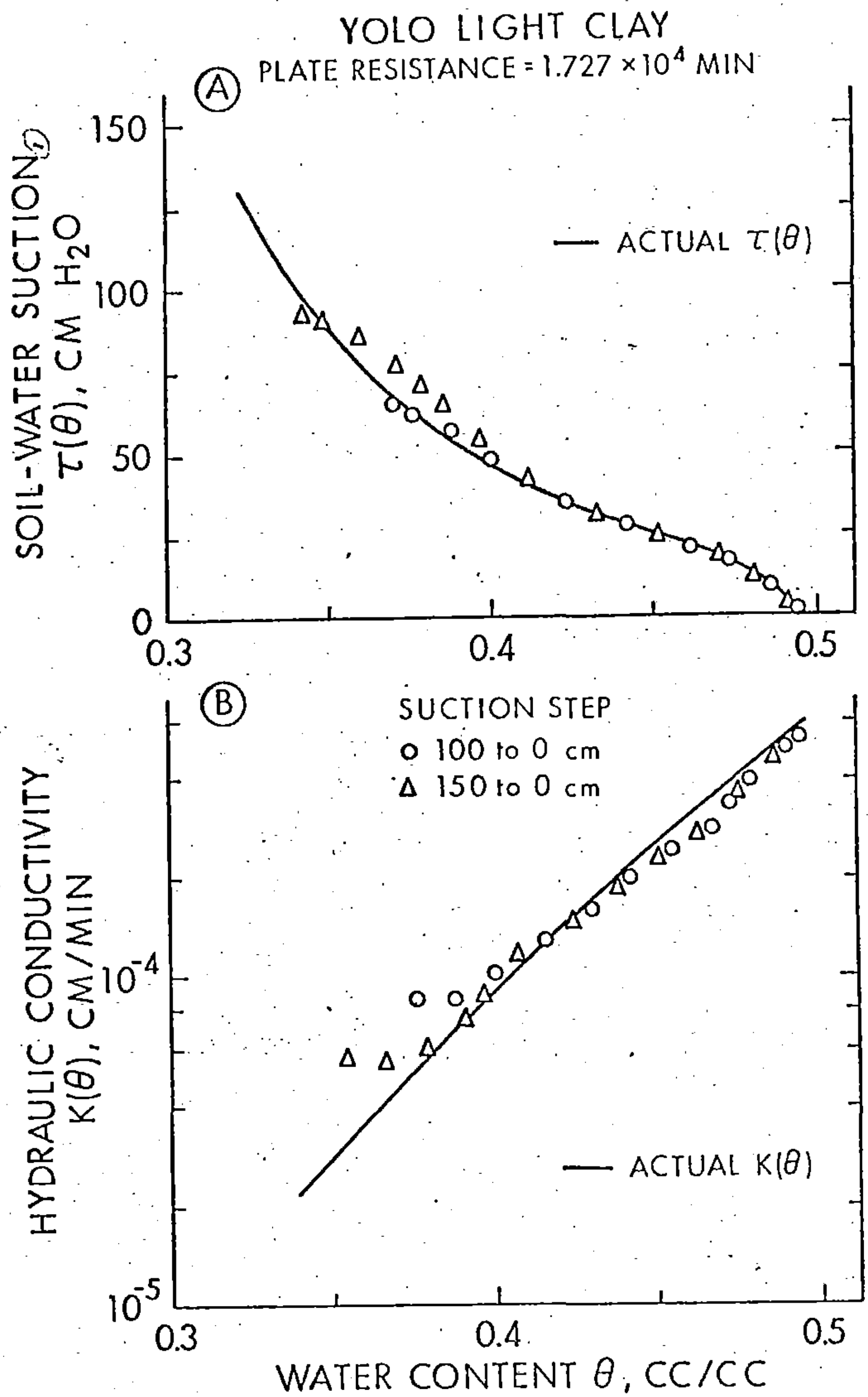

Fig. 4--Suction-water content and hydraulic conductivity relationships of Yolo soil calculated from absorption data for plate resistance of 1.727 x 10^4 min and suction steps of 100 and 150 cm.

Table 1 - Experimental Data and Calculated Suction - Hydraulic Conductivity - Water Content Relationships of Tantalus Silty Clay Loam

Time min	Flow Rate of Core cc/min	Suction at x= 7.5 cm	Suction at x = 0 cm	Mean or Wtd. Mean Suction cm	Hydraulic Conductivity cm/min	Average Water Content of Core cc/cc
			Suction Step 18 to 100 cm			
0.0	----	18.3	-----	18.3	------	.5540
1.4	.276	21.2	24.8	22.2	.00767	.5506
14.1	.214	32.7	42.0	35.8	.00230	.5401
32.9	.119	46.4	68.0	53.6	.00055	.5296
63.1	.085	55.0	77.0	62.3	.00039	.5168
131.0	.055	62.6	85.0	70.0	.00024	.4946
247.1	.035	70.3	90.5	77.0	.00017	.4862
420.5	.019	79.9	95.0	84.9	.00013	.4708
597.5	.012	87.0	97.0	90.3	.00012	.4606
1020.5	.004	94.0	99.0	45.7	.00008	.4512
			Suction Step 100 to 4 cm			
0.0	----	100.6	-----	100.6	------	.4497
3.9	.139	99.2	38.1	68.6	.00023	.4549
15.0	.125	87.4	34.6	61.0	.00024	.4601
34.0	.125	76.0	34.6	55.3	.00030	.4671
74.4	.091	57.0	26.3	41.6	.00038	.4801
133.2	.063	40.5	19.5	30.0	.00030	.4948
181.1	.048	30.3	15.8	23.0	.00033	.5049
203.0	.047	27.0	15.5	21.2	.00041	.5084
242.6	.041	22.0	14.0	18.0	.00051	.5154
327.2	.034	17.21	12.3	14.8	.00067	.5340
475.0	.020	11.4	8.9	10 1	.00133	.5411
1195.5	.007	5.1	5.72	5.4	------	.5746
			Suction Step 4 to 150 cm			
0.0	----	5.26	-----	5.26	------	.5746
8.2	.430	24.5	33.0	27.3	.00506	.5544
18.9	.263	45.7	78.0	56.5	.00081	.5404
29.5	.250	53.7	82.0	63.0	.00088	.5299
43.7	.181	60.5	101.0	74.0	.00045	.5194
76.4	.139	70.6	112.0	84.4	.00033	.5019
105.0	.100	77.8	133.0	92.9	.00018	.4907
135.0	.071	86.5	130.7	101.2	.00016	.4809
167.3	.068	92.9	132.0	105.9	.00017	.4718
215.9	.043	100.0	138.0	113.6	.00011	.4616
282.2	.026	110.0	143.0	121.0	.00008	.4536
464.2	.011	129.0	147.0	135.0	.00004	.4410
1925.0	----	149.0	-----	149.0	------	.4333
			Suction Step 150 to 4 cm			
0.0	----	149.3	-----	149.3	------	.4332
7.7	.137	148.5	37.6	93.0	.00012	.4419
27.9	.128	125.0	35.4	80.0	.00014	.4506
55.5	.119	100.5	33.2	66.8	.00018	.4611
86.4	.080	83.5	23.6	53.5	.00013	.4716
125.0	.100	68.0	28.5	48.2	.00025	.4839
147.5	.098	61.3	28.0	44.6	.00030	.4909
179.0	.087	54.5	25.3	39.9	.00030	.5010
232.6	.071	41.8	21.4	31.6	.00035	.5143
269.0	.063	28.5	19.4	23.9	.00069	.5283
341.3	.050	23.0	16.2	19.6	.00073	.5388
463.0	.030	13.5	11.3	12.5	.00136	.5549
555.5	.021	10.0	9.1	9.5	.00233	.5644
2698.0	----	3.6	4.6	4.1	------	.6008

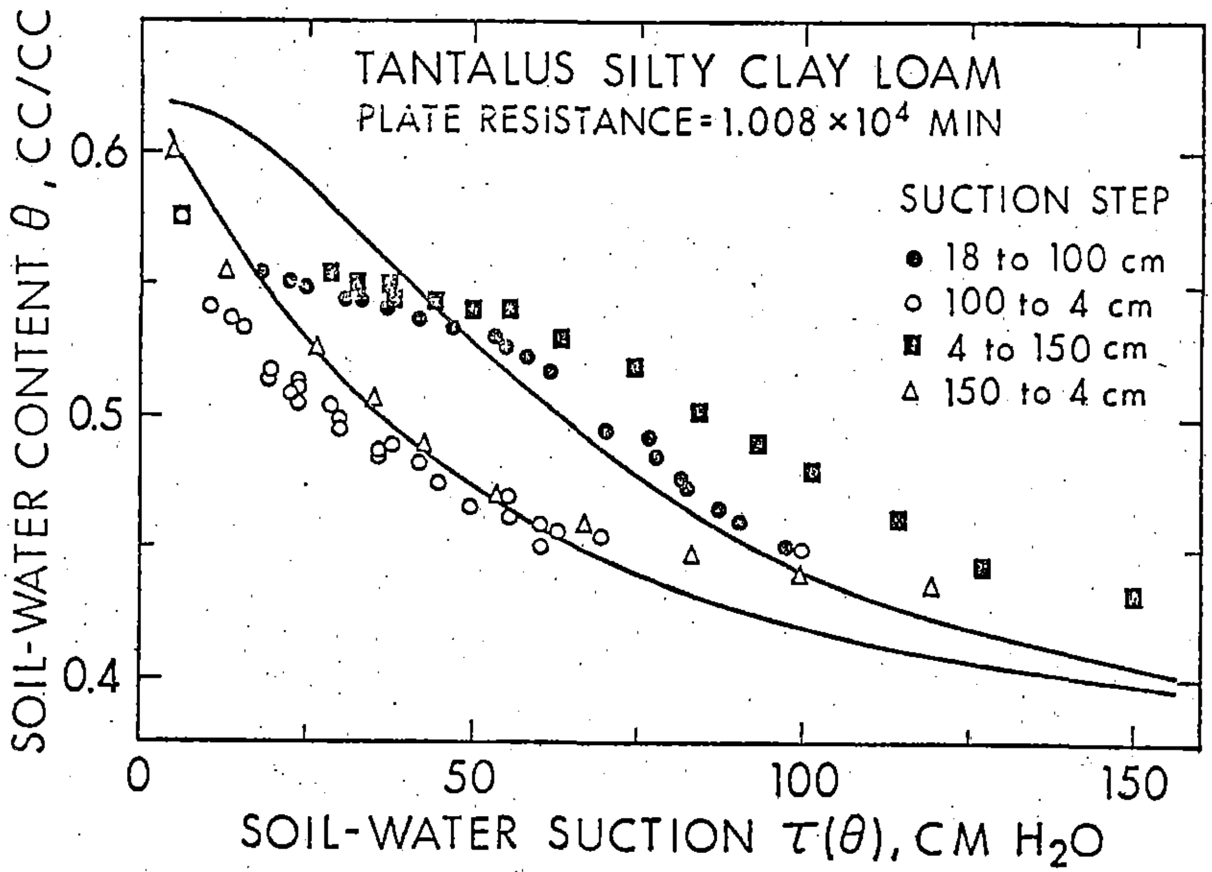

Fig. 5--Suction-water content relationships of Tantalus silty clay loam calculated from experimental measurements during desorption and absorption steps. The solid curves represent the main hysteresis loop between 0 and 200 cm suctions as determined experimentally by small equilibrium steps.

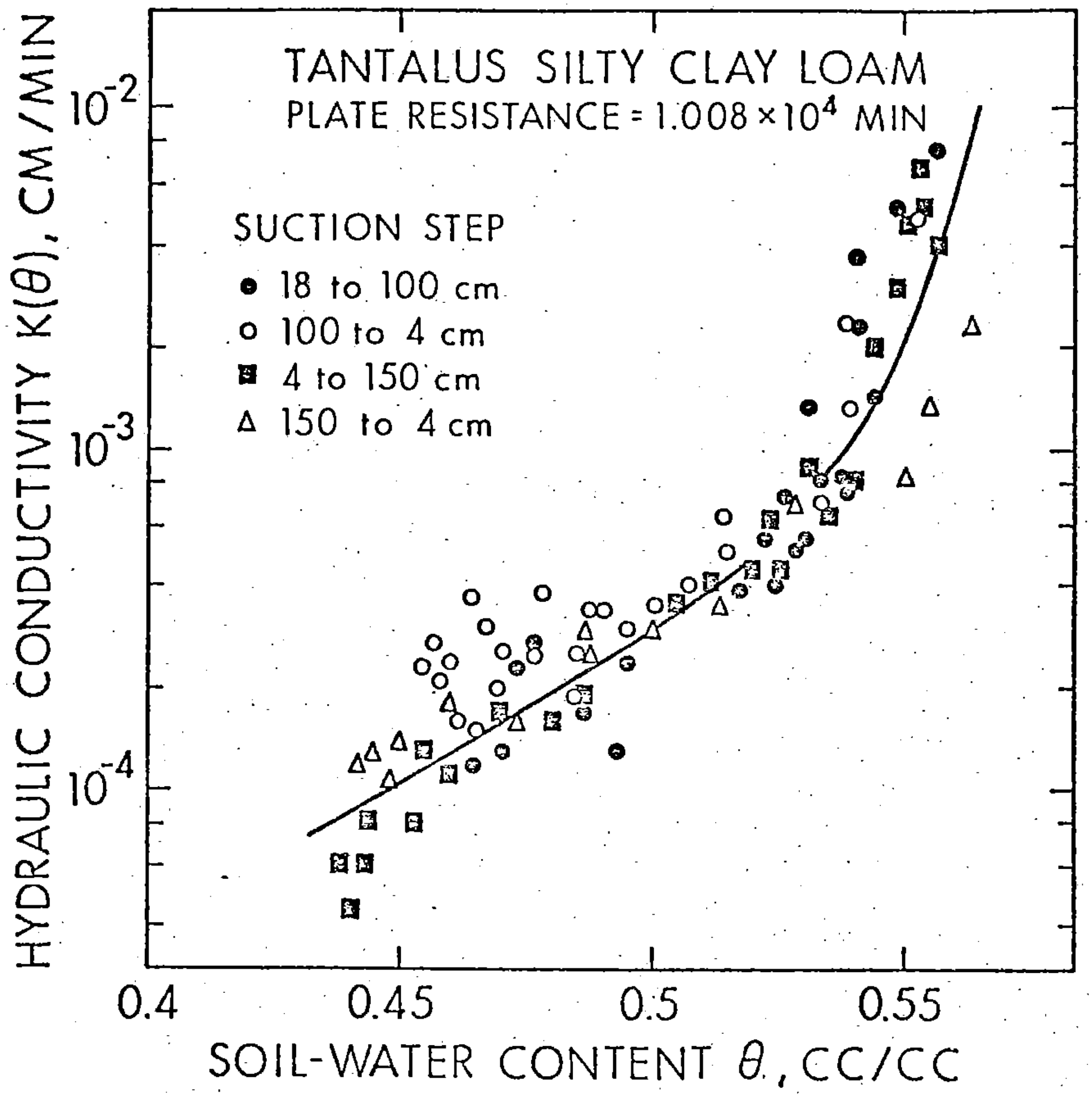

Fig. 6--Hydraulic conductivity-water content relationships for Tantalus silty clay loam calculated from experimental measurements during the different desorption and absorption steps. Dashed curve is a visual approximation of best data fit.

It is of interest to compare the soil-water characteristics and hydraulic conductivity changes with water content for the Yolo soil, a semi-arid-zone soil from alluvial origin and classified as a Non-Calcic Brown, and the Tantalus soil, a humid-tropical forest soil from volcanic ash origin and classified as an Inceptisol. Examination of Fig. 4A and 5 (obtained with relatively close plate resistances) reveals a much steeper change of water content for the second than for the first. This reflects the more aggregated nature of the (dried) Tantalus soil. This is further illustrated by comparing hydraulic conductivities in Fig. 4B and 6. It is seen that the Tantalus soil displays much higher hydraulic conductivities near saturation water contents, and a slightly lower hydraulic conductivity in the less wet range. This is consistent with observed properties of these soils. The Tantalus soil also undergoes a much sharper decrease in K with decreasing water content (particularly in the wetter range) than does the Yolo soil. Presence of stable aggregates favors uneven distribution of pore sizes, while the Yolo soil probably contains more gradation of different-size pores.

Conclusions

The results presented here show an interesting possibility of determining (subject to some tolerable error) both the water characteristic and hydraulic conductivity of a short soil core from a single transient flow experiment. The hysteresis in water characteristics is fairly well determined for two soils of widely different water retention and transmission properties. Theoretically, the method would be adaptable to larger suction steps by choosing a porous plate of high-enough resistance. However the applicability of the method may be limited to the wet soil-water region when adequacy of the plate-soil contact, time consumed for measurements, and other problems associated with very high-resistance porous plates are considered. But, then, this region is often of most interest, particularly in soils of wet forest watersheds such as are very common in Hawaii and the tropics. Preliminary data of the Tantalus soil in the field indicates that soil water suction was almost always within the range employed here. The method can be adapted for use with pressure-plate cells commonly available in soil-water laboratories. For measuring soil-water suction on one end of the core, ordinary tensiometers with water manometers may be used, as suction changes during wetting or drainage through a high-resistance porous plate would be slow.

One additional advantage of the proposed method is that it lends itself well for use with undisturbed soil cores.

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IV. MECHANISMS OF WATER RETENTION BY HAWAII"S TYPIC HYDRANDEPTS

Introduction

Research on water retention characteristics of Hawaii soils has been largely confined to soils that are under intensive agricultural cropping, primarily under irrigation (e.g., Thorne, 1950 and Sharma, and Uehara, 1968). Highly weathered volcanic ash soils, many of which are under foresta, have received little attention in this regard. Least understood of these soils are the Typic Hydrandepts, previously classified as Hydrol Humic Latosols.

Typic Hydrandepts are a Subgroup of the Hydrandepts Great Group, Andepts Suborder, of the Order Inceptisols. These soils are derived from volcanic ash and thus have been traditionally linked with the x-ray amorphous, allophanic, soils of Japan and New Zealand. They are characterized by very low field bulk densities (sometimes as low as 0.2 g/cc) and by thixotropic behavior, i.e., tendency to exhibit structural fluidity upon mechanical disturbance followed by a regain of rigidity upon setting (Trouse, 1964 and Rahman, 1974). Hydrologically, the most significant characteristic is the excessively high field water content, which may be as high as 4.0 g/g. In the absence of disturbance, such as forest clearing and subsequent cropping, these soils undergo no significant drying. Under the relatively high annual rainfall (normally 400 cm or more) received rather uniformly by such soils, it may be presumed that their field water contents fluctuate only between saturation and "field capacity".

Kanehiro and Sherman (1956), Sherman (1957), Bates (1960), Dias (1964), and Sherman et al. (1964), among others, reported that drying of Typic Hydrandepts resulted in significant changes in many of their physical and physico-chemical properties. They further reported that when the drying proceeded below a certain, yet undefined, point such changes are not reversible upon re-wetting. It was pointed out that the natural behavior of such soils is markedly influenced by the abundant presence of x-ray amorphous colloidal constituents. It was presumed by Sherman and his colleagues that the drying process, even at ordinary room temperatures, enhanced the transformation of these constituents into crystalline minerals which do not return to the amorphous form upon re-wetting. The clearly visible mixtures of light and dark-colored aggregates which segregate during soil drying were reported to be more enriched in such minerals as compared to the original soil. Sherman et al. (1964) elaborated on this crystallization process and proposed it as the mechanism responsible for changes in soil properties upon drying.

Other than the above works, little has been done to assess and explain reasons for the effects of drying on the physical properties of Typic Hydrandepts in general and on their abilities to retain water in particular. Available information relates only to effects of undefined drying treatments (e.g., air-drying or drying under direct sunlight). The objective of this study was to determine water retention by selected volcanic ash soils under defined environmental conditions and to attempt to explain mechanisms responsible for the large losses of water retention capacity upon drying.

Theory

Water present in any soil system experiences a variety of forces which may be gravitational, pressure caused, osmotic, or matric. Thus, the total potential of soil water, ψ_t, is normally expressed as the sum of four terms as follows

$$\psi_t = \psi_g + \psi_p + \psi_o + \psi_m \qquad [1]$$

where the four right hand terms represent the gravitational, pressure, osmotic, and matric potential components, respectively. Our concern in this study is the matric component ψ_m which applies to all forces originating from the soil matrix. This component, therefore, may be further subdivided into the following categories (El-Swaify and Henderson, 1967) in order of increasing energy of removal:

$$\psi_m = \psi_{me} + \psi_{mc} + \psi_{mh} + \psi_{ms} \qquad [2]$$

where the right hand terms represent the water retained due to expansion caused by interacting diffuse double layers (swelling), capillarity, ionic or surface hydration, and water incorporated within the mineral structure, respectively. The relative importance of each category depends on the make-up of the soil under study. Thus, when sufficient water is available, the capillary term prevails in sandy soils while the swelling term prevails in expansive heavy soils. For Typic Hydrandepts, however, this distinction is yet to be made.

Mineralogical transformations involving losses or gains of water may also be described theoretically. If, in Typic Hydrandepts, the change of amorphous aluminum gels into boehmite at 25°C and later proceeds as

$$2Al(OH)_{3\,amorphous} = Al_2O_3 \cdot H_2O_{boehmite} + 2H_2O$$

then the standard free energy change for the reaction may be calculated from the standard free energies of formation of water, amorphous alumina, and boehmite using available standard tables (Garrels and Christ, 1965). For the above reaction

$$\Delta G^o_{reaction} = G^o_{products} - G^o_{reactants}$$

$$= -435 + 2(-57) - (-272)$$

$$= -223 \text{ Kcal/mole}$$

indicating that the crystalline constituent is considerably more stable in soils than the amorphous. Although gibbsite is also more stable than the amorphous constituents, that transformation involves no loss or gain of water. It may be argued, therefore, that even long term dehydration would not cause crystallization of amorphous $Al(OH)_3$. Rather, the phase change still incorporates all OH groups as structural water.

Materials and Methods

Soils and Synthetic Hydroxides:

Most of the work reported here was conducted on Hilo silty clay, a member of the thixotropic isohyperthermic family of the Typic Hydrandepts. Mineralogical and chemical properties of this soil are given elsewhere (Voss, 1969 and Chan, 1972). Akaka silty clay, a thixotropic isomesic Typic Hydrandept, and Kawaihae silty clay loam, a medial isohyperthermic Ustollic Camborthid, were also used during certain phases of the study. Voss (1969) and Gardiner (1967) provide mineralogical and chemical information on these two soils, respectively. Surface horizons of all soils were used in this investigation.

Goethite, a hydroxide of Fe(III), and gibbsite, a hydroxide of Al, were synthesized from the precipitation products of $FeCl_3$ or $AlCl_3$ and NaOH in the manner described by El-Swaify and Emerson (1975).

In treatments involving controlled drying, the soils were either dried in the oven at 105°, over P_2O_5 at room temperature, or freeze dried. Organic matter removal from certain subsamples was achieved using H_2O_2 digestion at 70°C.

All x-ray diffraction analysis was conducted using a powder camera and a Norelco diffractometer with a CoK_α x-ray source. Electron-microscopic examinations were made using a Jeol Jem 6A electron microscope using the mounting technique described by El-Swaify and Emerson (1975).

Water Retention and Surface Area Measurements:

Water retention by filter cakes or molded flakes (containing approximately 1 g of soil) was measured at 0, 10, 20, 50, or 100 cm suctions using ceramic plates equipped with hanging water columns, with adequate protection provided against evaporation. Periods ranging from 3-6 weeks were allowed for equilibration before water contents were determined. Water vapor sorption at relative humidities of 76% and 96% were measured in dessicators containing saturated solutions of NaCl and K_2SO_4, respectively. Aggregate breakdown for rehydration studies was conducted in a Spex model 1800 mixer mill. B.E.T surface areas were measured using N_2 adsorption from defined oxygen- or helium-nitrogen mixtures following outgassing for 2 hours at 105°C.

Results and Discussion

The Basis for Water Content Measurements:

The relative humidity ($P/P_0 \times 100$) of an atmosphere overlying P_2O_5 in an evacuated dessicator at 25°C (room temperature) is zero. On the other hand, an oven adjusted at 105°C (for which P_0 = 906 mm Hg) in equilibrium with a surrounding environment at room temperature with $P/P_0 = 0.75$ (and thus a water vapor pressure of 0.75 x 23.8 = 17.9 mm Hg) would maintain a $P/P_0 = 0.0198$ or a 2% relative humidity. Therefore, if only differences in relative humidity are considered, water retention by soils in the oven would be expected to exceed retention over P_2O_5. Conversely, more water is expected to be driven out of moist soils by drying over P_2O_5 than by oven drying. Figure [1] shows that this was not the case for any of the soils under investigation when subjected to drying from field-moist conditions. For the Kawaihae soil, used in this study as a reference, the two methods differ only slightly. However for both typic Hydrandepts appreciably more water is driven out faster by oven than by P_2O_5 drying. This excess was more for the Akaka than for the Hilo soil. When oven drying is used, as usual, to express the water content of the soils after P_2O_5 drying, air drying, and freeze drying the results in Table [1] are obtained. It is noted that little difference exists between P_2O_5 and freeze drying, both exhibiting more water retention than oven drying. Freeze drying, however, is favored for studies involving natural soil structure as it is presumed to produce less collapse of structural units than other drying methods. As expected, air drying is shown to allow more water to be retained as a result of the relatively high relative humidity in the laboratory atmosphere. It was interesting to note that when oven dried soils were placed over P_2O_5 a water content gain of 3.56%, 3.23%, and 1.59% occurred in the Akaka, Hilo, and Kawaihae soils, respectively. However, the soils displayed water losses of 8.71%, 5.63% and 1.76% after a second cycle of oven drying. The reference, Kawaihae soil, behaves normally in exhibiting complete reversibility of water loss or gain under the two conditions. However, it is difficult to explain the higher water losses as a result of the second than the first drying. It is clearly illustrated, nevertheless, that when a higher temperature is involved during drying, water losses occur above and beyond the water present in a free or adsorbed state. This may be explained by the tendency of certain colloidal constituents, e.g., gibbsite, to exhibit losses of structural water (see Equation 2) near 100°C (Jackson, 1956). In terms of accurate assessment of free or reactive water, therefore, oven drying does not represent an ideal choice for Typic Hydrandepts.

Table 1--Water contents of soils subject to various drying methods

	θ_g^* %		
Method	Akaka	Hilo	Kawaihae
Air Drying	26.3	21.1	7.29
Freeze drying	4.50	3.28	0.584
P_2O_5	4.75	3.23	0.876
Oven	0.00	0.00	0.00

* All on oven dry gravimetric basis.

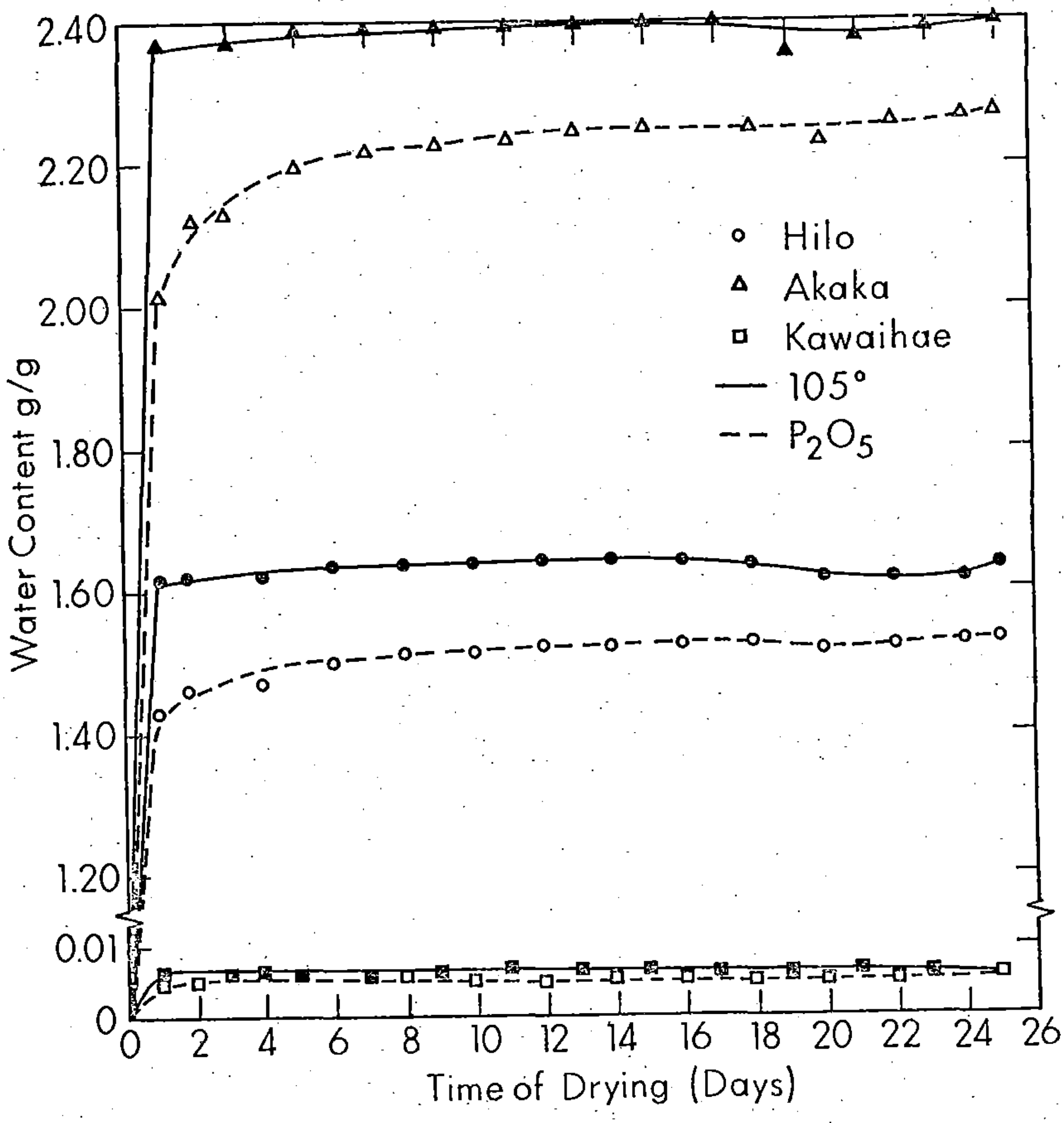

Fig. 1--Effect of drying time and method on water contents of soils. Water contents for each method were calculated based on the final soil weight obtained by each method.

Effects of Drying on Subsequent Water Retention Properties:

The very large volume losses associated with drying field-moist Typic Hydrandepts under low relative humidities are not fully compensated when the soils are rewetted. Rather, it is usually observed that the soil substantially retains its dried volume and absorbs only sufficient water to fill the pore space present therein. This implies that the swelling mechanism (equation 2) is responsible to a large extent for the water retention in natural soils but is eliminated after one drying cycle. Figure [2] shows that more than 1 g of water per g of soil was held in undried soil flakes by this mechanism which was not recoverable upon rewetting of dried flakes regardless of the drying method. It is interesting to note that while freeze-dried-soil had a more open structure with subsequent higher water retention than P_2O_5-dried soil, freezing drying still exhibited substantial irreversible changes. These, however, were shown to be physical rather than mineralogical in nature.

Rehydration of Hilo Soil:

The amount of water present with the soil during a shaking process can determine the effectiveness of a shaking process in achieving ultimate separation of soil particles for the purpose of regaining the original state of hydration. In theory, this is based on the fact that interpartical attractive forces decay rapidly with increasing distance between particles. Figure [3] shows that an optimum water content for dispersion exists for each of the untreated soils under study when subjected to vigorous shaking in a mixer-mill for 10 (Kawaihae) or 20 (Hilo and Akaka) minutes. For these three soils the optimum soil water ratios were 1:4, 1:6, and 1:8, respectively, which are probably good indications of their relative surface areas. At ratios corresponding to lower water contents, water film thickness would be insufficient to provide adequate interparticle separations. At higher water contents there is insufficient friction provided between aggregates during shaking to allow their adequate physical breakdown and release of constituent particles. In a separate experiment, it was shown that the full effectiveness of this shaking process required a period ranging from 20-30 min.

Table [2] shows that a substantial regain of water retention was obtained when dried Hilo soil samples were subjected to such vigorous shaking for 25 min. This indicates that when sufficiently high energies are provided, interparticle bonds formed during drying may be broken and the initial condition of the system substantially restored. The high organic matter contents of Typic Hydrandepts (Approximately 6% in the Hilo sample) appear to contribute significantly to interparticle cementation during drying. As shown in Table [2] removal of organic matter prior to drying substantially reduces the resulting irreversibility in water retention characteristics. However, it is recognized that the very fine fraction (e.g., x-ray amorphous) present in these soils must provide an important contribution to interparticle cementation during drying. This accounts for the remaining irreversibility in Hilo soil after organic matter removal. This is also illustrated in Table [2] by data on water retention by filter cakes of two rather poorly crystallized

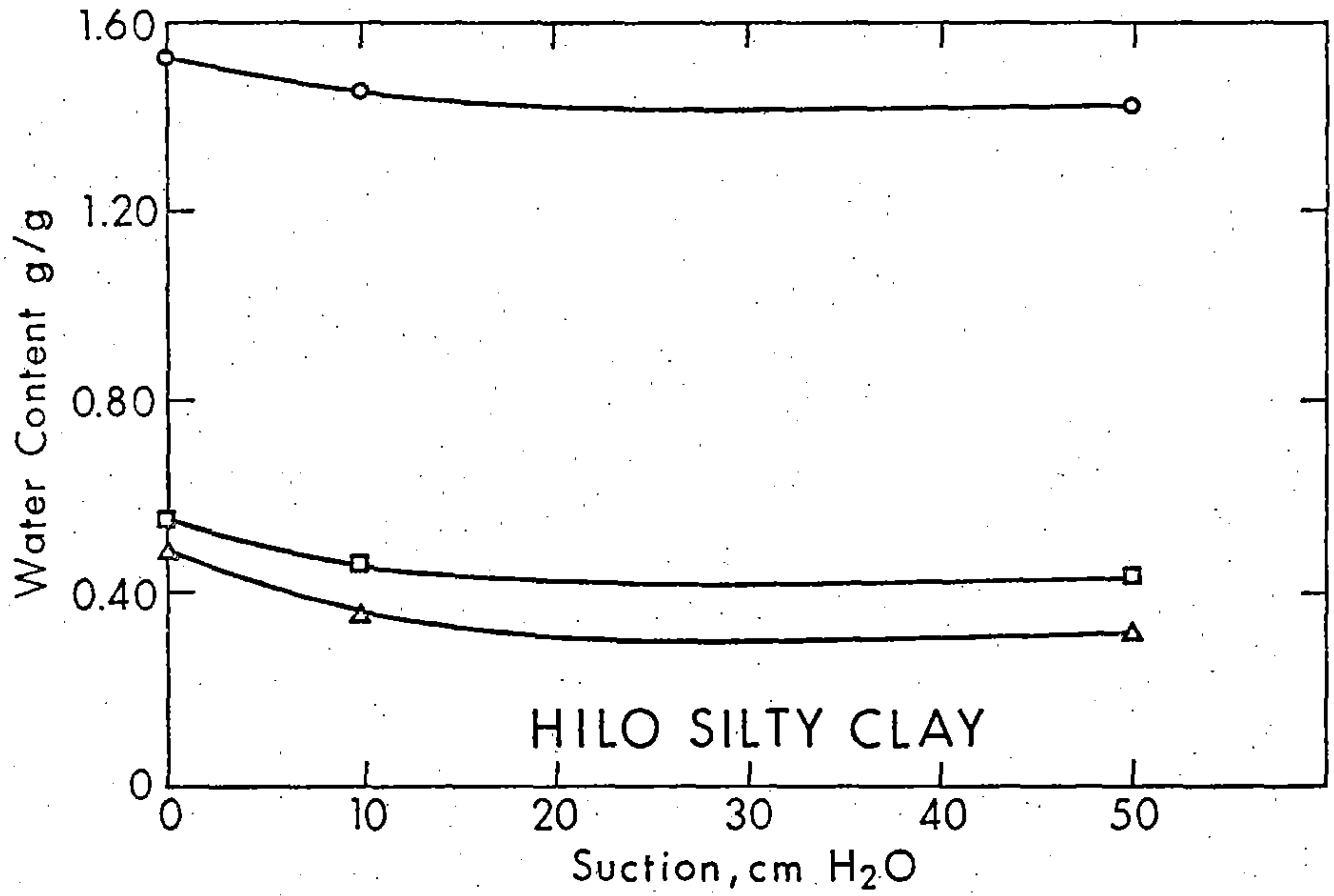

Fig. 2--Water release curves for water-saturated Hilo soil in the absence of a drying cycle and after drying by two methods.

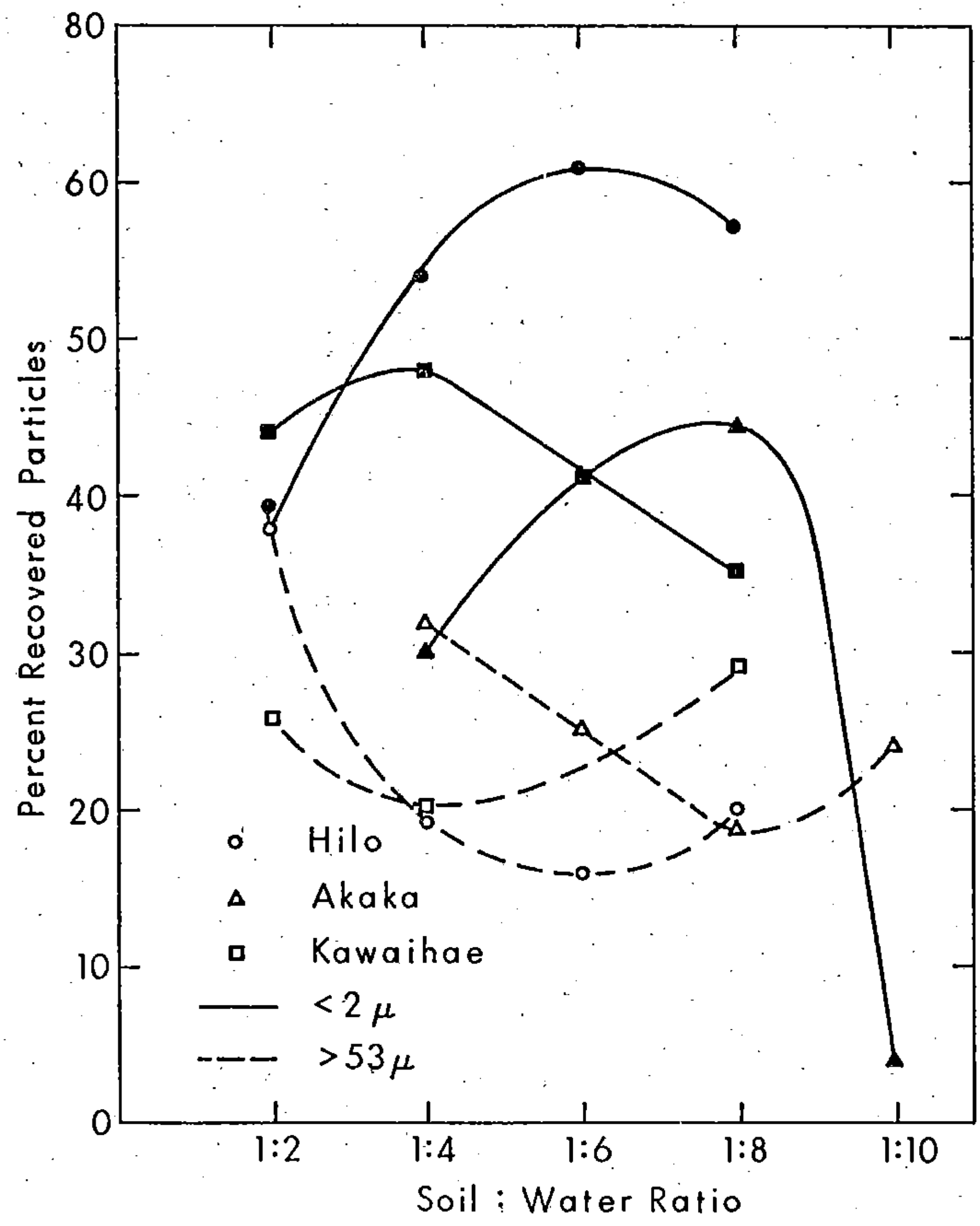

Fig. 3--Effect of soil water content on the breakdown of larger aggregates from 3 soils into clay-sized particles. Shaking time was 20 min.

synthetic hydroxides which reflect an extreme loss of water retention capacity after one drying cycle.

Table 2--Water retention (%) by filter cakes of Hilo silty clay, goethite and gibbsite at 50 cm water suction.

	Hilo silty clay				
Drying method	Mixer mill treated	H_2O_2 Treated control	H_2O_2	goethite	gibbsite
None	148	208	228	264	87
Freeze	138	---	---	---	--
P_2O_5	129	77	136	37	23

That the above changes are not mineralogical but rather physical, and specifically structural, in nature was confirmed by water vapor adsorption experiments at rather low relative humidities. Saturated samples from various drying treatments were equilibrated at P/P_0 = 0.76 or 0.96 and the results are shown in Table [3]. It is noted that the drying treatment had little effect on water retention in this range when soil or mineral samples for similar pretreatments are compared. It is also noted that removal of organic matter as such did not affect water retention in this range. Comparison with the control treatment indicates that the observed effects of the digestion are not as much due to organic matter as they are due to the mechanical disruption of soil structural units during the treatment and subsequent exposure of adsorptive surfaces. In the absence of heating verification of optimum conditions favoring mechanical disruption would be helpful in experimental restoration of natural soil reactivity.

Specific Surface Areas:

As indicated in Table [4], the N_2 specific surface area of the Hilo soil seems to undergo a slight decrease due to drying over P_2O_5 as compared with freeze drying. This confirms the previous conclusion that less structural collapse and mutual blocking of particle surfaces is experienced by the soil with the latter method. The water vapor surface area reflects no difference between drying treatments indicating that the soil surface or ions attached to it are equally able to hydrate regardless of prior drying methods (Quirk, 1955, reported a surface area of 165 m^2/g based on the water adsorption measurements for an unidentified soil from the Hilo coast as reported by Wadsworth, 1944). This emphasized the conclusion that changes upon drying are not mineralogical in nature. Direct electron-microscopic examination explained the high specific surface of approximately 200 m^2/g obtained by N_2 sorption measurements. Figure [4] shows that the bulk of the Hilo soil is

Table 3--Water vapor retention (g/g) over saturated NaCl (P/P_0 = 0.76) and K_2SO_4 (P/P_0 = 0.96)

Drying Treatment	Undisturbed Hilo	Mixer Mill treated Hilo			Goethite	Gibbsite
	$\frac{P}{P_0}$ = 0.76	$\frac{P}{P_0}$ = 0.76		$\frac{P}{P_0}$ = 0.96	$\frac{P}{P_0}$ = 0.76	
		cycle 1	cycle 2			
Non-dried						
whole	0.125	0.139	0.130	0.216	0.169	0.052
H_2O_2 control	0.229	-----	-----	-----	N.A.	N.A.
H_2O_2 digested	0.241	-----	-----	-----	N.A.	N.A.
P_2O_5-dried						
whole	0.102	0.142	0.132	0.198	0.180	0.045
H_2O_2 control	0.223	-----	-----	-----	N.A.	N.A.
H_2O_2 digested	0.238	-----	-----	-----	N.A.	N.A.
Freeze-dried						
whole	0.128	0.145	0.139	-----	0.181	0.051

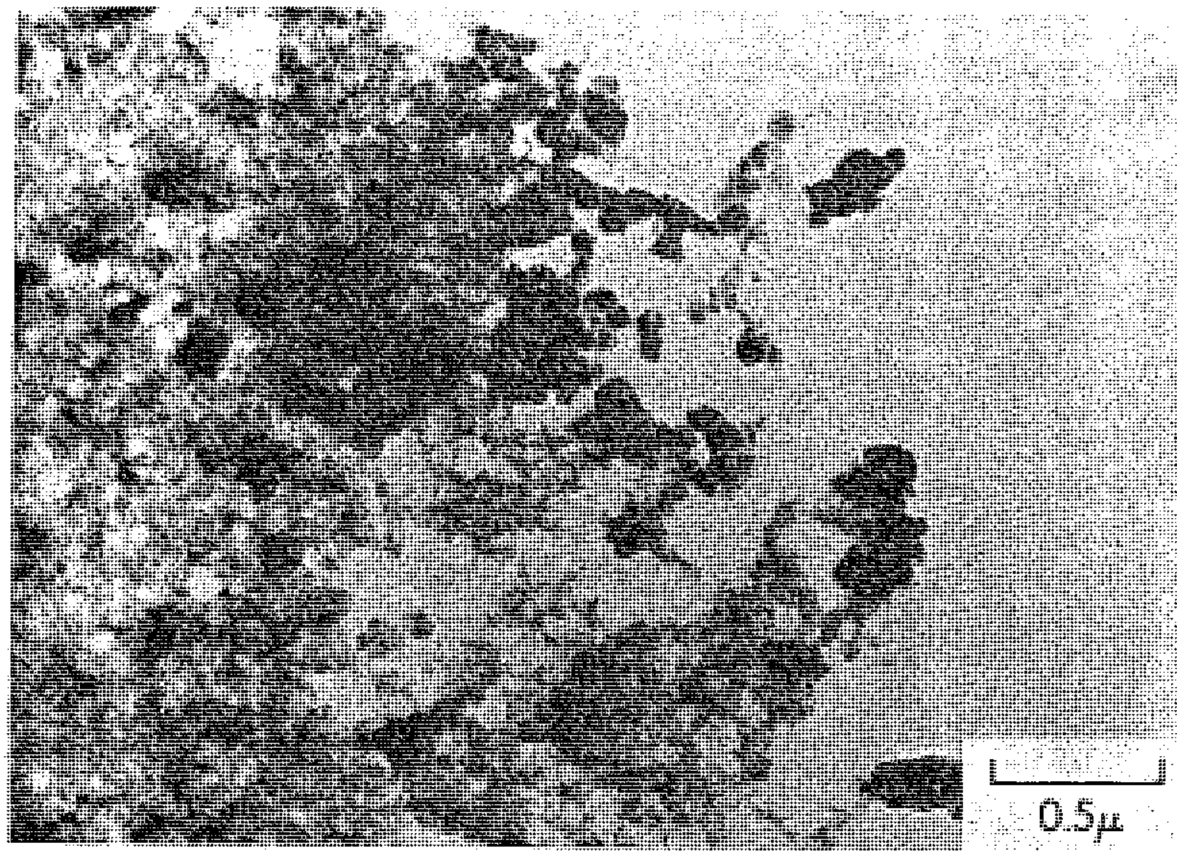

Fig. 4-- Electron-micrographs of carbon-grid mounted Hilo soil.
(a) Untreated sample.

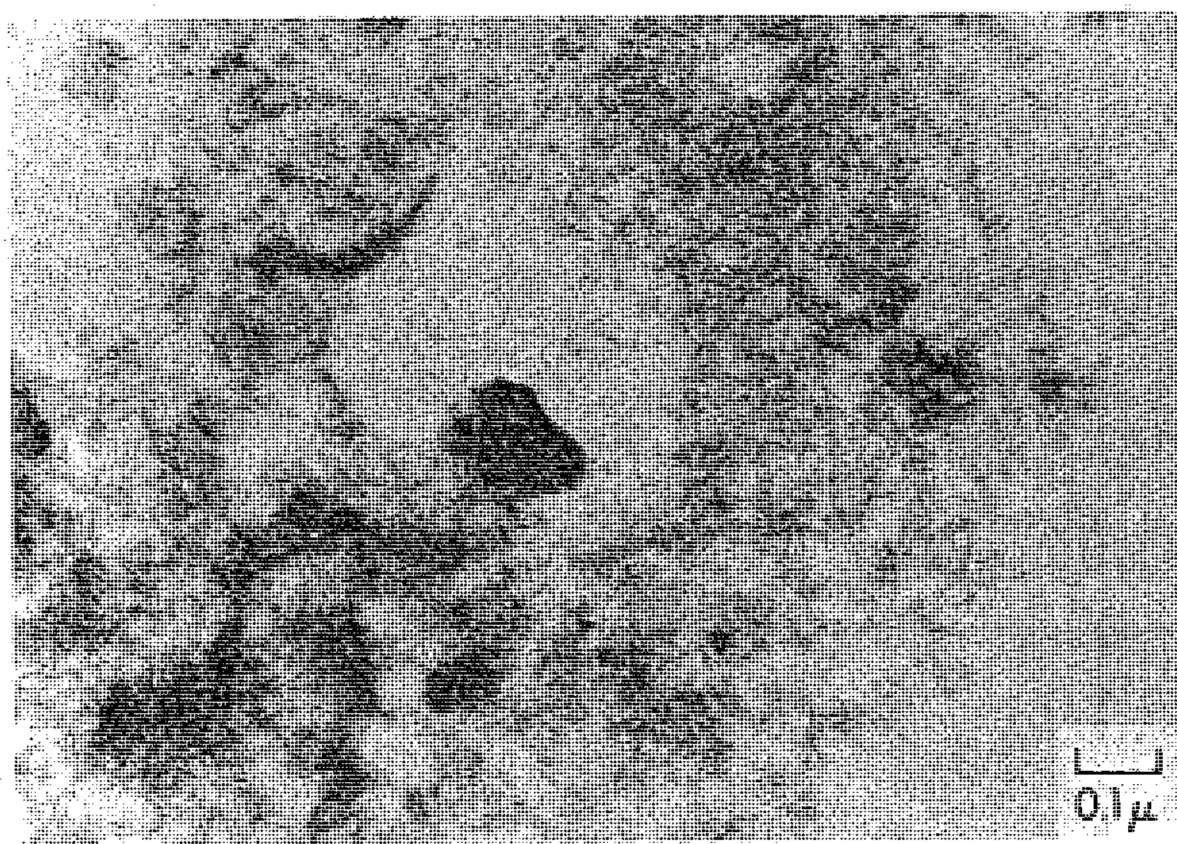

Fig. 4--Electron-micrographs of carbon-grid mounted Hilo soil.
(b) Untreated sample, higher magnification.

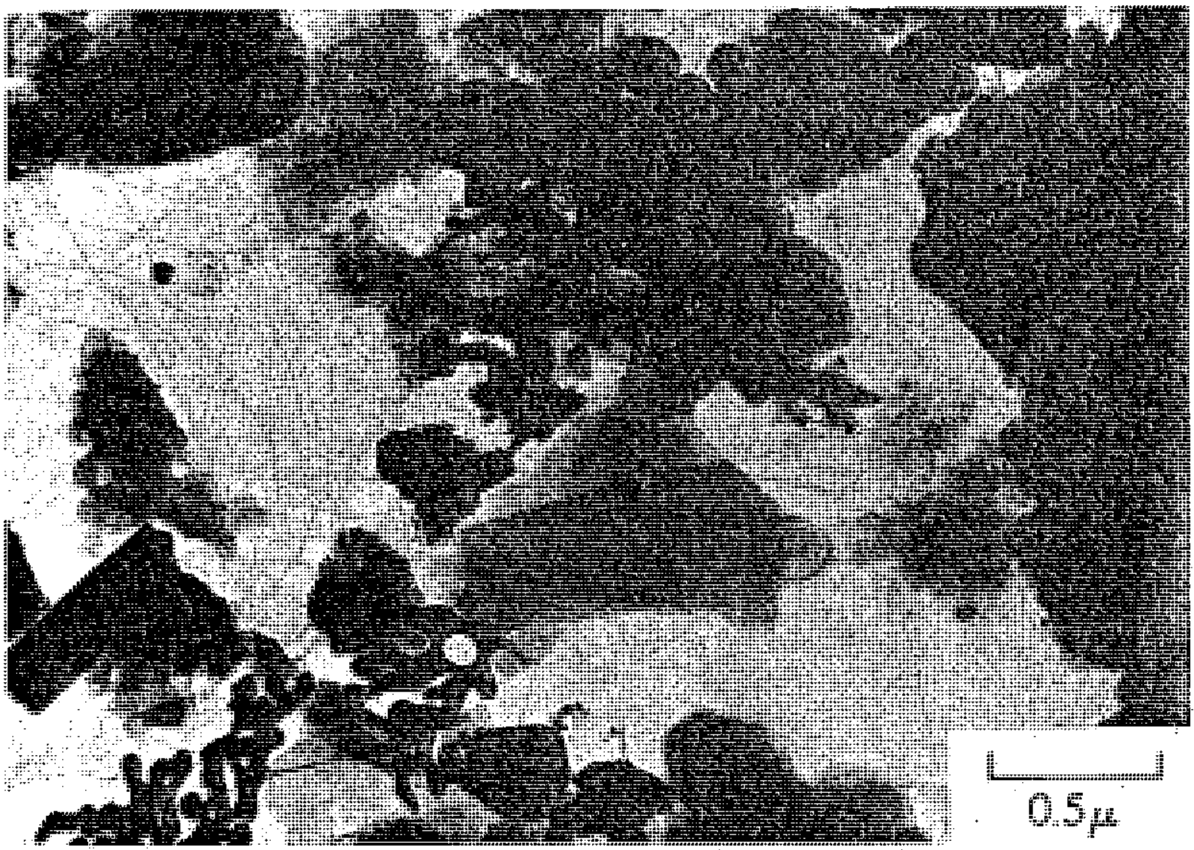

Fig. 4--Electron-micrographs of carbon-grid mounted Hilo soil.
(c) Defferated sample.

made up of beaded-rod-shaped particles admixed with other types of particles. Since x-ray diffraction indicated the presence of mainly goethite and gibbsite in these samples (see powder camera patterns in Figure 5) and since deferration treatment with sodium-diothionite resulted in eliminating the rod shaped particles, these particles are identified as goethite. The CoK_{α} x-ray radiation used in this study provides a better means of identifying Fe(III) minerals than does the CuK_{α} radiation which has been, thus far, the only source used on studies of Hawaii's Hydrandepts (e.g., Lai and Swindale, 1969 and Chan, 1972). These authors were able to confirm the presence of gibbsite in certain fractions of this soil.

Table 4--Surface area data for Hilo silty clay

Treatment	B.E.T. surface area m^2/g		
	O_2-N_2 adsorption	He-N_2 adsorption	H_2O adsorption
Freeze-dried	196	222	148
P_2O_5-dried	167	206	156

It is estimated that each goethite rod particle is 40A in diameter and 0.1μ in length. Using these dimensions to calculate the specific surface area for 1 g of pure goethite (density = 4.28 g/cc) would result in a specific surface area for the Hilo soil of 234 m^2/g or only slightly higher than the experimental value. The difference is clearly explained by the fact that other constituents, mostly larger in particle size and lower in particle density than is goethite, are present in the Hilo soil. The particle density for the Hilo soil as a whole was 2.90 g/cc. Removal of goethite by deferration enhances the presence of other constituents as shown in Figure 4c. This figure also shows the presence of certain fibrous constituents which resemble "imogolite" in appearance.

Conclusions

The water retention properties of Typic Hydrandepts are well accounted for based on its identifiable constituents. Of particular interest are the higher water retention capacity in the field and the effects of drying.

Swelling is presumed to provide an important water retention mechanism (equation 2) in field-moist Typic Hydrandepts. The fact that field water contents for the Hilo soil seldom fall below 150% and that the shrinkage limit for this soil is only 45-50% indicates that direct particle-particle contact under field conditions is probably only very limited. This is concluded from the thickness of the water layer surrounding each soil particle under field conditions which may be estimated as

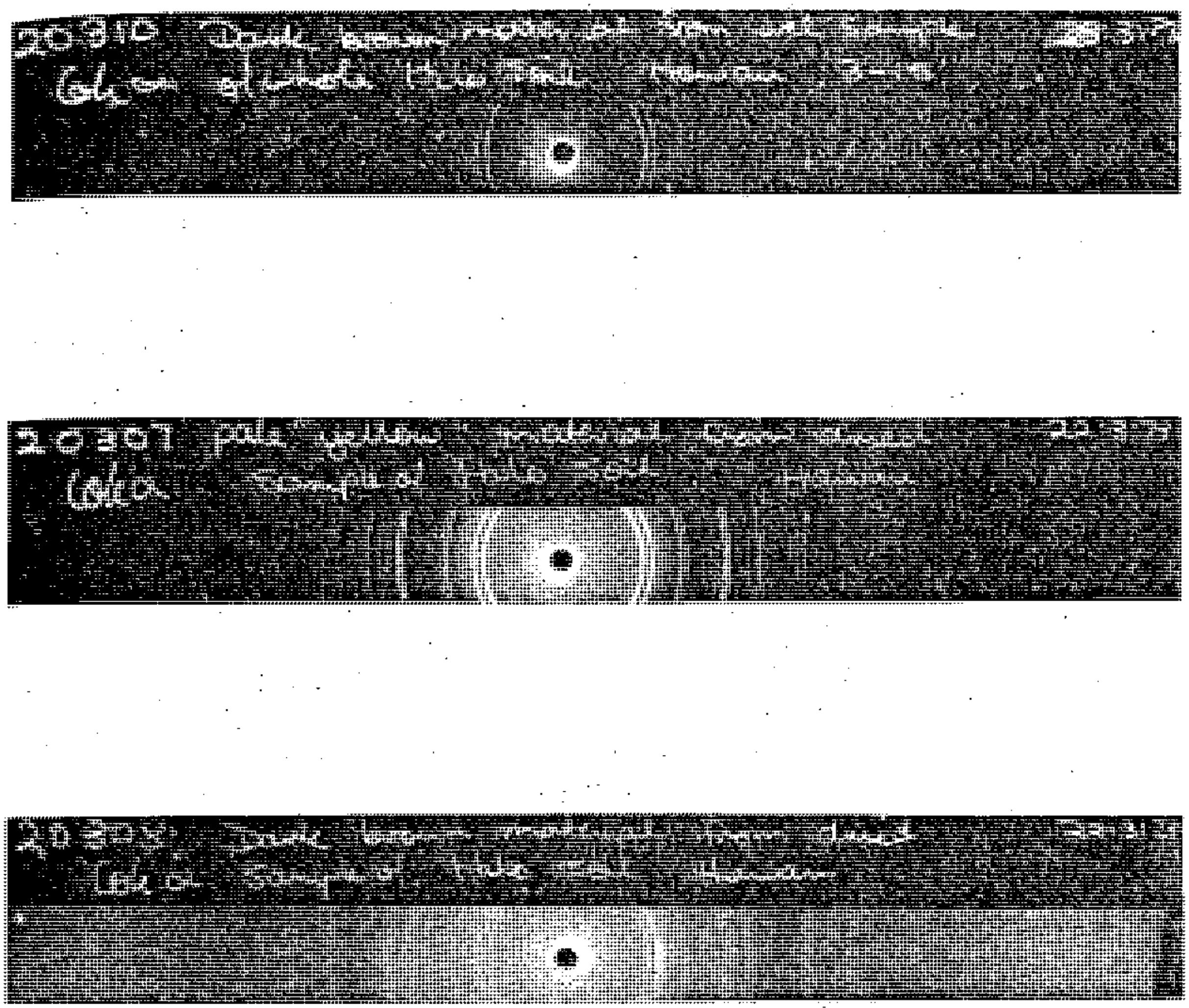

Fig. 5--X-ray camera powder diffraction patterns for Hilo soil.
(a) Whole, non-dried sample.
(b) Yellowish separate from dried soil.
(c) Dark brown separate from dried soil.

75A° from the volume of water held by 1 g of soil and the specific surface area assuming homogeneous water distribution. This indicates a particle separation of 150A° or roughly 4 times the magnitudes observed for cylindrical particle diameters. Drying to the shrinkage limit produces a mean particle separation of 45A° at that point which is the same order of magnitude expected when appreciable contact occurs between particles, perhaps by approaching a more or less parallel orientation. The closer contact between particles achieved during further drying enhances the formation of stronger interparticle attractions either directly due to electrostatic or hydrogen bonds, (El-Swaify and Emerson, 1975) or by indirect bridging due to the presence of abundant organic or gelatinous constituents as noted in the background of figures 1a, 1b and reported by Jones and Uehara (1973). As illustrated, these bond formations require much energy if particle separation is to be restored to original conditions.

In the dry range, i.e., at $P/P_0 = 0.76$ or 0.96, capillary water retention may be examined by use of the Kelvin equation (Aylmore and Quirk, 1962)

$$r_c = -\frac{2V\gamma}{RT} \ln\frac{P}{P_0}$$

where r_c is the radius of a cylindrical pore containing a hemispherical miniscus of water at an equilibrium vapor pressure of P, P_0 is the saturation pressure, V the molar volume, γ the surface tention (72 dynes/cm at 25°C), R the gas constant, and T the absolute temperature. The equation predicts that cylindrical pores with radii of 19A° and 46A° and smaller would be filled with water at relative humidities of 76% and 96%, respectively. For a meniscus occurring between parallel plates the radius of curvature r_p is

$$r_p = 1/2\ r_c$$

so that the above pore radii may be regarded as approximate particle separations resulting in film thickness of 9.5A° and 23A° at the above two relative humidities. Assuming uniform coverage around the substrate soil these values can be converted to water contents. The resulting values of 0.19 and 0.46 g/g compare with contents of approximately 0.13 and 0.22, respectively, as measured during dehydration of untreated Hilo soil (Table 3). It may be concluded that the Kelvin equation overestimates water retention by these soils or that only 68% and 48% of the volume of pores in the stated class participate in water retention in the manner predicted by the equation.

At lower relative humidities yet, the B.E.T. surface area measured for the Hilo soil by water vapor adsorption (reported above) reveals a water retention value of 0.045 g/g of soil as necessary for monolayer coverage. According to Quirk (1955) this best corresponds to a $P/P_0 = 0.20$. This indicates that the ionic and surface hydration term (ψ_{mh} in equation 2) represents only 3% of the total water held by the soil (1.5 g/g) at field moisture. No differences in this amount were noted for different drying pretreatments indicating that the surface and exchangeable cation hydration remained unchanged.

It has been indicated that the normal technique for measuring soil water contents by oven drying leads to inaccurate assessment of the water contents of oxide- or hydroxide-rich soils in general and of Typic Hydrandepts in particular. Losses of some structural water due to heat-drying may lead to overestimation of the quantity of soil water that is actually available for participation in important reactions, e.g., solute transport (Rao, 1974) and availability to plants. The overestimate amounts to approximately 10%. Vacuum drying over P_2O_5 is suggested as a better alternative for this purpose.

Finally, the results of this study indicate that freeze-drying is the best alternative studied here for drying Typic Hydrandepts (to ensure easy storage and handling for laboratory purposes) and also maintaining a relatively open structure. However, other drying methods need to be investigated to ensure preservation of natural structural conditions and thus easy restoration of soil properties upon rehydration.

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V. QUALITY TRENDS FOR WATERS FROM VARIOUS SOURCES AT THE UNIVERSITY OF HAWAII LYON ARBORETUM FOR THE CALENDAR YEAR 1974

Introduction

Waters yielded by undisturbed forest watersheds may be looked upon as subject to the least possible interference from humans. Rather, their characteristics and composition reflect only the contributions of rain, vegetation, and soil or rock under a natural steady-state balance. The quality of such water, therefore, provides a feasible baseline for judging whether or not changes in water characteristics resulting from management practices imposed along the watershed basin are detrimental. Realistic criteria may then be adopted for the purpose of establishing acceptable water quality standards in various regions.

Forest lands in temperate areas have been subjected to many studies which involved the cycles of nutrients and their distributions among various components, including soil and water, of the forest system (e.g., Duvigneand and de Smet, 1972). Some such information is also available for tropical forests (Greenland and Kowal, 1960 and Nye, 1961). Recently, in an intensive study of irradiation and eclolgy at El-Verde, Puerto Rico, Odum and Pigeon, (1972) presented some detailed information on mineral cycling in a tropical rainforest. Their study included investigations of the three parameters examined in this report, namely nitrates, electrical conductivities, and acidity.

In Hawaii, despite the availability of annual water quality records (USGS, 1967), little is known on the composition of waters of forest watersheds. The objective of this study was to establish trends for nitrate content, electrical conductivity, and pH under various vegetative types and in the rainfall and runoff waters in selected locations at the University of Hawaii Lyon's Arboretum, Manoa Valley, Oahu, Hawaii.

Experimental

Water collection sites:

Water samples were collected at biweekly intervals from the sites marked on the attached map of the Arboretum. Rainfall samples were collected from two sites: the first (R-1) on an open *Canna* lily field and the second (R-2) under a closed canopy of Chinese banyon (*Ficus retusa*) on the plot delineated for rainfall-runoff experiments. Runoff samples were collected from barrels installed under the above plot to collect runoff waters. Soil solution samples were collected by suction extraction from 15 and 120 cm depths from three locations. Soil water samplers consisting of ceramic cups installed on PVC tubing were used for this purpose. Vegetative covers at the three locations were dominated by a full canopy of *Eucalyptus* sp. (Site 1), a full canopy of mixed *Ceropia* sp. and *Citharexylum* sp. (Site 2), and by a partial canopy of *Terminalia* sp. (Site 3), respectively.

Samples were collected in polythelene bottles, returned immediately to the laboratory, and analyzed soon thereafter.

Analyses of water samples:

Acidity was evaluated using pH measurements with a Beckman Expandomatic or an Orion Model 8000 digital pH meter. Electrical conductivities were measured using an Industrial Instruments solu bridge and a conductivity cell with a constant of 5. Nitrates were always determined potentimetrically, using an Orion Nitrate ion electrode attached to the above pH-meters, and occasionally determined by reduction and subsequent distillation in a micro Kjeldahl unit followed by titration of boric acid-trapped NH_3 by standardized H_2SO_4. Values obtained by the two methods were generally comparable with slightly higher values obtained by electrode measurements (Fig. 1), particularly in the low range of NO_3^- concentration. It would appear, therefore, that interference errors during electrode measurements exceeded errors due to the recovery of forms other than NO_3^- during distillation which were, probably, also affected by incomplete recovery of produced NH_4 during distillation. A regression equation relating both measurement methods is presented in Fig. 1. The value of correlation coefficient for this equation was 0.92.

Results

Quality characteristics of rainfall waters:

The acidity of water collected from the open field (sample R-1) remained rather steady as indicated in figure 2 by the pH values which ranged from 6.0 to 6.8. Excessive acidity, occasionally reported in other regions and suspected during certain times of volcanic activity in Hawaii, was noted only on September 26 when the pH of the sample fell to 4.5. As expected, the electrical conductances of these samples were lowest among the samples investigated, ranging from 0.02 to 0.06 mmhos/cm and indicating a low content of soluble material (10-30 ppm). These values closely correspond to others previously reported for tropical rainfall. Nitrate contents were also extremely low ranging from 0.4 to 0.8 ppm most of the year. It would be reasonable to assume, therefore, that this sample provides a natural reference for discussion of effects of various forest components on water quality.

The second rainfall sample (R-2), collected under a relatively closed canopy, is considered to represent the effect of throughfall and contact with overlying tree leaves and branches on water quality. Figure 3 shows that pH values for this sample were slightly higher than those for sample R-1 from the beginning of collection until mid-July with close agreement between the samples noted thereafter. It is of interest to note, however, that on September 26, the sample pH fell only to 5.2 in contrast to the value of 4.5 measured for the R-1 sample. It would appear, therefore, that throughfall is subject to considerable decreases of acidity, compared to original rainfall, due to contact with overlying segments of the canopy. It must be also emphasized that rainfall waters are expected to be weakly buffered and that their pH values are, therefore, sensitive

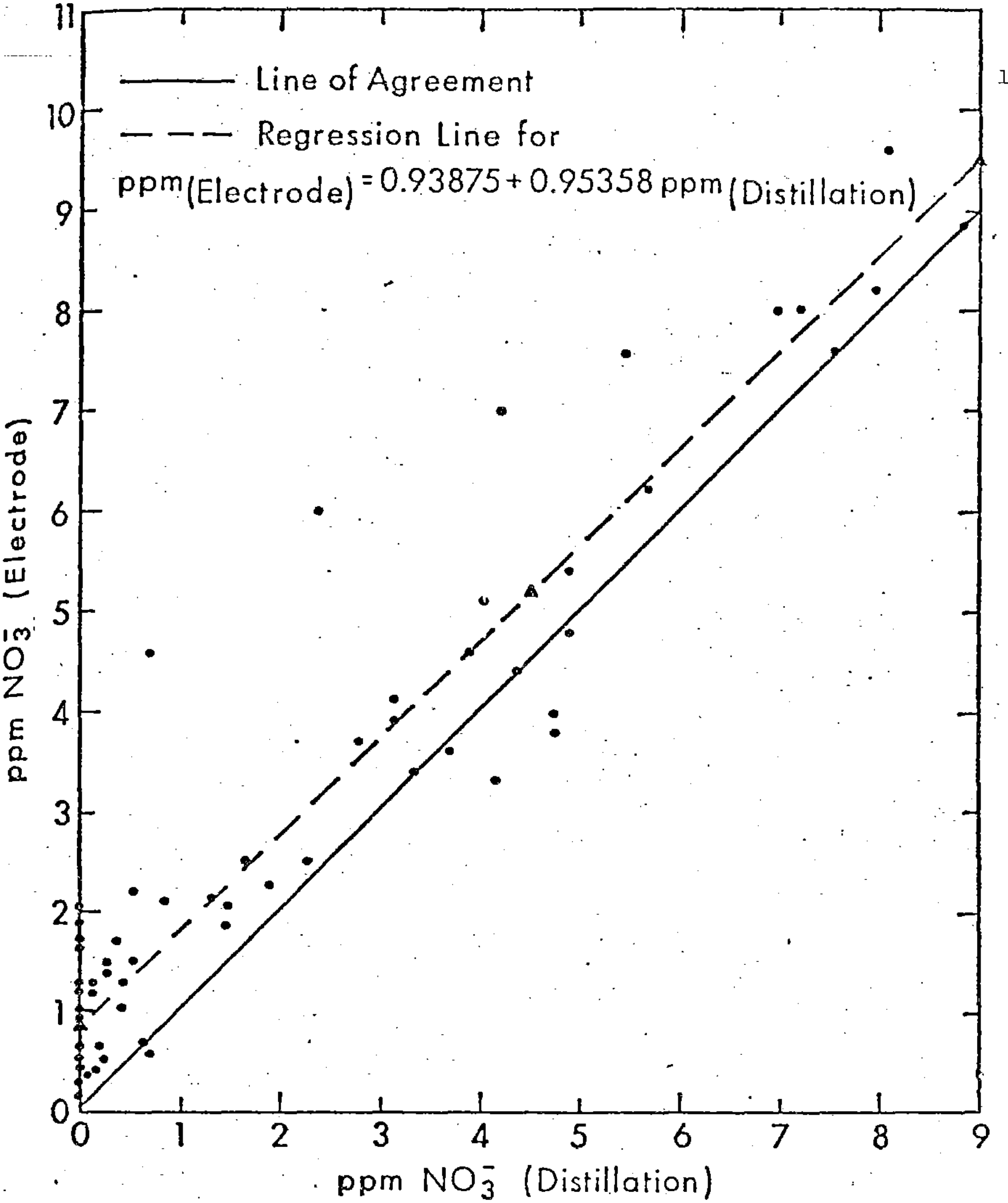

Fig. 1--Comparison between NO_3^- concentrations as measured by the nitrate electrode and by Kjeldahl distillation.

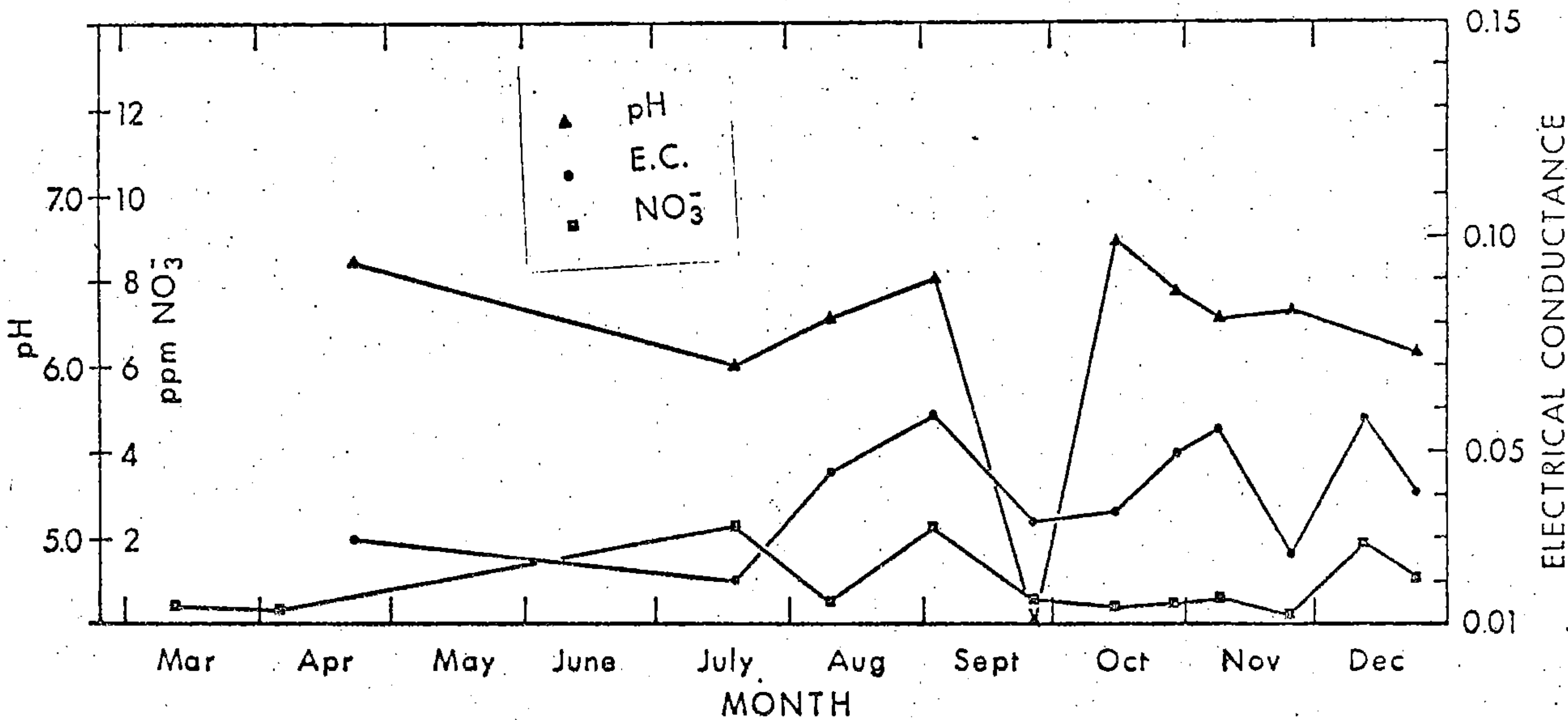

Fig. 2--Trends during 1974 of pH, Electrical Conductivity (E.C.), and nitrate concentration in rainfall samples collected from an open area.

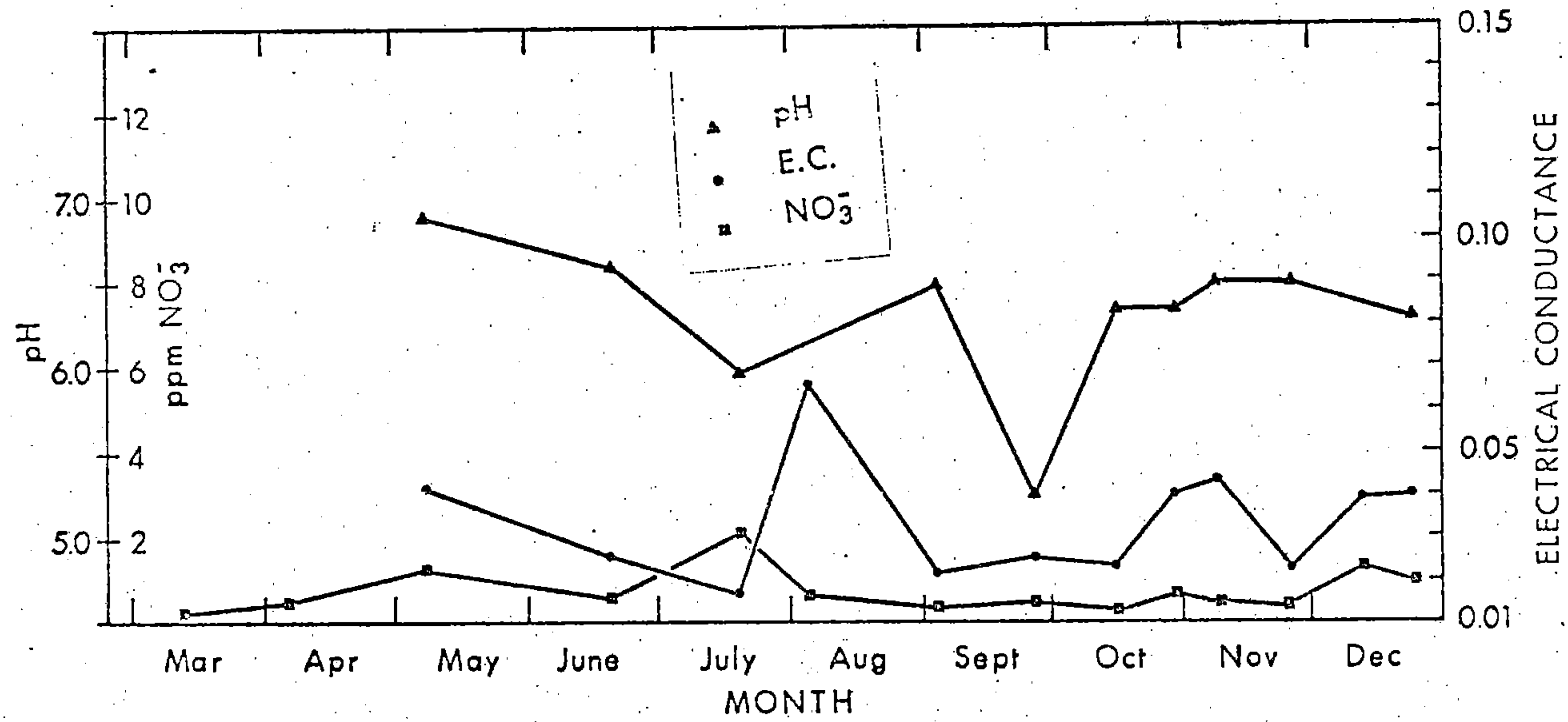

Fig. 3--Trends during 1974 of pH, Electrical Conductivity (E.C.), and nitrate concentration in rainfall samples collected under a relatively closed canopy (throughfall).

to exposure by contact. Electrical conductances of the R-2 samples exceeded their counterparts for the R-1 sample early in the year, a trend previously noted for a Puerto Rico forest by Sollins and Drewery (1970). However, after the collection of August 10, the trend was reversed for a while and then a closer agreement noted between the two samples progressively toward the year end. It would be difficult to explain the reduction of soluble ion concentration noted occasionally in throughfall except by the possibility of nutrient absorption from rainfall during contact with vegetations. Apparently this, if it did occur, did not involve NO_3 as comparison between figures 2 and 3 reveals nitrate contents to be nearly identical for rainfall and throughfall.

Quality characteristics of runoff water:

The composition of water collected from the runoff (upper plot) represents the contribution of brief contact with the forest to changes in the quality of throughfall. This is because, as stated in the Experimental section, throughfall sample R-2 was collected from raingages placed on that plot. Figure 4 shows that the pH of runoff water varied less with time than the pH's of either of the rainfall samples ranging only between 6.1 and 6.6. This indicates that the brief contact between rainfall and forest floor (litter and the uppermost mineral soil layer) results in sufficient stabilization of water acidity levels. It is also clearly indicated, from the above pH values, that litter contributes only slight acidity to runoff water.

Markedly higher total soluble ion contents are observed in runoff water than in either of the two rainfall water samples. The contact of rainfall with the decomposing forest litter and uppermost soil layer during overland flow resulted in approximately doubling the electrical conductivities. Sollins and Drewery (1970) recorded appreciably higher electrical conductivities for the stemflow than those for rainfall, buy no information is available in the literature on the contribution of overland contact to changes in electrical conductivities of water. Interestingly, the NO_3^- content of runoff water, as shown in fig. 4, was not appreciably different from that of either of the rainfall samples. Because NO_3^- salts are highly soluble, this may be explained by the tendency of any NO_3^- resulting from organic litter decomposition to be carried with the very first increments of rainfall. These increments enter the soil and by the time runoff is initiated, little NO_3^- is left in the litter. It is clear that insufficient amounts of NO_3^- are consistently produced by the litter to result in significant enrichment of runoff water within rainstorms. Only in few occasions, did its concentration in this water exceed 1 ppm.

Quality characteristics of extracted soil-water:

Samples were collected for this purpose from 15 and 120 cm depths at three locations. These samples will be referred to as top and bottom samples, respectively. Results of analysis of these samples are presented in figures 5 to 10.

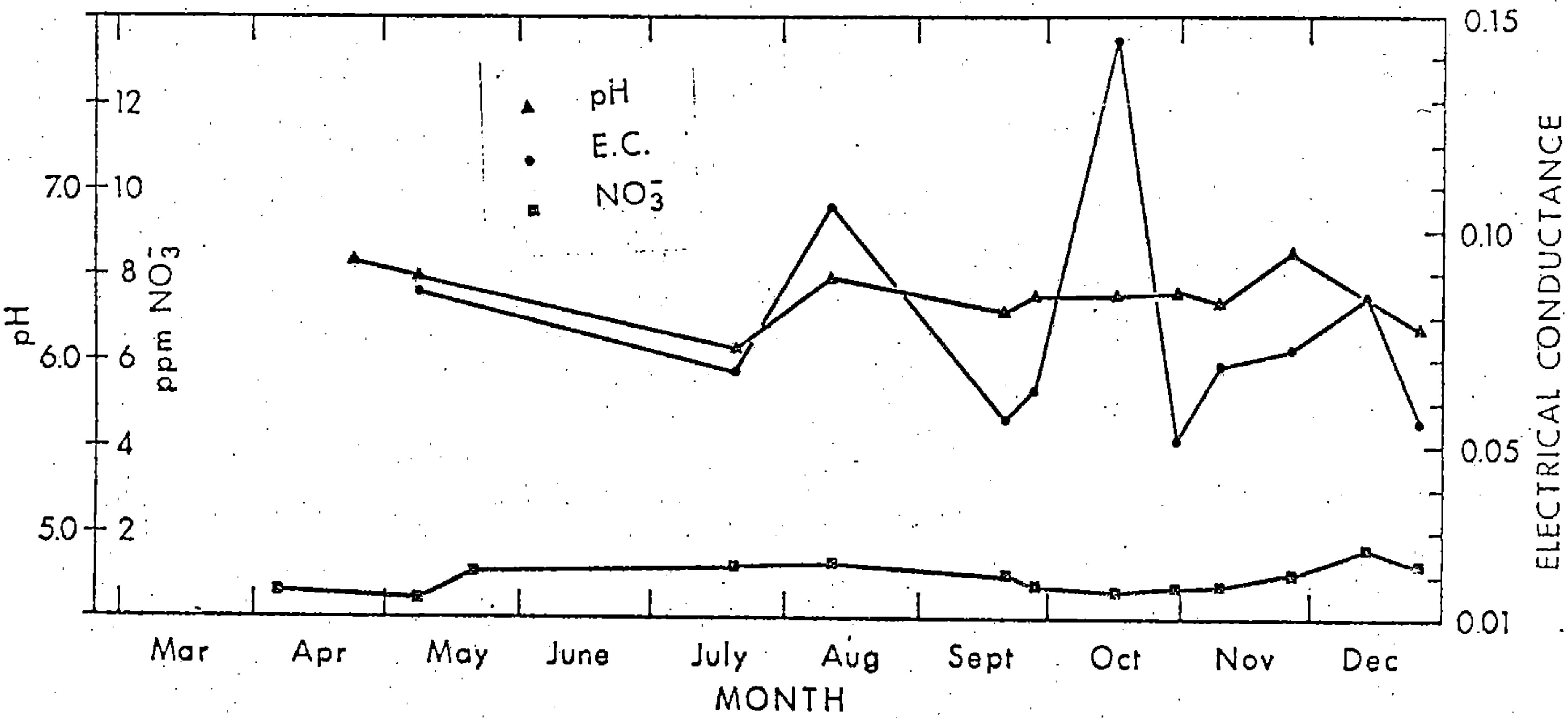

Fig. 4--Trends during 1974 of pH, Electrical Conductivity (E.C.), and nitrate concentration in runoff samples from the "upper plot".

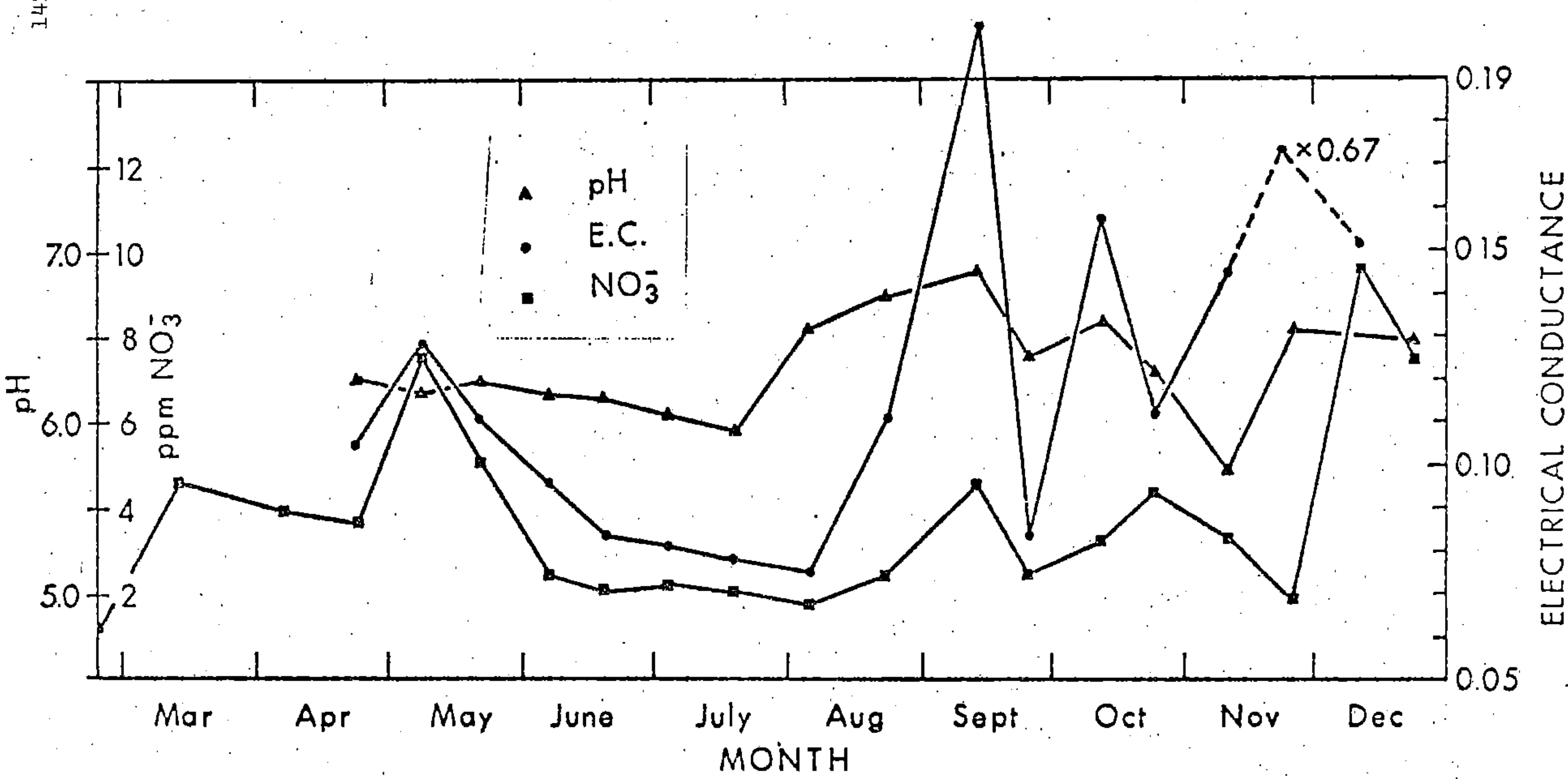

Fig. 5--Trends during 1974 of pH, Electrical Conductivity (E.C.), and nitrate concentration in soil solution extracted from the top 15 cm under a vegetation dominated by Eucalyptus trees and palm grass.

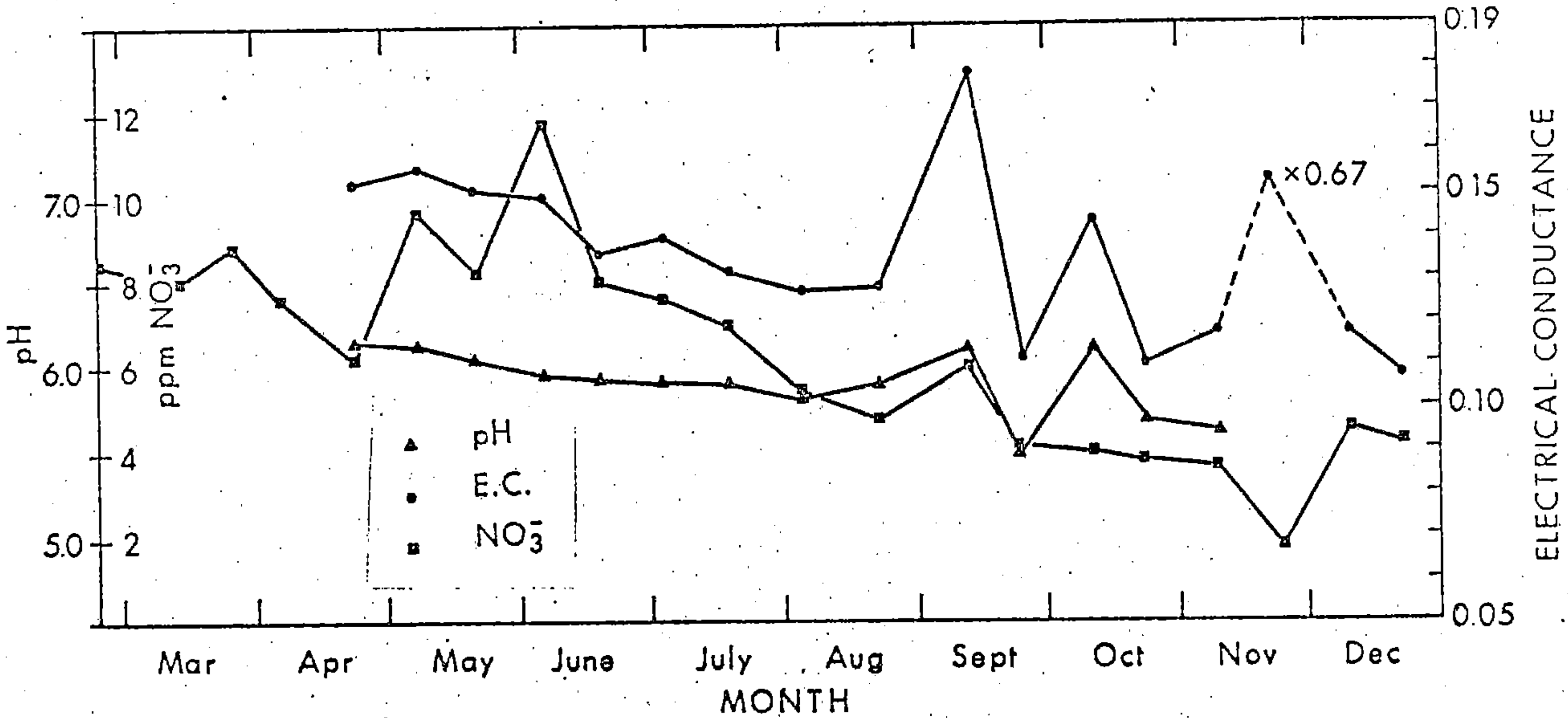

Fig. 6--Trends during 1974 of pH, Electrical Conductivity (E.C.), and nitrate concentration in soil solution extracted from a depth of 122 cm under a vegetation dominated by Eucalyptus trees and palm grass.

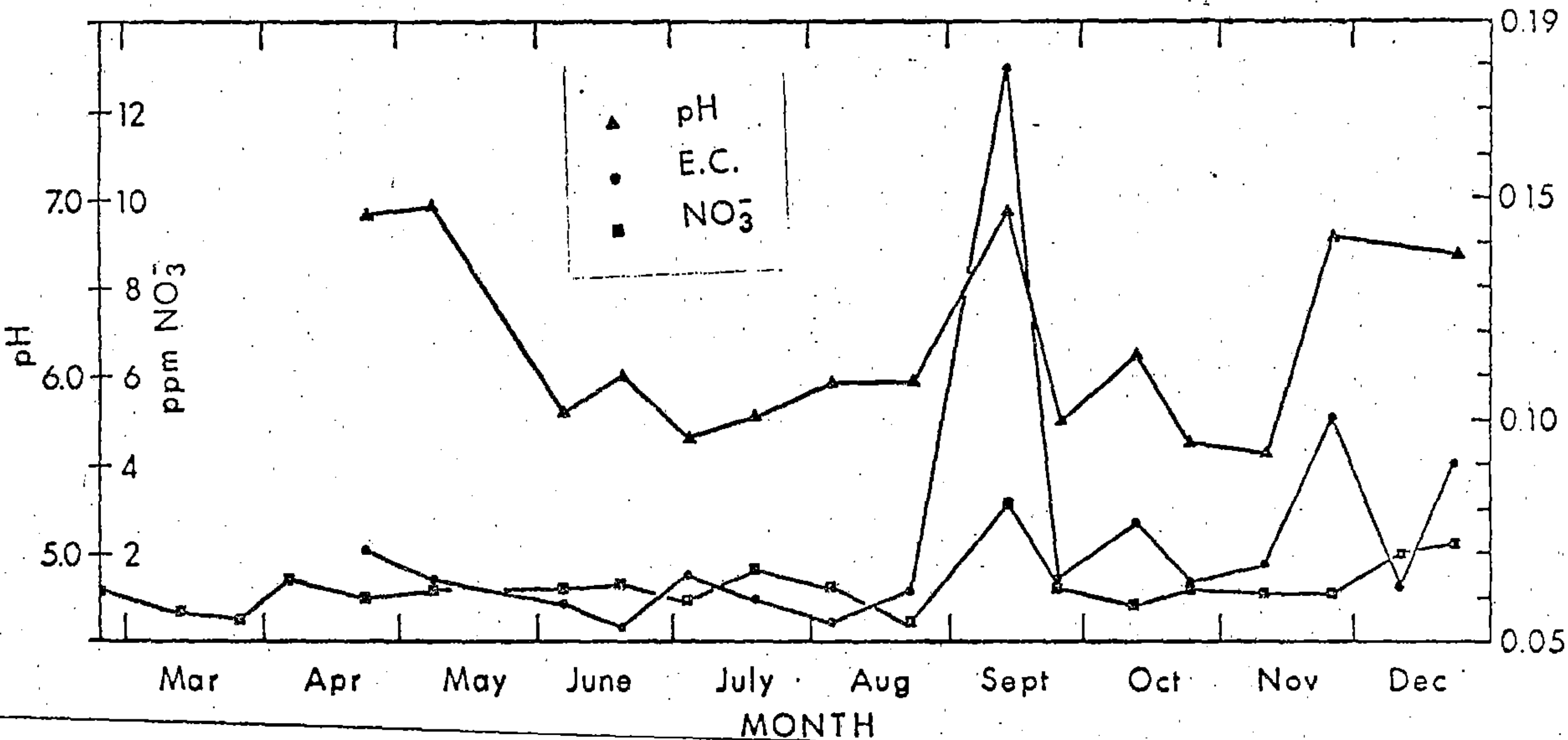

Fig. 7--Trends during 1974 of pH, Electrical Conductivity (E.C.), and nitrate concentration in soil solution extracted from the top 15 cm under a vegetation dominated by Cecropia sp. and Citharexylum sp.

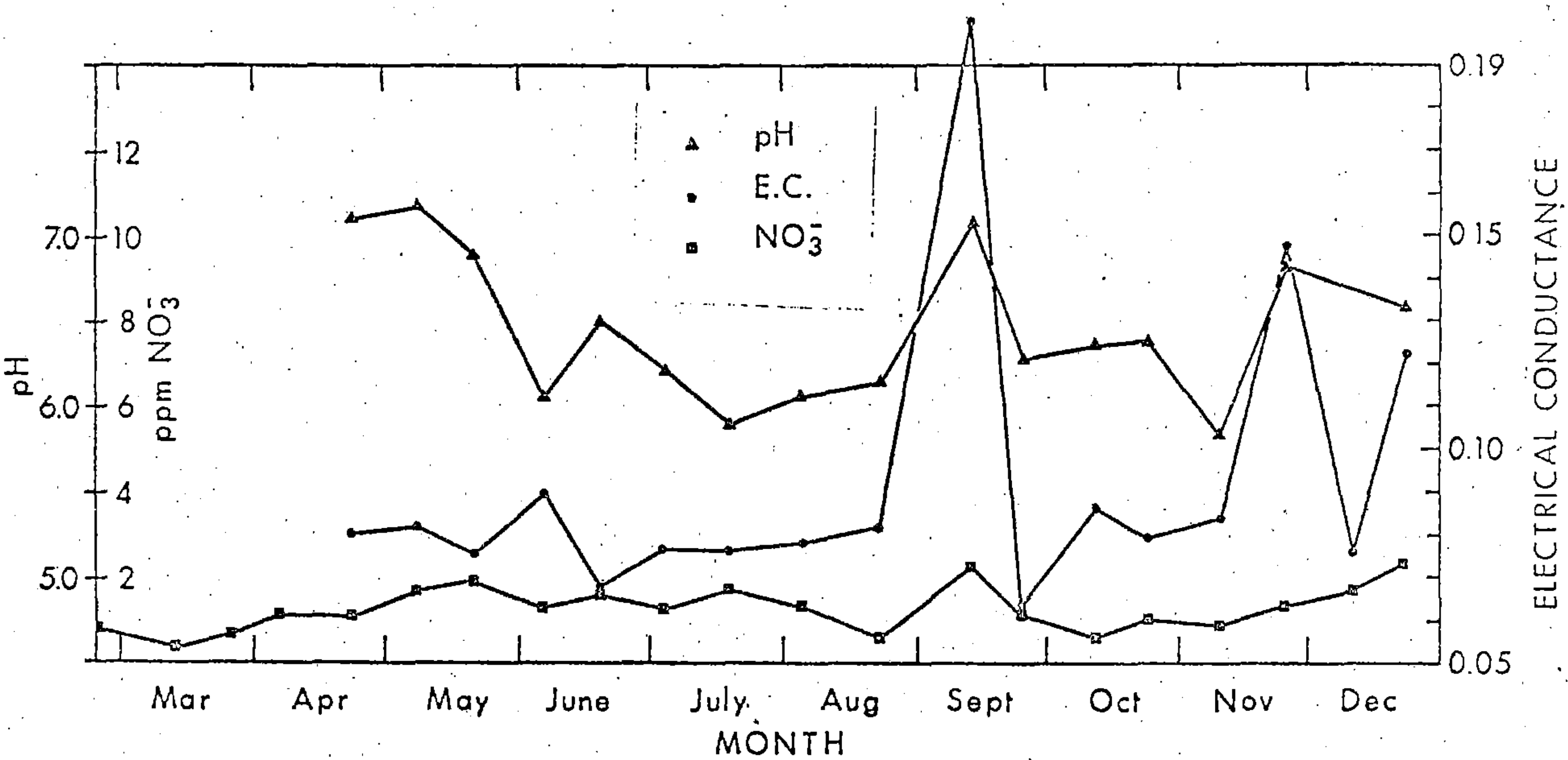

Fig. 8--Trends during 1974 of pH, Electrical Conductivity (E.C.), and nitrate concentration in soil solution extracted from a depth of 122 cm under a vegetation dominated by Cecropia sp. and Citharexylum sp.

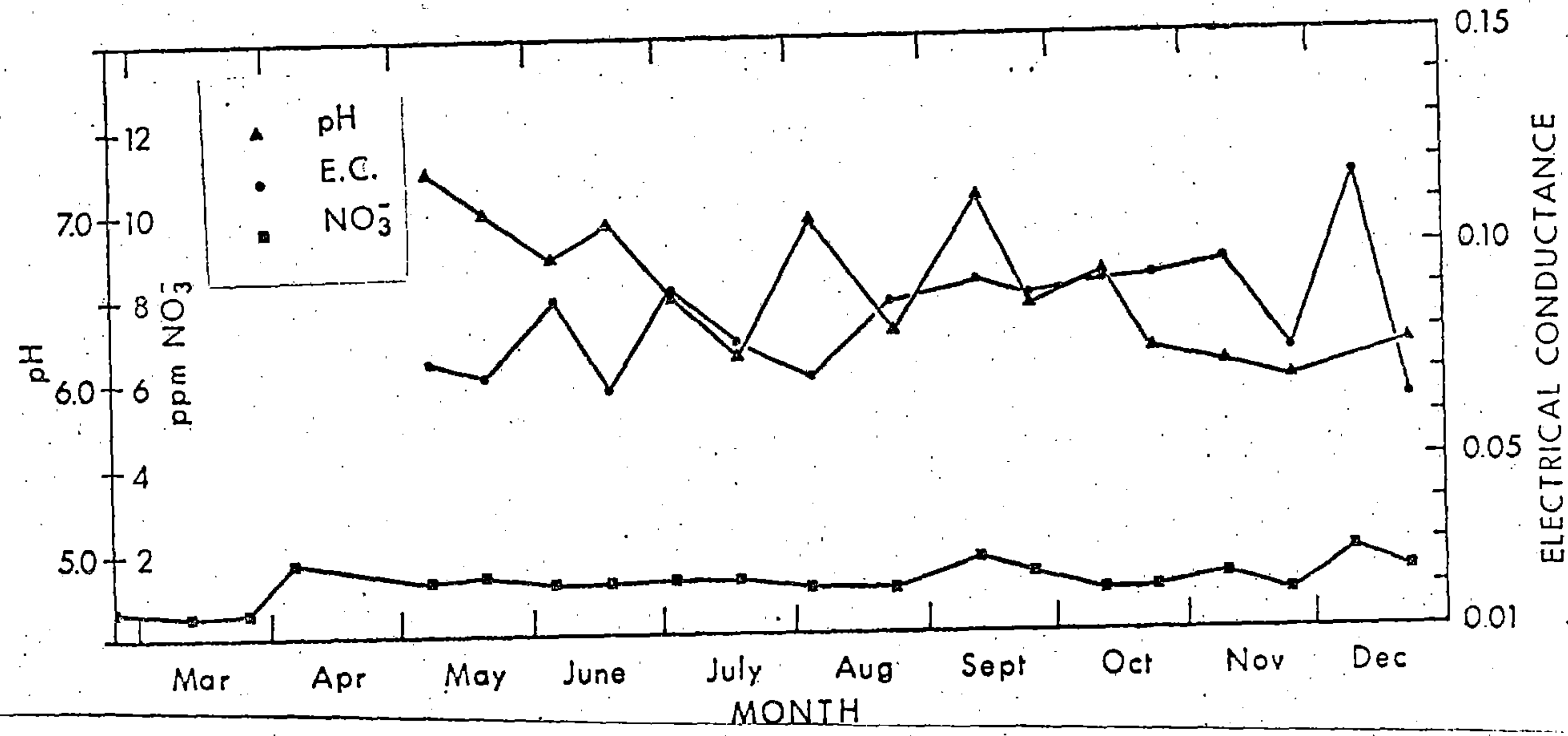

Fig. 9--Trends during 1974 of pH, Electrical Conductivity (E.C.), and nitrate concentration in soil solution extracted from the top 15 cm under a vegetation dominated by Terminalia sp.

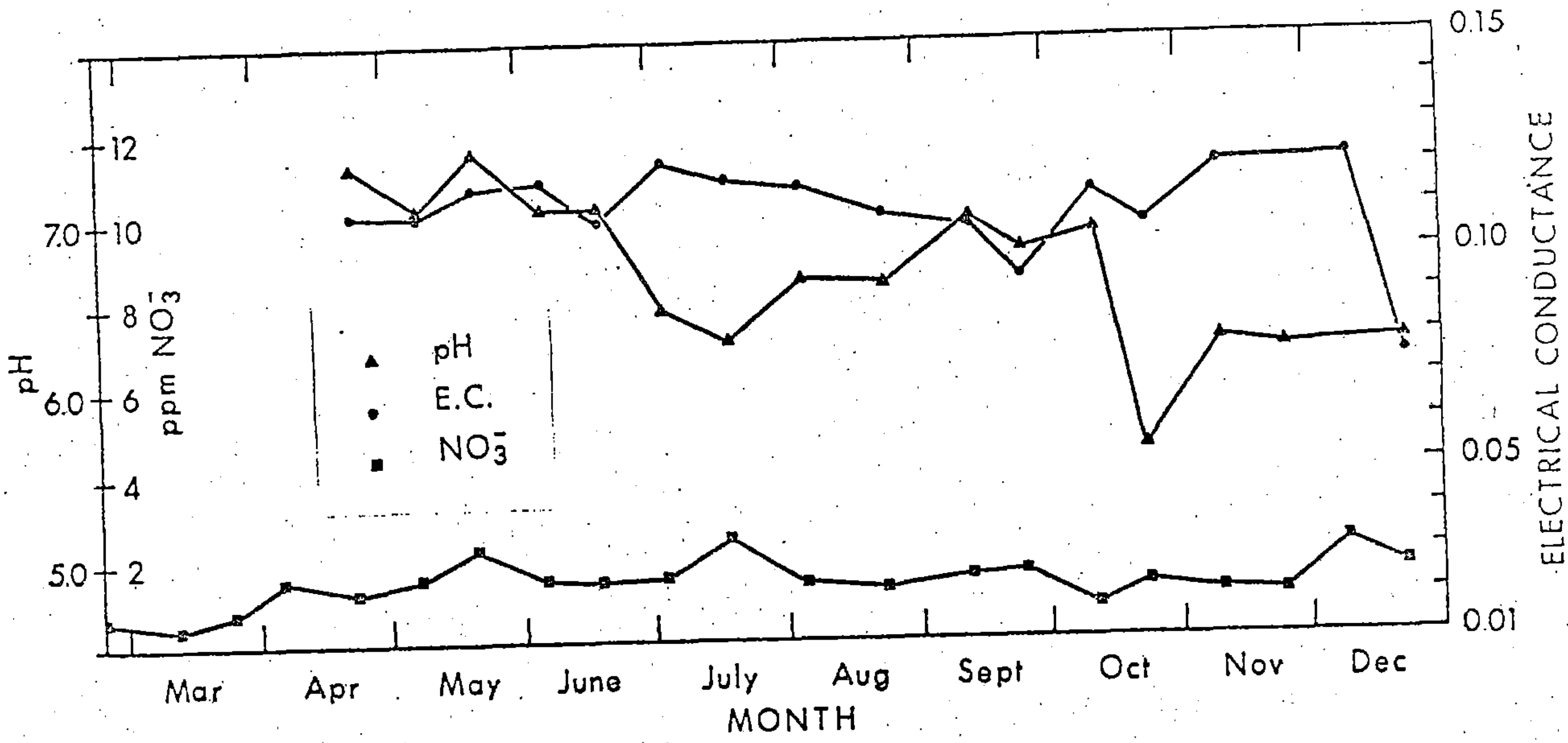

Fig. 10--Trends during 1974 of pH, Electrical Conductivity (E.C.), and nitrate concentration of soil solution extracted from a depth of 122 cm under a vegetation dominated by Terminalia sp.

Some differences in water acidity are noted in the top samples of site 1 (Eucalyptus) as compared to rainfall samples (figs. 2, 3, and 5). Values of pH were generally lower than those from rainfall until August at which time they began to be higher. This trend continued until October at which time, and for the remainder of the year, pH values were nearly equal to those of rainfall samples. In contrast, a very appreciable increase was noted in the electrical conductivities of these soil samples. As shown in fig. 5, E.C. values generally ranged from 0.08 to 0.2 mmhos/cm, representing a 3-4 fold increase in soluble ion content as compared to rainfall. This is a clear indication that appreciable mineralization of organic matter occurs continually at this site. This was confirmed by the very high NO_3^- concentrations noted in these waters, generally ranging from 2 to 7 ppm. When compared with the concentration in rainfall, this represents an enrichment of 5-9 fold. It is estimated, therefore, that nitrogen mineralization contributes twice as much soluble material as the mineralization of other elements on this site.

For the bottom sample on site 1, figure 6 shows that pH values were generally lower and E.C. and NO_3^- higher than for the top sample. Values for pH generally were below 6 and throughout the year ranged between 5.5 and 6.2, representing the highest levels of acidity noted among sites used in this study. Electrical conductivities significantly exceeded those for the top sample early in the year but had almost equal values after August. Similarly, NO_3^- concentrations for bottom samples exceeded those for the top until the month of October after which the samples had nearly the same concentrations for a short period before the trend was reversed for the latter part of the year. The NO_3^- levels observed for this sample, reaching as high as 12 ppm, were the highest observed in this study. What little such data is available in the literature (Viets and Hageman, 1971) indicate that these levels exceed expectations. The possible roles of Eucalyptus and ground cover (palm grass) in this phenomenon needs further investigation. The palm grass genus is known to accumulate large quantities of nitrates in the plant body. As high as 2000 ppm nitrates concentration has been measured (personal communication with Dr. Y. Kanehiro, Dept, of Agronomy and Soil Science, Univ. of Hawaii).

Top samples from site 2, where prevailing vegetation was composed of Cecropia sp. and Citharesylum sp., show no expected trends in their contents of acidity, total soluble constituents, or NO_3^- (fig. 7). The pH ranged between 5.6 and 7.0, the low values prevailing during the summer months, and the high during the winter. Electrical conductivities generally remained below 0.10 mmhos/cm and NO_3^- below 2.0 ppm. Except for the September interval, little fluctuations were noted in these two parameters throughout the year.

The quality of bottom samples from site 2 (figure 8) was generally comparable to that of top samples. However, pH and electrical conductivities values were consistently higher in the first than in the latter. Nitrate concentrations were almost equal for both throughout the year remaining in the range of 0.5 and 2.0 ppm.

Top samples from site 3 (figure 9) exhibited higher pH values than samples from other sites, ranging from 6.0 to 7.0. However, electrical conductivities for this site, dominated by Terminalia sp., were comparable in value to those observed for the Eucalyptus site. Nitrate levels, on the other hand, remained closer to those observed for site 2, generally ranging from 0.5-2.0 ppm. It would appear, therefore, that NO_3^- mineralization at this site does not comprise the appreciable properties relative to other elements as was the case under Eucalyptus.

For the bottom sample of site 3 (figure 10) similar patterns were noted as already described for the top sample. Thus, pH values ranged generally between 6.0 and 7.0. Electrical conductivities increased to a range of between 0.08 and 0.13, slightly higher than the top sample and also very high in comparison with the other sites. NO_3^- concentrations were only slightly higher than for the top sample but still in the expected range of 0.5 to 2.3 ppm.

Discussion and Conclusions

Variations of the amount of precipitations, as shown in fig. 11, offer some explanation for the variations of water composition throughout the year. This results from dilution of water constituents when rainfall is more abundant and from their concentration when rainfall is less. Examples of the first case include lower observed electrical conductivities and NO_3^- concentrations in the collections of June 13, July 3, September 26, and November 11 when preceding 24-hour precipitation was very high. Examples of the second case include the higher observed E.C. values and NO_3^- concentrations in the collections of September 12, October 23, and November 26. It is realized, however, that seasonal variations in mineral contents of plants are normal (Reichle, 1970) and can account for some of the seasonal variations in water composition. It is also important to emphasize the possible role of mineral inputs into the forest system from outside sources. Ocean-spray, although not well documented in the Hawaiian Islands, is expected to contribute soluble salts as noted by the relatively high values of electrical conductivities in certain rainfall samples (figure 2 and 3). This would be particularly true during the days of southern (Kona) winds or of strong northern (common trade) winds. After sufficient time has elapsed, runoff and soil-solution samples reflect such abnormally high electrical conductivities as noted in figures 4 to 10.

On the other hand, differences in composition among collected water samples are generally so consistent that water qualities on various locations are considered inherent to these locations, It is realized, however, that additional supporting data would be needed to verify why these differences occur. Most obvious of these would be the mass and composition of organic litter contributed by the prevailing vegetations. Also further delineations would be needed to establish the roles of various forest components, e.g., stem flow, throughfall from different vegetations, as well as proximity of sampling site from trees in affecting water composition. Finally, the definite possibility exists that some of the soil nutrients are in adsorbed form and therefore that soluble

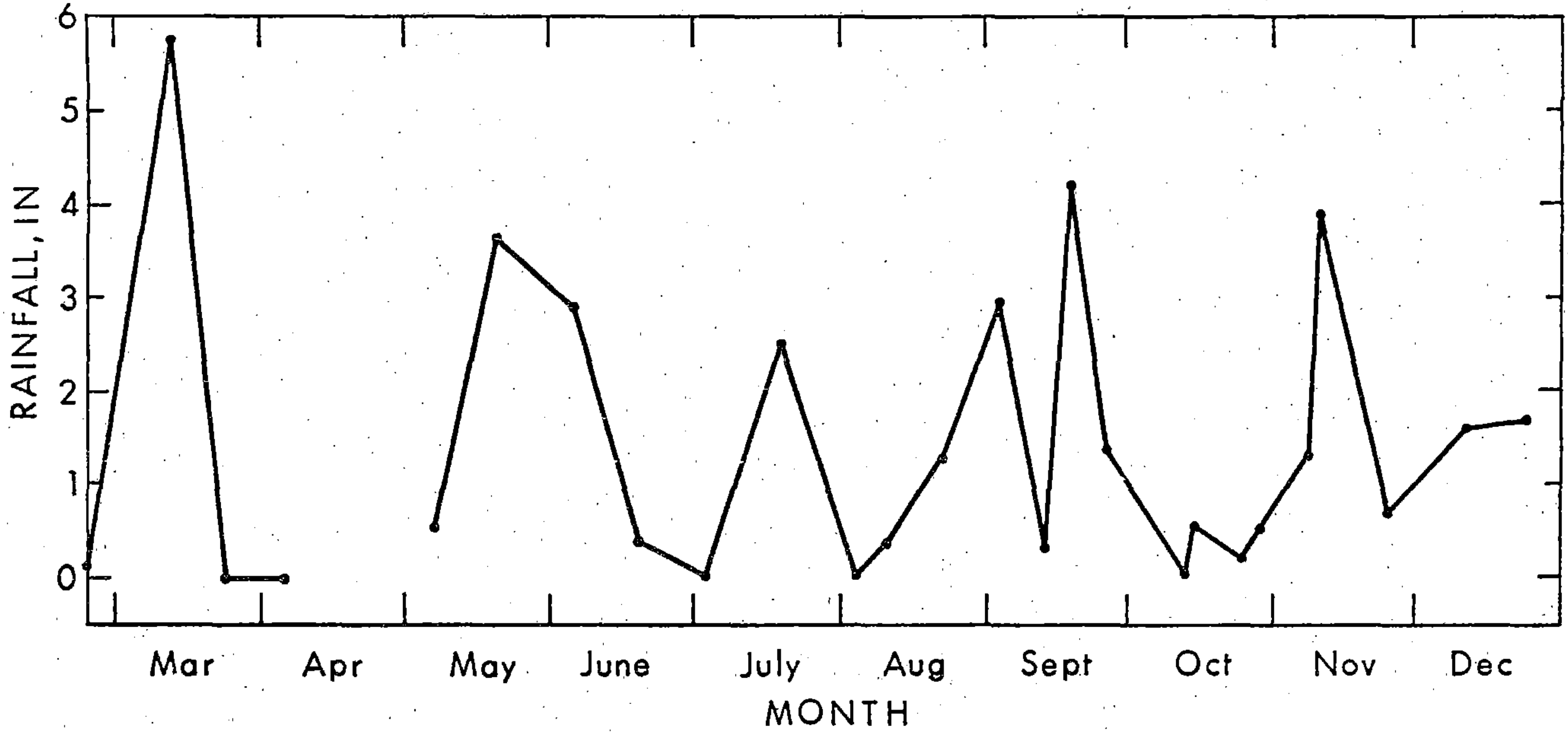

Fig. 11--Totals of 24 hours rainfall preceding the collection of water quality samples at the U.H. Lyon's Arboretum during 1974.

nutrient contents in water, as reported above, only represent a fraction of the total nutrient reservior in the soils. This would be true even for anions (e.g., NO_3^-) since at prevailing pH values in these locations, which ranges from 5.0 to 6.2 in dilute dispersions, considerable positive charges would be expected at surfaces of soil constituents.

The differences in soluble NO_3^- concentration among the three soil locations, with Eucalyptus providing the highest levels, are worthy of elaboration. Edmisten (1970) reported wide differences in NO_3^- concentrations from 4 to 21 ppm under six different vegetative types in soils of one rainforest. His values are rather high as they comprise total soil nitrate contents (not just the content of soil solution) of the upper 5 cm only. It is now well established that different plants, even within one species, tend to accumulate nitrates to different degrees in their tissue (Viets and Hageman, 1971) and thus would be expected to affect soil NO_3^- levels differently. Indeed, it is also well established (e.g., by Ovington and Olson, 1970) that different plant organs within one species contain different levels of nitrogen and that these vary with plant age. For a representative of Ceropia sp. on site 2 (C. peltata), the latter authors showed nitrogen contents to be 0.53-0.96% for small roots, 0.19-0.38% for butt roots, 0.12-0.40% for boles, 0.55-0.62% for branches, and 1.66-1.85% for leaves. Unfortunately, no such data is available for Eucalyptus species or any of the underlying ground covers at the various collection sites. However, even if nitrogen levels in Eucalyptus tissues are not abnormally high, these trees have been shown by some workers to enhance salt storage in forest catchments as indicated from chloride balance estimates (Peck and Hurle, 1973). It may be assumed, therefore, that very high NO_3^- concentration in the soil solution around these trees in enhanced, at least in part, by their tendency to use excessively large amounts of water and to thus cause large water and nutrient movement gradients toward the vicinities of their roots. The effects of depth on NO_3^- concentration in soil solution, i.e., the increased concentration in relation to depth, was most clearly noted for the Eucalyptus site and may either reflect the nature of gradients or resulting from continuous flushing of the soil surface by rainfall. Difference in soil properties in the upper and lower layers may also be responsible. These would include the nature of adsorptive surfaces which determine affinity for NO_3^-, such as the content of organic matter.

Although some of the NO_3^- levels detected in soil solutions exceeded the limits normally considered desirable for human water consumption (FWPCA, 1968), they remain safely under those which are permissible (10 ppm as N or 44 ppm as NO_3^-). It is hard, however, to estimate from the data presented here the extent to which NO_3^- may be allowed to percolate with ground water recharge. It may be safely assumed that the vigorously growing vegetation will act as a very effective sink for NO_3^- and other nutrients resulting in much less concentrations in deep water than measured here. It is important also to emphasize that the majority of the soil solution samples contained extremely low NO_3^- concentration as did all runoff waters.

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VI. SUMMARY

The present study on hydrologic characterization of soils on a forest watershed in Hawaii had three specific objectives, which may be briefly stated as: (1) evaluating alternative methods of measuring infiltration and deep percolation, (2) studying mechanisms of soil water retention and movement, and (3) studying interrelationships between the prevailing vegetation, soil and chemical composition of water yielded by the watershed. The study, thus, included the appropriate balance between direct, practical, field measurements and interpretive laboratory and theoretical investigations which is required for a scientifically sound investigation of the hydrologic characteristics of watershed soils. This was the first effort of this kind to be undertaken in Hawaii. Accomplishments under each of the above objectives are summarized below in the same sequence in which the objectives are stated:

1. The study established that the well designed use of multi-depth tensiometers in a double ring infiltrometer is a good means of determining ponded-water infiltration, lateral flow, saturated hydraulic conductivities of different soil horizons, drainage water yield, and unsaturated hydraulic conductivities. It was noted that lateral flow decreased with time during infiltration and generally was not appreciable for wet soils of the University of Hawaii Arboretum. That the final lateral flow percentages are not appreciable was also confirmed by direct measurements. However, it is recognized that lateral flow may be more appreciable for different soils or in the same soil under different initial moisture conditions. Considering this and the need to know the initially changing infiltration rates as well as the final rates and saturated conductivities of each different soil horizon, it is important that full hydraulic characterization of the soil profile be established. This study indicates that the combined use of ring infiltrometers and multiple-depth tensiometers achieves this purpose. The set-up can also be used for measuring the equally important unsaturated hydraulic conductivities of soil and deep percolation during the drainage phase, the methodology for which has been presented. The set-up is portable and lends itself well for field use.

   Measurement of soil-water status in addition to rainfall-runoff relationships on a forest watershed plot under natural conditions is shown to be useful for characterizing the infiltration of natural rain and subsequent drainage. Saturated hydraulic conductivities of different soil horizons determined <u>in-situ</u> from measurements during selected heavy rainstorms were in very good agreement with the values determined on undisturbed soil cores. Detailed analysis of a variety of rainfall-runoff - infiltration patterns indicated that the saturated flow properties of the soil (are alone) insufficient to describe the process of rain infiltration. Methodology has been developed by which tensiometric measurements in the field plot during the process of drainage are shown to give satisfactory determination of unsaturated flow properties, provided the plot is well protected from subsurface lateral flow of rain water from the surroundings. These unsaturated flow properties did not appear to be influenced by land slope which, in this study, was 18%. The study provided a practical guide for predicting infiltration of natural rain by way of runoff to rainfall ratios. Interestingly, the runoff represented only 0.5 to 7% of rainfall at the University of Hawaii Lyon's Arboretum.

A system for continuously monitoring the soil-water status on forest watersheds, which runs on battery power, has been devised and tested. This portable system lends itself well for use in remote forest watersheds. Results are presented which illustrate its usefulness under a wide variety of rainfall conditions for deriving different components of the forest water balance, including infiltration, deep percolation and evapotranspiration.

Three new simplified methods have been developed for measuring water conductivity and suction-water content relationships on undisturbed soil cores. The methods, which require simple laboratory measurements, are promising, economical, and convenient, particularly for establishing hydrologic properties of soils of remote forest locations.

Among the alternative techniques investigated under this objective 1, one would be better suited than the others for certain conditions as stated in the report. In practice, a judicious combination of two or more techniques is often desirable.

2. Water retention properties of Typic Hydrandepts, which contain excessive amounts of water in the field, were well accounted for based on their identifiable constituents. The swelling mechanism was found to be responsible for the majority of such water. Calculations of water film thickness based on surface area measurments showed that little particle-particle contact occurs in the soils under field conditions but that appreciable contact is present at the shrinkage limit at which the capillary mechanism becomes most dominant. Ionic hydration and surface adsorption represents only a small fraction of the water retained even at the shrinkage limit.

Dehydration of the soils under controlled conditions of low relative humidity results in significant changes in the water retention characteristics. However, such changes were found to be physical (structural) rather than mineralogical in nature as evidenced by water vapor adsorption and by B.E.T. N_2 surface area measurements. Furthermore, when sufficient disruptive energy is applied to water dispersions of the dried soil, it is possible to gradually restore the initial water retention properties. Removal of agents which enhance cementation upon drying was shown to reduce the severity of changes in properties as a result of drying. Freeze-drying was the best alternative studied here for drying Typic Hydrandepts (to ensure easy storage and handling for laboratory purposes) and also maintaining a relatively open structure. However, other drying methods need to be investigated to ensure preservation of natural structural conditions and thus easy restoration of soil properties upon rehydration. The tendency of structural water to be lost from constituent minerals upon oven drying suggests that this, and other drying methods of water content determination that involve heat, overestimate the quantity of "free" water present in the soil. Therefore, drying over P_2O_5 is favored for more accurate assessment of water content in Typic Hydrandepts.

Studies on intact cores established detailed water sorption, desorption, and hysteresis characteristics of two Arboretum soils in the low suction range. The successful use of these characteristics for describing water movement under saturated and unsaturated conditions indicates that the theory of soil-water movement based on Darcy's Law and conservation of mass holds well in these soils.

3. Quality trends for rainfall, throughfall, runoff, and extracted soil-water samples from the University of Hawaii Lyon's Arboretum were established for the 1974 Calendar year. It was found that seasonal variations occur in pH, electrical conductivity, and nitrate contents of the waters, some of which may be due to rainfall fluctuations. Consistent differences in these properties were noted among collected samples which indicated that canopy contributions to water composition are appreciable. Of particular interest was the very high NO_3^- concentration measured in the soil solution on a site in a Eucalyptus grove with ground cover of palm grass, reaching as much as 11 ppm in certain samples. Whether Eucalyptus or palm grass is responsible for high nitrate levels has not been definitely established. It is important to note, however, that despite the high content of NO_3^- noted in some soil-water samples, the measured levels remain safely under those that are permissible for human consumption. Runoff waters seldom contained more than 1 to 2 ppm of this constituent.