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DETERMINING SOIL HYDROLOGIC CHARACTERISTICS ON A REMOTE FOREST WATERSHED BY CONTINUOUS MONITORING OF SOIL-WATER PRESSURES, RAINFALL AND RUNOFF

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ABSTRACT

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Continuous monitoring of soil-water pressures, rainfall and runoff under natural conditions was tested as a technique for determining soil hydrologic characteristics of a remote forest watershed plot. A completely battery-powered (and thus portable) pressure transducer—scanner—recorder system was assembled for monitoring of soil-water pressures in the tensiometric range. Measurements during several heavy rainstorms incorporating a period of steady infiltration rate were utilized to determine the saturated (or near-saturated, because of entrapped air) hydraulic conductivities of different soil horizons. Unsaturated hydraulic conductivities were obtained as usual from drainage data. Use of the monitored soil-water pressure data under natural conditions in conjunction with the measured unsaturated soil properties to calculate deep percolation, infiltration-minus-evapotranspiration and evapotranspiration is illustrated.

INTRODUCTION

Under natural conditions of a watershed, where the rainfall intensities are often erratic and the frequency of rainstorms varies widely, the soil profile may often be unsaturated. The proportion of rainfall entering the ground water resource may then be very significantly influenced by the soil's unsaturated hydraulic conductivities and negative water pressure (or suctions), both of which are very strong functions of the soil-water content. Knowledge of both saturated and unsaturated properties and of the dynamic soil-water status through the season will be required for the physically based models in predicting the rainfall—runoff relationships, drainage water yield and storage capabilities of a watershed.

The hydraulic conductivities of a field soil are best measured in situ. A commonly used method for level lands (Nielsen et al., 1964; van Bavel et al., 1968; Cassel, 1971) is to choose a representative plot, near the center of which tensiometers are installed to several different soil depths. Saturated hydraulic conductivities of soil horizons are determined from steady-state water flow rates and tensiometric data during the process of ponded-water infiltration. (The term "saturated" is used in this manuscript in a relative sense. It is recognized that the soil may not be completely saturated because of entrapped air and that the latter may appreciably affect the value of hydraulic conductivity.) The unsaturated hydraulic conductivities are determined from the soil-water suction vs. time data collected during the process of drainage following infiltration, using Richard's equation (Darcy's law combined with equation of continuity) of unsaturated flow as a basis of analysis. The suction—water content relationships needed in this analysis are determined either by field sampling or neutron-meter measurements during drainage or separately by laboratory measurements on undisturbed soil cores. The use of the above field-plot tensiometric technique on many of the forest watersheds with hilly terrain requires an alternative to the ponding technique for application of water during infiltration and obtaining saturated hydraulic conductivites. Automatic continuous monitoring of tensiometers, rainfall and runoff during natural heavy rainstorms provides an interesting possibility. This technique will also yield very useful information on the infiltration of variable-intensity natural rainfalls.

The dynamic soil-water status before the major rainstorms, needed as initial condition in rainfall—runoff models, can be obtained directly by continuous monitoring of the soil-water pressures. With knowledge of the unsaturated soil-water properties at a certain depth, the monitored data could also be used to calculate deep percolation, infiltration during the rainstorms and evapotranspiration between the sotrms. Perhaps ultimately for large-scale application, these quantities, as well as the dynamic soil-water status, should be predicted by an evapotranspiration—drainage model linked to a rainfall—runoff model. Nevertheless, for initial soil—water—plant characterizations and experimental verification of the concepts, continuous monitoring will be an extremely useful tool.

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 pressures or suctions in the profile at several locations. The technique can only be used in the tensiometric range of 0—0.8 bar. The soil-water contents can be derived from the pressure measurements using the pre-determined suction—water content relationship for each soil horizon. Rice (1969) described and tested a hydraulic scanning system in which twleve 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-V line. Rice pointed out some limitations of the hydraulic scanning system, the important ones 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 limitation are critical, it would be best to use an electrical 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 transducers.

The objective of the present study was to assemble completely battery-powered transducer—hydraulic scanning valve—timer—recorder system for use on remote forest watersheds, and test its use to determine soil hydrologic characteristics on a Hawaiian forest watershed plot.

DESIGN OF THE MONITORING SYSTEM

Design of a completely battery operated monitoring system for studies on remote watersheds 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 24-V d.c. pulses 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 a 24-V d.c. current obtained from two 12-V batteries connected in series. The pressure transducer

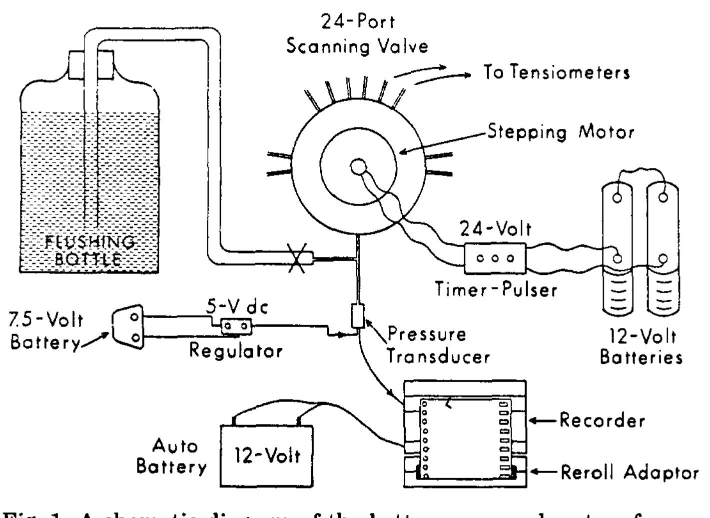


Fig. 1. A chematic diagram of the battery-powered system for monitoring soil-water pressures.

required an energizing current of constant 5-V d.c. voltage, which was obtained from a 7.5-V battery connected to a 5-V d.c. 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 (Weather-Measure®, EPR-2T), which was operated on a 12-V automobile battery. The recorder had a regulated motor, which was not affected by normal changes of the battery's voltage. A 96-A automobile battery performed well for a 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 onto a reroll adapter, powered by two flash-light cells (3 V d.c.).

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 tubing 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.

EXPERIMENTAL PROCEDURE

In the watershed of the University of Hawaii's Lyon Arboretum, a nearly 46 m^2 (11 × 4.2 m) plot was demarcated in a relatively undisturbed forest area. The watershed receives nearly 400 cm of rainfall annually, which keeps the soil in wet condition most of the time. The soil was an alluvial variant of Tantalus silty clay loam (Typic Dystrandepts), tentatively classified as Fluventic Humitropepts, clay loam, mixed, isothermic family. Tall trees covered the plot all around, but the plot itself contained only the undergrowth of grass and some short plants. The plot surface was uneven, but generally sloped in one direction, along the length, with an average slope of nearly 18%.

In order to prevent outside runoff and the subsurface lateral flow from interferring with measurements within the plot, a water-impermeable siding, made from 3 m × 1.2 m × 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 collection of runoff from the plot. Three sets of tensiometers were installed in the plot along the middle line running parallel to the slope and length. The middle set of tensiometers was located around the center of the plot, and the other two sets were about 3.7 m 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, a hole slightly bigger than required was made with a screw auger. It was filled with a medium-thick soil slurry and then the tensiometer stem was slid into it gently to the required depth. This slurry was intended to plug the gap between the tensiometer stem and the surrounding soil. 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 reference channels. Six additional channels were available on the 24-port scanning valve. 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 in situ for some time indicated that a switching interval of 2 min was satisfactory for all different channels. The problem of air bubbles entering the tensiometers occurred frequently as the soil-water tension increased, especially those located deep in the profile. Continuous vigilance, flushing of only the problem channels when necessary and biweekly to monthly flushing of all the units with subsequent refilling with boiled water, was required.

Rainfall and runoff on the plot were continuously recorded on daily charts. Rainfall was measured by three siphon-type recording gages, placed strategically with respect to tree canopies over the plot to obtain a good average. Runoff was collected in two or four inter-connected 50-Gal barrels, in which the water level was monitored by a Stevens® water-level recorder. The data from the charts were read at 5-min. interval. Measurements during several heavy rainstorms incorporating a period of nearly steady infiltration rate were utilized in conjunction with the monitored soil-water pressures during the same period to determine the saturated hydraulic conductivities of different soil horizons. Some of the other data were utilized in illustrating the calculations of transient-phase infiltration-minus-evapotranspiration made from the monitored soil-water pressure data and the unsaturated soil-water properties determined as described below.

Following one heavy rainstorm, the vegetation was cleared and the entire plot was covered with double-layer black polyethylene sheeting. Holes were made in the plastic sheet to allow the tensiometer tubes to come through. The openings around the tubes were sealed with water-repellent tapes to prevent rainwater seeping through them. Soil-water pressure measurements were continued as the process of drainage occurred. The tensiometer readings near soil surface showed appreciable fluctuations, possibly due to temperature and atmospheric pressure 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 any rain-water seepage through the tapes. The drying of the plot progressed very slowly and the measurements were continued for five months.

A pit was dug near the plot and three to four undisturbed soil cores were collected from each tensiometric depth. A San Dimas® core sampler, which consists of an auger rotating around a stationary 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 various field soil horizons were assumed to be given by laboratory measurements on these cores. These were conducted using 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 H_2O cm suctions. It is recognized that field variability may require more sampling sites than allowed here.

The soil-water pressure data recorded during the drainage and the suction—water content relationships 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 main difference was that a least-squares cubic spline fitting (de Boor and Rice, 1968) was employed to evaluate the hydraulic gradients, and a sliding least-squares parabolic fit was used to evaluate the time derivative for the determination of flux.

RESULTS AND DISCUSSION

Table I shows the steady-state infiltration rates derived from the measured rainfall and runoff on the plot during certain time intervals of ten heavy rainstorms. The rate obtained in this manner varied between 0.79 and 1.52 cm/hr., with a mean of 1.036 cm/hr. Variability in rates may have been caused by the recognized complications of varying amounts of entrapped air and the degree of soil-water saturation under different antecedent soil-moisture and rain-intensity conditions (Gerard, 1974; Ahuja et al., 1976). It may also be that the steady state was not quite achieved in some cases. The mean rate was used in conjunction with the steady water hydraulic gradients measured during two rainstorms to determine saturated hydraulic conductivities of different soil horizons. (The soil-water pressure monitoring unit was in the process of testing and improvements in early stages. Therefore, hydraulic gradients were not measured during all rainstorms.) The results are shown in Fig. 2. Hydraulic conductivities measured in the laboratory on undisturbed soil cores taken from the site are also shown in the figure for comparison. Each core data point is a mean of three measured values. The in situ field data and the soil-core data agree fairly well, except at 15-cm soil depth. Perhaps, such a variability with the surface layer is normal. Average hydraulic conductivity of 1-m soil profile

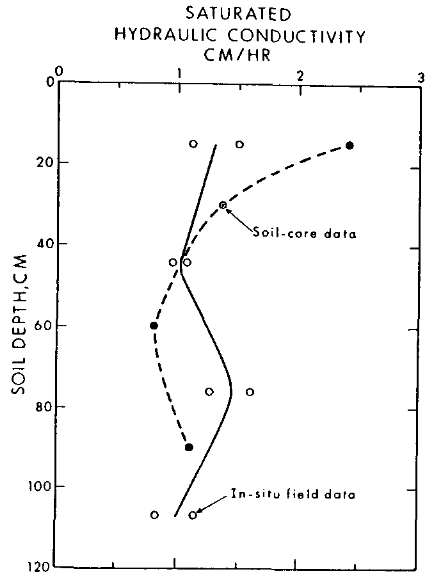
TABLE I

Steady infiltration rates recorded during heavy rainstorm 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
7-06-74	6:20— 7:00	1.10
7-06-74	8:35— 9:35	1.52
7-16-74	2:50— 4:30	0.91
11-20-74	12:46—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

calculated from the core data was 1.117 cm/hr., which closely matches the mean steady infiltration rate of 1.036 cm/hr. measured in situ.

Unsaturated hydraulic conductivities were determined by analysis of hydraulic head (soil-water pressure minus depth) data measured during the drain-



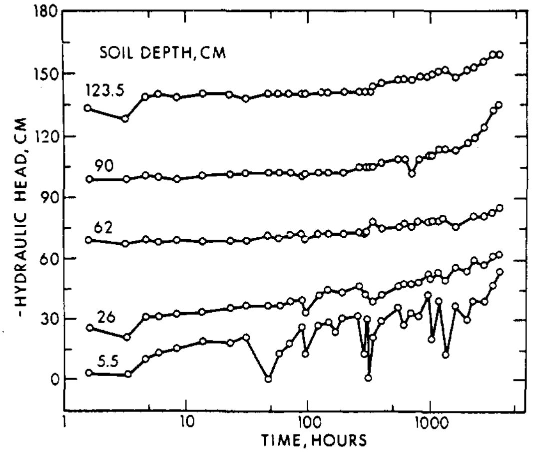


Fig. 2. Saturated hydraulic conductivities determined from the monitored rainfall, runoff and hydraulic gradients during heavy rainstorms, compared with the measurements on soil cores.

Fig. 3. Hydraulic head changes with time at different depths in the soil profile during the process of drainage at one of the tensiometric locations.

age process, using the suction—water content relationships of undisturbed soil cores. The hydraulic head changes with time at different depths in the soil profile as measured by individual units in one of the tensiometer-set locations are presented in Fig. 3. The data indicate that the changes in soil-water pressures are very slow. This suggests that the water conductivities are very low at even small soil-water suctions. There was an appreciable fluctuation in soil-water pressures measured at 5.5 cm from the soil surface, which may be due to temperature fluctuation and condensation beneath the plastic, as well as to sensitivity of the pressure transducer to even small changes in atmospheric pressure and wind effects on nylon water leads. Overall fluctuation in air temperatures was between 21° and 28°C, which is not very great because of the Island of Hawaii conditions. 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. A smooth curve was drawn through the data for the purpose of calculations. The suction—water content relationships for two of the soil depths are presented in Fig. 4, as an example. Only the desorption data out of the figure were used in the analysis. The unsaturated hydraulic conductivities for 45-cm soil depth determined at two different tensiometer-set locations are presented in Fig. 5. The values from two locations are fairly close, indicating no appreciable effect of the position along the slope on unsaturated soil-water movement. The determinations for other soil depths were similar to those shown in Fig. 5. At the third tensiometer-set location, two of the in-

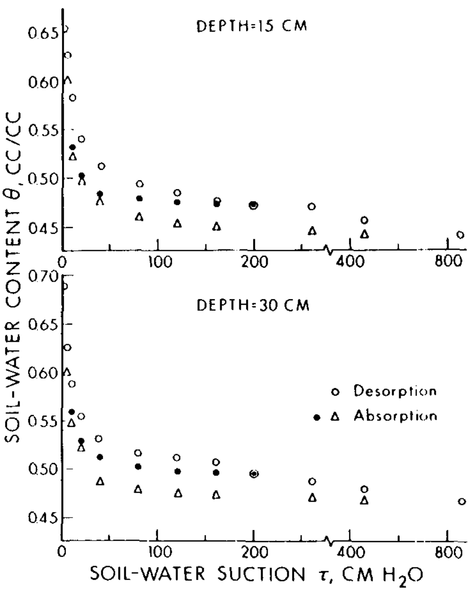


Fig. 4. Soil water content—suction relationships of undisturbed soil cores from 15- and 30-cm depths. Each point is a mean of three to four measurements.

dividual units malfunctioned and, hence, the data from this set were not utilized.

The following three figures show the relationship between monitored rainfall and soil-water suction changes (average of two tensiometer locations) under natural conditions on three particular days. Fig. 6 shows the cumulative rainfall and soil-water suction changes at 5.5- and 26-cm soil depths for 24 hr.

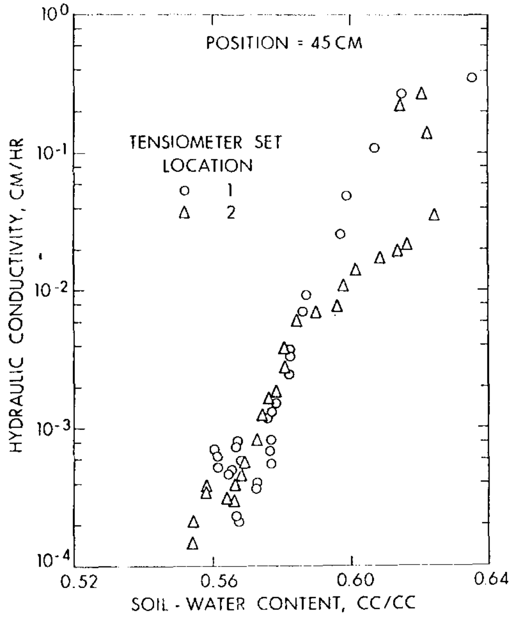


Fig. 5. Unsaturated hydraulic conductivities for 45-cm soil depth as determined at two tensiometer-set locations.

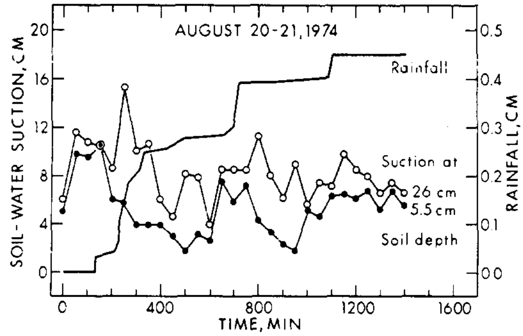


Fig. 6. Cumulative rainfall and soil-water suction changes at 5.5- and 26-cm depths for a 24-hr. period.

beginning with 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-hr. period, indicating that the potential gradients and water flow were downwards. Fig. 7 shows the suction changes at these two depths for another day which received no rainfall at all. The soil-water suction increased at both the depths, more so near the soil surface due to evapotranspiration and deep percolation. Some of the fluctuations noted in Figs. 6 and 7 may be due to sensitivity of soil-water pressures in the very wet region to even small changes in atmospheric temperature, pressure and wind conditions. Overall fluctuation is within 4 cm H_2O, but even these small changes are picked up by the pressure transducers. Fig. 8 shows rainfall and

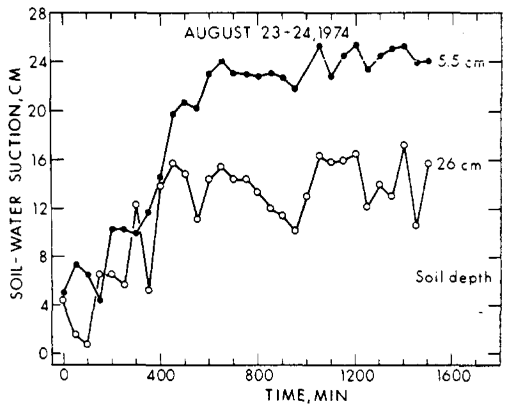


Fig. 7. Soil-water suction changes at 5.5- and 26-cm depths for a day which received no rainfall.

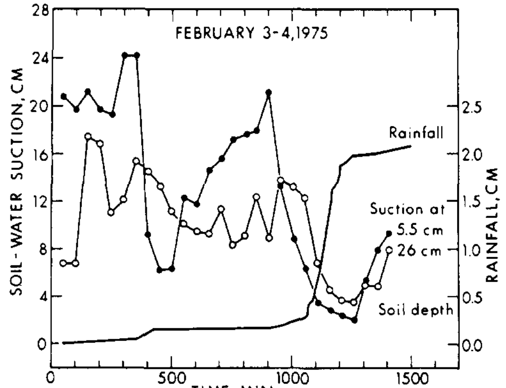


Fig. 8. Cumulative rainfall and soil-water suction changes at two depths for a day which received relatively higher rainfall.

suction changes in the soil on a day in February 1975 when the rainfall was higher than that shown in Fig. 6. The results are an example of more rapid changes of suctions with weather conditions. The maximum suction recorded on above three days did not exceed 26 cm H_2O in this rain forest.

Figs. 9 and 10 illustrate the use of monitored data for calculating deep percolation, evapotranspiration, and infiltration-minus-evapotranspiration in the profile. The deep percolation rate below any given soil depth was computed by Darcy's law as a product of the transient hydraulic gradient and appropriate unsaturated hydraulic conductivity as a function of suction or soil-water content, as determined and presented above (Fig. 5). The water

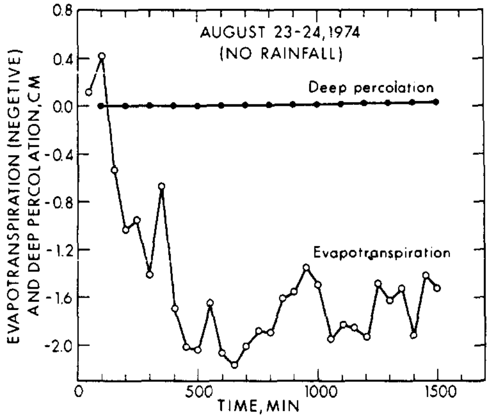


Fig. 9. Deep percolation and evapotranspiration calculated from the monitored soil-water pressure data for a day which received no rainfall.

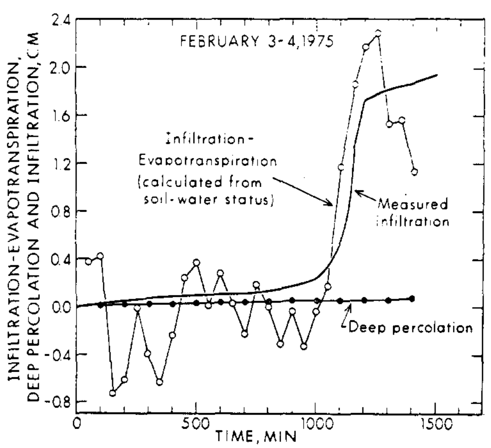


Fig. 10. Infiltration-minus-evapotranspiration and deep percolation calculated from the monitored soil-water pressure data compared with infiltration derived from monitored rainfall and runoff data.

storage in the profile at any given time was calculated by converting the measured soil-water suctions to water contents using the suction—water content relationships presented in Fig. 4. Hysteresis in these relationships, which in a narrow suction range under consideration would be less than that shown in Fig. 4, was neglected. The commonly measured and used desorption curve was employed in the calculations. The sum of deep percolation and water storage gain in any time interval represented the amount of water infiltration-minus-evapotranspiration. The sum of soil-water storage loss and some rainfall, if any, minus deep percolation represented the evapotranspiration.

Fig. 9 shows the calculated cumulative deep percolation and evapotranspiration from the upper 75 cm of soil profile on a day in August 1974 which received no rainfall. Deep percolation was very small, as the unsaturated hydraulic conductivity is very low even at small suctions in this soil. Evatranspiration was extremely high, probably because of windy conditions.

Fig. 10 shows the calculations of infiltration-minus-evapotranspiration and deep percolation for a day which received nearly 2.2 cm of rainfall, resulting in some runoff. The measured infiltration shown in the figure is the difference of monitored rainfall and runoff on the watershed plot. There is a fairly good correspondence between the measured infiltration and calculated infiltration-minus-evapotranspiration, considering the errors involved in measuring both suctions and rainfall representative of the plot under the tree canopies. The fluctuations in the monitored soil-water suction, as shown in Figs. 6—8 and discussed earlier, would account for most of the fluctuations in the calculated values since the soil-water content changes very rapidly with change in suction in the wet region (Fig. 4). However, a lag between the time the rainfall water first infiltrates the soil surface and the time it reaches the first tensiometric depth (5—7.5 cm) as well as the hysteresis effects also enter into the picture. Time of concentration of runoff from this 11 m long plot was ~ 2 min. causing no appreciable lag between rainfall and runoff. Errors in measuring rainfall under the tree canopies would be a much more important factor.

In conclusion, the results presented above indicate a utility of continuous monitoring of soil-water pressure, rainfall and runoff under natural conditions for measuring saturated and unsaturated soil-water properties under special conditions of sloping and remote watersheds. The technique is problem-oriented, as it not only yields the hydraulic conductivites but also the needed information on infiltration of natural rainfalls, dynamic soil-water storage, deep percolation and evapotranspiration through the year. However, the technique is applicable only in the tensiometric range of 0.8-bar suction and requires measurements over a period of time covering several heavy rainstorms. Precision of measurements can be further improved by shielding above-ground water leads against temperature fluctuations, minimizing the volume of water in the sytem, choosing more sensitive tensiometers and using a separate transducer for each tensiometer with an electronic scanner.

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