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AN EXPERIMENTAL STUDY OF THE UPTAKE OF WATER BY SOYBEAN ROOTS

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ABSTRACT

AN EXPERIMENTAL STUDY OF THE UPTAKE OF WATER BY SOYBEAN ROOTS

The water extraction from soil by plant roots was treated by assuming that such extraction could be represented as a continuously distributed sink (negative source) function. Preliminary results with soybeans grown in soil columns showed that a small part of the root system could extract most of the water used in transpiration. Root density as measured by root length per unit volume of soil was not directly correlated with water uptake. Both the hydraulic conductivity of the soil and root density played a major role in determining the rate of extraction of water at a given depth in the soil.

Water uptake per unit root length ranged up to about o.5 cm^3/cm of root/day. This kind of data gives more insight into the conditions at the root-soil interface.

The experimental work in this project was developed from a numerical analysis which was supported by an earlier OWRR project (Project No. 65-03G), and is an example of a basic approach to the study of the interaction of the plant with its environment in which the available degree of understanding of the water flow process in soil is brought to bear upon the plant-soil interaction.

The importance of evapotranspiration is well known in the hydrologic cycle. The experimental work described in this report makes a further contribution toward our understanding of this process.

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KEYWORDS--*evapotranspiration / evaporation / transpiration / *soil water movement / unsaturated flow / *water uptake / source function / *root density / soil moisture / *soil-plant-water relationships.

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INTRODUCTION

It has been estimated that about 70% of the rainfall received on the land surface in the United States returns to the atmosphere as evapotranspiration. The flux of water through the soil-plant-atmosphere system is the dominant "consumptive" flow process in the hydrologic cycle. Research on the physics of the water transport processes has concentrated largely on the separate parts of the system. Soil physicists have studied soil water flow for many years, and a fair degree of understanding of the physics of flow of water in unsaturated soil has been attained. In recent years there has been increasing attention given to the water transport process in the plant and in the atmosphere immediately above the plant canopy. As our understanding of the behavior of the parts of the system has developed there has come a growing awareness of the need for integrated studies of the water transport phenomenon in the entire soil-plant-atmosphere system. The need for such studies arises because of the interactions between the parts of the system so that the behavior of one part of the system is affected by the behavior of the other parts.

The process of extraction of water from soil is fundamentally involved in the evapotranspiration phenomenon. The analysis and study of water uptake by plant roots has developed using either of two types of models: (1) the single root model, and (2) the distributed sink model.

In the single root model the water flow in a region of soil surrounding a single root is examined. The flow system is bounded internally by the root-soil interface. In order to develop an analysis it is necessary to postulate the nature of the boundary condition that applies at this interface. However, this boundary condition is the resultant of the interaction between the soil water flow and the flow in the plant and atmosphere.

The distributed sink model takes a more macroscopic view of the water extraction process. The roots are considered to be acting as a sink for the water, and the sink is treated as a continuous function of position in the soil profile. A sink strength measured in terms of volume of water per unit soil volume, per unit time is considered to apply at each point in the soil. When this approach is used it is necessary to make some postulate regarding the nature of the sink function, i.e., factors affecting it, etc.

The research described in this report is based on the distributed sink model. A previous analytical study of this problem (OWRR Project No. 65-03G) utilized the flow theory for water in unsaturated soil. A source term (assigned negative values to represent a sink) was added to the flow equation and certain postulates as to the nature of the sink were made. The flow equation was solved numerically for steady state flow and the effect of variation of the parameters in the source was studied. However, there was very limited experimental information on which to base the selection of parameter values. The present work is an experimental study of the flow system designed to measure the distribution of the source function under conditions such that a complete water balance could be obtained on the soil column.

THEORETICAL BACKGROUND

Assuming constant density for the soil water, the continuity equation for one-dimensional flow may be written:

$$\frac{\partial \theta}{\partial t} = - \frac{\partial v}{\partial z} + s \qquad (1)$$

where θ is the volumetric water content, v is the volumetric water flux or Darcy velocity, t is time and z is the vertical position coordinate taken as positive upwards. The source function s is the time rate of production of volume of water per unit volume of soil. For representation of water uptake by roots the source function will assume negative values.

Measurement of the source term based on equation (1) requires measurement of the water content distribution $\theta(z,t)$ and the flux distribution $v(z,t)$. If the flow is steady state, so that $\partial\theta/\partial t$ is zero, then only the flux needs to be measured.

The flux v may be obtained by applying the Darcy equation

$$v = -K(\theta,z)\,\frac{\partial H}{\partial z} \qquad (2)$$

in which H is the hydraulic head, and $K(\theta,z)$ is the conductivity function. The conductivity of unsaturated soil depends strongly on the water content, and if the soil profile is non-uniform the functional dependence of K upon θ will depend upon the position, hence the notation: $K(\theta,z)$. According to equation (2) the flux $v(z,t)$ can be assessed from measurements of $H(z,t)$ and knowledge of the conductivity function $K(\theta,z)$.

There are a number of variations in the manner of application of equations (1) and (2) to the determination of the source function. For example, the conductivity at a given position may be inferred from measurement of the water content distribution and a $K(\theta,z)$ function. Alternatively, the conductivity may be regarded as a function of pressure head and position and inferred from measurement of the pressure head distribution. The conductivity function $K(\theta,z)$ or $K(h,z)$ may be obtained by direct measurement or it may be calculated from the water content-pressure head relationship by one of the methods proposed for this in the literature. The water content distribution may be directly measured or inferred from the pressure head distribution and a water content-pressure head function. The pressure head distribution may be measured or inferred from the water content distribution and a water content-pressure head function. Finally both the water content and pressure head distributions may be measured. In all the variations one must take proper recognition of the hysteretic behavior of the K(h,z) and θ(h,z) functions.

The particular variations used in this work will be described below under the heading: Multiple Column Experiments, Results and Analysis of Data.

OBJECTIVES

The objective of the research described in this report was to study the effect of root distribution, evaporation rate at the soil surface, and transpiration rate, on the water content and tension profiles in a soil profile (column) and on plant water stress under controlled environmental conditions.

More specific objectives which were developed as the research proceeded were:

1. To measure the distribution of the source function (sink) representing uptake of water by plant roots in a soil column under conditions such that a complete water balance could be determined on the soil column.

2. To determine root density distributions and to relate these to the distribution of the source function.

3. To estimate the rate of water uptake per unit root length.

With regard to attainment of the original general objective much remains to be done. Preliminary results have been obtained that bear upon the more specific objectives. The development of the equipment that would allow the simultaneous measurement of transpiration rate, soil water content, soil water pressure head (tension) has been a lengthy and slow process which is just now being accomplished. The systems for measurement of evaporation at the soil surface and transpiration have been designed and constructed but have had only preliminary testing. The tensiometry system for measuring soil water hydraulic and pressure head has been developed and tested and is operational. The gamma attenuation apparatus for non-destructive measurement of water content in the soil column has also been developed and is operational.

It is planned to continue the research with support coming from other sources.

RESEARCH PROCEDURES

The experimentation conducted may be divided into two major parts; a phase involving the use of multiple soil columns, and another phase involving a more highly instrumented single soil column. In the former, plants were grown in soil columns and the water content distribution $\theta(z,t)$ and root density distribution were compiled by destructive sampling of soil columns at various times. In the single column work, the aim was non-destructive measurement of both $\theta(z,t)$ and $H(z,t)$ on a single soil column, thereby avoiding some problems connected with packing of replicate soil columns.

Multiple Column Experiments

Experimental Methods and Materials

Soybean plants were grown in soil columns 122 cm long by 10.2 cm diameter. The soil columns were contained in polyvinyl chloride pipe. The soil, from the lower horizons of Dickinson sandy loam, contained 74 percent sand, 16 percent silt, and 10 percent clay. The soil was passed through a 710 μ sieve and packed into the sample containers by pouring the air-dry soil through a funnel with a long tube that extended to the soil surface.

While the soil was being poured into the column, the extension tube was moved about over the soil surface, and the column was tapped and vibrated. A continuous stream of air-dry soil was maintained until the column was full. The average bulk density of the soil obtained in this manner was 1.60 gm/cm^3. There was no discernible subsidence when the columns were wetted.

The columns were initially wetted with about 2 liters of deionized water. The remainder of the water was supplied through the bottom of the column in the form of a dilute Hoagland's solution. A water table was maintained 100 cm below the top of the soil column by a Mariotte bottle arrangement.

The columns were placed in a growth cabinet in which the soil temperature was maintained at 25.0 ± 0.5^{o} C. The lower portion of the growth cabinet which contained the soil columns was completely enclosed and partitioned from the upper portion of the cabinet which contained the aerial portions of the plant. No attempt was made to control the temperature and humidity of the aerial environment. The extremes in air temperature ranged from about 20^{o} C during the night to about 30^{o} C during the day. Light was provided by a combination of Lucalox lamps (LU-400) located about 120 cm above the soil surface and by cool white fluorescent lamps placed vertically beside the plants. An intensity of 0.37 langley per minute at 15 cm above the soil was obtained. The daylength was set at 14 hours.

The tops of the soil columns were covered by plexiglass discs with a 1.2 cm diameter hole drilled in the center for the plant stem. The soil columns were placed in the growth cabinet so that the top of the plexiglass disc was level with the top of the thermostated cabinet. Aluminum foil was placed over the tops of the soil columns to reduce radiative heating of the soil surface and the consequent development of temperature gradients in the columns.

After the sealed columns had equilibrated for four weeks, three soybean seeds of the Clark variety were planted in all columns except the control. A small amount of soil was removed through the top of the soil column with a cork borer and the seeds were deposited. The soil that had been removed was then packed over the seeds. After germination, the plants were thinned to one plant in each column. Ten days after planting, a small piece of foam rubber was wrapped around the plant stem to seal the hole in the plexiglass disc and prevent evaporation from the soil surface. All plants showed normal growth throughout the experiment.

Twenty-four days after planting, two columns were removed from the growth cabinet for detailed analysis. The plant top was cut off at the soil surface. The soil columns were cut into 10 cm lengths starting from the top of the column. Soil samples were taken for water content. The remainder of the soil was washed from the roots with a gentle stream of cold water. The washed roots were spread uniformly over the bottom of a black tray and were photographed. The root length per unit volume of soil was determined from the photographs by a method described by Newman (1965) and modified by Reicosky[1/]. The technique is based on the application of probability theory to randomly dispersed line segments and proved to be more rapid than a direct method or the inch counter or opsimeter method[2/], and was as precise as the direct method. Three hundred random locations were used to estimate the root length. The slide was then reversed and the same 300 random locations were used to give a second estimate of root length. The root lengths in a given depth increment of a column are an average of these two estimates.

1/ Reicosky, D. C. The effect of root distribution on water and nutrient uptake by soybean plants grown in soil columns. Ph.D. thesis, University of Illinois, June 1969.

2/ Shearer, R. C. Water flux and ion uptake by wheat seedlings. Ph.D. thesis, University of Adelaide, Adelaide, South Australia.

Further harvests and analyses were made on pairs of columns at 38, 52, 59, 66 and 73 days after planting. The control columns (unplanted) were analyzed at the end of the experiment in the same manner as the previous columns. It was assumed that soil water profiles in all columns were initially the same and that the observed differences as a function of time resulted from plant uptake of water.

Water content-pressure head data were obtained by standard techniques using separate samples of soil. The data are shown in Figure 1.

Results and Analysis of Data

The water content profiles at each harvest are summarized in Table I and several of the profiles are shown in Figure 2. The results are reported as the average of the data from the two soil columns analyzed on a given day. The data in Table I are a numerical representation of the function $\theta(z,t)$. The data from the control columns show a gradual increase in θ with depth down to about 80 cm below the surface. At 80 cm the soil is essentially saturated and remains so down to the water table at 100 cm. The water contents found below 50 cm in the columns sampled at 24 days were somewhat higher than those found in the control. They were expected to be essentially the same. Probably the differences are due to packing variability between columns.

The calculation of the source function was based on equations (1) and (2). The water content data were plotted against time with the mean value of the depth increment as a parameter (for example, see Figure 3). The slope of these plots was used to evaluate $\partial\theta/\partial t$.

The calculation of the flux v in the upper portion of the column was based on equation (1). The conductivity function $K(\theta)$ was calculated from the water content-pressure head curve using the method of Millington and

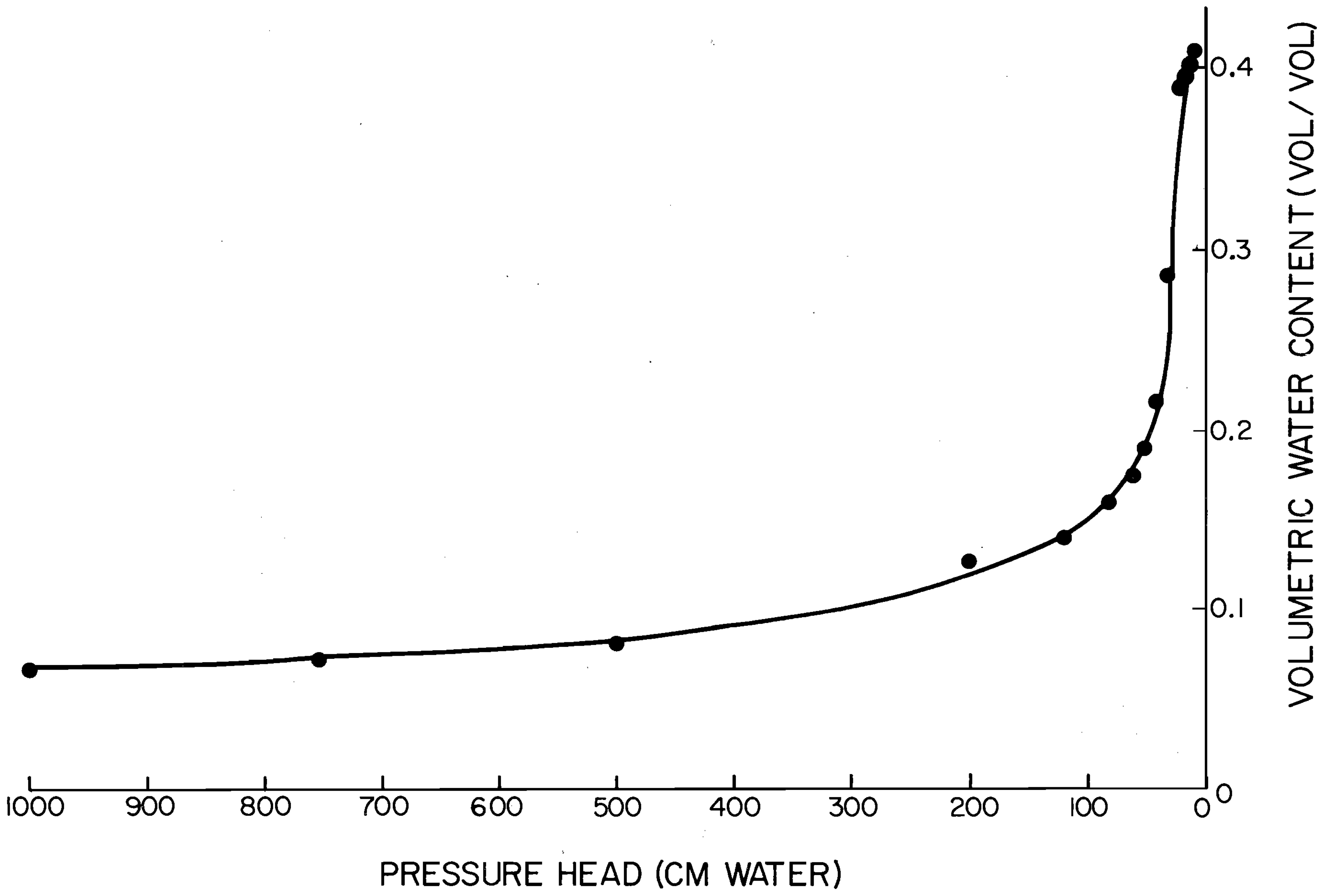

Figure 1. Water content-pressure head relationship for the soil used in the multiple column experiments.

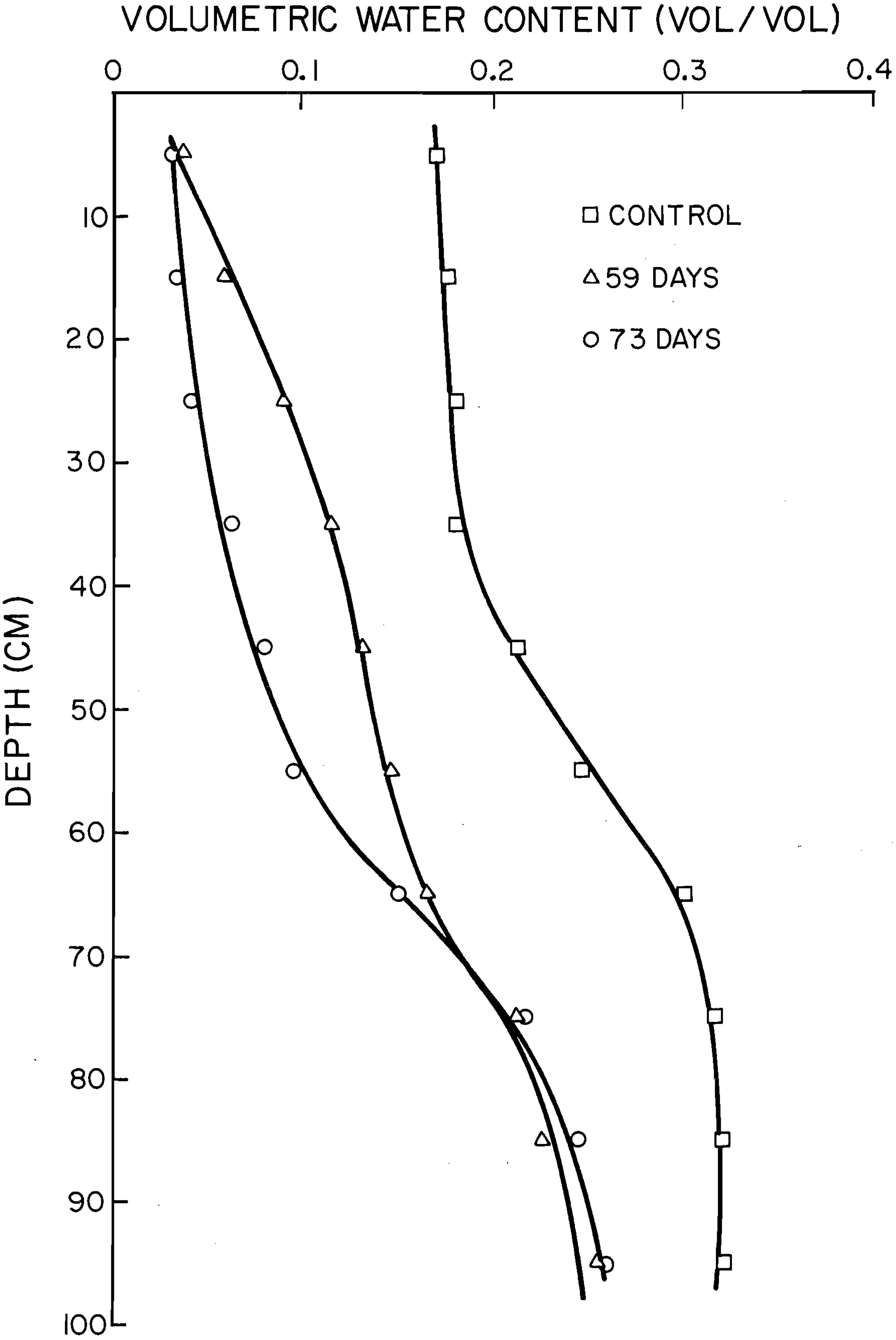

Figure 2. Volumetric water content versus depth.

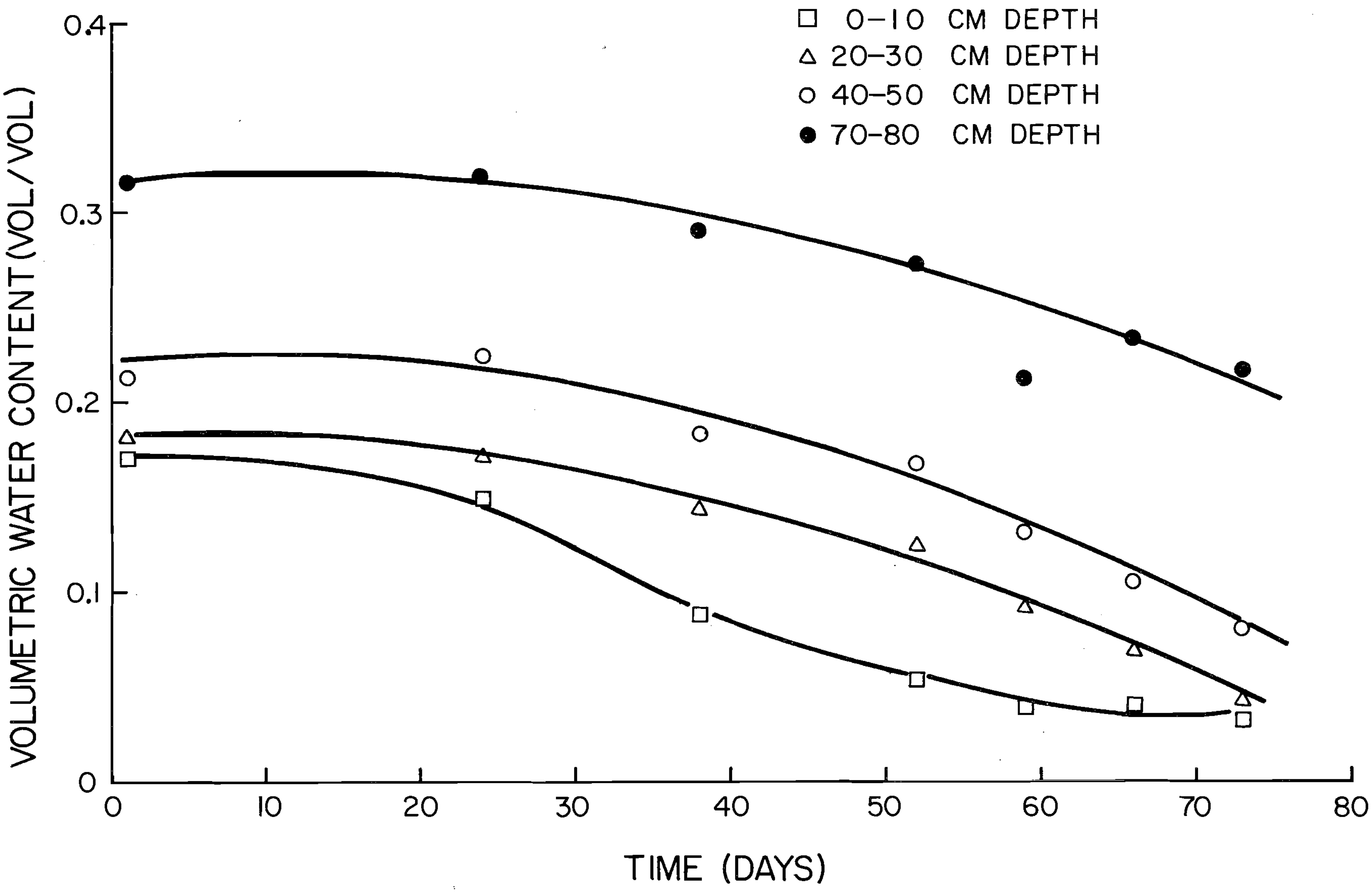

Figure 3. Volumetric water content in selected depth increments versus time.

Table I. The average volumetric water content in the soil columns (cm^3/cm^3).

Days After Planting	24	38	52*	59	66	73	Control
Depth (cm)							
0-10	.149	.087	.052	.037	.039	.031	.170
10-20	.158	.112	.100	.057	.057	.033	.176
20-30	.170	.142	.123	.090	.067	.041	.180
30-40	.192	.163	.147	.115	.080	.063	.181
40-50	.224	.183	.167	.131	.105	.080	.213
50-60	.294	.225	.191	.146	.174	.095	.246
60-70	.311	.235	.245	.164	.197	.150	.300
70-80	.319	.290	.273	.212	.233	.216	.316
80-90	.362	.293	.306	.225	.242	.244	.320
90-100	.360	.283	.291	.254	.269	.259	.320
100+	.308	.287	.305	.260	.284	.289	.290

*These values represent only one column.

Quirk (1960, 1961) as modified by Kunze <u>et al</u>. (1968). The hydraulic conductivity of the saturated medium was determined (using a constant head permeameter) to be 45 cm/day. The calculated hydraulic conductivity-water content function is shown in Figure 4. The same function was assumed to apply at all depths.

Equation (1) may be rewritten as

$$v = -K(\theta)\frac{dh}{dz} + K(\theta) \qquad (3)$$

where Z = -z is the depth taken as positive downward. The pressure head h versus Z and t using the θ(h) function shown in Figure 1. For $0.068 \geq \theta \geq 0.020$, corresponding to $-1200 \geq h \geq -10{,}000$ cm of water, estimates of h were based on the assumption of a linear relation between θ and h within these limits. The pressure head gradient, dh/dZ was determined graphically from a plot of pressure head versus depth.

Below the root zone in the lower part of the column determinations of dh/dZ were much less precise; and the flux was determined by a different

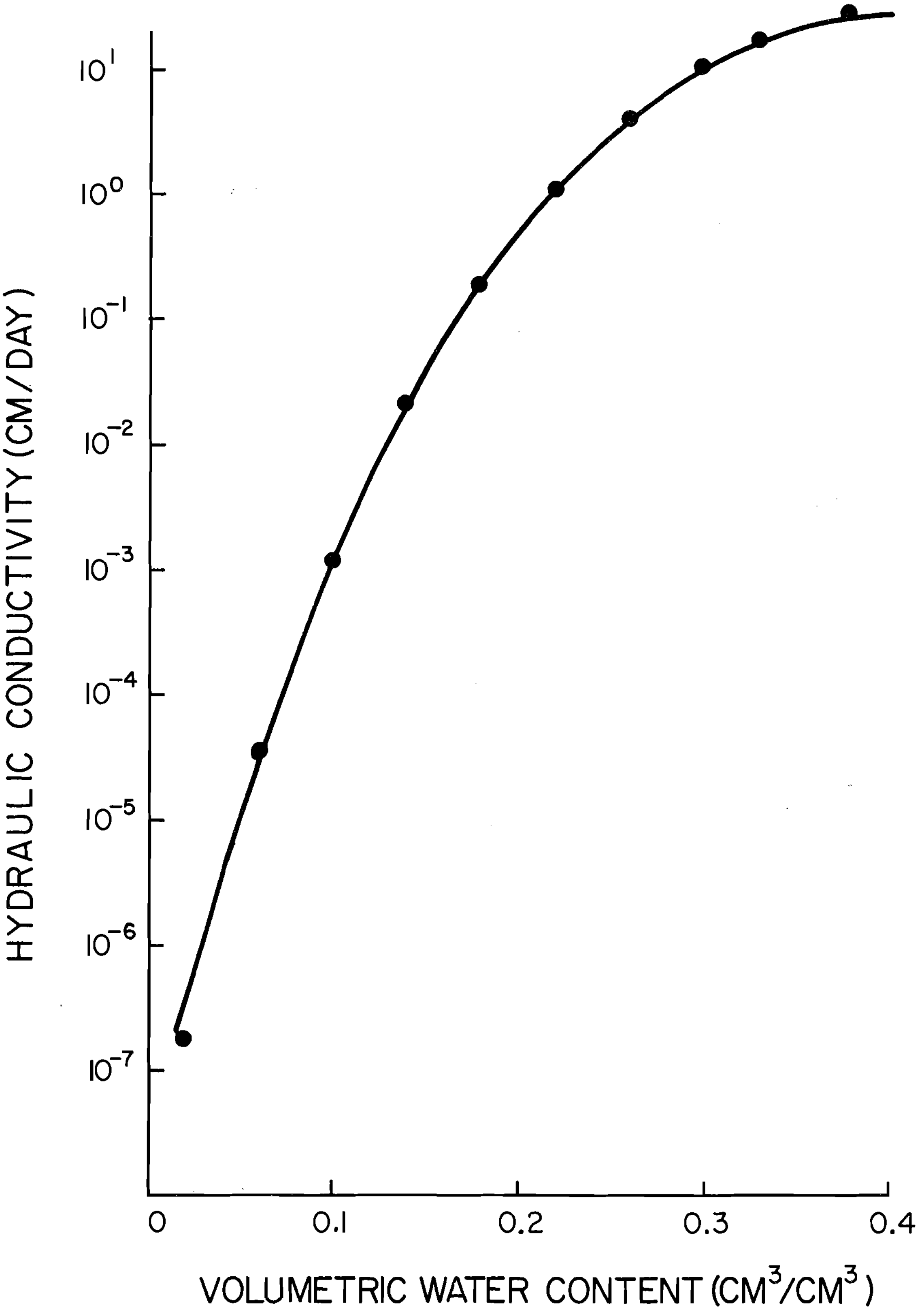

Figure 4. Hydraulic conductivity-water content relationship calculated by the method of Kunze _et_ _al_. (1968) for the Dickinson sandy loam.

method. In a region of the column where there are no roots the continuity equation becomes

$$\frac{\partial\theta}{\partial t} = -\frac{\partial v}{\partial z} \qquad (4)$$

which can be integrated

$$\int_{t_1}^{t_2}\int_{Z_1}^{Z_2} \frac{\partial\theta}{\partial t}\, dZdt = -\int_{t_1}^{t_2}\int_{Z_1}^{Z_2} \frac{\partial v}{\partial Z}\, dZdt \qquad (5)$$

The right hand side of equation (5) can be approximated by

$$-\int_{t_1}^{t_2}\int_{Z_1}^{Z_2} \frac{\partial v}{\partial Z}\, dZdt = -\int_{Z_1}^{Z_2} d\overline{v} \qquad (6)$$

where

$$\overline{v} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} vdt \qquad (7)$$

Thus equation (5) becomes:

$$\int_{t_1}^{t_2}\int_{Z_1}^{Z_2} \frac{\partial\theta}{\partial t}\, dZdt = [\overline{v}(Z_1) - \overline{v}(Z_2)]\ (t_2 - t_1) \qquad (8)$$

The left hand side of (8) was evaluated graphically from the water content depth profiles at times t_1 and t_2 and over the depth increment of interest. In application to the data from the soil columns, $\overline{v}(Z_1)$ was taken as the time average flux through the 90-100 cm depth increment and was evaluated from the inflow rates at the bottom of the column. The time averaged flux through the 80-90 cm depth increment was then calculated from equation (8).

The calculated soil water flux values are shown in Table 2 and some of the data are plotted in Figure 5. Plots of v versus Z were used to estimate $\partial v/\partial Z$ as a function of depth and time. In the 70-80 cm depth

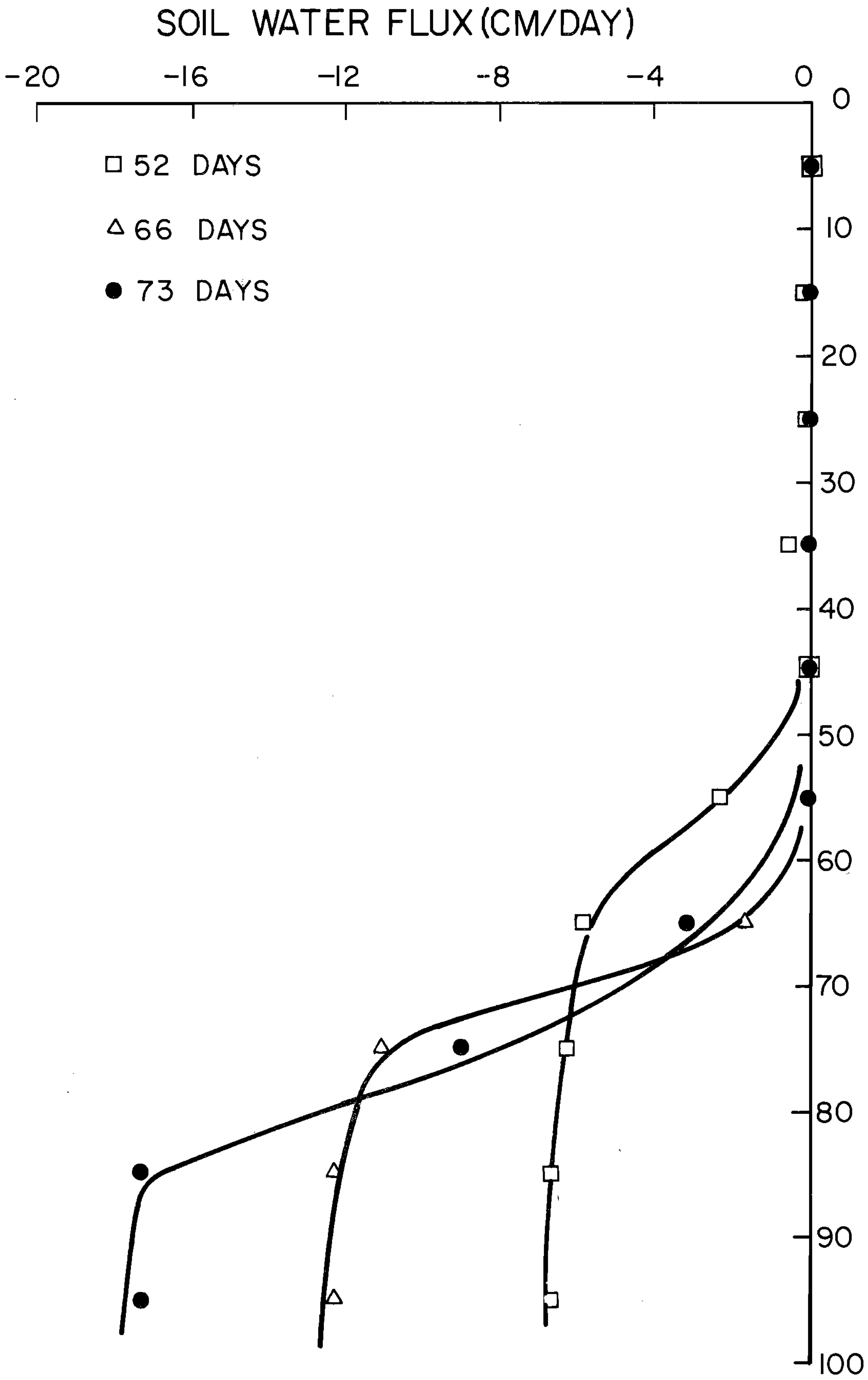

Figure 5. Soil water flux versus depth at selected times.

Table 2. The soil water flux in the soil column (cm/day).

Days After Planting	24	38	52	59	66	73
Depth (cm)						
0-10	-.0600	-.1290	-.0040	-.001	-.0009	-.0001
10-20	-.0480	-.9500	-.1970	-.0099	-.0067	-.0003
20-30	-.1000	-.2940	-.1450	-.0385	-.0032	-.0022
30-40	-.1650	-.1110	-.5510	-.0360	-.0120	-.0097
40-50	-.3780	*-.5100	-.1900	-.3100	-.0100	-.0100
50-60	-.3780	-1.3500	-2.3100	-1.8700	-.0500	-.0500
60-70	-.3780	-1.3500	*-5.8700	*-9.7300	-1.6700	-3.2000
70-80	-.3780	-1.3500	-6.2900	-10.1100	*-11.1000	*-9.0000
80-90	-.3780	-1.3500	-6.6900	-11.4500	-12.3000	-17.3000
90-100	-.3780	-1.3500	-6.6900	-11.4500	-12.3000	-17.3000

*The values determined by interpolation.

increment difficulties were encountered with both methods of calculation of the flux and in this region the flux was determined by interpolation.

The source function values as calculated from equation (1) using the values of $\partial\theta/\partial t$ and $\partial v/\partial Z$, obtained as described above, are tabulated in Table 3. Some of the data are plotted in Figure 6. The results show the source strength to be relatively small in magnitude in the early part of the experiment in all portions of the column. At 52 days after planting the source strength showed a marked increase in magnitude at the 50-60 cm depth. Thereafter the peak source strength increased in magnitude and moved down the column toward the water table. In these columns, where lateral root growth was limited, the roots near the wetted portion of the soil absorbed the major portion of the water, and the zone of maximum uptake remained relatively narrow as it moved downward through the column.

The results of the root density measurements expressed as length of root per unit volume of soil are given in Table 4. Some of these data are plotted in Figure 7. The most significant feature of the root density profiles is the bulge observed at 50-70 cm depth. The roots grew rapidly

Table 3. Time averaged values of the source strength versus depth in the soil columns ($cm^3/cm^3/day$).

Time Period	24-38 Days	38-52 Days	52-59 Days	59-66 Days	66-73 Days
Depth (cm)					
0-10	-.0357	-.0357	-.0214	-.0000	-.0000
10-20	-.0000	-.0000	-.0000	-.0000	-.0000
20-30	+.0286	-.0000	-.0214	-.0000	-.0000
30-40	-.0007	-.0007	-.0214	-.0070	-.0000
40-50	-.0760	-.0322	-.0429	-.0429	-.0070
50-60	-.0143	-.2870	-.4290	-.1142	-.0429
60-70	-.0000	-.0357	-.1142	-.5720	-.7150
70-80	-.0007	-.0179	-.0429	-.5720	-.7870
80-90	-.0000	-.0079	-.0429	-.0429	-.0357
90-100	-.0000	-.0000	-.0011	-.0011	-.0011

Table 4. Root density in the soil columns (cm/l soil).

Days After Planting	24	38	52	59	66	73
Depth (cm)						
0-10	941	2842	3343	3370	3510	3517
10-20	604	1328	1320	1564	1500	2023
20-30	240	799	833	963	1469	1917
30-40	112	546	1126	916	1016	2111
40-50	34	408	662	739	1240	1736
50-60	--	307	896	1088	2059	2457
60-70	--	139	1496	1454	1982	2899
70-80	--	--	757	1205	1714	1452
80-90	--	--	169	79	164	881
90-100	--	--	--	--	--	--
100+	--	--	--	--	--	--

downward through the soil until they met the nearly saturated zone above the water table. Here they proliferated where there was an ample supply of water. Lateral root growth was limited by the narrow columns in order to keep the problem one-dimensional. Visual observation indicated that the roots were uniformly distributed in any given cross section and that there was no proliferation of roots about the perimeter of the columns.

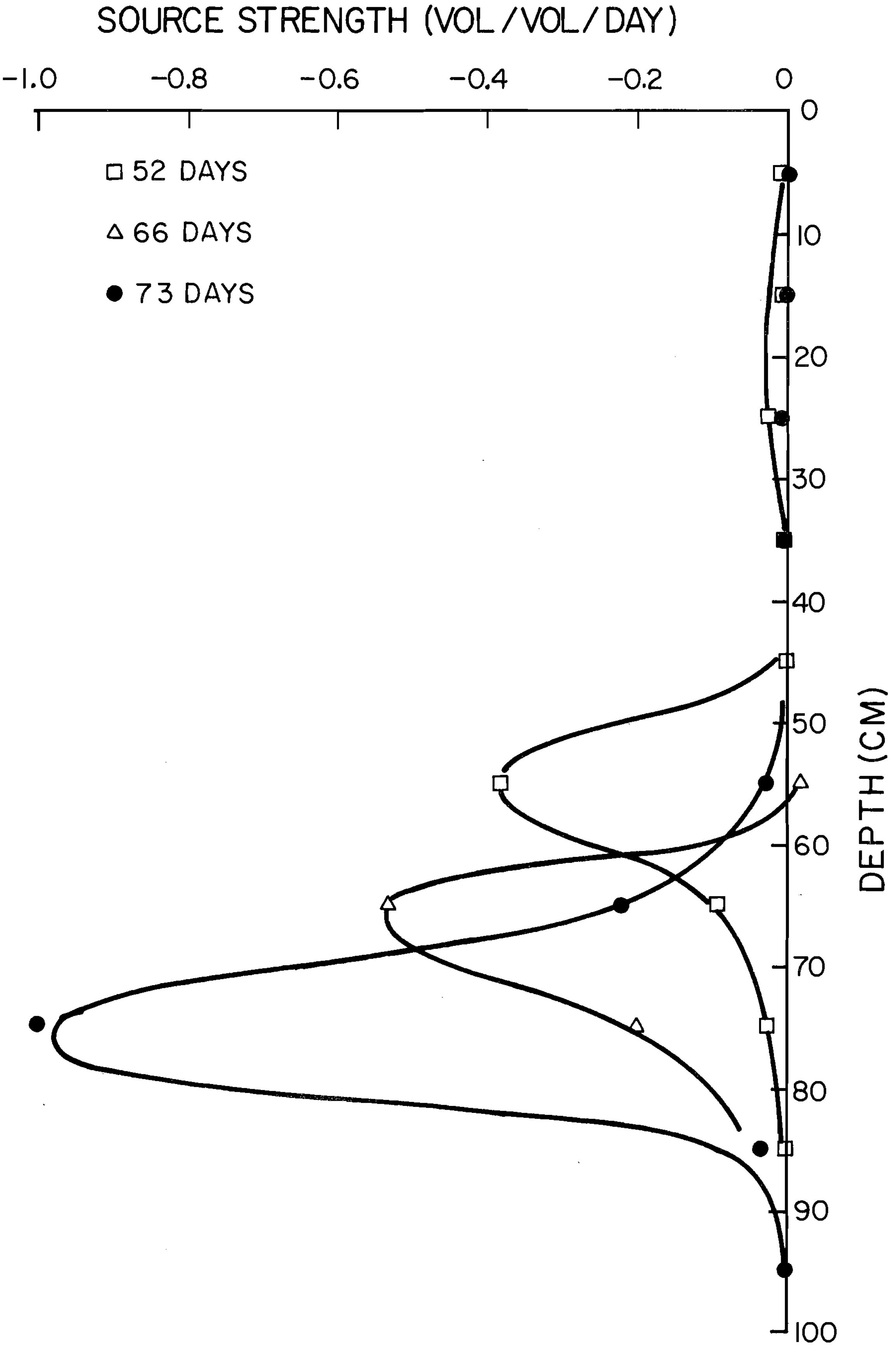

Figure 6. Source strength versus depth at selected times.

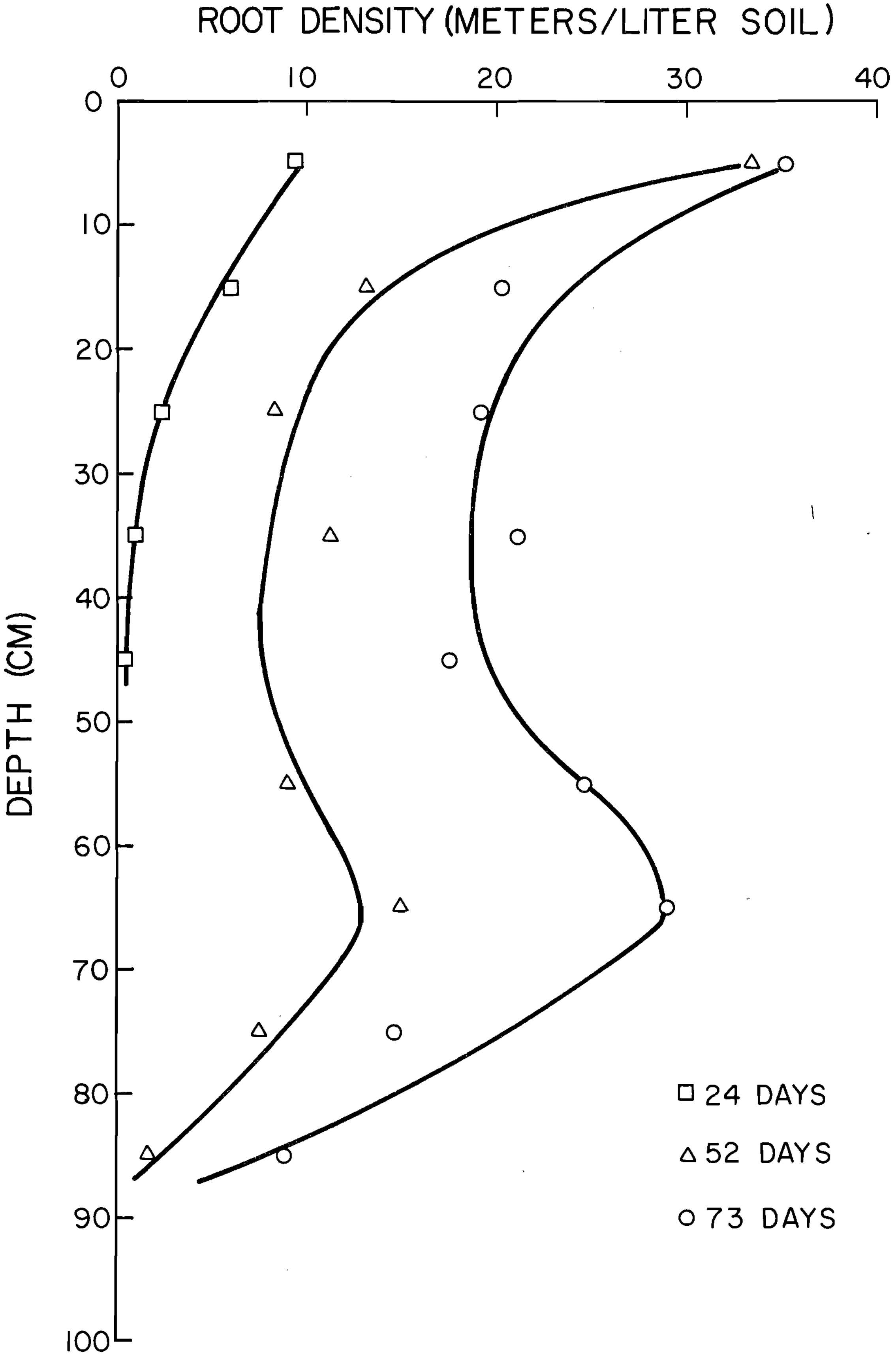

Figure 7. Root density in length per unit soil volume versus depth at selected times.

Figure 8 shows the root density versus time for selected depths. In the 0-10 cm depth the root density increased rapidly during the first half of the experiment, but tended to remain constant during the latter half of the experiment. The results indicate an inhibited root growth rate at higher soil water tensions (more negative pressure heads). From the data for $\theta(h)$ Figure 1 and the data for $\theta(Z,t)$ Figure 2 and Table 1, it appears that the rate of root growth was inhibited at pressure heads less than -1000 cm of water.

From a comparison of the root density data (Table 4 and Figure 7) and the source function distribution (Table 3 and Figure 6) it can be seen that root density is not an index of water uptake. In the upper portion of the column the root density did not correspond to the pattern of extraction of water. There was however an increase in root density at the depth of maximum water uptake. The results of this experiment indicate that under suitable conditions, a small portion of the root system can be responsible for the major portion of the uptake of water.

In the upper part of the column where the hydraulic conductivity was low due to the low water content, relatively low values of the soil water flux were obtained, and the magnitude of the source term S was determined primarily by $\partial\theta/\partial t$. In the wetter parts of the column, just above the water table the magnitude of the source was determined primarily by the term $\partial v/\partial t$.

Small amounts of water were absorbed from the upper part of the columns until the soil moisture tension approached approximately 1 bar, but this amount was negligible compared with that taken up from the capillary fringe. Above the capillary fringe, the roots were able to extract water fast enough to keep the water content low, resulting in a low hydraulic conductivity,

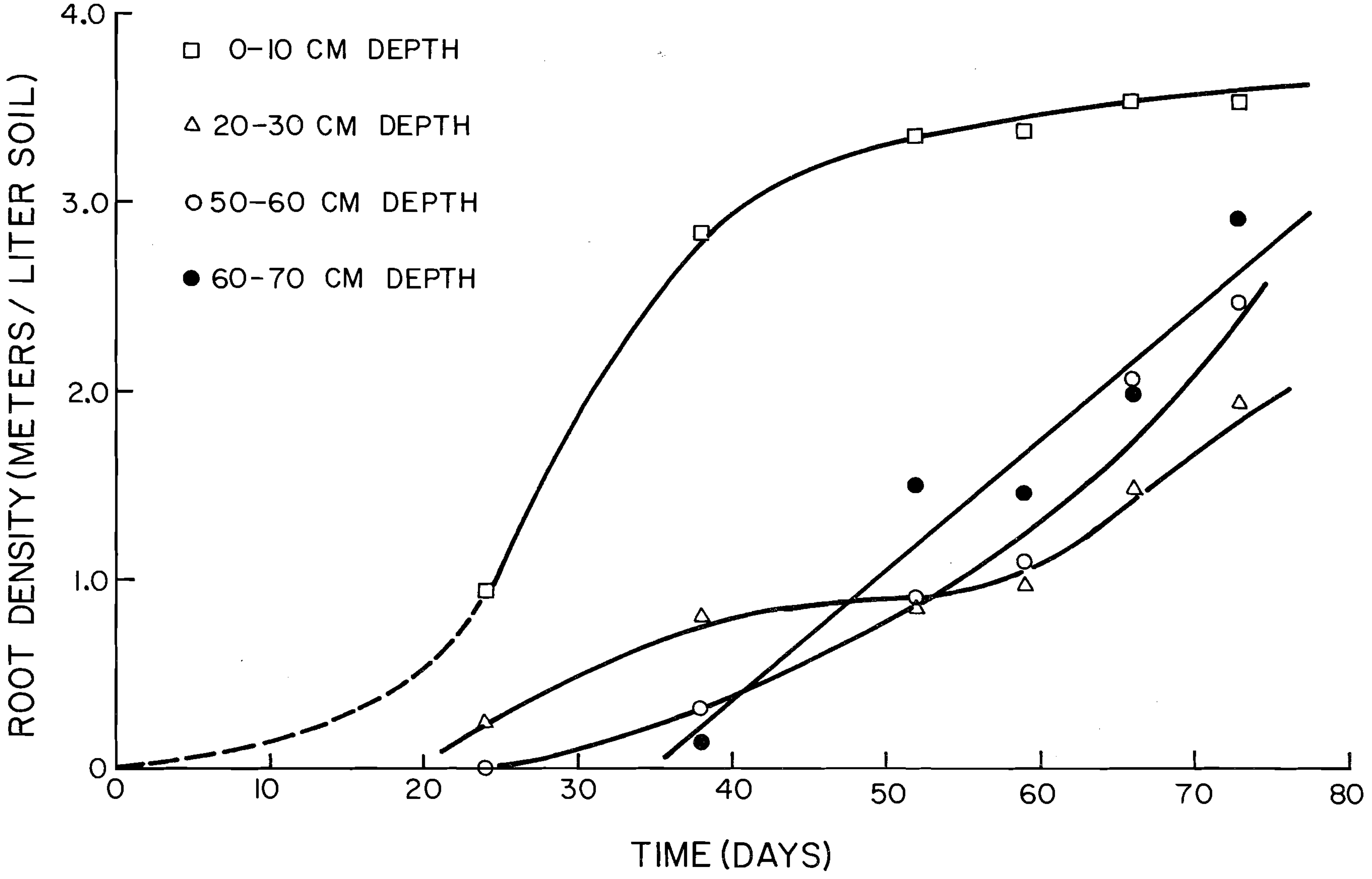

Figure 8. Root density (length basis) versus time at selected depths.

and little upward movement of water. It is quite evident that both root density and hydraulic conductivity contribute to the source strength.

The water uptake per unit length of root was estimated by dividing the source strength (cc water/cc soil/day) by the root density (cm root/cc soil). The results shown in Table 5 indicate that the uptake of water can approach 0.5 cm^3/cm root/day. In the treatment of the uptake of water by plant roots using a single root model one of the problems encountered is the specification of the boundary condition at the root surface. Data of the kind quoted above for uptake per unit root length is essential when this boundary condition has to be specified as a flux at the root surface.

Table 5. Water uptake per unit root length.

	Uptake, cm^3/cm root/day				
Depth	24 days	38 days	52 days	59 days	66 days
0-10 cms	0.0045	0.024	0.0036	0.00042	0.00020
10-20	0.0035	0.0021	0.0058	0.0026	0.0015
20-30	0.031	---	0.034	0.0035	0.0027
30-40	0.086	0.0018	0.0023	---	0.0054
40-50	0.16	0.14	0.0049	0.0057	0.0045
50-60	0	0.025	0.43	0.42	0.0092
60-70	0	0.026	0.061	0.18	0.28
70-80	0	0	0.038	0.11	0.12
80-90	0	0	0.016	0.023	0.25

Single Column Experiments

The determination of the water content-depth-time profiles by gravimetric sampling required the use of multiple columns sampled at a sequence of times to obtain the data. The variability in packing that occurred between columns caused considerable scatter in the data and the analysis for the source term was correspondingly uncertain.

In the multiple column experiments the pressure head of the soil water was inferred from the water content. This is an uncertain practice especially in the lower, wetter portion of the column, below the root zone. Furthermore, in the multiple column experiments no provision was made for measuring the transpiration rate or the evaporation from the soil surface and this component of the flux had to be maintained at zero.

As an alternate approach it was decided to develop a highly instrumented flow column, with provision for (1) non-destructive water content measurement, (2) measurement of the evaporation from the plant leaves separately from the evaporation at the soil surface, and (3) measurement of the hydraulic and pressure head of the soil water. The gamma absorption method (Gardner, 1965) was selected for the water content measurements, and strain gauge tensiometry (Klute and Peters, 1966) for the hydraulic and pressure head measurements.

A diagram of the experimental arrangement that has been evolved is shown in Figure 9. The development and application of this arrangement for the purpose of measuring the sink strength distribution in a soil column is still going on. It is intended that the research on water uptake by root systems will be continued and that the experimental arrangement devised will be used in this work.

The experimental arrangement consists of four major segments, (1) a vertical column of soil, (2) a gamma apparatus for measuring the soil water content, (3) a strain gauge tensiometry system and (4) an evaporation measuring system. The soil column is held in an aluminum box approximately 15 × 15 cm in cross section and 107 cm high. Ports are provided in the walls of the box to allow the insertion of tensiometer cups and thermistor probes for measuring temperature. Additional ports are provided to permit gravimetric sampling for water content in the column at the end of the flow experiment.

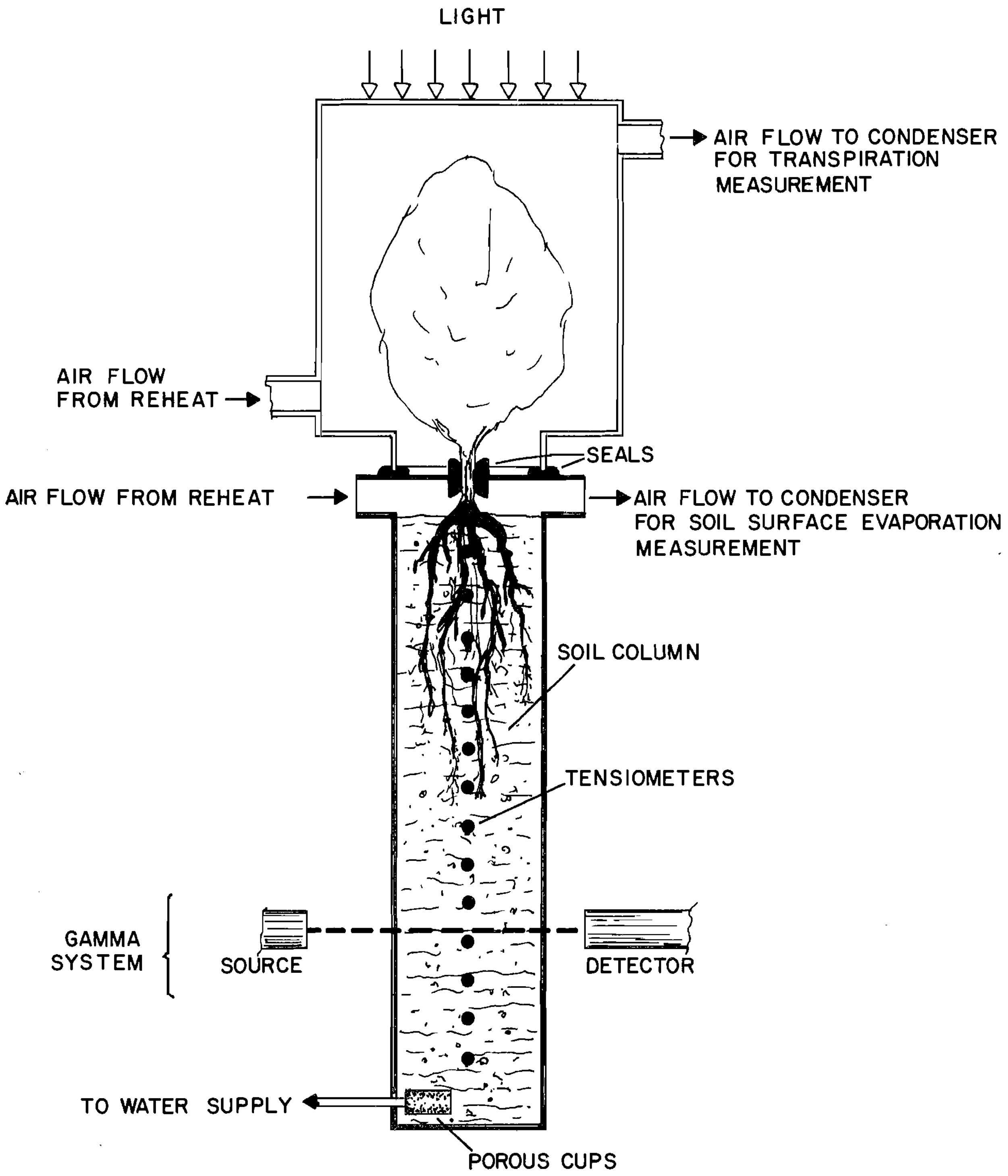

Figure 9. Diagram of the experimental arrangement for source term measurement using a single soil column.

One side wall of the box can be removed to permit sampling for root distribution at the end of an experiment.

A diagram of the gamma apparatus is shown in Figure 10. The source and detector are mounted on a lift platform to allow the measurements to be taken at any desired elevation on the column. The lift is on wheels and can be rolled away from the column to permit more convenient access to the column or to allow the gamma measurements to be made on more than one column. A standard brass absorber is mounted below the soil column so that gamma transmission measurements may be made on it at intervals to permit corrections for instrument drift to be made.

A diagram of the strain gauge tensiometry system is shown in Figure 11. Hydraulic switching (plug type valves) is used to connect any one of a number of tensiometer cups to a pressure transducer. Electrical switching is used to select the output of a given transducer and apply it to an amplifier-recorder system.

Each of the evaporation measuring systems is a closed air-flow loop (Figure 12). A fan drives the air around the loop. The air which crosses the upper part of the soil column is passed through a condenser where the air is chilled and condensation of water vapor occurs. The condenser consists of a PVC pipe with a copper pipe covered with splines inside it. Cold water is circulated through the copper pipe. The air flow is along the axis of the pipe. Water vapor condenses on the cold copper surface and is collected in a burette. The air from the condenser is passed over a reheat coil and back through the evaporation chamber. Reheat is thermostatically controlled with a sensing probe located in the evaporation chamber. The rate of evaporation is assumed to be the same as the rate

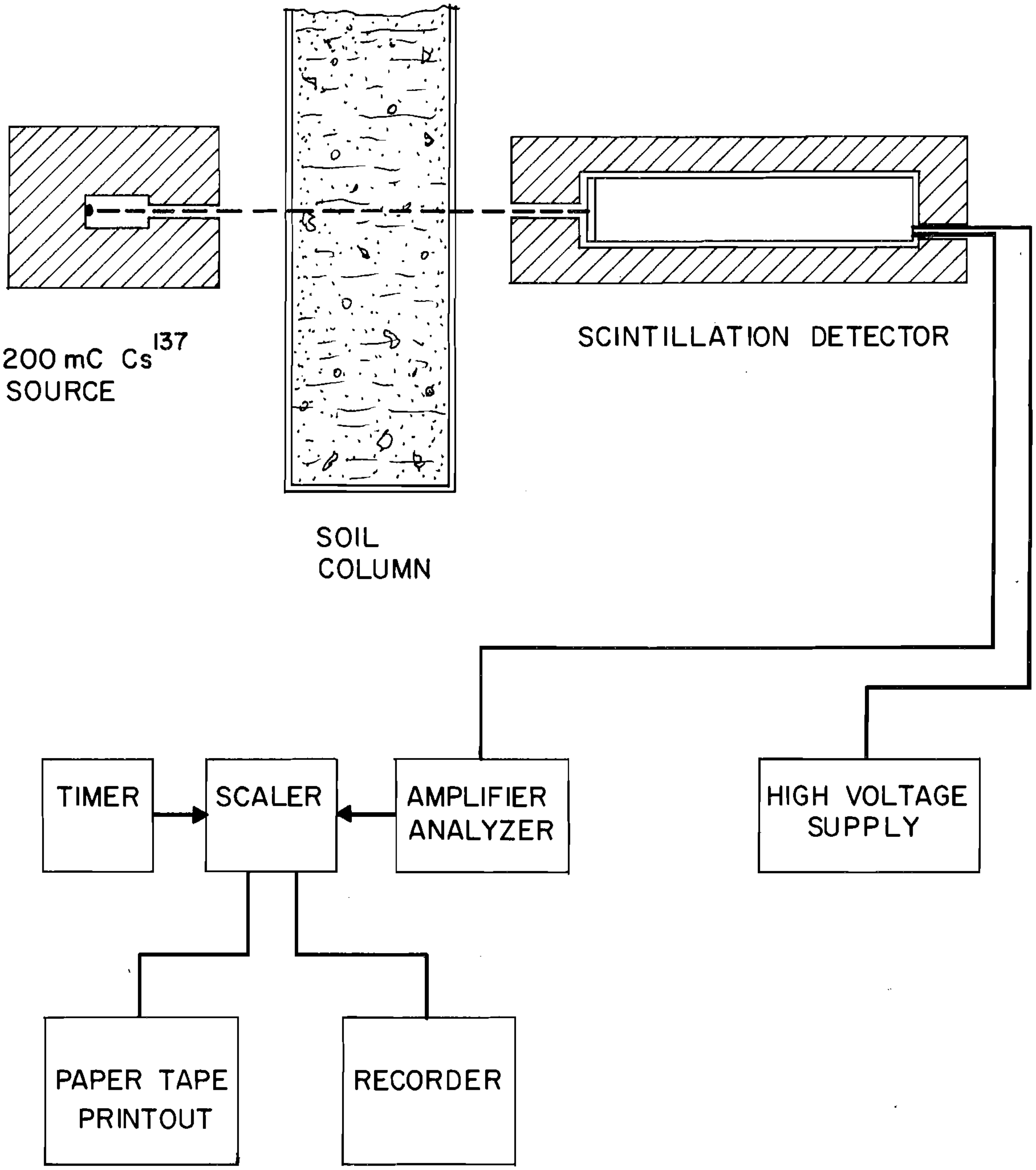

Figure 10

DIAGRAM OF GAMMA ATTENUATION APPARATUS FOR DETERMINATION OF WATER CONTENT

DIAGRAM OF THE STRAIN GAUGE PRESSURE TRANSDUCER TENSIOMETER SYSTEM

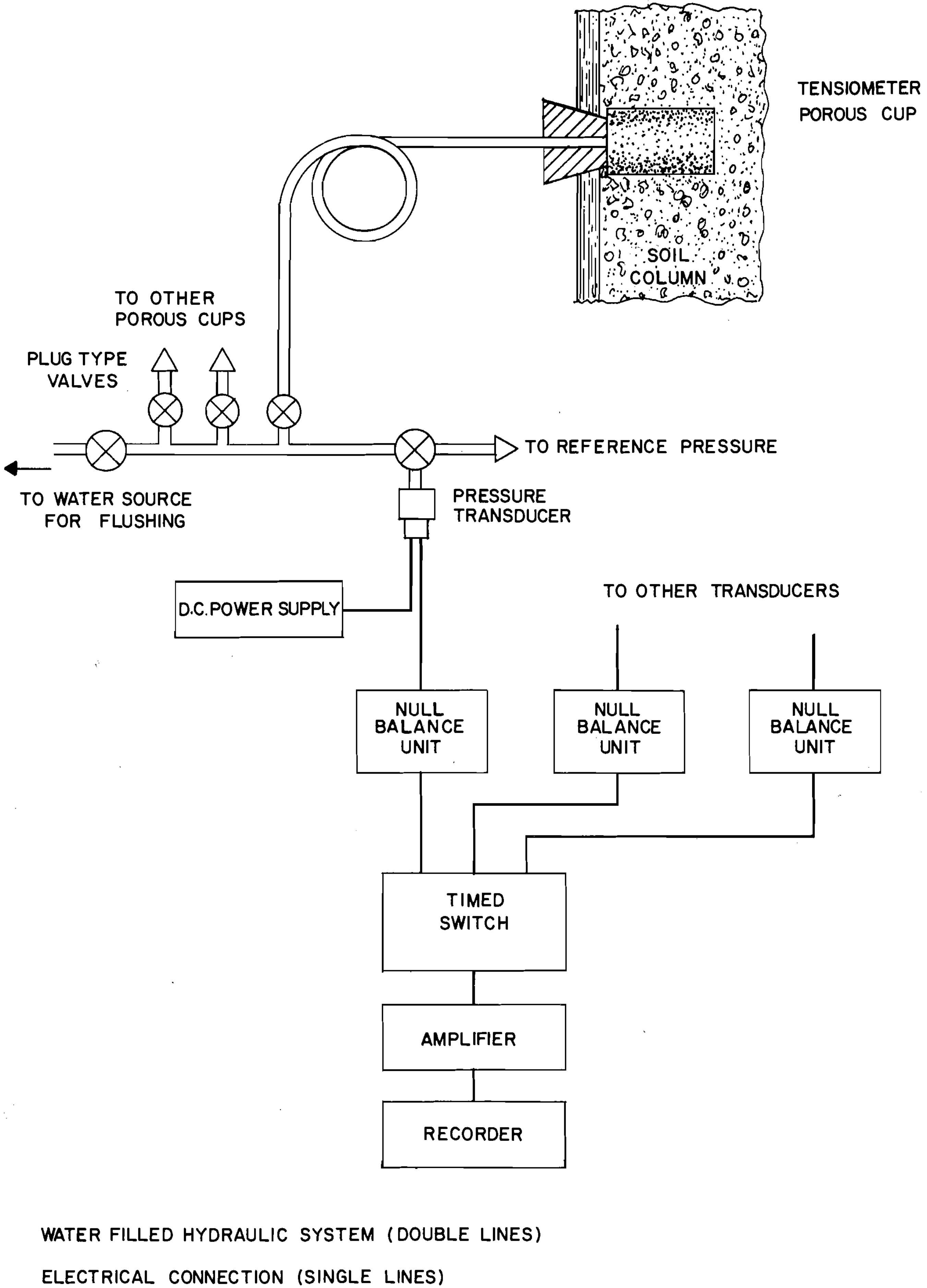

Figure 11. Diagram of the tensiometer system.

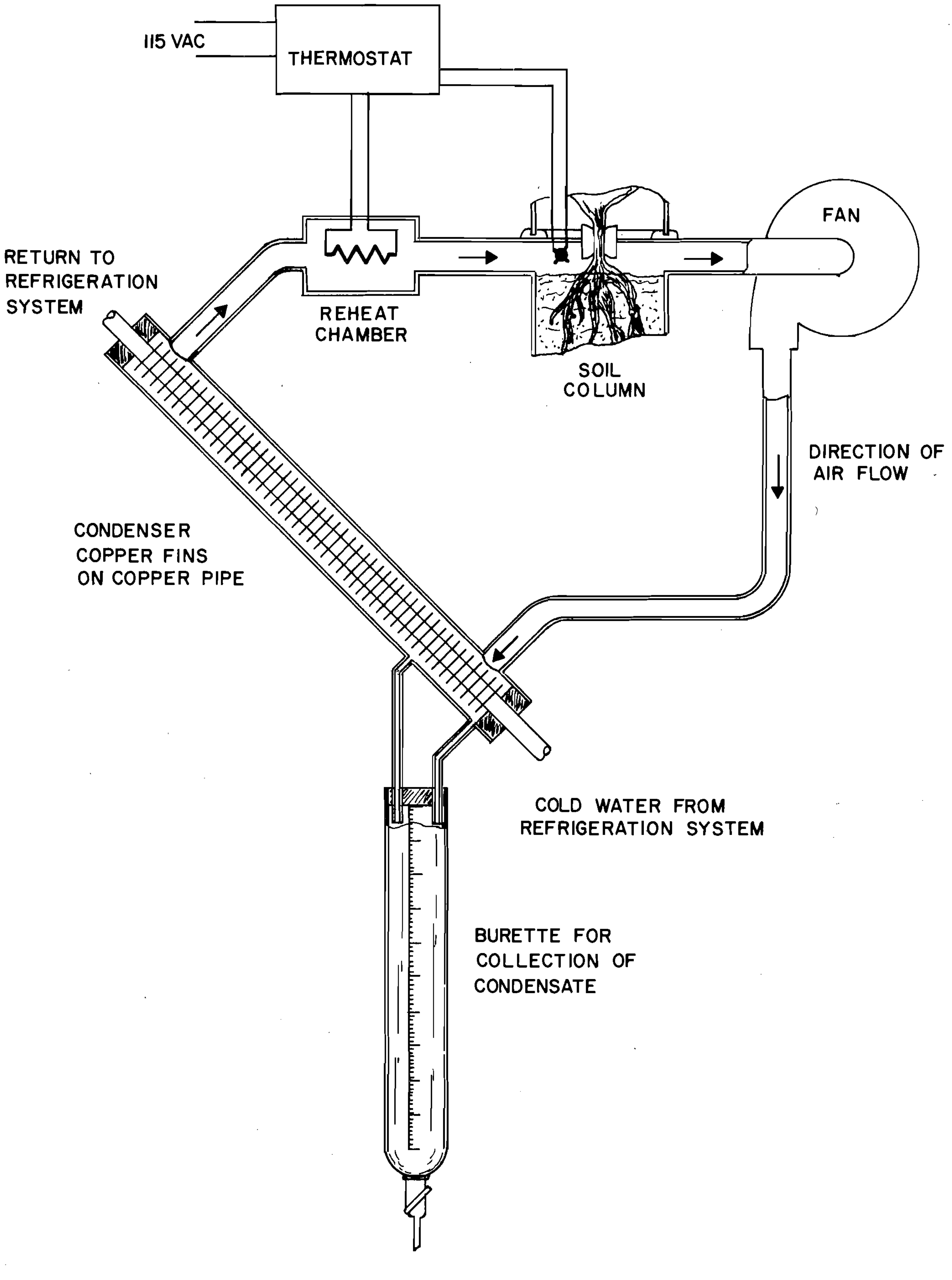

Figure 12

DIAGRAM OF EVAPORATION MEASUREMENT SYSTEM of collection of water in the burette. For quasi-steady state conditions, tests have indicated that this assumption is valid.

Two closed-loop evaporation systems are used, one for the soil surface evaporation and one for the transpiration. The soil surface is covered with a shallow box which forms the evaporation chamber for water loss from the soil. The top of this box has a hole in it through which a plant stem can be led so that the leaves of the plant can be enclosed in another evaporation chamber. A soft pliable seal is used around the plant stem.

PUBLICATIONS

Reicosky, D. C., Millington, R. J., Klute, A. and Peters, D. B. Patterns of water uptake and root distribution of soybeans in the presence of a water table. Manuscript in preparation. Will be submitted to the Proc. Soil Sci. Soc. Am.

Reicosky, D. C., Millington, R. J. and Peters, D. B. A comparison of methods for estimating root length. Submitted for publication in the Proc. Soil Sci. Soc. Am.

SIGNIFICANT RESULTS

The work conducted on this project on water uptake by plant roots has yielded the following results:

(1) The nature of the source function in the macroscopic distributed source approach to water uptake has been elucidated. In particular, the combined importance and interaction of the hydraulic conductivity function and the root density distribution in determining the magnitude of the source function has been demonstrated.

(2) Data on the water uptake per unit root length have been obtained which give further insight into the conditions at the root surfaces. These data are necessary to model studies of water uptake by the single root, and have a bearing on the question of the applicability of the limiting flux concept (Whisler *et al*., 1968) at the root surface.

(3) A more rapid and reliable method of evaluation of root density in soil has been evolved.

(4) A basic method and pattern of approach to the study of the interaction of the plant with its environment, both soil and aerial, has been initiated.

POTENTIAL APPLICATION TO WATER RESOURCES PROBLEMS

The importance of evapotranspiration in the hydrologic cycle is well known and has already been stressed. Energy balance approaches to the study of evapotranspiration, as presently constituted, suffer from their inability to deal with (1) advection of sensible heat and (2) soil or plant limitation of evapotranspiration. The present experimental work, developed from the initial numerical analysis, has demonstrated how soil conditions effectively control the pattern and intensity of activity of the extraction of water by plant roots. Root density and radiation load might be considered as major determinants of the potential sink strength for water. However, the expression of this potential is dependent on the interplay between the ability of the soil to supply water and the ability of the plant to conduct it to sites of evaporation in the leaves.

Extension of the methods of analysis embodied in this report are now being undertaken. The basic information required in the aerial environment are some knowledge of the plant water potential and plant water content distribution and the energy disposition as a function of height in the plant canopy. With the insight gained from studies of the kind described herein plus treatment of the water transport in the plant, an attempt can be made to couple the two half-systems together and give a complete account of water flow in the soil-plant-atmosphere system.

Such a treatment of the soil-plant-atmosphere system is a major goal since utilization of the total environmental resources hinges heavily on a thorough understanding of evapotranspiration. Utilization of soil resources, either for agriculture or for recycling of components and products of the ecosystem, can only be made more effective with better understanding of the water balances and fluxes.

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