Technical Report No. 6

SOIL WATER STUDY OF A SHORTGRASS PRAIRIE ECOSYSTEM

PAWNEE SITE

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GRASSLANDS BIOME

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1. REVIEW OF SOIL WATER STUDY PROPOSAL

1.1 The IBP Grasslands Study

The main goal of the grasslands biome study is the evaluation of biological productivity in a grasslands system. Biological productivity results from a complex interaction of the physical, chemical, and biological components operating in a grasslands ecosystem. An understanding of ecosystem productivity requires a method of prediction. The method of prediction chosen for the grasslands biome study is a compartment model describing the trophic states of the ecosystem (Bledsoe and Jameson, 1969). The hydrology of the grassland ecosystem is an abiotic element of the model with initial state levels and dynamic behavior, influencing many biological processes elsewhere in the model.

1.2 The Hydrology Study

The hydrology is designed to investigate the cycling of water through the grassland ecosystem, represented at the Pawnee site. The occurrence of precipitation by duration, intensity, and amount; the disposition of precipitation by interception, infiltration, and surface runoff; and the redistribution of soil water by evaporation, transpiration, percolation, and lateral flow are the pathways in the water cycle of primary interest. Of these, infiltration is the key mechanism in the transfer of water within the ecosystem. Changes in the rate of infiltration caused by grazing (Dunford, 1949; Rauzi and Hanson, 1966), or freeze-thaw effects (Schumm and Lusby, 1963), can alter the runoff, soil water recharge pattern.

1.3 The Soil Water Study at the Pawnee Site

The original proposal contained two major sections. One section concerned soil water relations at the eight microwatershed installations. The other section outlined a study of the site factor influence on soil water. The site factor design has some serious drawbacks due to the nature of the topographic combinations of soil type, slope position, aspect, grazing intensity which occur at the Pawnee site. For this reason the site factor section of the study has been eliminated from the proposal.

The revised study will concentrate upon the soil water relationships of the eight microwatersheds. The objectives of the study can be framed in groups of questions relating to these major topics.

A. Amount of Soil Water

1. Prior to and during a growing season how much water is added to the soil system?
2. What is the disposition of soil water during the growing season?
3. What is the relative importance of processes which deplete the supply of soil water?

B. The Rate of Change in Soil Water

1. Can quantitative functions be developed which adequately describe the change in soil water content?
2. What factors are important for predicting the amount of evapotranspiration which takes place?

C. Factors Affecting Soil Water

1. What is the gross effect of grazing intensity upon the change in soil water content during the growing season?

2. Does seasonal, spatial variation in the soil water content relate to topographic, vegetational, and/or rooting distribution patterns?

3. Using the difference between precipitation and total microwatershed runoff as an index, are there significant differences in the infiltration capacities of the microwatersheds?

D. Soil Water and Plant Growth

1. How much of the water in a soil profile is available for plant growth?

2. To what extent is soil water potential a factor limiting to plant growth?

3. How much of the variation in plant growth, expressed as biomass productivity, can be explained by changes in evapotranspiration?

1.4 Progress of the Soil Water Study

1.41 *Instrumentation*

Soil water instrumentation at each of the eight microwatersheds, Fig. 1 and 2, consists of 10 access tubes for the neutron probe, arranged in an equidistant spacing, and a stack of Coleman electrical resistance units located in the side walls of a six inch diameter pit; the pit is approximately 1.5 ft downslope of access tube Number 7, Fig. 3. Eight of the access tubes are five feet deep in the profile. The remaining two tubes, in the center line Numbers 5 and 7 for the most part, are greater than five feet deep, up to 10 ft in some instances. The electrical resistance units are located at depths of 2, 10, 20, 40, and 80 cm. Two neutron probes are being used for the measurement of soil water. Both are manufactured by Nuclear of Chicago and contain an Americium-Beryllium 241 source in a 30 to 80 mc strength range. The Coleman electrical resistance units will be monitored via a remote system, connecting all eight microwatersheds with a central data processing unit at the Pawnee site headquarters building. Each stack of Coleman units is wired at the pit to an alternating current wheatstone bridge module, which converts the resistance to a voltage signal for transmission on line.

Supporting instrumentation includes a transducer rain gauge and a water stage recorder at the H-flume, both of which are on the remote system, Fig. 3.

1.42 *Soil Analysis*

Collecting of soil samples for determination of the hydrological properties in the Ascalon series, on which the eight microwatersheds are located, was begun in the fall of 1968. During this period some 400 samples were collected from outside the boundaries of the microwatersheds. The purpose of the soil analyses is to determine:

1. The textural distribution by approximate sand, silt and clay fractions.
2. The bulk density.
3. The pore space distribution, greater or less than 0.1 Bar tension.
4. The water retention characteristics as a function of the soil water potential.

For all these analyses a comparison of the A, B, and C horizons is being made. In the spring of 1969 an additional 400 samples were collected within the microwatersheds at the time the access tubes were installed.

The bulk density determinations have been completed. The relationship of bulk density variation by horizon and grazing intensity is given in

Fig. 4. The summary bulk density statistics are presented in Table 1. The range of variability was greatest in the surface, A, horizon, as might be expected from the differential effects of cattle compaction, rainfall impact, and freeze-thaw. Bulk density increase with depth is probably related to the change of structure in the three horizons; A--granular, B--blocky, and C--structureless; and also to the decrease in root material with depth.

The relationship of grazing intensity is not quite as well defined. If cattle compaction is a major influence, then the bulk density values of the A horizon would be expected to show a systematic change with grazing intensity. Although a decrease from moderate to light to no grazing is indicated by Fig. 4, the heavy grazed microwatersheds have nearly the same bulk density as the light. The statistical result may be that only the no grazing treatment will show a significant reduction from the others. As more bulk density determinations become available from the water retention analysis, the relationship, if any, between surface bulk density and grazing intensity may become better established.

The textural analysis will be completed in February, 1970. The hydrometer method as described by Day, 1965, is being used. The main objective of the textural analysis is to test the homogeneity of the Ascalon series. Also of interest is the distribution of the clay fraction with depth. Subsequent investigation may indicate that variation in soil water content can be reduced by covariance analysis on the clay fraction (Douglass, 1962).

The pore space distribution and water retention analysis have been started recently. A preliminary test suggests that horizon differences in soil water energy relations exist, Fig. 5. At this time the pattern shown in Fig. 5 is only suggestive, until an adequate number of samples can be analyzed. This information will be used to develop a characteristic water desorption curve for each microwatershed. Differences in amounts of depletion between microwatersheds and grazing intensities may be related to changes in the water retention properties. The method being employed is the standard pressure chamber technique described by Richards, 1965. A modification of this method has been made, in that the same undisturbed core is used for all points in the 0.0 to 1.0 Bar range. The water retention analysis should be completed by June 1970.

1.43 *Soil Water Measurement*

Soil water measurements with the neutron probe were begun in late June 1969. At first some difficulty was experienced in keeping the access tubes sealed between measurements. The cattle pulled out more than half of the rubber stoppers, with the result that four to five inches of water from rainfall stood in these tubes until it was removed and a successful method for keeping the tubes sealed was devised in late August. For that reason, reliable readings at depth extended to only 90 cm. The summary results of measurements through mid September are given in Table 2. The graphical presentation of the soil water trend, expressed as an average value for each microwatershed can be seen on Fig. 6 to 9. The calibration used to convert the neutron readings was based upon a water standard count alone, so that individual values are 5% accurate at best. Improvement of the calibration is discussed below. The series of measurements were not sufficient to show a grazing intensity pattern, if any exists, but do indicate a negative exponential form of depletion.

It will be necessary to sample soil water on the microwatersheds at short intervals. The schedule which is planned for the coming year will provide measurements at three-week intervals until mid-March, two-week intervals until early May, and one-week intervals from May to October. During the growing season, May to October, in addition to the regular one-week interval, measurements will be taken following each significant rainfall. This sampling schedule should account for soil water recharge during the January to April period and minimize the error in accounting for evapotranspiration from May to October.

2. CALIBRATION OF INSTRUMENTS

2.1 Neutron Meter

2.11 *Surface Calibration*

Given the pattern of precipitation distribution during the growing season, with a high frequency of short duration, high intensity rainfalls, it is probable that the most active zone of water penetration and withdrawal is the surface 15 cm of the soil profile. Two approaches to measurement of the soil water in the surface horizon will be made. One involves the stack of Coleman units, discussed below; the other will be a surface calibration of the neutron probe at a 15 cm depth. Preliminary tests of a field procedure this summer were encouraging, enough so that a surface calibration will be made. Surface calibrations of neutron probes by Jeffrey, 1968, and Van Bavel and Stirk, 1967, have shown that this technique is feasible.

The method will consist of locating eight access tubes in the soil water calibration plot, just to the south of the Pawnee site headquarters building. A dike will be mounded around each tube and then all tubes will be flooded with five to 10 cm of water. After infiltration of the water, simultaneous samples of the soil water content by gravimetric sampling and the neutron probe counts per time interval will be taken throughout a drying cycle. Each of the eight tubes will represent one point on the drying cycle and eventual calibration function. The ability to take many gravimetric samples for each point should reduce the variability in soil water content for a given point to an acceptable minimum. The results of one such run this past summer gave a standard deviation of less than 0.1% water by volume at an average water content of 24.5%. A regression of counts per time interval against soil water as a percent by volume may be linear throughout the range of field soil water conditions (Van Bavel, 1967), or polynomial (Jeffrey, 1968). Rather than conditioning the intercept to pass through zero, an air count will be used to represent zero soil water content.

2.12 *Depth Calibration*

The calibration of neutron probes at depths sufficiently below the soil-air interface has been the subject of considerable experimentation by individual investigators. Both laboratory and field calibrations have been conducted. A careful laboratory calibration is considered to be more accurate (Douglass, 1966; Van Bavel, 1963), but involves a great deal more overall preparation, materials, and time for the relatively small increase in accuracy. Several field calibrations of one type or another have been reported (Lewis and Burgy, 1963; Marston, 1965; Merriam, 1959; Sartz and Curtis, 1961; Ziemer et al, 1967). Most of the field calibrations have employed a method similar to that outlined above for the surface calibration.

The calibration procedure which is being developed probably will involve three independent calibrations as counter-checks. One calibration will be accomplished by polyethylene standards, on order, which vary in the percent of H atoms by volume. A second calibration will be by means of gravimetric sampling at two or three depths for two access tubes. The third, which may be the most accurate field calibration, involves metering volumes of water, which are applied evenly in a double cylinder surrounding an access tube[1/]. Counts are taken to a depth well below the horizon of infiltration. Metered s are taken to a depth well below the horizon of infiltration. Metered water is applied and the counts repeated. The difference in total counts is due to the water added, which is known volumetrically. The procedure can be repeated at the same location.

2.13 *Accuracy of Measurement*

The statistical variation of any measurement is given by this formula (Texas Nuclear, 1968):

$$SWE = \pm (K)(N/T)^{\frac{1}{2}} \div (SL) \qquad \text{where} \qquad (1)$$

SWE = Soil water error in %

K = Standard deviation unit associated with assigned confidence level

N = Average count rate for total counting time

T = Counting time unit

SL = Slope of calibration function--cts/time/dH_2O%

From this equation it can be seen that for a probe with a given calibration and for the same time interval, N is the only variable increasing or decreasing as a function of soil water. Therefore, as a per cent of the soil water content, the statistical error is highest for the largest values of soil water.

1/ Van Bavel, 1969, Personal communication.

The accuracy of the calibration and of any individual measurement is also a function of the neutron flux rate, determined by the source. As shown by Van Bavel, 1963, the count rate is controlled by both the soil water content and the radioactive source strength:

$$N = (E)(S)(\Theta) \quad \text{where} \qquad (2)$$

N = Count rate in cts/sec

E = Efficiency or proportionality factor derived from the calibration function--cts/sec/mc

S = Source strength in millecuries

Θ = Water content as a volume fraction

so that:

$$\Theta_{se} = \pm(N/T)^{\frac{1}{2}} \div (E)(S) \quad \text{where} \qquad (3)$$

T = Total counting time

Θ_{se} = Standard error of water content

Equations (1) and (3) show that error of measurement can be decreased by:

1. Decreasing the standard error of the calibration relation, i.e., increasing the number of sampling points and/or taking more volumetric samples for each point.
2. Increasing the source strength.
3. Increasing the counting time.

Experience to date with neutron measurements at the Pawnee Site has shown the desirability of using a counting time of no more than 30 seconds. A counting time of 30 seconds would allow two operators to complete measurements on all eight microwatersheds in one day, approximately 600 measurements. With this capability, the time difference between measurements on all microwatersheds is reduced to six hours at a maximum. The change in soil water content due to evapotranspiration during the measurement period will permit weekly or more frequent rounds, as dictated by rainfall. The relatively short time of counting, 30 seconds (one minute is standard), will require that considerable care be given to attaining as precise a field calibration as possible. Hopefully the maximum measurement error can be kept to 1% to 2%.

The accuracy of individual measurements is a factor in the subsequent analysis of data when microwatershed and grazing intensity comparisons are made. For a microwatershed, the average soil water content for each horizon will be calculated, and then these averages will be summed to give a single value for the entire microwatershed and the total soil profile.

If H_2O = Soil water content for a point

E = Error for the same point, equation (1)

A_h = Average soil water content for a horizon

then:

$$A_h = \sum_{i=1}^{N} (H_2O_i + E_i)/N \qquad i = 1, 2, \ldots, N \qquad N = 10 \text{ max}$$

and:

A_{mws} = Average soil water content for a microwatershed

$$A_{mws} = \sum_{j=1}^{K} A_{hj} \qquad j = 15\text{cm}, 30\text{cm}, \ldots, 290\text{cm}$$

but since:

$$A_{hk} = \sum_{i=1}^{N} H_2O_i/N \pm \sum_{i=1}^{N} E_i/N$$

The average for a microwatershed accumulates the errors for each horizon so that:

let $\sum_{i=1}^{N} H_2O_i/N = H_2O_h$

$\sum_{i=1}^{N} E_i/N = E_h$

then:

$$A_{mws} = \sum_{j=1}^{K} H_2O_{hj} \pm \sum_{j=1}^{K} E_{hj} \qquad (4)$$

In other words, the total error increases with depth.

2.2 Electrical Resistance Units

As described previously, each microwatershed has been instrumented with a stack of Coleman electrical resistance units. These units respond to changes in soil water content by a varying resistance signal. The resistance units are important to the soil water study in two ways.

1. Telemetry contact with these units permits continuous monitoring of changes in soil water content, during and following any rainfall.
2. At present, the resistance units provide the only means of measuring soil water potential continuously.

The importance of the first point is that the resistance units can supplement neutron measurements for those rainfalls when no neutron measurements immediately following are possible. The resistance units should allow a determination of minimum precipitation amounts, below which no effective change in soil water content takes place. The relatively fast response time of both the thermistor and monel screen components may permit calculation of infiltration rates.

A field calibration of the resistance units against the neutron probe will begin as soon as the telemetry system is operational. A regression of resistance against soil water, percent by volume, will constitute the calibration. The calibration will be a continual operation, and in time will act as a check on the drift of the resistance units.

The second property of soil water which the resistance units will measure is soil water potential or tension. The knowledge of this property for plant growth relationships and possible plant distribution may be essential. Also, in conjunction with neutron probe measurements, the measurement of soil water potential would enable the calculation of soil water conductivities in the field. Because of the significance of soil water potential, a laboratory calibration on pressure chamber equipment was conducted to give the resistance-soil water tension relationship. This calibration was time consuming (over four months for 40 units), difficult, and did not accomplish the objective of giving a calibration throughout the range of 0 to 15 Bars tension. For 28 units, a calibration was achieved to 8.0 Bars, but for the remaining 12 units only to 1.0 Bar, due to a failure in the ohmmeter. It is possible that the resistance units can be calibrated to soil water tension *in situ* by use of thermocouple psychrometers, which are currently being tested as an offshoot of the soil water study. The calibration results for the electrical resistance units is shown in Table 3.

2.3 Thermocouple Psychrometers

Although only now in the laboratory testing stage, the potential of thermocouple psychrometry to the area of plant-soil-water relations in the overall grassland study is quite promising. This summer's field assistant to the soil water study has taken on the assignment of developing laboratory calibration procedure and preliminary field testing of these instruments. The addition of soil water potential to field measurements will increase the information content of soil water many fold, if the technique can be developed.

3. A SOIL WATER BALANCE ANALYSIS

3.1 The water Balance Equation

Verigo and Razumova, 1963, give a complete water balance for any soil volume as:

$$W_i - W_f = (M_s + M_g + M_i + L) - (E + T + N_g + N_s + N_i) \quad \text{where} \qquad (5)$$

W_i, W_f = Initial and final soil water contents

M_s = Total precipitation reaching soil surface

M_g = Influx from ground water

M_i = Lateral water influx within soil

L = Atmospheric vapor condensed in soil

E = Evaporation from soil

T = Transpiration

N_g = Outflow to ground water

N_s = Surface runoff

N_i = Lateral water outflow within soil

For the soil water study at the Pawnee Site, several assumptions concerning the water balance have been made to reduce the number of terms in Equation (4) which cannot be accounted for. Precipitation, as measured in the rain guage, will include interception by vegetation and therefore will be greater than that amount reaching the soil surface. Interception, which is not a total loss to plant growth due to transpiration reduction effects, increases as a fraction of precipitation with decreasing amounts of precipitation (Striffler, 1969). Therefore, the annual effect of interception depends largely upon the annual distribution of precipitation.

Preliminary findings from this past field season indicate that ground water exchanges do not take place at the microwatershed sites, Fig. 10. Lateral flows are probably insignificant, since saturated flow conditions rarely occur and impermeable layers do not occur within the first 10 ft of the soil profile. Condensation of atmospheric water vapor in the soil is likely to be negligible, given the low vapor pressure regime of the Pawnee Site.

These assumptions and findings reduce the soil water balance equation to:

$$W_i - W_f = M_s - N_s - E - T \qquad \text{or}$$

$$dSH_2O = P - RO - ET \qquad \text{where} \qquad (6)$$

dSH_2O = Change in soil water content

P = Precipitation

RO = Surface runoff

ET = Evapotranspiration

If Equation (6) proves to be a realistic model of soil water exchanges at the microwatershed sites, then soil water balance analysis becomes essentially an estimation of evapotranspiration for each microwatershed.

3.2 Analysis of Soil Water Balance Data

Grazing intensity variation is the major controlled variable in the experimental design of the soil water study. The impact of grazing may affect the hydrologic regime, primarily at the soil-plant-atmosphere interface. Specifically, grazing intensity effects could alter two of the processes, infiltration and evapotranspiration, by which water is redistributed within the ecosystem. If compaction reduces the infiltration rate at the soil surface, then increased runoff would be expected. Such an increase in runoff has been observed in other grazing studies, cited in Striffler, 1969. At the Pawnee Site, a thunderstorm in mid-September gave the first evidence of differential runoff due to grazing intensity. Table 4 shows the precipitation and runoff for each microwatershed. Considerable amounts of runoff occurred on both the heavily grazed microwatersheds; whereas only one other microwatershed, medium grazing, had runoff in excess of that amount contributed by the collection troughs. Increased runoff could further reduce infiltration by transporting litter downslope and thereby exposing more soil surface to rainfall impact. Active litter removal was observed on Microwatershed 1, heavily grazed, and at several places throughout the pasture. Antecedent soil water was probably not a factor in explaining the differences in runoff since the vegetation in all microwatersheds was in an advanced stage of wilting.

As yet there is no evidence of changes in evapotranspiration due to grazing effects. Differential consumption of vegetation could affect transpiration by:

1. Changing the stomatal, cross sectional area available for evaporation.
2. Changing the amount of root growth.

As described more fully below, a study conducted on an annual grassland type in California was able to correlate differences in soil water depletion to grazing intensities (Liacos, 1962). In terms of a water balance, differences in annual totals of evapotranspiration between microwatersheds and grazing intensities may be significant. The significance of evapotranspiration variation can be tested in an analysis of variance, using each access tube as a sampling point having a seasonal water balance. An abbreviated analysis of variance table is shown below.

ANALYSIS OF VARIANCE

Source	*Degrees of Freedom*	
Grazing	a - 1 = 3	, a = 4
Replication	a(b - 1) = 4	, b = 2
Error	= 72	N = 80
Total	= 79	

Should the difference in growing season precipitation between microwatersheds be large, then it may be necessary to use the ratio of evapotranspiration to precipitation as the variable of analysis.

4. SOIL WATER DEPLETION ANALYSIS

4.1 Water Available for Plant Growth

The analysis of soil water depletion over a series of growing seasons should answer the question as to what is the range of soil water available to plant growth. For the current season, more reliance may have to be placed on available water as determined by laboratory tests of soil water retention in the 0.1 Bar to 15.0 Bar range. This standard method may be sufficiently accurate, if permanent wilting occurs in the 15 to 20 Bar range. For the long range of the study, however, a more precise estimate of available water can be achieved by using average maxima and minima values obstained in the field by the neutron probe (Krumbach and Stearns, 1957).

4.2 The Grazing Effect

In the study cited above, Liacos, 1962, the investigator reviewed some of the literature in support of the hypothesis that soil water depletion is characterized by a negative exponential form. The depletion results for 1969, Fig. 6 to 9, tend to support this conclusion. A general exponential model was then applied by Liacos to the depletion data as follows:

$$Q_t = Q_o e^{-kt} \qquad \text{where} \qquad (7)$$

Q_t = Soil water content at time t

Q_o = Soil water content at time beginning

k = A constant

t = Time in days

The analysis showed that the constant, k, changed according to the grazing intensity with the result that depletion rates were greatest on the lightly grazed pasture, followed by the ungrazed, and least on the heavily grazed. The Mediterranean type climate of California's coastal region made this type of analysis quite suitable, since only traces of rainfall occur during the growing season.

At the Pawnee Site, significant amounts of rainfall come during the growing season, so that the exponential analysis is not quite so straightforward. However, by using the end points of individual depletion periods in an exponential model, as illustrated in Fig. 11, the same type of analysis may be suitable for application to soil water depletion at the Pawnee Site. If the slope constants of the model show significant differences between grazing intensities, this should corroborate the analysis of variance results from the water balance analysis.

5. SOIL WATER SPATIAL VARIATION

5.1 The Vertical Profile of Soil Water

In the vertical scale Fig. 12 shows the profile retreat for Microwatersheds 2 and 3 during this past summer period, 1969. One feature of interest is the apparent percolation of water to the 60 cm and 90 cm depth, Fig. 13, during the three-week period following the June measurement. That water can be withdrawn from the 90 cm depth is shown in Fig. 14. The depletion trends by horizon, as shown for two adjacent watersheds in Fig. 15, indicate greater recharge on the non-grazed as opposed to the heavily grazed site. With greater sampling frequency, and thereby increased precision in the evapotranspiration estimates, these patterns should become better defined in the 1970 growing season.

5.2 The Horizontal Distribution of Soil Water

Whether or not groupings of plants, variations in soil properties, the contribution of slope position, or interactions of these factors produce small scale changes in the soil water content within a microwatershed is a subject of interest. An isohyetal plot of Microwatershed 1 in late June, Fig. 16, can be compared with a similar map for mid-September, Fig. 17, when most of the available water had been depleted, and again with another plotting in early November, Fig. 18, after recharge had taken place. The similarity of the isohyets on all dates suggests that soil variation, rather than vegetative or topographic differences, is responsible for the pattern. If the isohyets of mid-September had been produced by differential evapotranspiration due to distinctive plant groupings, then it would seem logical that the isohyet pattern would be different after recharge.

infiltration rates would be higher on the drier locations, tending to change the September pattern. By the same reasoning, slope position and infiltration opportunity downslope should have changed the pattern, if this were a factor.

Another type of isohyetal map for Microwatershed 4 of evapotranspiration for a six-week period during the growing season, 1969, Fig. 19, reveals considerable variation. The high and low amounts of the period, over 5 cm of water, occurred at adjacent sampling points. The overall pattern lends no support to the slope position concept of overland flow redistribution. In fact without detailed vegetative, contour, or soil mapping the isohyet pattern is difficult to interpret. Vegetative patterns could be a factor in soil water horizontal distribution, if the distribution of cool and warm season plants is distinct (Sharp et al, 1964), or if the ability of plants to extract soil water against energy gradients varies considerably (Branson et al, 1967).

Topographic variation in microscale could also explain differences in soil water content. It is quite probable that sharp contrasts in infiltration rates exist between bare and vegetated portions of the grassland. Observations at the microwatersheds discovered that the bare areas are interconnected to a certain degree, forming a drainage network of microchannels. It seems likely that runoff takes place mainly in the microchannel net, where infiltration rates are lower and surface friction to flow at a minimum. The variation in microchannel development across a microwatershed could account for differences in soil water content. In addition if grazing intensity has an effect on microchannel development or on the percentage of bare ground, then the soil water content should reflect this influence.

Isohyetal mapping will be continued and expanded to all microwatersheds throughout the measurement periods in 1970.

6. EVAPOTRANSPIRATION ANALYSIS[1/]

6.1 The Position of Evapotranspiration in the Study

Central to the soil water study is the consideration of evapotranspiration in the soil-plant-atmosphere system of the Pawnee Site. If the preliminary findings and basic assumptions are correct, then nearly all of the soil water depletion is caused by evapotranspiration. Reference has been made to the analysis of soil water contents at depths greater than 1.5 m, Fig. 10, which suggests that percolation below the root zone is minimal. For this reason, the water balance model, Equation (6), shows evapotranspiration as the single depletion term. The model will be programmed so that daily estimates of evapotranspiration will be produced. These daily estimates will be calculated from changes in soil water content between successive measurements, during which time no rainfall occurred. If a minimum sampling frequency of one week can be maintained, then the daily estimate should be reasonably accurate.

In the discussion of grazing effects the procedure of developing a water balance for each access tube position was mentioned, so that 80 estimates of evapotranspiration across the four grazing intensity pastures will be produced. These 80 estimates also will result in a single estimate of evapotranspiration for each microwatershed, and, if appropriate, replicate microwatersheds can be combined for comparative purposes.

1/ The term "evapotranspiration" is a misnomer, but its long tradition and widespread use probably have "institutionalized" the word.

6.2 The Development of an Evapotranspiration Function

The worldwide approach to evapotranspiration study has treated the problem as primarily a meteorological phenomenon (Rosenburg et al, 1968). Yet it is generally accepted that soil factors and mechanisms of plant physiology are equally involved. The overall grassland study offers an excellent opportunity to combine the simultaneous measurement of soil, plant, and atmospheric variables in an analysis of evapotranspiration.

As a first step in the development of a quantitative expression for evapotranspiration a multiple linear regression is proposed. The dependent variable will be the change in soil water content as determined by the neutron probe and/or electrical resistance measurements. The independent variables will be those soil, plant, and atmospheric factors which are believed to be important in the processes of evaporation and transpiration and which are being monitored on or near the microwatersheds. As a practical matter, data from Microwatersheds 2 and 3 will be used in the analysis, since the permanent micro-meteorological station will be set up near these adjacent microwatersheds, which have the added advantage of representing the extremes in grazing intensity.

Soil factors which will be measured and may be significant in the process are the soil water potential, temperature, and heat flux. Plant measurements from the biomass studies are root, standing dead, standing live, and litter amounts; and from the proposed phytosociological study leaf area, or some index related to plant cover and transpiring surface. Atmospheric variables should include net radiation and air temperature, relative humidity, and wind velocity gradients or other parameters which can be derived from these. In the case of the micrometeorological and soil variables, measurements will be taken on hourly and, for some, one-minute intervals. The biomass and soil water measurements with the neutron probe will be sampled at weekly or biweekly intervals. It will be necessary to use averaging or scaling techniques for those variables measured more frequently than change in soil water content.

The multiple regression model initially will be of the form:

$$ET = b_o + b_1X_1 + b_2X_n + . . . + b_nX_n \quad \text{where} \tag{8}$$

b_n refers to the multiple regression coefficient

X_n refers to the independent variable or interactions among them

The value of a multiple regression model as a first step in the evapotranspiration analysis is the opportunity to show the relative importance of major groups of independent variables, soil-plant-atmosphere, by a screening process. Secondly, the individual contribution of each variable within a group can be assessed and compared to other independent variables (few of the independent variables are truly independent of soil water change). As a result of the regression analysis, conclusions (hypothetical) can be made such as:

1. Atmospheric factors limited evapotranspiration during the early spring period of plant dormancy and soil water recharge. Changes in the vertical gradient of specific humidity explained more of the variation in ET than did any other atmospheric factor included in the analysis.
2. Plant factors became increasingly important to the evapotranspiration process as growth occurred rapidly in the late spring. Changes in root biomass were the most important variable.
3. Soil factors became dominant as plant growth decreased in the

wilting period of late summer and early fall. Soil water potential accounted for most of the change in ET attributable to soil factors.

A third contribution of the multiple regression model will be to the prediction of soil water depletion.

7. SOIL WATER PREDICTION MODELLING

7.1 A General Hydrologic Model

One of the principal objectives of the Grasslands Biome study is the development of a quantitative model which will describe the dynamics of grassland ecosystem productivity. This general model will include submodels referring to distinct processes or systems within the larger ecosystem (Bledsoe and Jameson, 1969). Eventually, an overall hydrologic model will be one of the submodels. The hydrologic model in the initial development probably will contain both stochastic and deterministic elements, precipitation being the main stochastic component and the disposition of rainfall at least quasi-deterministic. A study to develop a hydrologic model for the closed basin which contains all but one of the microwatersheds is planned by another member of the hydrologic study. Microwatershed models also will contribute to a general hydrology model.

7.2 Microwatershed Modelling

A microwatershed model will be concerned with the redistribution of precipitation after it occurs. Overland flow, infiltration, and evapotranspiration will be the primary processes in a microwatershed model. Dr. Robert Burman, University of Wyoming, will be responsible for the development of an overland flow model based upon kinematic wave theory. An infiltration term, probably the well known function proposed by Horton, will be employed in the overland flow model to generate runoff. This same infiltration function can be used to produce additions to soil water.

As emphasized repeatedly in this report, depletion of soil water at the microwatersheds is likely to be accounted for by evaporation and transpiration alone. There is no technique in the measurement design for separating the two components of evapotranspiration, so the combined effect will be used in soil water modelling. Ideally, a soil water prediction model should be time dependent, so that once the amount of water in a profile is known, the depletion can be predicted as a function of time. It is possible that many years of data and analysis at the Pawnee Site could lead to such an ideal function, with a limited number of parameters and measurement requirements. For the time being, something less than ideal will have to serve.

The evapotranspiration model, Equation 8, if successful, could be incorporated into a soil water model directly. It is likely that this multiple regression model could be improved, perhaps by a step-wise regression procedure to reduce the number of independent variables. One drawback to this approach is that measurements of all independent variables used in the prediction equation are required. However, since these measurements will be available over the next few years, a multiple regression model can be tested and refined.

Another alternative would be to employ the exponential model, Equation 7, should this analysis prove reliable. For soil water prediction purposes, each individual depletion cycle might have to be used in the modelling, rather than using the end points of depletion periods, as discussed in Section 4.2. In any event, this model may be workable.

A third set of alternatives is the use of some or all of the micrometeorological models which have been developed for evapotranspiration estimation (Rosenburg et al, 1968). The micrometeorology study will apply both the aerodynamic and energy balance, Bowen ratio, methods for determining fluxes of water as well as energy. The required measurements for the Penman, Thornthwaite, Jensen-Haise and other evapotranspiration formulae also will be available.

Soil water prediction techniques have been developed by investigators for modelling purposes. The well known Stanford model in the field of hydrology is one of the better examples. More recently, a soil water model was reported as part of an agronomic study (Shanholtz and Lillard, 1968). Most of these models employ a potential evapotranspiration formula which is then modified by the amount of soil water as a fraction of available storeage in the soil profile. Adoption or modification of one of these existing models is another possibility for soil water prediction at the Pawnee Site.

It is probable that real progress in defining the evapotranspiration process at the Pawnee Site will come after the lysimeter installation.

8. CONCLUSIONS

There may be other forms of analysis which can be applied to the microwatershed soil water data. Spectral frequency analysis is one such possibility. The studies will look into this methodology which has been used with some success in hydrology and micrometeorology, but I suspect that cross spectrum analysis, Fourier series, and the like may require more than one season or cycle to yield information.

It is also possible that multivariate rather than multiple regression statistical methods should be employed in the evapotranspiration analysis, Section 6. Use of principal component, factorial, or discriminate analysis will be investigated.

To summarize, the principal analyses proposed to answer the questions raised in Section 1.3 are:

1. A water balance for each microwatershed
2. An analysis of variance for evapotranspiration across all four grazing intensities and all microwatersheds.
3. A soil water depletion analysis applying the exponential model to each microwatershed.
4. A descriptive analysis of soil water spatial variation.
5. A multiple regression analysis on factors contributing to evapotranspiration.

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Table 1. Summary statistics of the soil bulk density measurements taken on the eight microwatersheds at the Pawnee Site.

Microwatershed	Horizon	Bulk Density	Standard Deviation	Range	# Samples
1	A	1.44	0.06	1.36-1.50	7
	B	1.43	0.04	1.36-1.47	5
	C	1.51	0.02	1.47-1.53	4
2	A	1.32	0.06	1.17-1.39	9
	B	1.39	0.10	1.29-1.50	5
	C	1.56	0.04	1.51-1.61	5
3	A	1.36	0.04	1.32-1.43	6
	B	1.41	0.09	1.30-1.49	5
	C	1.42	0.07	1.32-1.51	6
4	A	1.44	0.07	1.33-1.52	5
	B	1.51	0.04	1.44-1.55	5
	C	1.61	0.05	1.56-1.69	5
5	A	1.44	0.09	1.28-1.51	5
	B	1.48	0.05	1.43-1.55	5
	C	1.57	0.01	1.56-1.59	5
6	A	1.42	0.05	1.35-1.48	6
	B	1.48	0.03	1.43-1.52	5
	C	1.57	0.05	1.52-1.63	3
7	A	1.38	0.08	1.22-1.49	7
	B	1.43	0.04	1.36-1.48	5
	C	1.56	0.06	1.45-1.62	5
8	A	1.28	0.10	1.08-1.43	10
	B	1.44	0.08	1.38-1.58	5
	C	1.48	0.05	1.4 -1.55	5

Table 2. Summary of average soil water contents.

Depth (cm)	MICROWATERSHED 1	2	3	4	5	6	7	8
			(June 23,24, 1969)					
15	3.4	3.3	4.0	3.1	2.8	3.2	3.0	3.3
30	4.4	5.2	5.8	4.5	3.9	4.2	4.6	5.3
45	3.9	5.2	4.5	4.2	3.6	4.6	5.0	5.7
60	3.4	3.6	3.4	3.9	3.5	4.4	4.8	4.8
75	2.8	3.0	2.8	3.7	3.5	3.1	4.1	3.5
90	2.3	2.9	2.7	3.6	3.4	2.4	3.4	2.7
TOTAL	20.2	23.2	23.2	23.0	20.7	21.9	24.9	25.3
			(July 15,17, 1969)					
15	1.6	1.5	1.8	1.4	1.3	1.7	1.5	2.8
30	2.6	3.2	3.9	2.6	2.4	2.7	2.8	4.5
45	2.7	4.3	4.0	2.9	2.6	3.6	3.6	5.1
60	2.5	3.8	3.3	3.0	2.7	4.0	3.9	4.6
75	2.4	3.2	2.8	3.1	2.8	3.4	3.5	3.5
90	2.2	3.1	2.7	3.3	3.0	2.8	3.1	2.9
TOTAL	14.0	19.1	18.5	16.3	14.8	18.2	18.4	23.4

(table continued)

Table 2. Continued.

	MICROWATERSHED							
	1	2	3	4	5	6	7	8
Depth (cm)				(August 6-8, 1969)				
15	1.3	1.0	1.7	1.3	0.9	0.9	1.2	1.3
30	2.1	2.3	3.4	2.3	1.9	1.8	2.4	2.9
45	2.1	3.1	3.4	2.4	2.0	2.2	3.2	3.7
60	2.0	3.0	3.1	2.5	2.1	2.6	3.6	3.3
75	2.0	2.8	2.9	2.7	2.3	2.4	3.5	2.6
90	2.0	2.7	2.8	2.9	2.5	2.2	3.3	2.4
TOTAL	11.5	14.9	17.3	14.1	11.7	12.1	17.2	16.2
				(September 15-17, 1969)				
15	2.6	0.7	1.1	0.7	0.9	2.0	2.3	1.7
30	2.3	2.0	3.0	1.7	2.0	2.2	2.6	2.8
45	2.0	2.8	3.2	1.8	2.1	2.2	2.8	3.4
60	1.8	2.7	2.9	1.8	2.2	2.3	3.0	3.0
75	1.8	2.5	2.7	1.9	2.4	2.2	2.9	2.4
90	1.9	2.6	2.7	2.1	2.5	2.0	2.8	2.3
TOTAL	12.4	13.3	15.6	10.0	12.1	12.8	16.4	15.6

Table 3. Calibration Table for Coleman Resistance Units.

Unit No.	Temp. Corr. Coeff.	b_o Intercept	b_1 Coeff.	b_{11} Coeff.	MWS	Depth (cm)
1	1.00	2.66960×10^{-1}	-2.76742×10^{-7}	1.12689×10^{-13}	1	2
2	1.00	2.86353×10^{-1}	-3.45440×10^{-7}	8.52316×10^{-14}	1	10
3	1.00	2.58441×10^{-1}	-3.35551×10^{-7}	2.11178×10^{-13}	1	20
*13	1.00	3.21677×10^{-1}	-3.61519×10^{-7}	8.34027×10^{-14}	1	40
*21	1.01	2.32364×10^{-1}	-1.51457×10^{-7}	6.40986×10^{-14}	1	60
4	1.00	2.65176×10^{-1}	-3.13774×10^{-7}	1.83607×10^{-13}	2	2
5	1.00	1.58098×10^{-1}	1.32670×10^{-7}	3.46513×10^{-14}	2	10
6	1.00	1.85646×10^{-1}	8.17886×10^{-10}	1.21979×10^{-13}	2	20
37	1.04	1.05151×10^{-1}	1.41068×10^{-7}	1.26827×10^{-14}	2	40
*14	1.00	1.55675×10^{-1}	1.34338×10^{-7}	9.27559×10^{-14}	2	60
7	1.00	2.32845×10^{-1}	-1.59340×10^{-7}	8.56026×10^{-14}	3	2
8	1.00	2.16718×10^{-1}	-9.97268×10^{-8}	5.00858×10^{-14}	3	10
9	1.00	1.97600×10^{-1}	-4.90548×10^{-8}	1.34513×10^{-13}	3	20
38	1.04	1.21033×10^{-1}	1.71742×10^{-7}	1.85300×10^{-14}	3	40
*15	1.00	3.32979×10^{-1}	-3.87804×10^{-7}	6.31690×10^{-14}	3	60
10	1.00	1.66770×10^{-1}	1.83477×10^{-8}	3.04064×10^{-14}	4	2
11	1.00	2.34614×10^{-1}	-1.50186×10^{-7}	7.46848×10^{-14}	4	10
12	1.00	1.83545×10^{-1}	2.47975×10^{-8}	5.69402×10^{-14}	4	20
[illegible]	1.04	1.68687×10^{-1}	-4.88031×10^{-8}	6.34344×10^{-14}	4	40
*16	0.99	1.63868×10^{-1}	1.01523×10^{-7}	7.20091×10^{-14}	4	60
24	1.01	2.76587×10^{-1}	-4.34487×10^{-7}	1.74925×10^{-13}	5	2
25	1.01	2.21301×10^{-1}	-2.34835×10^{-7}	2.40107×10^{-13}	5	10
27	1.02	3.44410×10^{-1}	-8.69235×10^{-7}	4.95899×10^{-13}	5	20
*17	0.99	1.99239×10^{-1}	-2.57315×10^{-8}	7.32002×10^{-14}	5	40
*22	1.01	1.86420×10^{-1}	-2.47546×10^{-8}	4.31164×10^{-14}	5	60
28	1.02	3.28477×10^{-1}	-8.69174×10^{-7}	5.41372×10^{-13}	6	2
29	1.02	2.62087×10^{-1}	-2.70563×10^{-7}	8.45114×10^{-14}	6	10
30	1.02	2.27902×10^{-1}	-1.96390×10^{-7}	1.49353×10^{-13}	6	20
40	1.04	2.01999×10^{-1}	-5.91470×10^{-8}	5.25935×10^{-14}	6	40
*18	0.99	2.12545×10^{-1}	-1.00869×10^{-7}	8.96308×10^{-14}	6	60
31	1.03	2.27902×10^{-1}	-1.96390×10^{-7}	1.49353×10^{-13}	7	2
32	1.03	2.04625×10^{-1}	-8.30099×10^{-8}	7.85874×10^{-14}	7	10
33	1.03	1.47793×10^{-1}	-2.29089×10^{-10}	4.64674×10^{-14}	7	20
*19	0.99	1.86104×10^{-1}	-3.28954×10^{-8}	4.87513×10^{-14}	7	40
*23	1.01	2.83467×10^{-1}	-2.63157×10^{-7}	5.81371×10^{-14}	7	60
34	1.03	2.12169×10^{-1}	-1.04527×10^{-7}	6.27626×10^{-14}	8	2
35	1.03	2.67827×10^{-1}	-2.16044×10^{-7}	7.16392×10^{-14}	8	10
36	1.04	7.37966×10^{-2}	2.17773×10^{-7}	5.41939×10^{-14}	8	20
*20	0.99	1.88129×10^{-1}	-2.17077×10^{-8}	6.65192×10^{-14}	8	40
*26	1.02	2.21007×10^{-1}	-1.15499×10^{-7}	5.68937×10^{-14}	8	60

* Actual calibration does not extend beyond 1 B. Tension.

Table 4. Peak runoff rates for storm of September 17, 1969.

Micro-watershed	Grazing Treatment	Storm Precipitation (inches)	Peak Discharge (cfs)
1	Heavy	0.76	0.220
2	None	0.76	0.001
3	Heavy	0.76	0.093
4	Moderate	0.60	0.010
5	Moderate	0.60	0.045
6	Light	0.52	0.010
7	Light	0.52	0.005
8	None	0.52	Trace

Notes:

MWS 1 - Wash lines observed extending upslope from outlet approximately 2/3 of total slope length; most heavily concentrated in lower 1/3.

MWS 2 - No wash lines present. Coarse material in bore area exhibited microchannel flow.

MWS 3 - Wash lines found only in few open grassed channels near the collection trough.

MWS 4 - No wash lines, some evidence of microchannel flow.

MWS 5 - No wash lines, some evidence of microchannel flow.

MWS 6 - No wash lines, some evidence of microchannel flow.

MWS 7 - No wash lines, some evidence of microchannel flow.

MWS 8 - No wash lines, some evidence of microchannel flow.

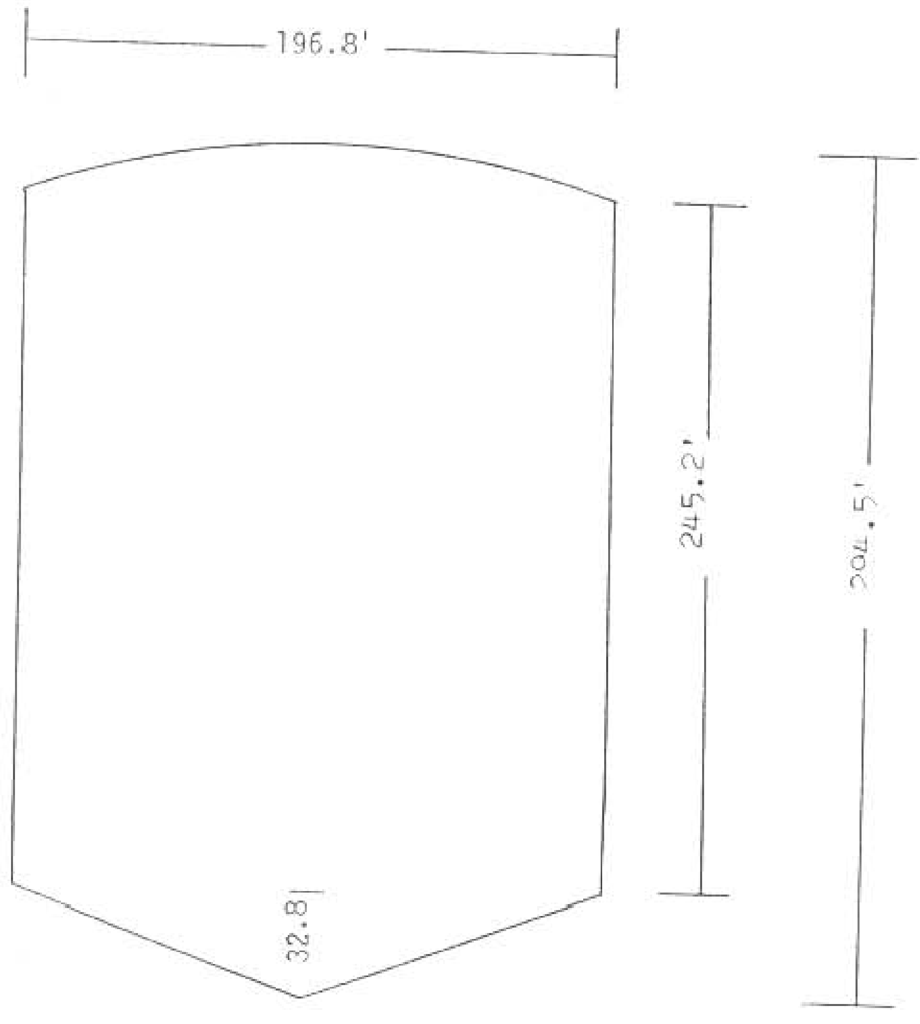


Figure 1. Dimension and shape of ½ hectare microwatershed.

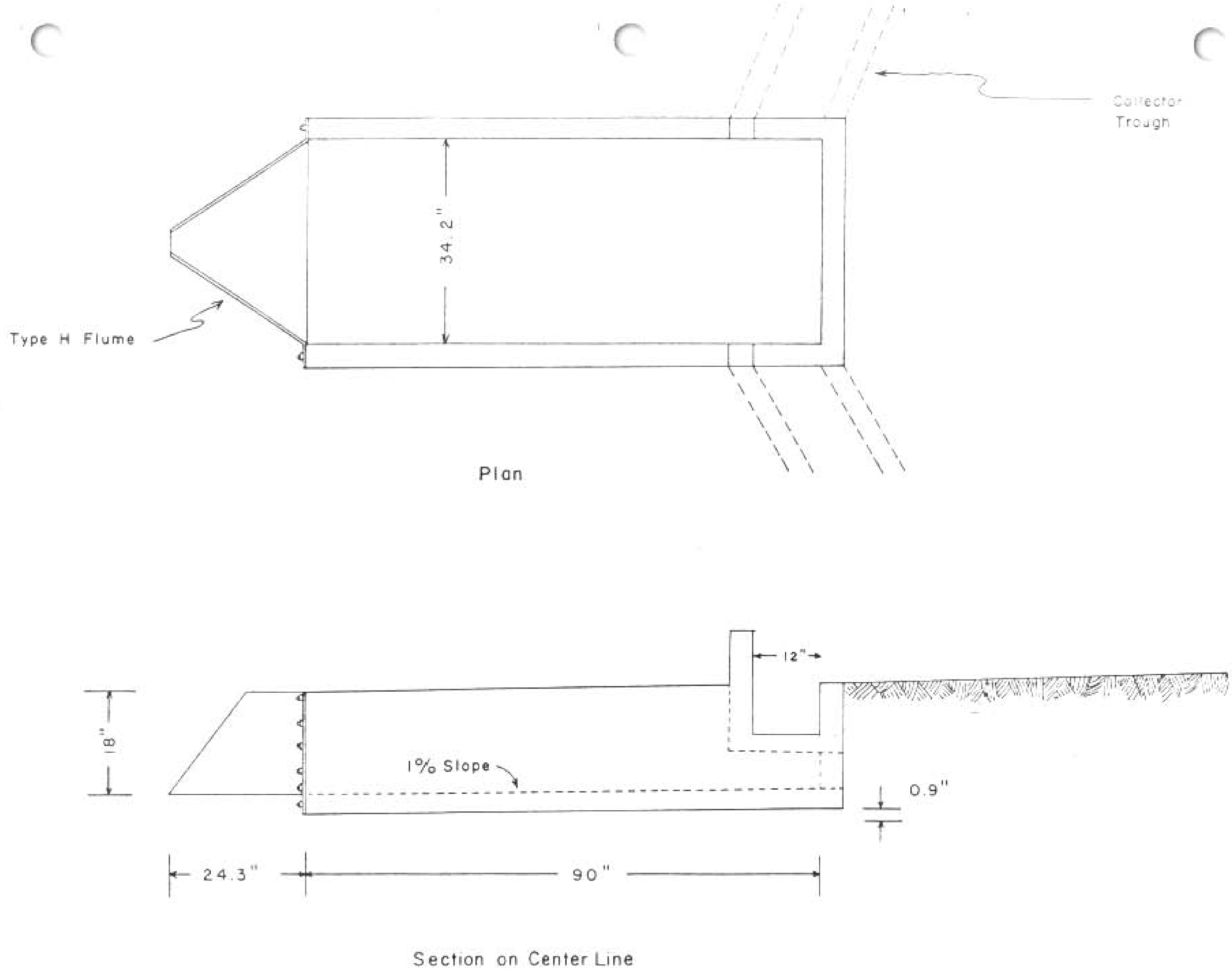


Figure 2. DROP BOX STRUCTURE FOR H FLUME

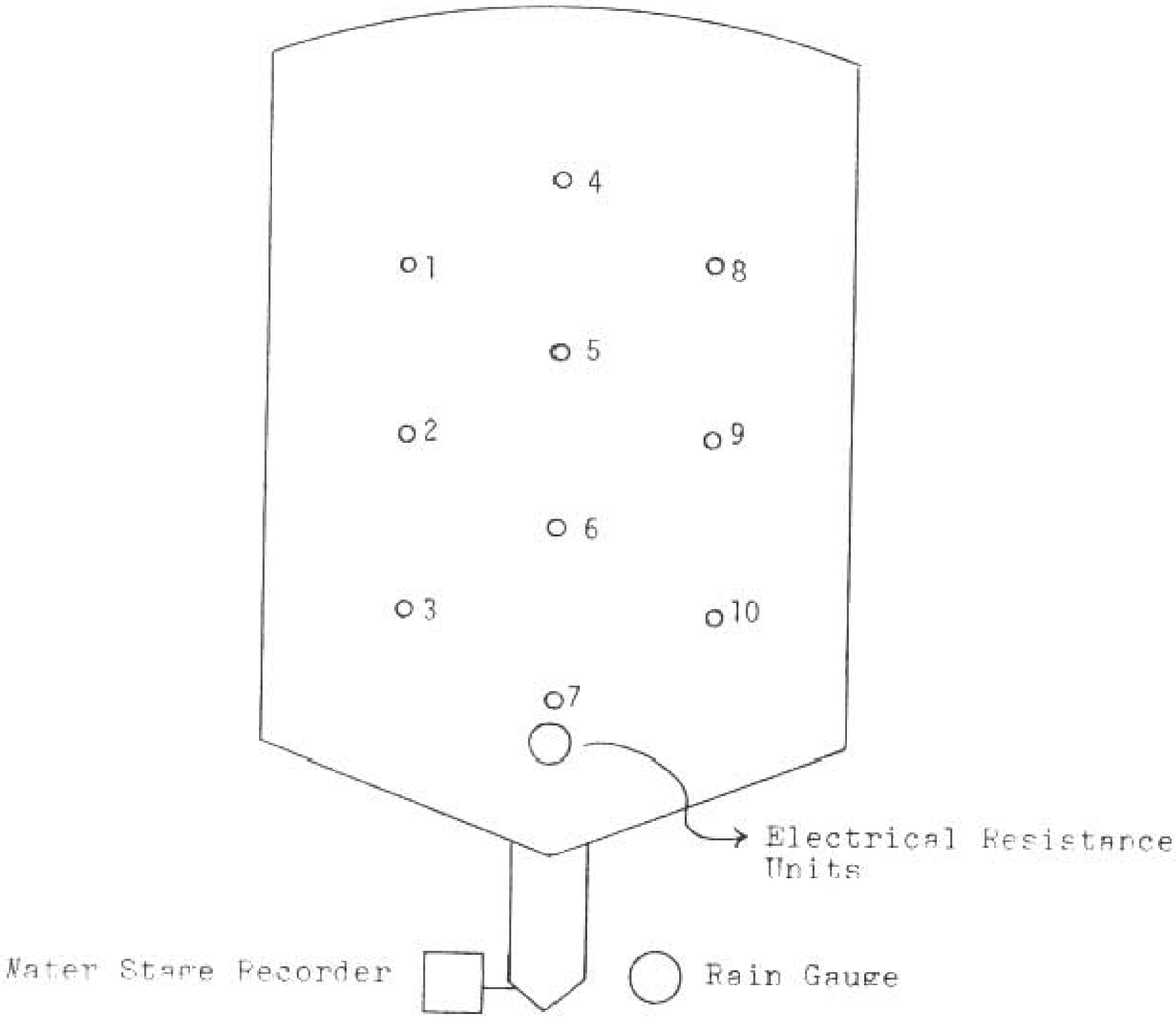


Figure 3.
LOCATION OF SOIL MOISTURE ACCESS TUBES ON MICROWATERSHEDS

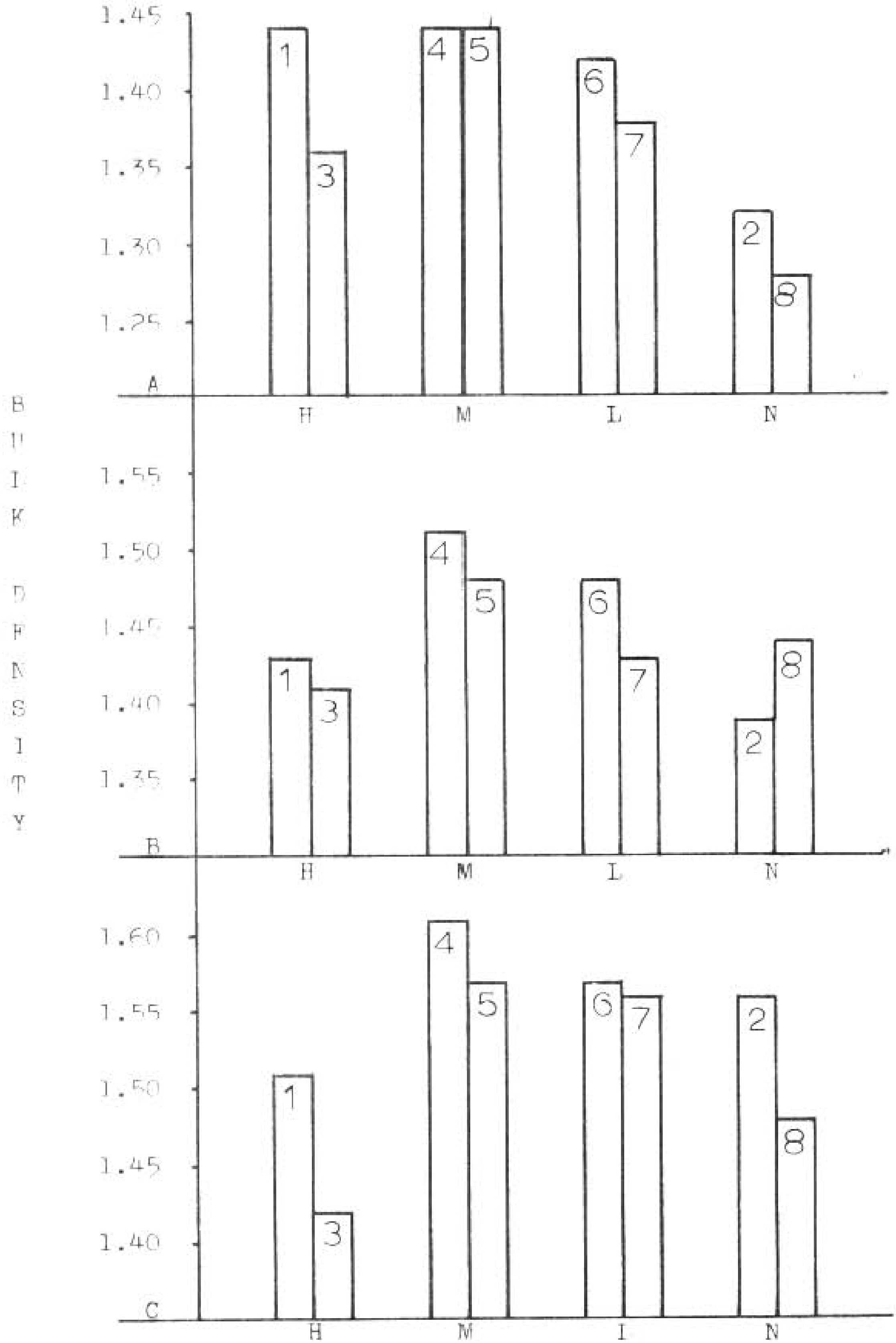


Figure 4. Bulk density distribution by soil horizon and grazing intensity; H-heavy, M-medium, L-light, N-no grazing.

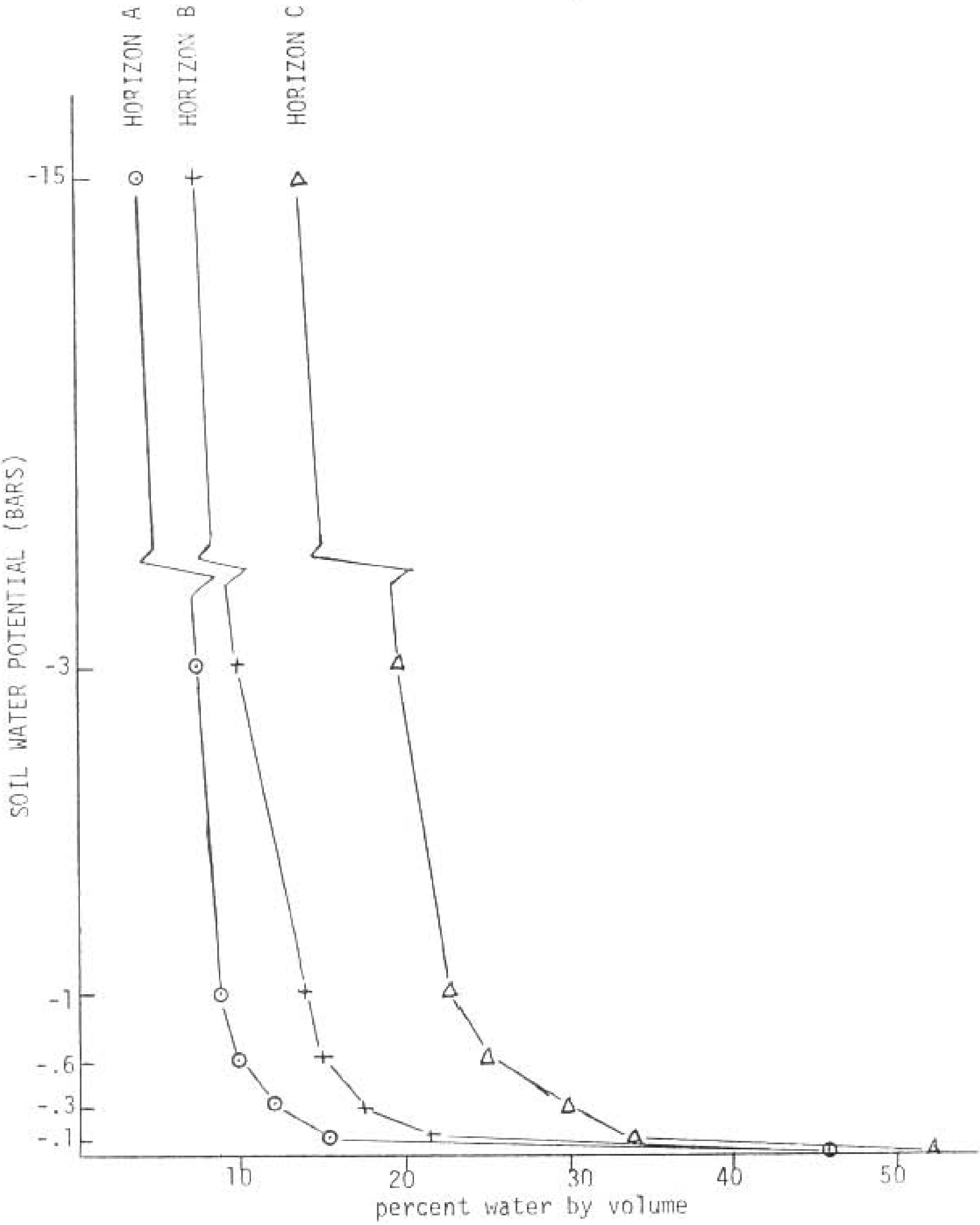


Figure 5.
REPRESENTATIVE SOIL WATER POTENTIAL CURVES, ASCALON SANDY LOAM

NO GRAZING

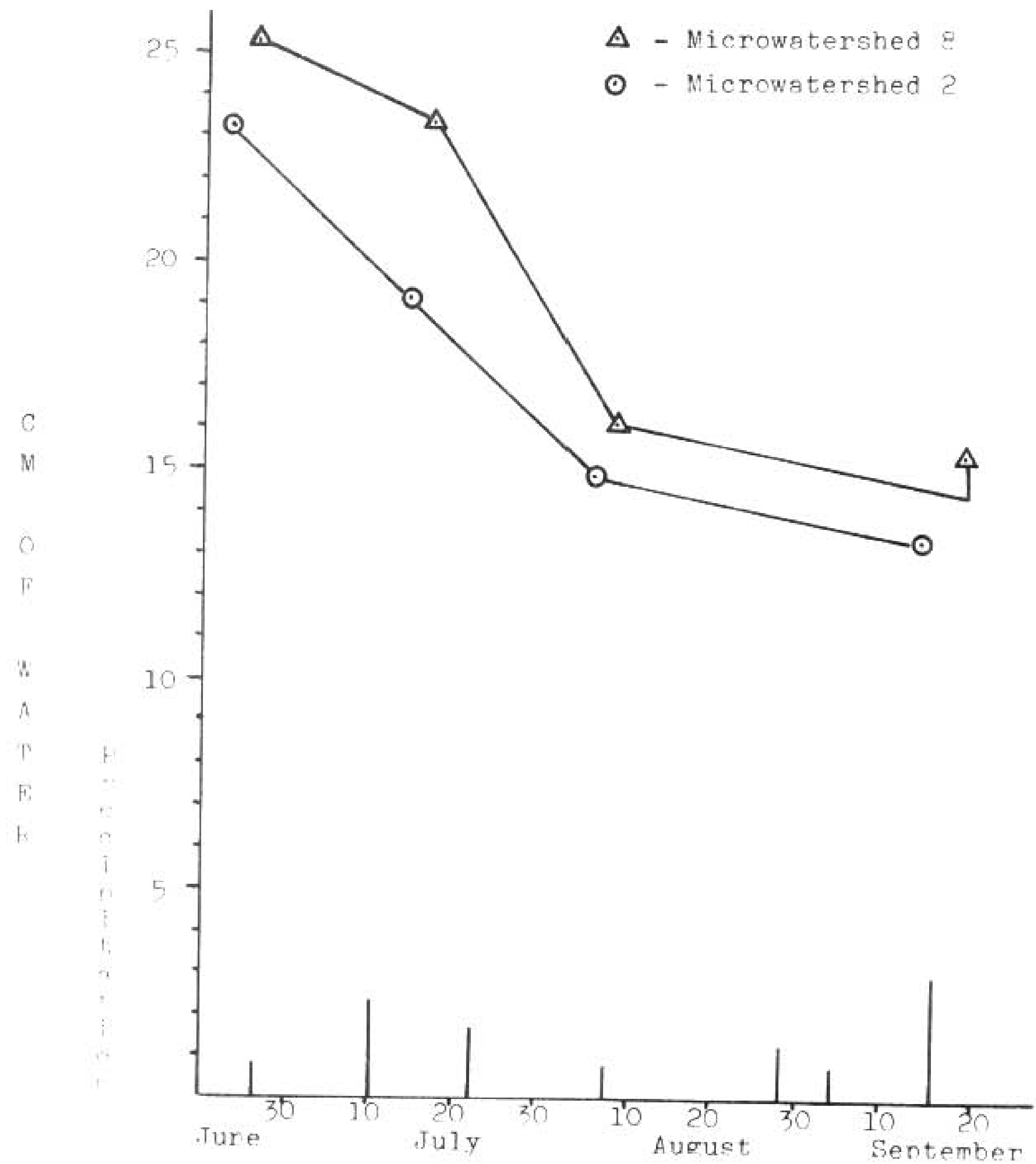


Figure 6. Soil Water depletion, the average water content for the surface to 90 cm. depth of the watershed.

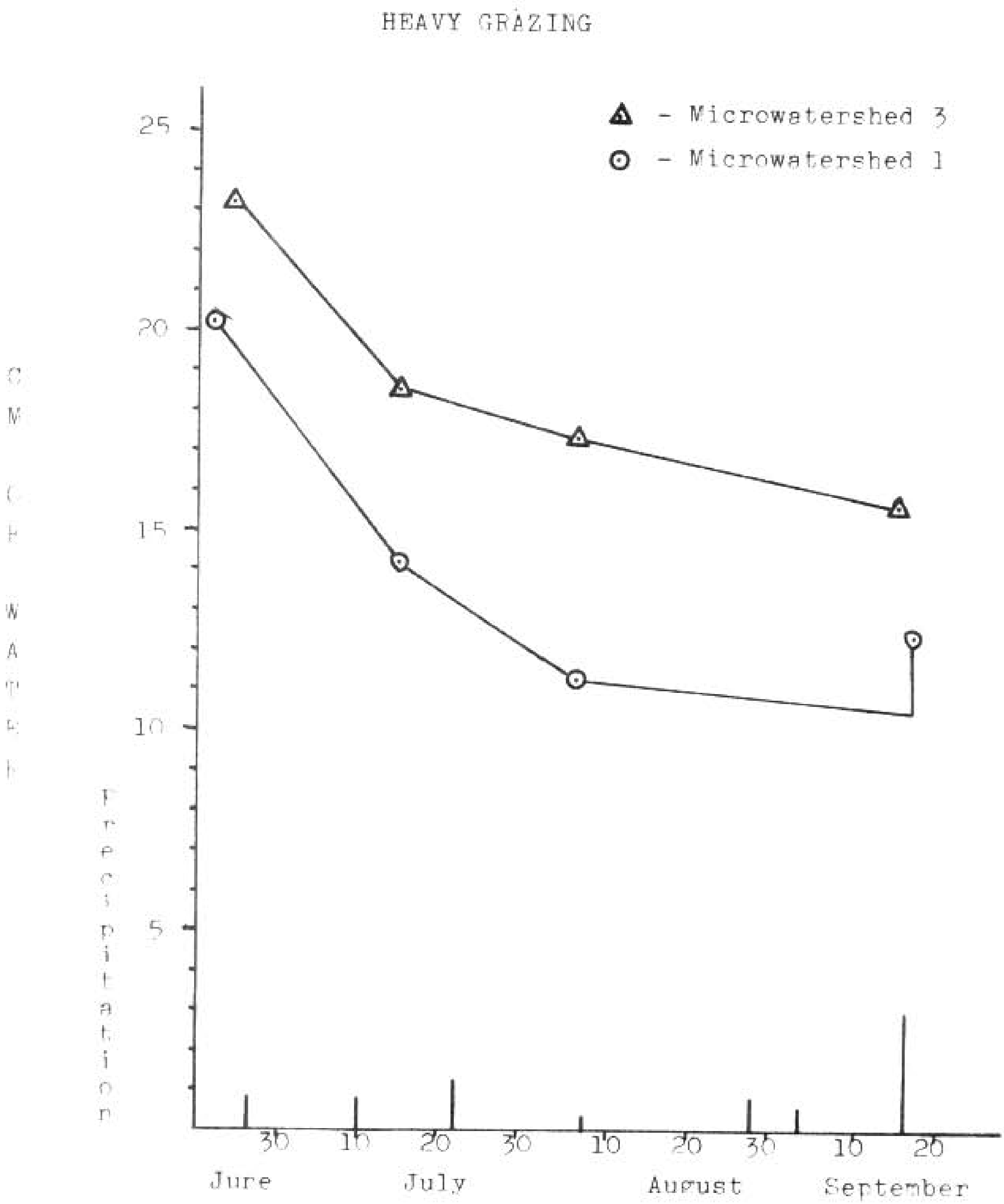


Figure 7. Soil water depletion, the average water content for the surface to 90 cm. depth of the watershed.

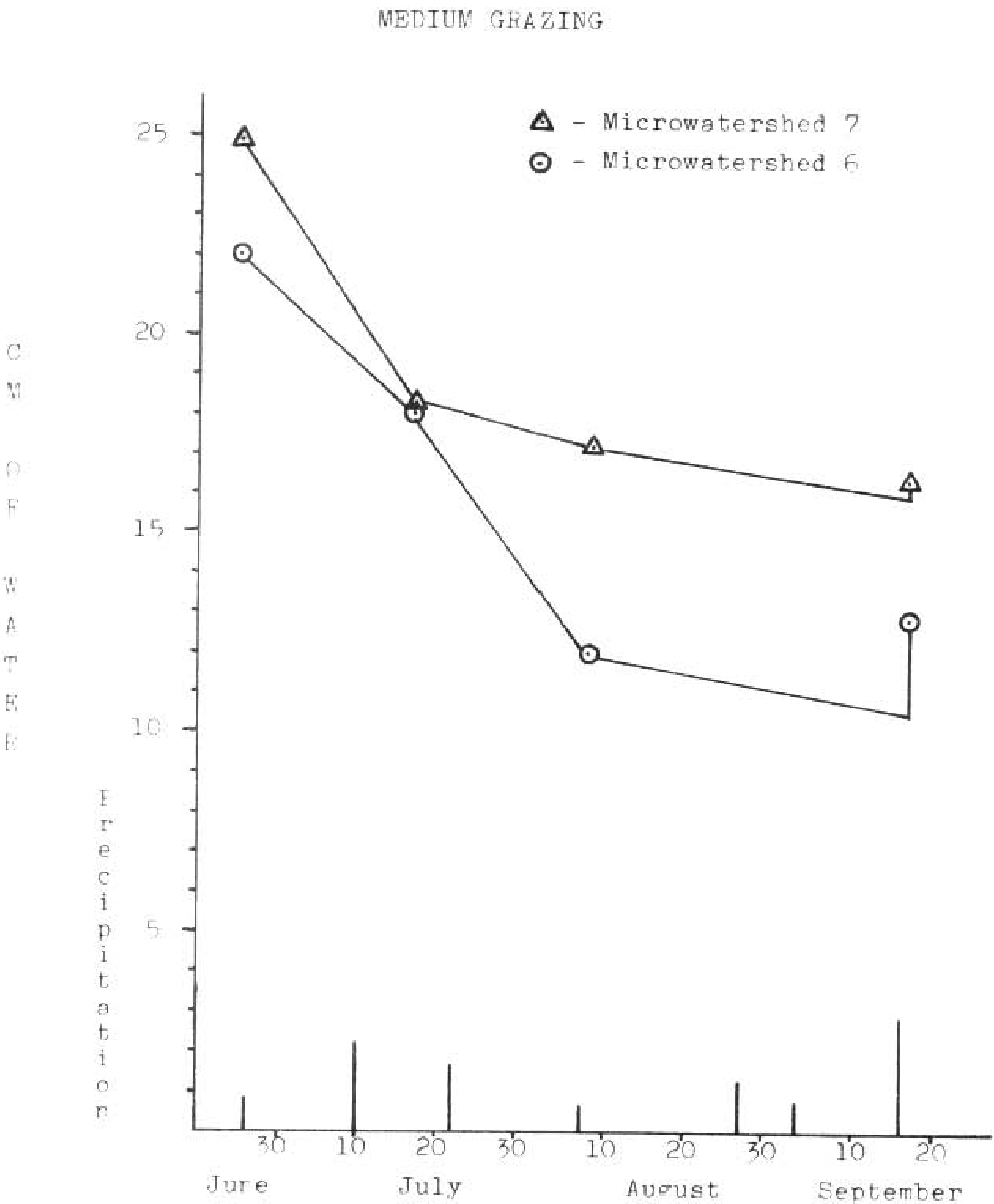


Figure 8. Soil water depletion, the average water content for the surface to 90 cm. depth of the watershed.

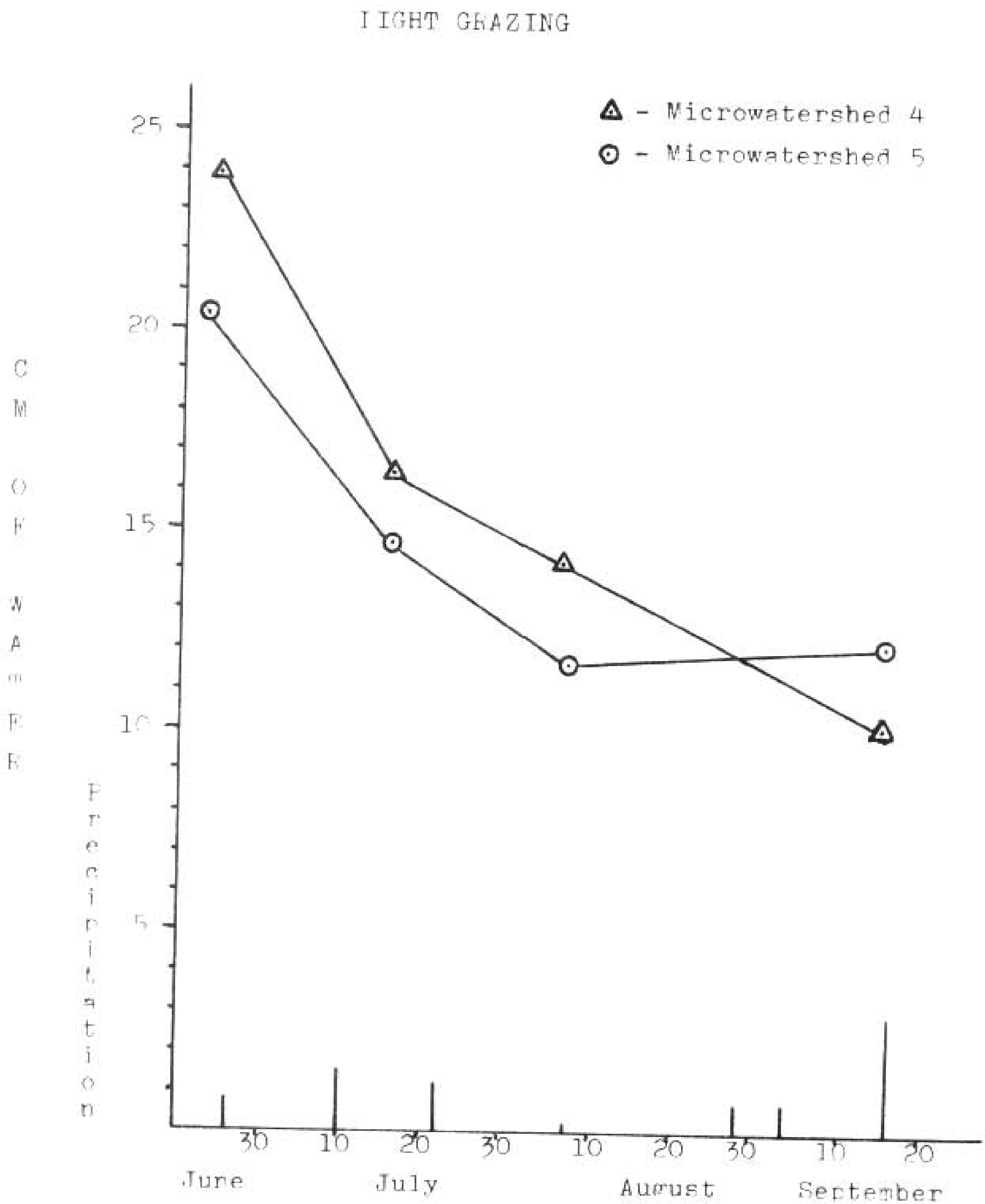


Figure 9. Soil water depletion, the average water content for the surface to 90 cm. depth of the watershed.

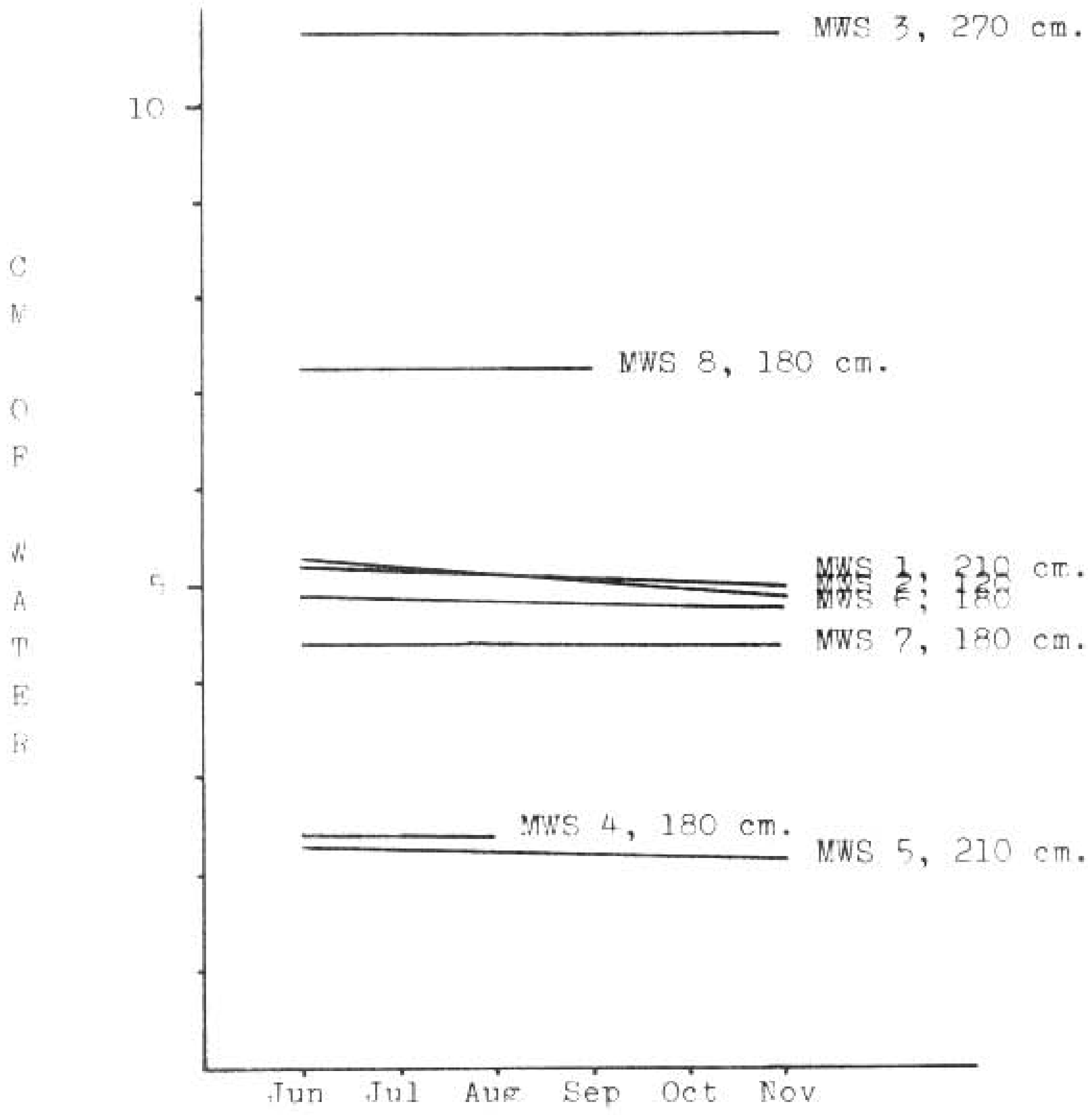


Figure 10. The lack of change in soil water contents during the measurement period at depths greater than 90 cm. is shown for each microwatershed (MWS).

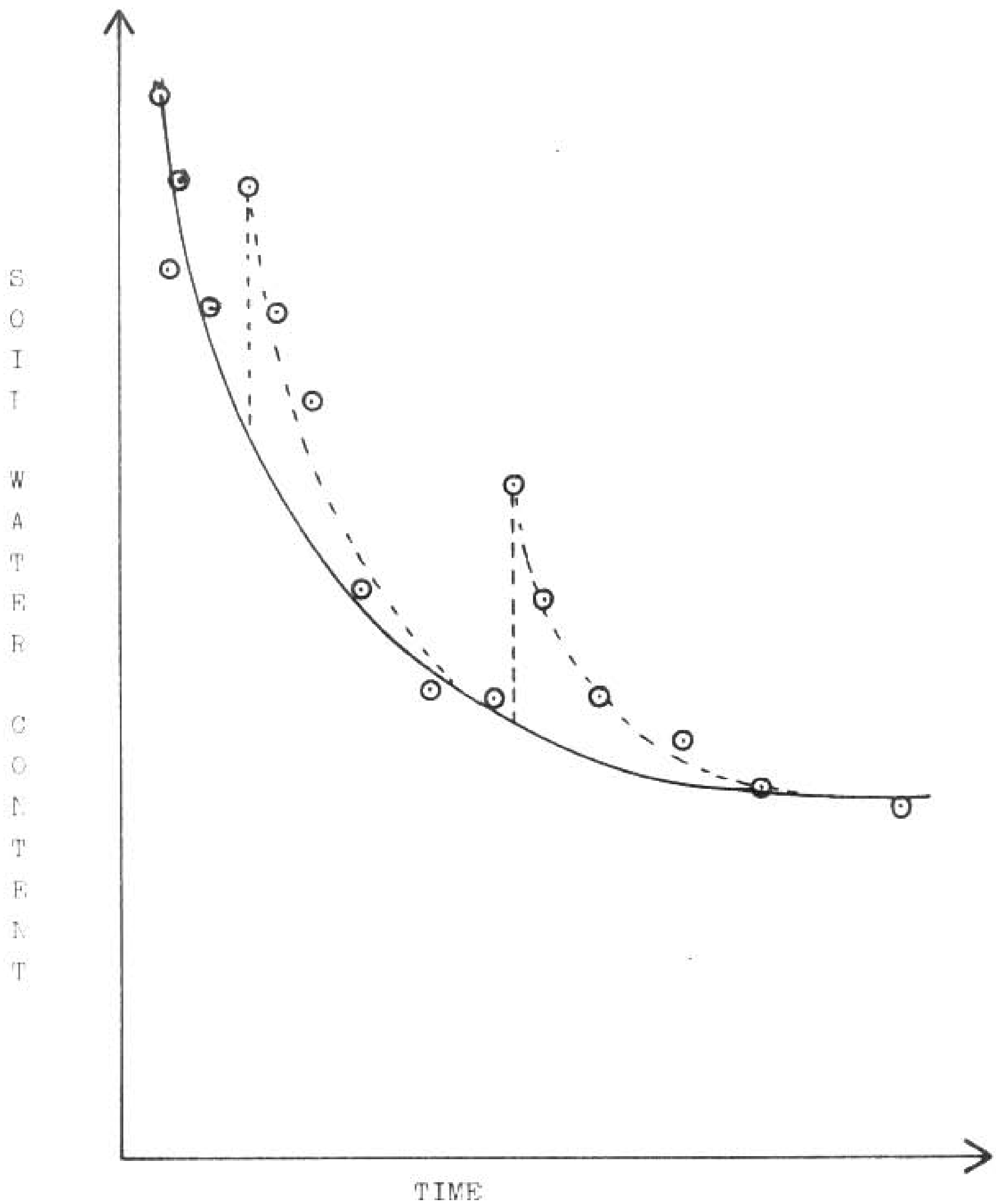
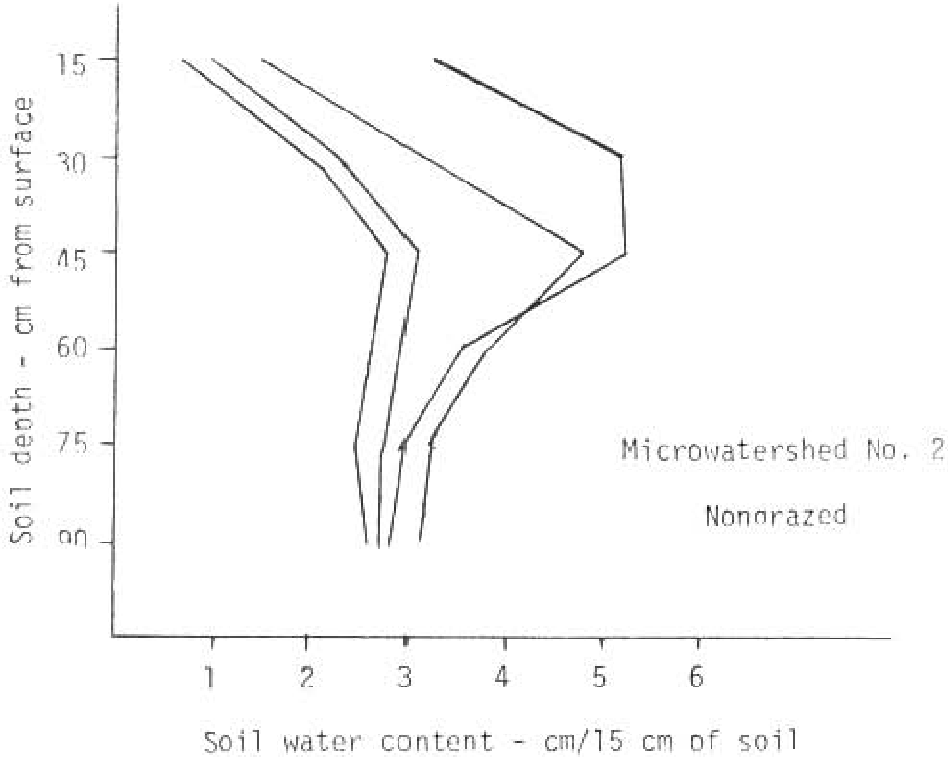


Figure 11. The graph illustrates an hypothetical soil water depletion pattern for a given grazing intensity. The solid line connects the end points of depletion periods following rainfall, shown as broken lines.



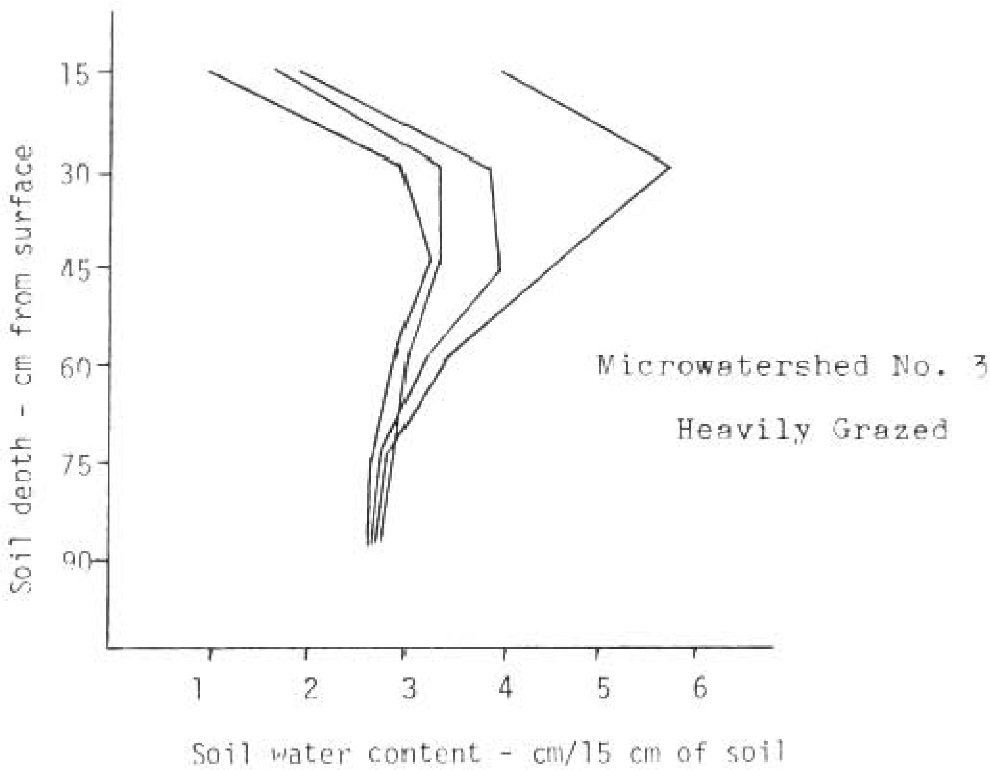


Figure 12. Soil water profiles by sampling date.

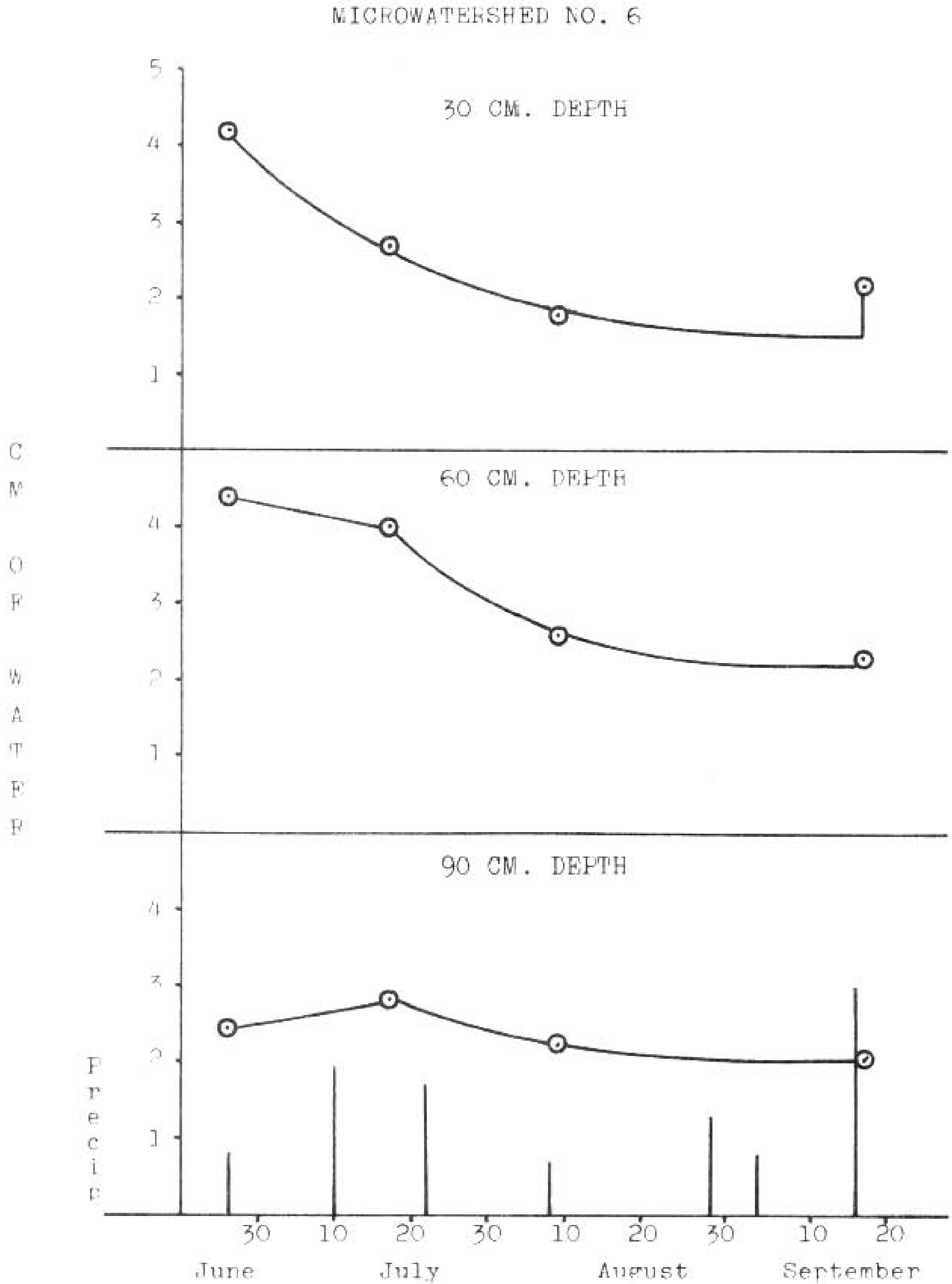


Figure 13. Soil water depletion by horizon.

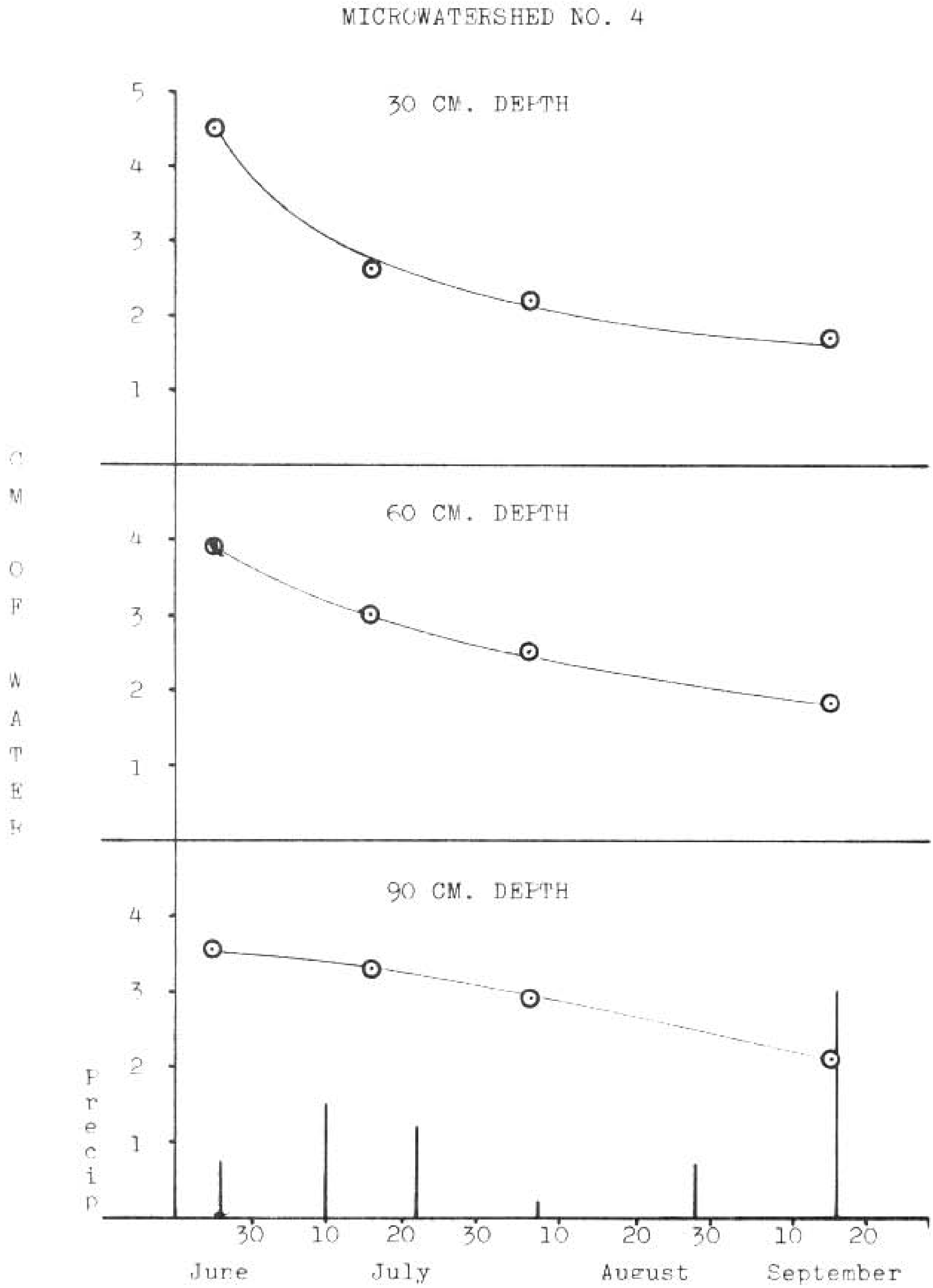
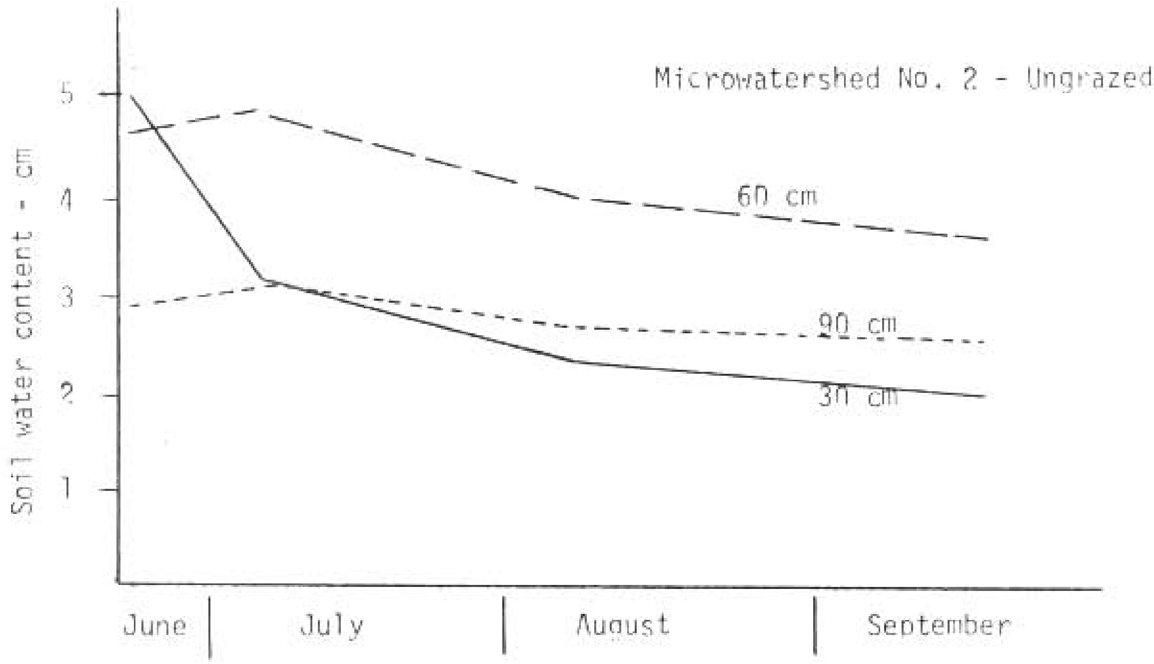


Figure 14. Soil water depletion by horizon.



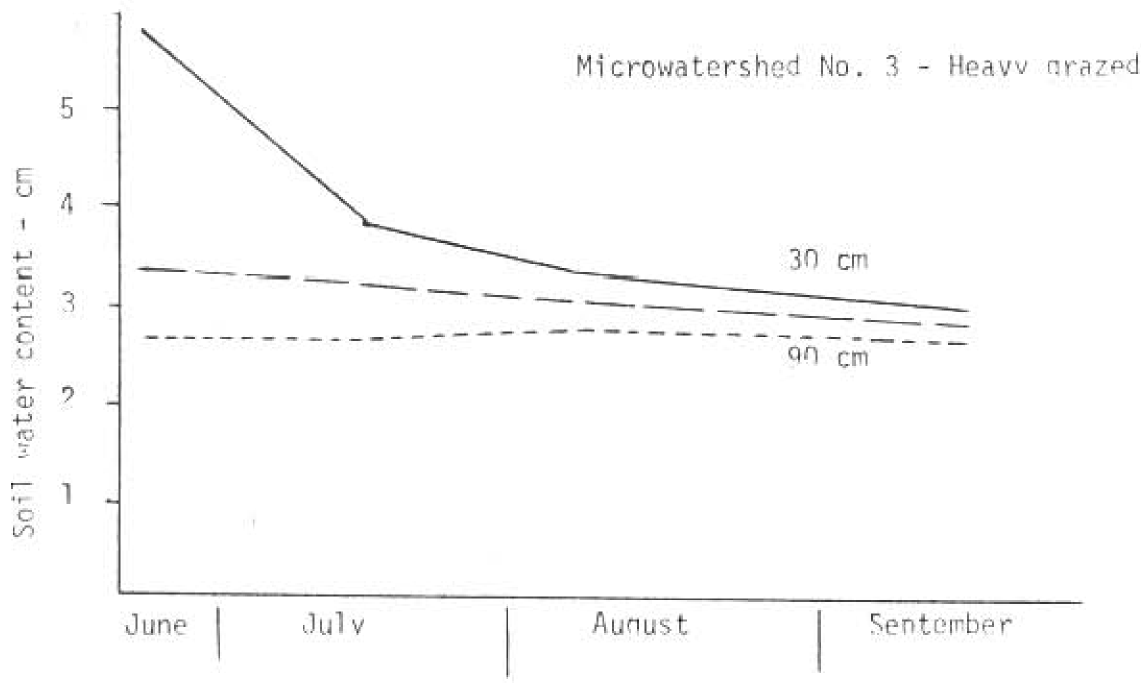


Figure 15. Soil water depletion by soil depth and treatment.

Microwatershed No. 1

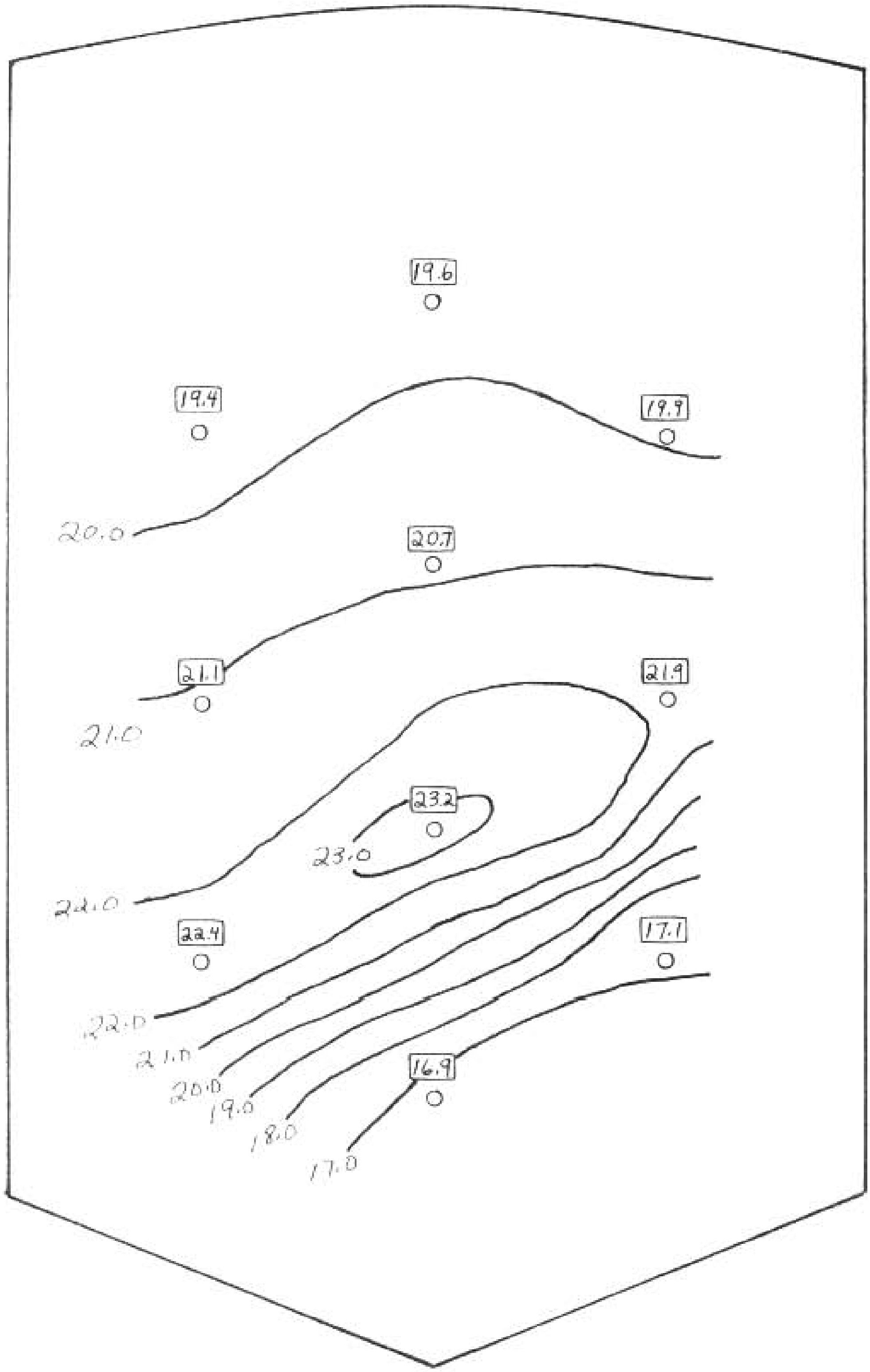


Figure 16. Isohyet map of soil water content for June 25, 1969.

Microwatershed No. 1

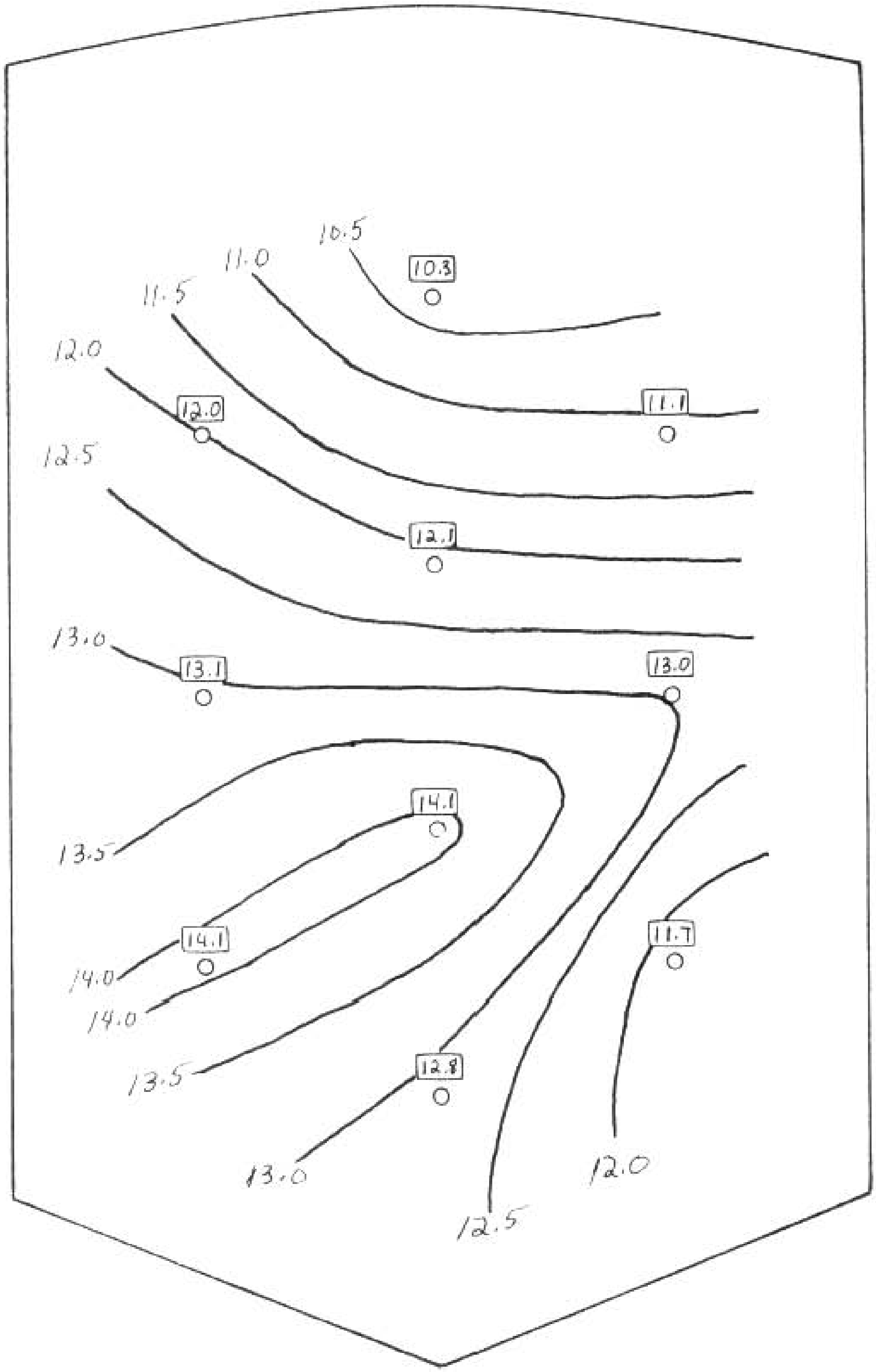


Figure 17. Isohyet map of soil water content for Sept. 15, 1969

Microwatershed No. 1

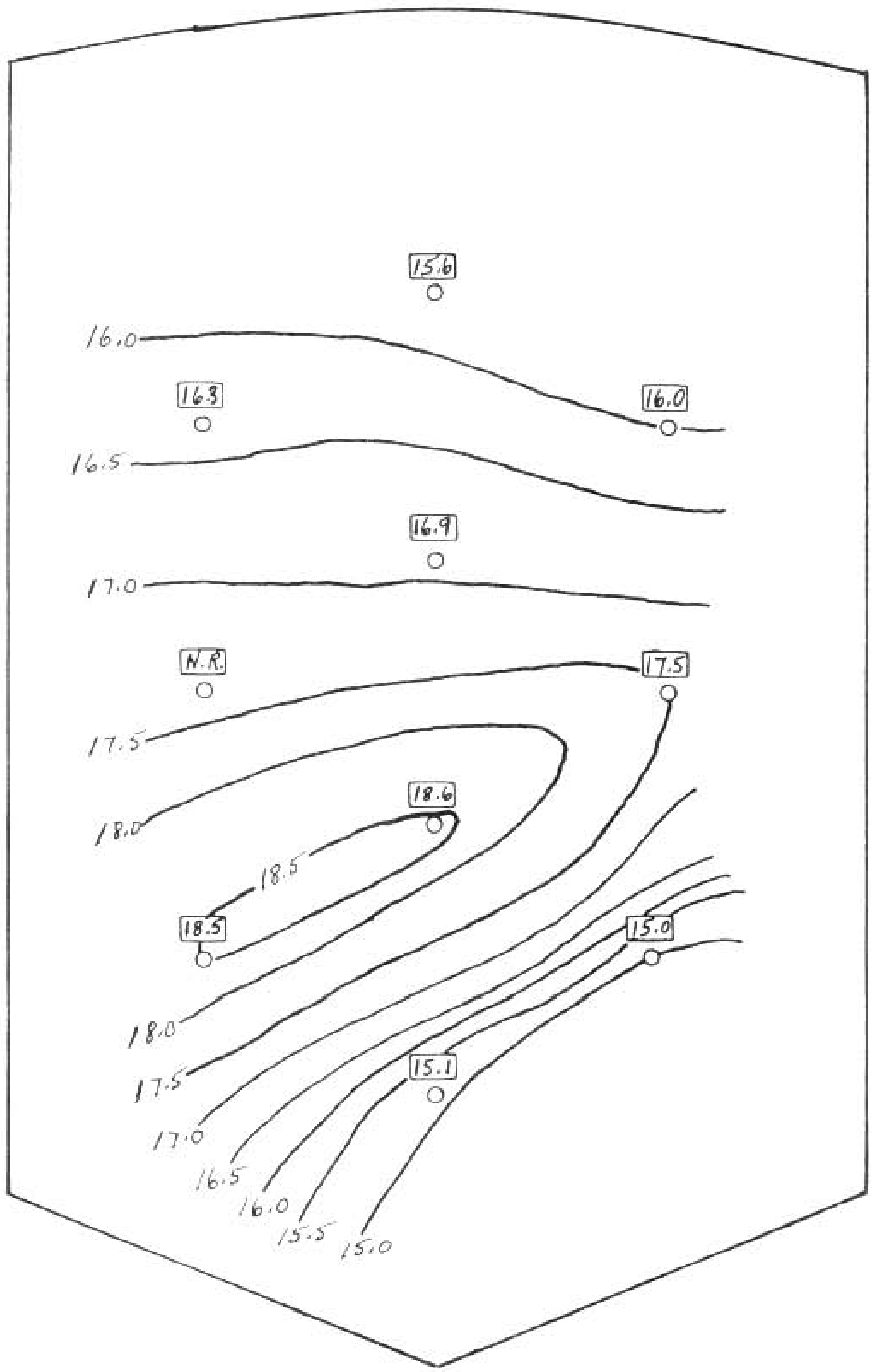


Figure 18. Isohyet map of soil water content for Nov. 5, 1969

Microwatershed No. 4

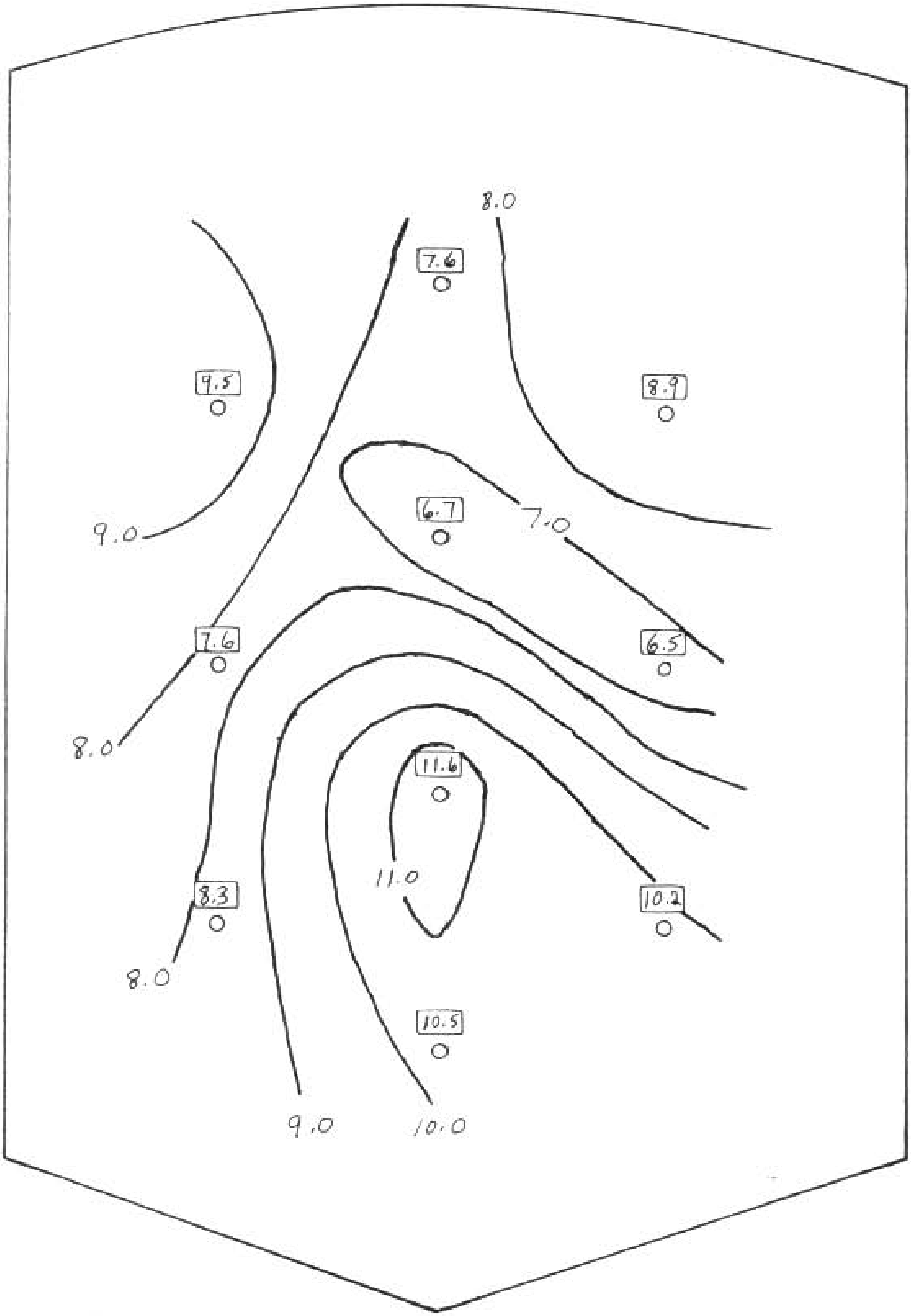


Figure 19. Isohyet map of evapotranspiration from June 26 to August 8, 1969.