PREDICTION OF SOIL MOISTURE FROM SELECTED CLIMATIC DATA

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Thesis submitted to the Graduate Faculty of the

Virginia Polytechnic Institute

in candidacy for the degree of

MASTER OF SCIENCE

in

Agricultural Engineering

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April, 1966

Blacksburg, Virginia

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INTRODUCTION

A plant needs large amounts of water for its growth and development. To produce one unit of dry organic matter, several hundred units of water are absorbed by plants through their roots and then evaporated through their leaves. The chief source of this water is the moisture of the soil.

Soil moisture is seldom ideal for best crop yields. Either excessive water or lack of water is hazardous to the growth of plants. In order to assess the best agricultural management, a knowledge of the soil moisture content throughout the soil profile is indispensable.

In watershed hydrology, soil-water-plant relationships play a very important role. Many factors may affect these relationships. Among them, soil moisture is normally a major aspect to be considered, for the antecedent soil moisture determines the amount of water which can be retained in the soil at any given time. It also can be used in estimating the surface runoff for any specific storm. Therefore, the measurement of soil moisture content has received much attention in the past as well as the present.

The soil moisture is a dynamic quantity that is constantly being changed by precipitation and evapotranspiration. Other factors such as deep percolation, infiltration rate, high water table, seepage, etc., may affect the soil moisture locally, but they are not normally as significant as rainfall and evapotranspiration. Precipitation which increases the amount of soil moisture is relatively easy to measure and long-term records are usually available. Evapotranspiration presents a more difficult problem.

Evapotranspiration is the combination of evaporation of water from soil and transpiration of water by plants. It depends on several variables that cannot be easily measured. The main factors are:

1. The energy available for the evaporation process.
2. The rate of vapor movement from evaporating surface.
3. The vegetation on the soil.
4. Soil moisture tension.

In spite of past research, no single satisfactory method has been developed for measuring soil moisture rapidly, accurately, and repeatedly without undue expense. A wide gap still exists between measuring principles and their application. The most commonly used methods are:

1. Gravimetric method.
2. Resistance blocks method.
3. Tensiometer method.
4. Neutron scatter method.

Each of these methods has its disadvantages. At the present time, only the gravimetric and neutron scatter methods are considered accurate over a wide range of soil and moisture conditions. Neither method is readily adaptable to automatic recording. Thus for quick and on-the-field use, daily readings over a large area are impractical. These limitations in measuring and the ever increasing need of soil moisture information have led many researchers to search for new approaches to determine soil moisture.

Early in this century, it was reported that evapotranspiration could be correlated to such climatic variables as pan evaporation, temperature, solar radiation, and wet bulb depression readings (2).* Many attempts have been made to calculate evapotranspiration by certain easily measured climatic variables. Air temperature, relative humidity, wind velocity, pan evaporation, and rainfall are the most commonly available data for the calculation.

When the soil moisture level is high, many formulas, some empirical and some theoretical, based on climatic factors have been developed which estimate the evapotranspiration quite well. When the soil moisture level becomes sufficiently low, the availability of soil moisture limits the evapotranspiration process. In this case, none of the formulas are accurate. Additional information about soil moisture tension is needed to predict the evapotranspiration accurately at low soil moisture levels.

If the actual evapotranspiration can be accurately calculated from climatic measurements, a soil moisture accounting system could be developed to evaluate the soil moisture. Such a system would work quite well, if rainfall, deep percolation, and runoff records were reliable.

In recent years, detailed climatic records and soil moisture data have been collected by investigators in the Agricultural Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia, for specific investigations. The data were sufficiently comprehensive to

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*Numbers in parenthesis refer to Bibliography.

warrant an investigation to determine whether or not a soil moisture prediction technique could be developed using some easily measured climatic variables.

L I T E R A T U R E   R E V I E W

A close relationship between transpiration and air temperature, solar radiation, pan evaporation, and wet bulb depression readings was found by Briggs and Shantz early in this century (2). Since that time, this problem has been studied by many researchers.

In numerous published papers, formulas have been developed for computing evapotranspiration from one or more climatic variables. Also, climatic data have been used to estimate the change of soil moisture storage. Most of these methods are basically bookkeeping systems for estimating the accumulation of soil moisture from rainfall and its removal by evapotranspiration. An estimate of the amount of stored soil moisture could be obtained by a soil moisture balance table.

The methods used in estimating evapotranspiration can be grouped into three categories (14):

1. Theoretical methods based on the balance of energy which is available for the evaporation process.
2. Theoretical methods based on the aerodynamic assumption of transporting the vapor away from evaporating surface.
3. Empirical methods to fit the existing data.

All three approaches have been used with some success. However, empirical methods are the most popular in the United States. Among the most commonly used are those of Blaney and Criddle (1), Thornthwaite (12), and Penman (7). Whereas, most subsequent works have consisted of application or adaptation of methods described by these authors.

The Blaney and Criddle method has been widely used for estimating consumptive use in the Western United States. By this method, evapotranspiration is calculated on a monthly basis from mean monthly temperature, monthly percentage of daytime hours, and a coefficient for crops. The formula used is:

$$U = K \times F$$

where

U: monthly consumptive use in inches.

F: monthly consumptive use factor which equals $\frac{t \times p}{100}$

t: mean monthly temperature in degrees Fahrenheit.

p: monthly percentage of daytime hours of the year.

K: empirical consumptive use crop coefficient for the growth period.

Thornthwaite introduced the concept of potential evapotranspiration and used it to classify climatic conditions (12). He defines the potential evapotranspiration as the maximum amount of water that can be removed from a fully vegetative surface under a given set of atmospheric conditions where available soil moisture is at no time a limiting factor. In the empirical formula he used evapotranspiration as an exponential function of mean monthly temperature. The value of the exponent depends on latitude. This formula is:

$$e = ct^a$$

in which e is monthly evapotranspiration in centimeters and t is mean monthly temperature in degrees centigrade. The coefficients c and a vary from one place to another but may be defined as:

$$a = 675 \times 10^{-9} I^3 - 771 \times 10^{-7} I^2 + 1792 \times 10^{-5}\ I + 49239 \times 10^{-5}, \text{ and}$$

$$c = 1/I$$

where I is the annual heat flux and is equal to the summation of monthly heat fluxes ($I = \sum_{i=1}^{12} ti/5^{\,1.514}$). Hence:

$$e = 1.6\ (10t/I)^a$$

Penman used solar radiation and wind velocity in addition to air temperature and evaporating power as criteria to determine the evaporation from free water surface, bare soil, and evapotranspiration from vegetation (7). The formula he used for crop is:

$$Et = \frac{H + 0.27Ea}{\triangle + 0.27}$$

where

Et: evapotranspiration in mm/day.

$\triangle = \frac{de}{dt}$ Ta in which e is vapor pressure in mm Hg and t is temperature in degrees Fahrenheit.

Ta: air temperature in degrees Fahrenheit.

Ea: evaporation rate in mm/day which equals

$0.35\ (e_a - e_d)\ (1 + 0.0098U_2)$.

U_2: wind velocity at two meters above ground in miles/day.

e_a: saturation vapor pressure of air in mm Hg.

e_d: actual vapor pressure of air in mm Hg.

H: net radiation

This formula is based on the result of sink strength theory and energy balance theory. Under ample soil moisture conditions, Penman assumes that the evaporation from free water surface approximates the evapotranspiration.

These and related techniques have been applied to various crops by Slatyer (11), Pierce (8), and Marlatt (6). Both the Blaney-Criddle and Thornthwaite methods provide simplified approaches for estimating evapotranspiration with temperature as a primary factor. They reported that for short periods of observation these simplified approaches result in reduced accuracy (3). The Penman method requires climatic data that are available only at larger weather stations. It also requires more computational time (3). In order to obviate the objections, a nomogram based on the Penman method has been prepared by Van Bavel (14) in which only the daily sunshine percentage and daily air temperature are needed. This nomogram has the advantage of providing a prediction technique for on-the-farm use.

High correlation of the rate of water use by crop and pan evaporation has been reported in recent years (9). As an alternative to using empirical formulas for predicting evapotranspiration, these correlations suggest that an evaporimeter may be used to obtain an estimate of soil moisture depletion. According to Hartman (5), pan evaporation appears to be the best single index of the climatic variables that affect evapotranspiration. Various types of evaporimeters have been used. Halkias, et al, (4) used the evaporation difference between black and white atmometers. Shaw (10) used a USWB class A evaporation pan with a factor to account for reduced water loss when soil moisture stress exists. Pruitt (9) used six different types of evaporation pans. He found that under ample moisture supply and fully covered conditions, estimates of soil moisture loss based on pan evaporation data are quite reliable. He also concluded that the USWB class A pan seems to give a better result than other pans.

As previously stated, soil moisture tension is one of the factors which affects evapotranspiration. But there seems to be no agreement among authorities as to how soil moisture deficiency affects evapotranspiration. Some workers are convinced that evapotranspiration varies inversely with the deficit between field capacity and wilting percentage (13). Others have found that soil moisture is equally available until it approaches the wilting percentage, after which it drops abruptly to some low value (15). The results of recent studies by Pierce (8), Marlatt (6), and Shaw (10) indicate that it lies somewhere in between these two opposing viewpoints. This relationship could be affected by local soil conditions.

The literature reviewed here has been selected from a great number of publications. It provides the essential background information needed for this study.

O B J E C T I V E S

1. To determine the relationship between soil moisture loss and pan evaporation using existing soil moisture data and climatic data collected at the Agricultural Engineering Farm, Virginia Polytechnic Institute, Blacksburg, Virginia.
2. To determine the correlation between pan evaporation and daily evapotranspiration.
3. To develop an empirical or statistical relation for predicting soil moisture from climatic data.
4. To propose an experiment designed to establish a reliable technique for predicting soil moisture from selected easily measured climatic factors.

PROCEDURE

Analytical procedures in this study are primary statistical analyses of the observed soil moisture data and climatic data. The data available for the study may be divided into two general categories:

I. Climatic data:

1. Air temperature.
2. Soil temperature.
3. Relative humidity.
4. Sunshine duration and sunshine percentage.
5. USWB class A pan evaporation.
6. BPI class B pan evaporation.
7. Rainfall.

The data for these climatic factors, except soil temperature, have been recorded daily by the Agricultural Engineering Department, Virginia Agricultural Experiment Station, Blacksburg, Virginia, at a weather station near the experimental plots. The soil temperature was measured at the experimental plots by an automatic recording soil thermograph.

II. Soil moisture data:

The soil moisture data were collected from mixed forage crop plots by gravimetric sampling technique during the 1957 through 1959 growing seasons. The amount of moisture in the soil was also checked by tensiometers and resistance blocks. The depth of sampling was from zero to twelve inches at the beginning of the growing season, then gradually increased to forty-eight inches by twelve-inch increments. The interval between sampling dates ranged from three to twenty-five days.

A soil moisture characteristic curve for this soil (Fig. 1) was determined in 1957 by J. E. Moody of the Virginia Agricultural Experiment Station. The field capacity and wilting percentage were determined from this curve at soil moisture tensions of one-third atmosphere and fifteen atmospheres, respectively. Using this curve, the soil moisture content by percentage of weight was transformed to inches of available water by:

$$SMa = (SMc - SMp) \times B \times D \div W$$

where

SMa: available soil moisture in inches.

SMc: measured soil moisture content by percentage of weight.

SMp: soil moisture content by percentage of weight at 15 atm. soil moisture tension.

B: bulk density of the soil in pounds per cubic inch.

D: depth of the soil in inches.

W: water density in lb/in^3

The prepared data were then subjected to the following analyses.

I. Relation of soil moisture loss and USWB class A pan evaporation.

The depletion of soil moisture in the soil tends to follow an exponential type curve. It has been reported by many of the researchers that to use a straight line to evaluate the soil moisture depletion is very close to the result evaluated by an exponential type curve, if the interval between sampling dates is reasonably short and regular (5) (6).

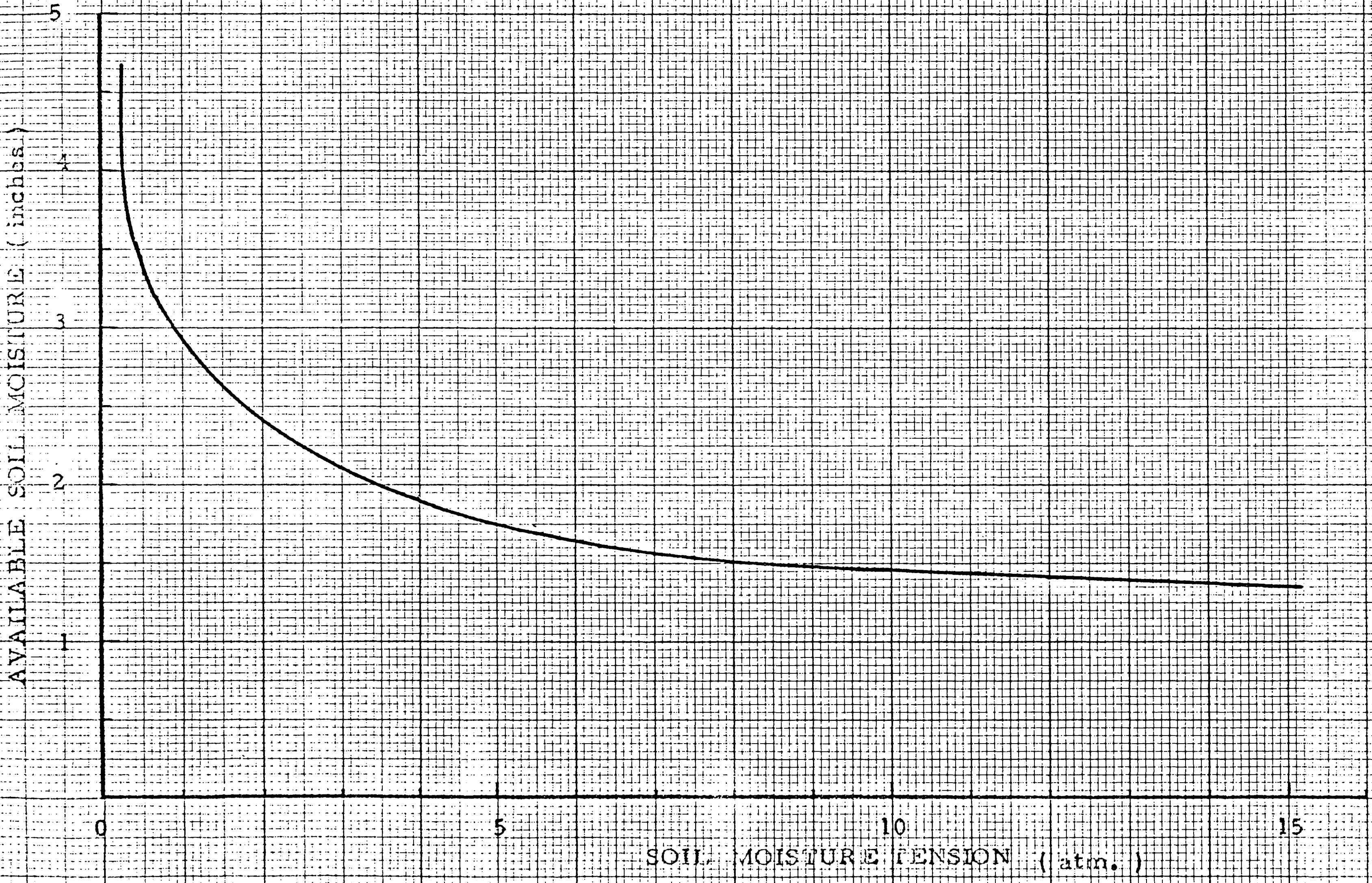

Fig. 1. Soil moisture characteristic curve of experimental plots by J. E. Moody.

Therefore, for simplifying the calculation, the straight line interpretation of soil moisture depletion was adopted to evaluate the soil moisture depletion and accretion curves of 1957, 1958, and 1959 (Figures 2-4). According to this assumption, the average soil moisture loss over a sampling period was determined by:

$$La = \frac{SMt - SMo + R}{t}$$

where

La: average daily soil moisture loss.

SMo, SMt: respectively the initial and final soil moisture of a t-days period.

R: rainfall of the period.

t: days of the sampling period.

The average daily soil moisture loss and corresponding pan evaporation data were plotted for comparison (Figures 5-7).

After the comparison was made on an average daily basis, the soil moisture loss and evaporation were summed for each sampling period for blocked comparison. In this case, the water loss was evaluated by:

$$Lb = SMt - SMo + R$$

where: Lb is the loss of water during sampling period.

The correlation coefficients (r) between moisture loss and pan evaporation for each year were calculated. The r-values were then transformed to z-values by Fisher's transformation ($z = \frac{1}{2} \, l_n \left(\frac{1+r}{1-r}\right)$) in which z is approximately normally distributed (Table 1).

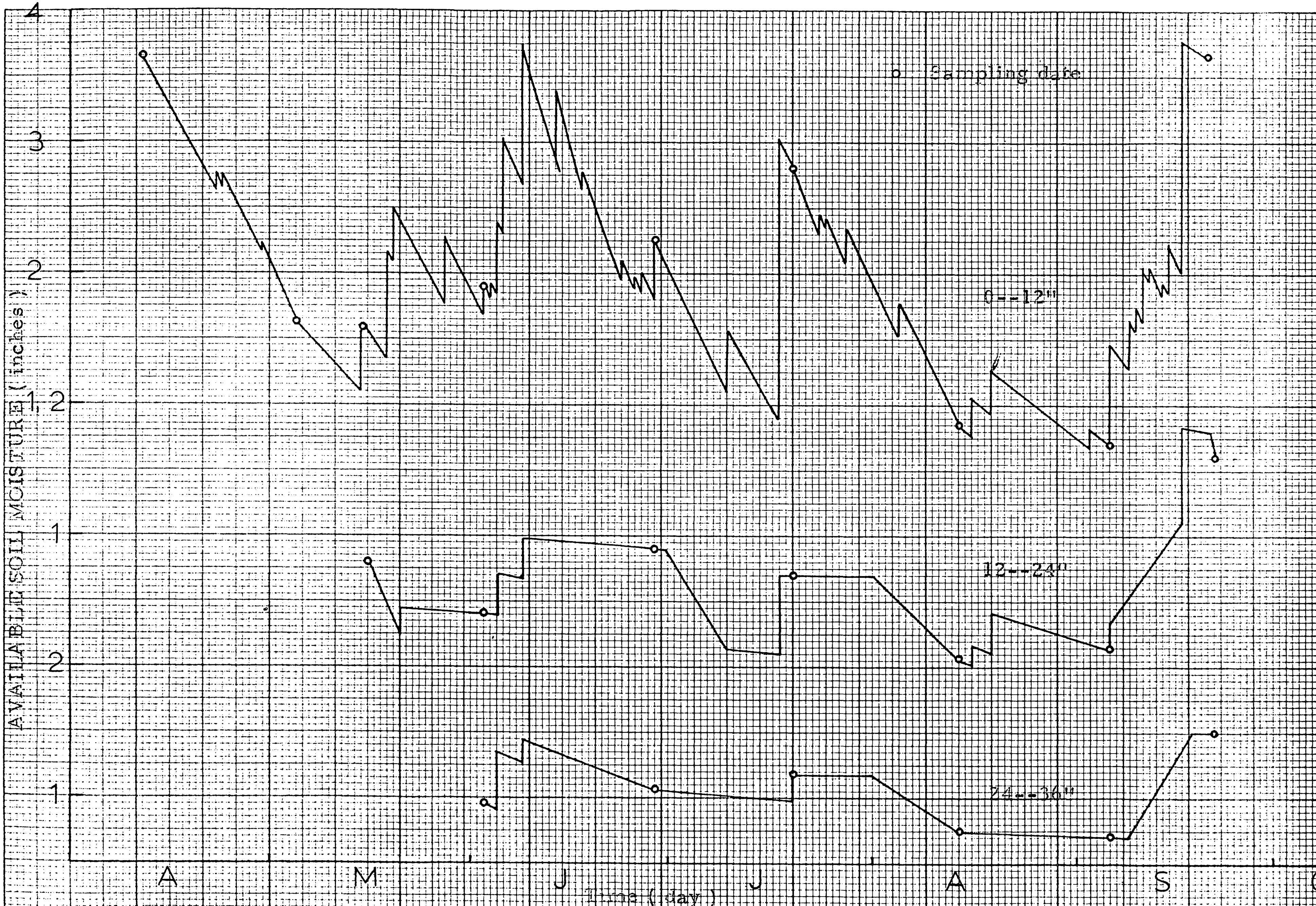

Fig. 2. soil moisture depletion and accretion curve of 1957 growing season.

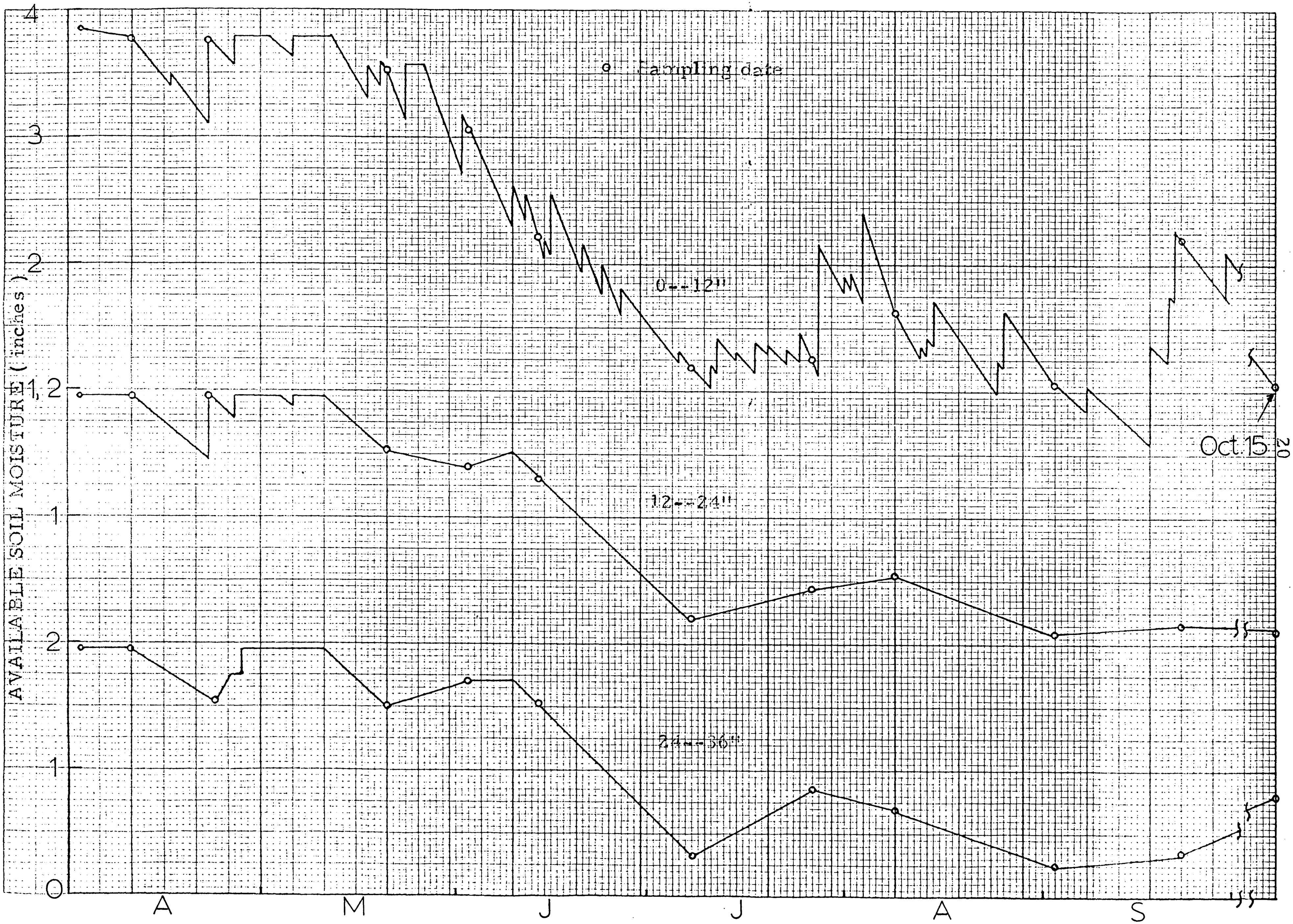

Fig. 3. Soil moisture depletion and accretion curve of 1958 growing season.

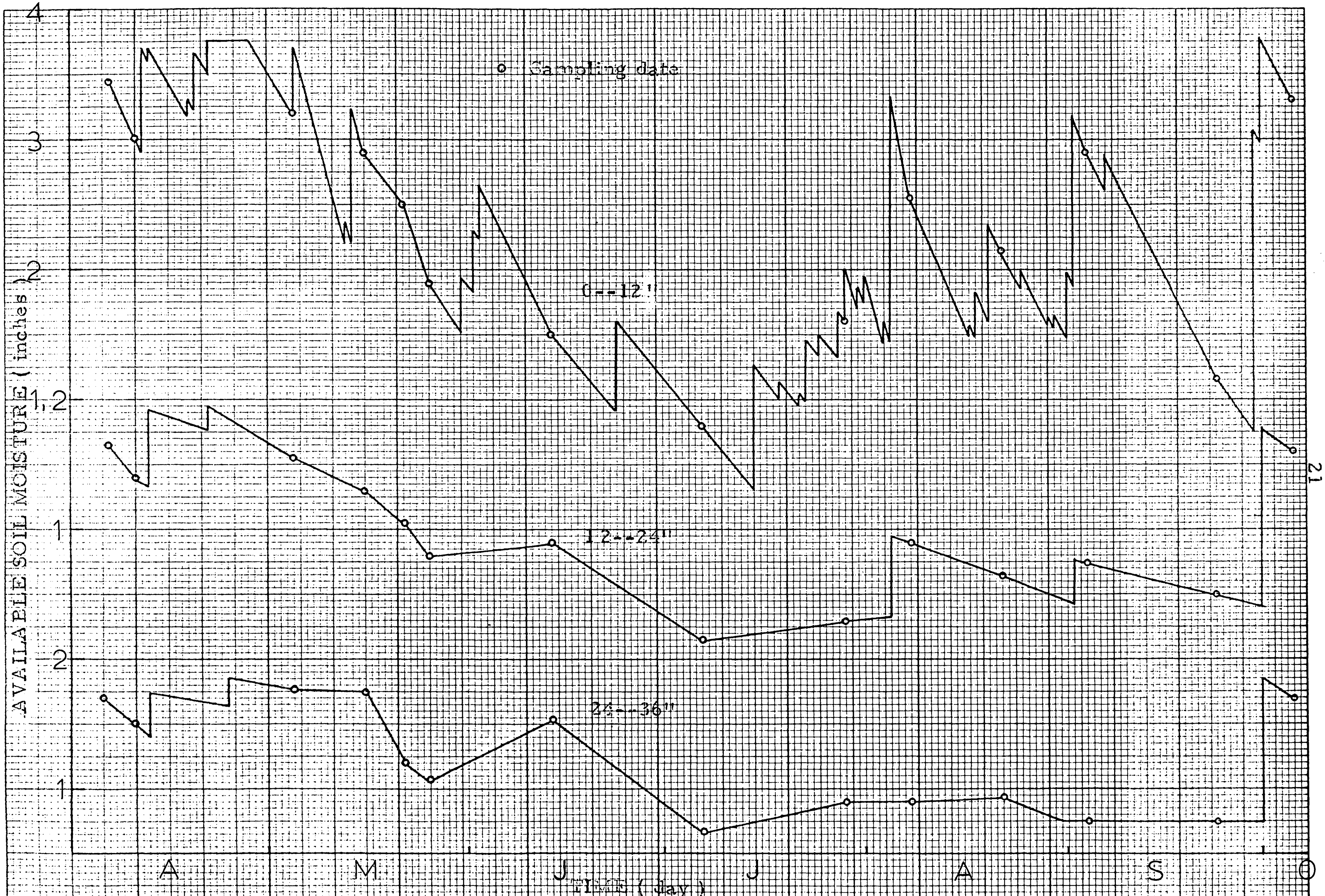

Fig. 4. Soil moisture depletion and accretion curve of 1959 growing season.

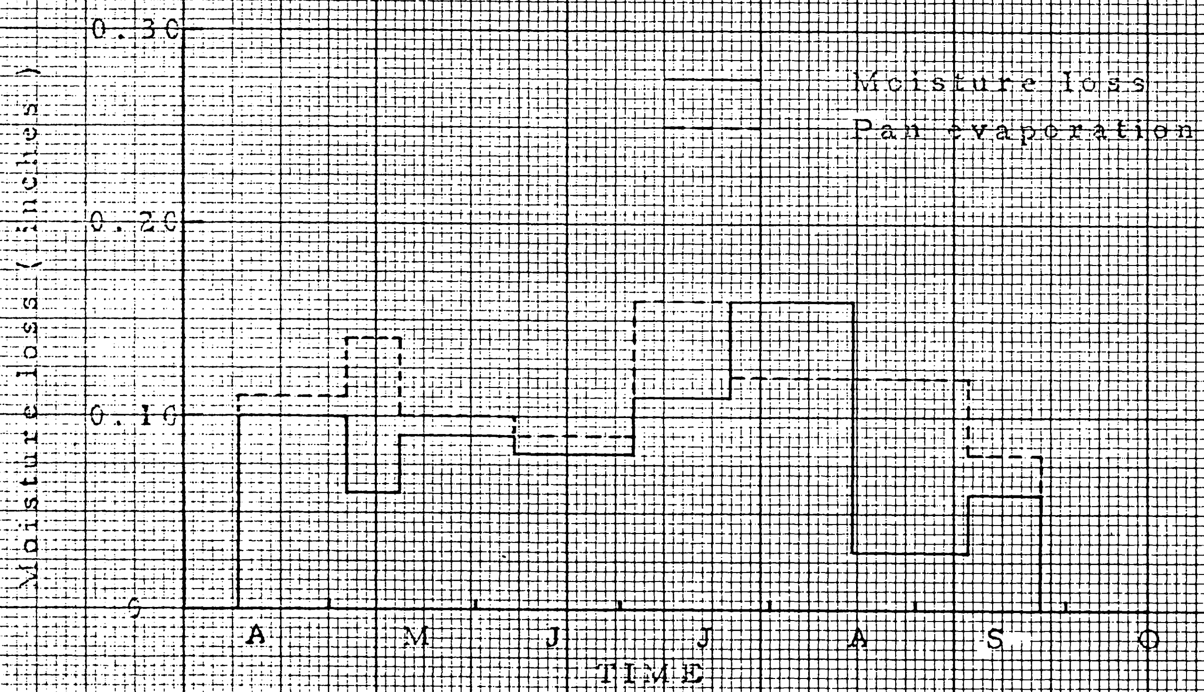

Fig. 5. Comparison of average daily soil moisture loss and USWE class A pan evapration 1957.

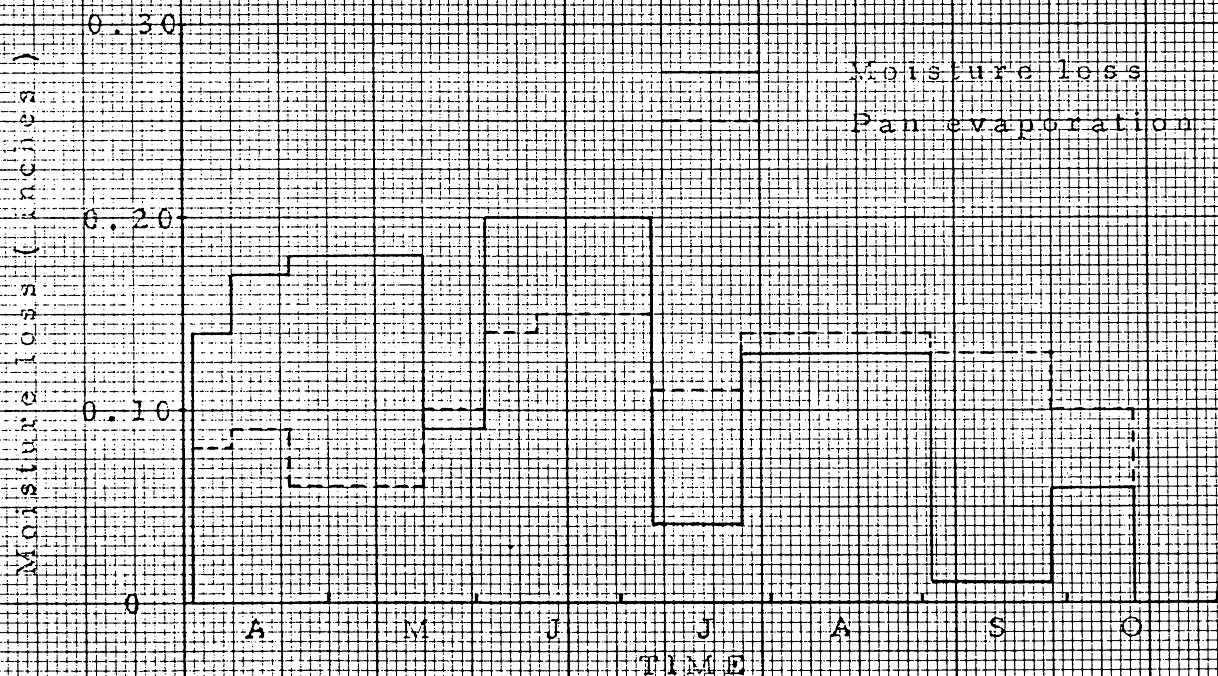

Fig. 6. Comparison of average daily soil moisture loss and USWB class A pan evaporation 1958.

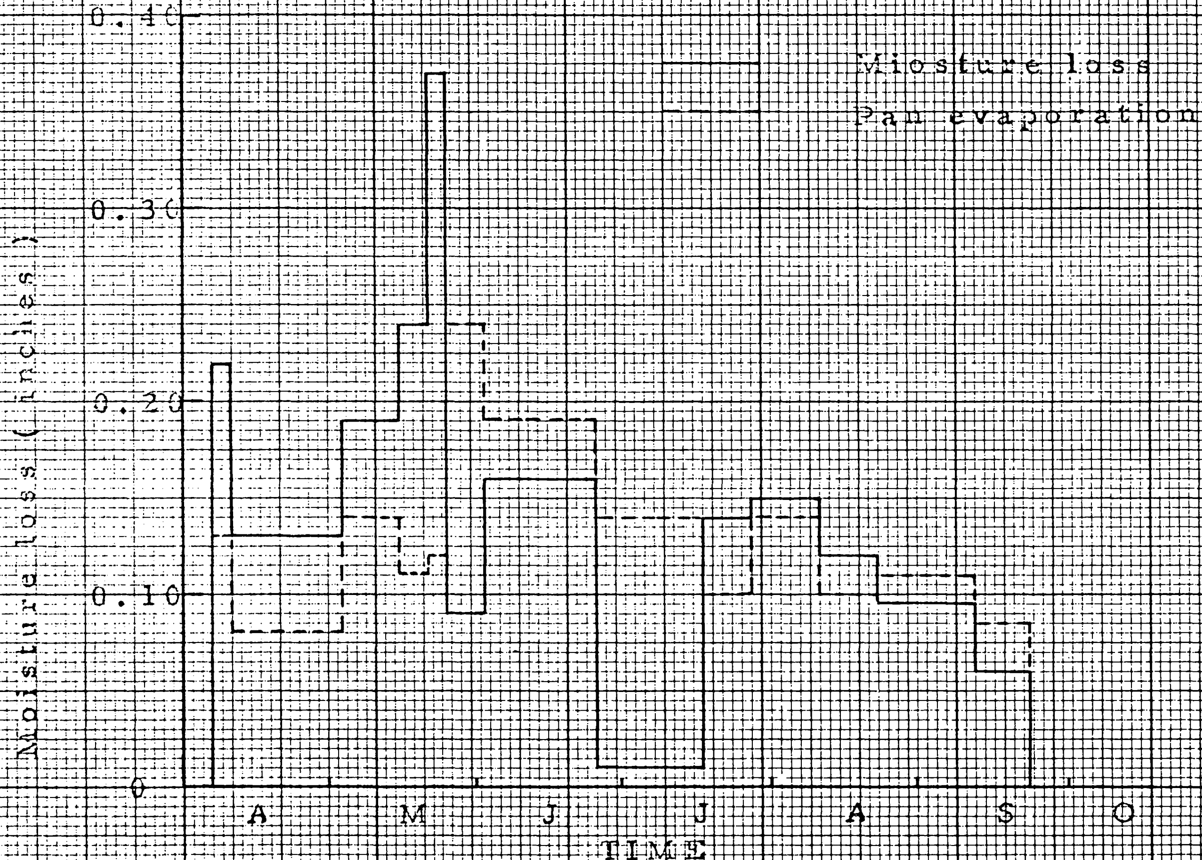

Fig. 7. Comparison of average daily soil moisture loss and USWB class A pan evaporation, 1959.

Finally, the scatter diagram of cumulated soil moisture loss and cumulated pan evaporation of each year was plotted (Fig. 8). The correlation coefficient and regression equation of each year were also calculated (Table 2). The test of significance of these regression equations indicated that the linear regressions were significant at the five per cent level for 1957 and 1958 and were significant at the ten per cent level for 1959.

This indicated a definite relationship between pan evaporation and soil moisture loss. But it did not provide any possibility of establishing a reliable procedure for estimating soil moisture. The following procedures were used to calculate daily evapotranspiration and to estimate the ensuing soil moisture.

II. Estimation of soil moisture by a soil moisture accounting system.

Daily evapotranspiration was calculated by Van Bavel's nomogram (14) method using average air temperature, daily sunshine percentage, and extroterrestrial radiation. Then a soil moisture accounting system (Appendix) was set up using the soil moisture balance principle. In this moisture balance table, the daily soil moisture is estimated by:

$$SMe = SMo - Et + R - Q$$

where

SMe: estimated soil moisture.

SMo: the soil moisture at the end of the previous day.

Et: daily evapotranspiration calculated by Van Bavel's nomogram for computing evapotranspiration.

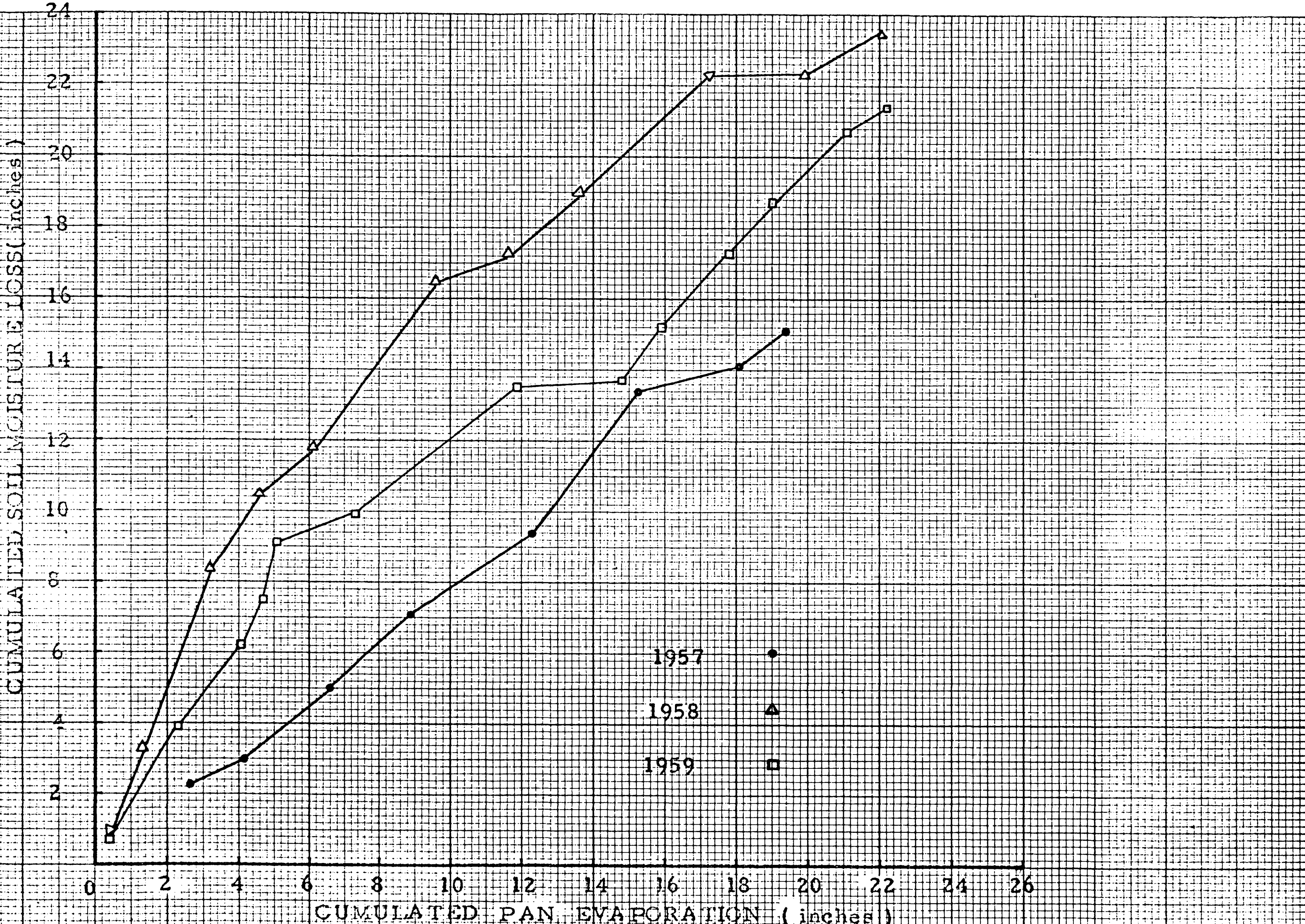

Fig. 8. Relation between cumulated soil moisture loss and cumulated pan evaporation.

R: rainfall during the day.

Q: surface runoff (normally zero on the plots studied).

The estimated soil moisture and the measured soil moisture on each sampling day were plotted on a scatter diagram (Fig. 9) and their significant differences were tested by student t-test for paired observations. Regression equations of estimated and measured soil moisture for each year were calculated to adjust the estimated soil moisture values. These adjusted soil moisture values and their corresponding measured soil moisture were again plotted on a scatter diagram. The difference was also tested by student t-test.

III. Correlation between daily evapotranspiration and pan evaporation.

Finally, the relationship between daily evapotranspiration (Van Bavel's nomogram method) and pan evaporation was determined by calculating their correlation coefficients (Table 6).

Following the analysis, a 2 x 2 x 2 split-plot experimental design was recommended for a more accurate and systematic investigation of this problem. In this proposed experiment, soil moisture level (l), growing stage of crops (G), and types of land use (L) were considered as affecting factors of the soil moisture depletion rate. Using "analysis of variance" techniques to test the affecting factors, the data were formed into several groups having the same physical characteristics. The relationship between soil moisture loss and pan evaporation was determined for each group. This relationship provided a simple method to

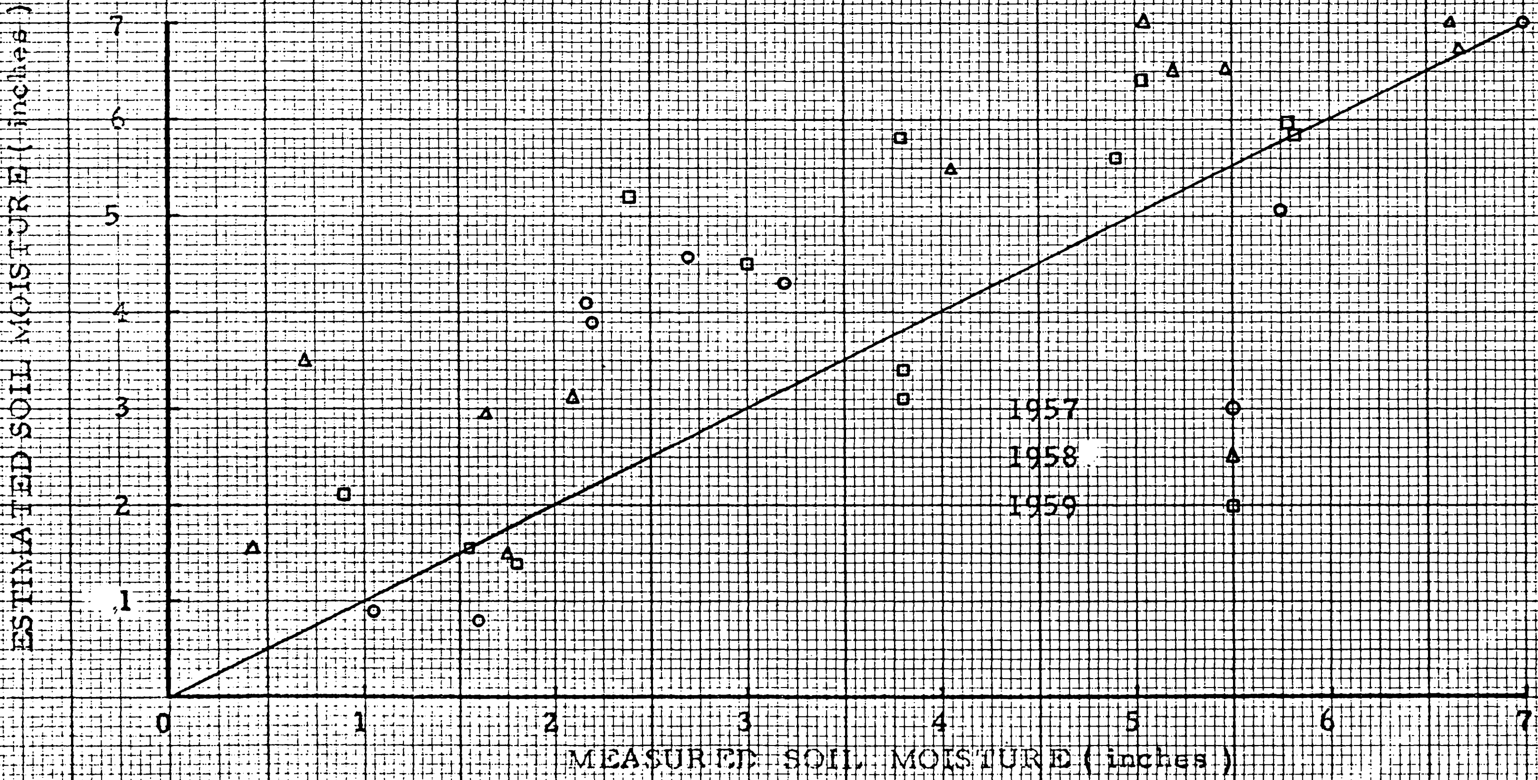

Fig. 9. Comparison of estimated soil moisture and measured soil moisture.

estimate soil moisture loss accurately. A soil moisture accounting system was then set up to predict daily soil moisture.

RESULTS

The analyses of the data by the procedures stated gave the following results.

In Figures 5-7, the average daily soil moisture loss was compared with average daily pan evaporation. It was obvious that no constant relationship existed through the growing season for any year. The average difference between soil moisture loss and pan evaporation and corresponding standard deviation was 0.03, 0.004; -0.01, 0.006; and -0.018, 0.01 for 1957, 1958, and 1959 respectively.

The comparison of blocked soil moisture loss for each sampling period and the corresponding pan evaporation was made by calculating correlation coefficients (r). The values of r were then converted into normal z values of Fisher's z transformation. The test of hypothesis indicated that none of the coefficients was significant at the five per cent level. The results are shown in Table 1.

Table 1. Correlation of blocked soil moisture loss vs corresponding pan evaporation

Year	N	r	z
1957	8	0.55	0.62
1958	11	0.35	0.37
1959	13	0.48	0.52
Overall	33	0.40	0.42

The results of the statistical analysis indicated no workable relationship between blocked soil moisture loss and corresponding pan evaporation.

The relationship between cumulated soil moisture loss (L) and corresponding pan evaporation (P) for each season was plotted in Fig. 8. The results of this statistical analysis is summarized in Table 2.

Table 2. Results of statistical analysis of cumulated soil moisture loss vs cumulated pan evaporation

Year	N	r	Regression Equation	t_o	t
1957	8	0.92	$L = -0.09 + 0.80P$	3.40	2.447**
1958	11	0.78	$L = 3.91 + P$	2.80	2.262**
1959	13	0.80	$L = 2.66 + 0.84P$	2.15	1.796*

The data in Table 2 indicated a high correlation between soil moisture loss and pan evaporation.

The estimated daily soil moisture was indicated in the soil moisture balance table (Appendix) by the column "Soil moisture balance." The comparison of these estimated values with the actual measured values by student t-test for paired observations gave the results shown in Table 3.

Table 3. Student t-test of "Null Hypothesis" for difference between measured and estimated soil moisture

Year	N	d	Sd^2	t_o	t (0.05)
1957	8	0.86	0.82	2.67	2.356
1958	11	0.68	0.75	2.61	2.228
1959	13	0.74	1.14	2.39	2.179

*at 10% significant level.
**at 5% significant level.

The regression equations calculated from estimated soil moisture (Y) and measured soil moisture (X) are shown in Table 4.

Table 4. Regression equations of estimated and measured soil moisture

Year	Regression Equation
1957	$Y = 1.46 + 0.81X$
1958	$Y = 1.74 + 0.86X$
1959	$Y = 0.99 + 0.93X$
Overall	$Y = 1.27 + 0.91X$

The soil moisture values were adjusted by using the above regression equations and compared with measured soil moisture by student t-test for paired observations and also plotted on scatter diagram (Fig. 10). The results are shown in Table 5.

Table 5. Student t-test of "Null Hypothesis" for the difference between measured and adjusted soil moisture

Year	N	d	Sd^2	t_o	t(0.20)
1957	8	0.24	0.60	0.88	1.415
1958	11	0.38	0.59	1.47	1.372
1959	13	0.40	1.54	0.26	1.356

The results in Table 5 indicated the adjustment of the estimated soil moisture provided some improvement in the accuracy of the estimation.

The relationship between USWB class A pan, BPI class B pan, and daily evapotranspiration as estimated by Van Bavel's nomogram were determined. The correlation coefficients (r) and normal z values by Fisher's transformation are shown in Table 6.

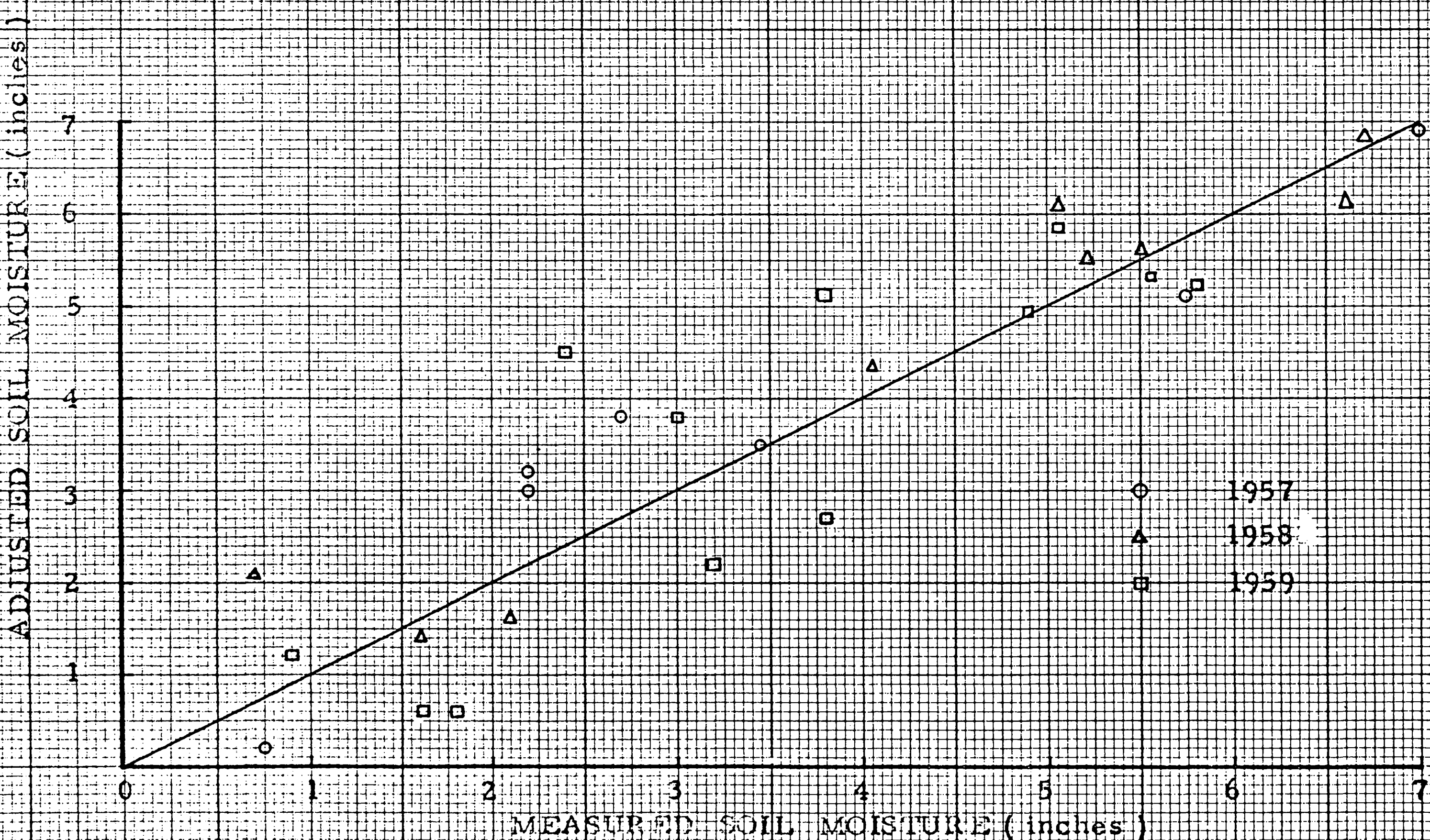

Fig. 10. Comparison of estimated soil moisture adjusted by regression equation and measured soil moisture.

Table 6. Correlation of pan evaporation and evapotranspiration

	1957		1958		1959		Overall	
	r	z	r	z	r	z	r	z
Class A pan vs Evapotranspiration	0.84	1.42	0.78	1.04	0.87	1.33	0.82	1.15
Class B pan vs Evapotranspiration	0.75	0.97	0.72	0.91	0.74	0.95	0.70	0.86
Class A pan vs Class B pan	0.86	1.30	0.85	1.26	0.90	1.47	0.84	1.22

D I S C U S S I O N

The results of this study indicated that a poor relationship existed between soil moisture loss and pan evaporation on both daily average basis and blocked sampling period basis. This lack of correlation may have been caused by the loss of sensitivity when averaging the data and by the errors introduced in blocking where the sampling periods were irregular. It has been reported in many published papers that a straight line evaluates the soil moisture depletion fairly well when the sampling periods are reasonably short and regular (5) (6). However, in this case of sampling periods as long as twenty-five days, a straight line may not give a satisfactory estimate of soil moisture depletion. This situation actually prevailed in these analyses.

A relationship between soil moisture loss and pan evaporation existed in a cumulated basis for each season. In Fig. 8, the mass curve of cumulated soil moisture loss and cumulated pan evaporation shows a sharp increase of water loss at the beginning of the season, followed by a fairly constant rate of water loss until the end of the season. This can be explained by the fact that crops use water more rapidly during their fast development in spring and early summer. At the end of the growing season in each of three years there was a marked retardation of soil moisture loss. From these curves, the influence of the stage of growing on the loss of water from soil is indicated. The variation in these curves from year to year indicates an influence from climate. Comparing 1957 and 1958 indicated that water losses were higher in 1958. However, the weather records show that 1958 was a relatively wet year and 1957 a rather dry year. This can be further explained by the fact that the greater soil moisture tension in dryer soil tends to decrease the rate of water loss from soil.

As reported by many of the researchers (5) (13), a soil moisture accounting system can give quite accurate estimates of daily soil moisture, if daily evapotranspiration can be accurately calculated and if the surface runoff data and deep percolation data are available. Referring to the soil moisture balance table in this study (Appendix), the estimate of soil moisture is based on daily evapotranspiration and rainfall only. The lack of information on surface runoff and deep percolation may reduce the reliability of the estimates. However, for applying the soil moisture accounting system to these data, the following assumptions seemed acceptable:

1. When soil moisture is plentiful, evapotranspiration depends primarily on weather conditions.
2. The moisture content of soil at a given time equals that at a previous time plus change in storage.
3. During the test period, the surface runoff losses were assumed negligible.
4. The excessive water over field capacity, if any, is considered to be lost to deep percolation and not available to the soil moisture withdrawal process.

In Fig. 9, which shows the plotting of estimated soil moisture vs measured soil moisture, most of the plotted points are located above the line of equal value. This fact indicated that the Van Bavel's nomogram for computing evapotranspiration underestimated the daily evapotranspiration. The difference between estimated and measured soil moisture values was tested. The results (Table 3) indicated that differences were significant at the five per cent level. The estimated soil moisture values were adjusted by using the regression equations of estimated and measured soil moisture. These values were then plotted in Fig. 10. However, as shown in the figure, only slight improvement in the relationship was achieved by this adjustment. The student t-test for paired observations indicated the difference was significant at the five per cent level for 1957 but was not significant at the ten per cent level for 1958 or 1959. Since the variation in soil moisture measurement is to be expected, this much error may be tolerable. Therefore, a soil moisture accounting system, using Van Bavel's nomogram for computing daily evapotranspiration, may be a usable method for estimating soil moisture under Virginia conditions.

The correlation coefficients of daily evapotranspiration and pan evaporation during the three year test period were converted to normal z-values by Fisher's transformation. Test of this hypothesis indicated that the correlation between evapotranspiration and pan evaporation are significant at the five per cent level. This fact indicates a possibility for using pan evaporation data to estimate the soil moisture depletion rate. The use of pan evaporation data has the following advantages:

1. General availability of the data.
2. Simplicity of use in application.

For more systematic investigation of this problem and the development of more precise estimating procedures, a new investigation designed to measure these relationships in a highly controlled and well designed experiment is strongly recommended.

CONCLUSIONS

1. A highly significant relationship between soil moisture loss and pan evaporation was found on a seasonal cumulated basis. For shorter period observations, the results were disappointingly poor.
2. A useful estimation of soil moisture under Virginia conditions can be made by using a soil moisture accounting system in which daily evapotranspiration is calculated by Van Bavel's nomogram.
3. High correlation between daily evapotranspiration calculated by Van Bavel's nomogram and measured pan evaporation exists. This relationship warrants further investigation in an experiment especially designed to establish correlating procedures and confidence levels over a wide range of field conditions.

RECOMMENDATION

The high correlation between consumptive use and pan evaporation has been found in this study. A soil moisture accounting system using Van Bavel's nomogram for computing daily evapotranspiration was found feasible for estimating daily soil moisture under local conditions. However, an experimental procedure is presented here that, hopefully, through a more accurate and systematic investigation of this problem, will lead to the development of a workable mathematical model between pan evaporation and soil moisture loss for predicting soil moisture.

The experiment was designed so that the topographic and watershed factors can be considered constant throughout the experimental period. The following assumptions must be adhered to:

1. Soil and other physical factors must be essentially uniform throughout the plots.
2. The water available for release from soil will be restricted to the soil moisture content between permanent wilting percentage and field capacity.
3. Deep percolation during the experimental period will be accurately measured or accounted for.
4. Surface runoff will be accurately measured.

The main purpose of the design is to test the difference of soil moisture depletion rate with respect to its affecting factors. Therefore, the soil moisture depletion rate (X) is chosen as a dependent variable.

The major factors affecting the rate of soil moisture depletion will be chosen as independent variables. They are:

1. Availability of soil moisture (I).
2. Growing stage of crop (G)
3. Types of land use (L).

The availability of soil moisture will be controlled by irrigation to keep a certain soil moisture level.

1. High soil moisture level (I_1): use irrigation to keep soil moisture always above 70% of totally available water.
2. Low soil moisture level (I_2): no irrigation treatment.

The two general land use classifications are row crops and full covered crop. These are represented by corn (row crop) and mixed forage crop (full covered crop). They are denoted by L_1 and L_2 respectively. The growing stage cannot be clearly divided, however, the following two stages are suggested:

1. G_1: 91 days of April, May, and September.
2. G_2: 92 days of June, July, and August.

Since the growing stage is a factor of time which cannot be randomized in the experimental plan, a 2 x 2 x 2 split-plot design will be used. Four replications are suggested to eliminate the possible error caused by soil and climatic variations. A field layout of the experiment which is proposed to measure pan evaporation as covariate and to compare the factors and their interaction with respect to soil moisture depletion rate is shown in Fig. 11. The mathematical model of this experiment would be:

$$X = I_i + L_j + IL_{ij} + G_k + IG_{ik} + LG_{jk} + ILG_{ijk}$$

The data to be taken can be divided into two categories:

1. Climatic data which affect the rate of soil moisture depletion.
2. Soil moisture data required for evaluating soil moisture. depletion rate.

There are many climatic factors which affect the rate of soil moisture depletion. The most important that should be measured are:

1. Air temperature.
2. Soil temperature.
3. Relative humidity.
4. Wind velocity and wind direction.
5. Sunshine duration, sunshine percentage, and net radiation.
6. USWB class A pan evaporation.
7. Precipitation.

All these factors, except soil temperature, can be continuously recorded by automatic equipment at a weather station located near the experimental plots. The soil temperature must be collected at the experimental plots and can be recorded by an automatic recording potentiometer.

The major field work will be the collection of soil moisture data and crop growth information. The neutron scatter meter should be used to measure the soil moisture. Because this method is quite accurate when the instrument is properly calibrated and is reasonably rapid, it is the most feasible procedure available for measuring moisture conditions in the soil.

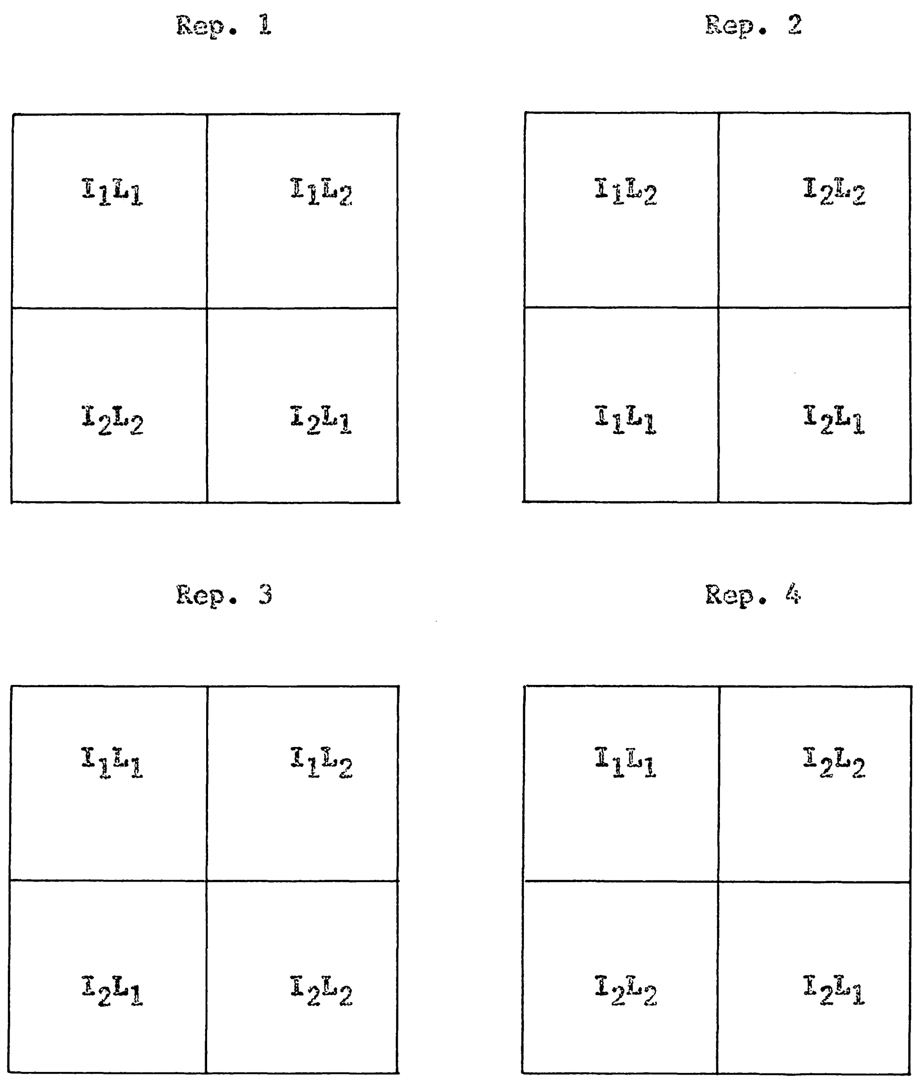

Fig. 11. Field layout of the proposed experiment.

The soil moisture measurements should be taken regularly on a Monday, Wednesday, and Friday schedule. They should be taken from 0-60 inches at 6-inch increments in the first foot of the soil and at 12-inch increments for the deeper horizons. Initially, soil samples for determining the soil moisture depletion curve must be taken from each depth increment of each plot.

Suitable surface runoff measuring equipment will be installed at each plot.

The data collected will be prepared for analysis as follows:

1. Climatic data will be tabulated in time running tables.
2. Soil moisture depletion curves for each plot will be developed.
3. Daily soil moisture loss will be evaluated by plotting soil moisture depletion and accretion curves throughout the growing season.

The "analysis of variance" techniques will be used to test the significant difference of each affecting factor and their interactions with respect to daily soil moisture loss. The data will be formed into several groups having the same physical characteristics, according to the results obtained from the analysis of variance. Each group of data will then be compared with pertinent climatic data for the corresponding period. Scatter diagrams of daily soil moisture loss and corresponding pan evaporation will be plotted. Curve fitting techniques will be used to determine the best fit curve through the resulting points. A multiple regression analysis concerning some of the climatic variables will help to explain errors of estimation resulting from using pan evaporation only.

The results from this statistical model will depend mainly on the accuracy of the experimental data. This design considered these requirements for consistency and completeness of the data on the several affecting factors and hence it will provide a systematic investigation of the problem. Therefore, the development of a more accurate and simple method for estimating soil moisture and soil moisture depletion rates from easily measured climatic factors, such as pan evaporation, is expected.

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A C K N O W L E D G E M E N T S

The author wishes to express his appreciation to many people who assisted in this study. In particular, he wishes to express his deepest gratitude to Prof. J. H. Lillard, major professor, for his guidance and encouragement given throughout the course of research and writing the thesis, to Prof. V. O. Shanholtz, Agricultural Engineering Department, and Mr. J. N. Jones, Agricultural Engineer, ARS, USDA, for their helpful assistance and suggestions in the study. Also, the author would like to express his sincere thanks to Dr. F. M. Cunningham and Dr. R. H. Myers for their careful reviewing of the thesis.

He wishes also to thank the Virginia Agricultural Experiment Station, Blacksburg, Virginia, for providing the experimental data for analysis. Appreciation extends to Miss Louise Howard for her cooperation and assistance in preparing the detailed climatic data for the study.

Finally, the author wishes to thank   for her care and interest in typing this thesis.

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A P P E N D I X

Soil Moisture Balance Table

Table 7. Soil moisture balance table - 1957

April

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	Measured soil moisture 12-24	Measured soil moisture 24-36	Measured soil moisture 0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.00	0.00	0.003		0.42					
2.	0.06	0.05	0.040		0.16					
3.	0.11	0.07	0.025		0.01					
4.	0.02	0.02	0.003		1.50					
5.	0.01	0.07	0.037		0.73					
6.	0.11	0.16	0.048							
7.	0.16	0.11	0.102							
8.	0.02	0.01	0.007		0.95					
9.	0.23	0.16	0.083							
10.	0.16	0.11	0.109							
11.	0.17	0.11	0.075	7.000			2.700	2.300	2.000	7.000
12.	0.19	0.14	0.111	6.889						
13.	0.11	0.13	0.065	6.844	0.02					
14.	0.17	0.17	0.096	6.748						
15.	0.11	0.05	0.087	6.661						
16.	0.07	0.10	0.017	6.644						
17.	0.13	0.08	0.060	6.584						
18.	0.08	0.04	0.042	6.542						
19.	0.11	0.07	0.098	6.444						
20.	0.14	0.07	0.137	6.307						
21.	0.19	0.12	0.139	6.186						
22.	0.13	0.08	0.042	6.126	0.03					
23.	0.06	0.02	0.061	6.065	0.17					
24.	0.12	0.04	0.061	6.004	0.02					
25.	0.22	0.16	0.168	5.836						
26.	0.23	0.16	0.172	5.664						
27.	0.23	0.17	0.158	5.506	0.04					
28.	0.20	0.12	0.127	5.379	0.01					
29.	0.17	0.10	0.134	5.245						
30.	0.26	0.19	0.153	5.092						
31.										
Total	3.97	2.88	2.460							
Avg.	0.132	0.096	0.082							

Table 7. Soil moisture balance table - 1957 (continued)

May

Date	Pan evaporation Class A	Pan evaporation Class B	Et	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	12-24	24-36	0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.23	0.18	0.154	4.938						
2.	0.19	0.17	0.118	4.820						
3.	*	0.14	0.063	4.757						
4.	*	0.19	0.122	4.635						
5.	*	0.23	0.103	4.532						
6.	0.17	0.18	0.132	4.400						
7.	0.19	0.16	0.127	4.473						
8.	0.22	0.20	0.139	4.134						
9.	0.22	0.17	0.144	3.990						
10.	0.16	0.12	0.112	3.878						
11.	0.08	0.02	0.025	3.898	0.07					
12.	0.25	0.11	0.125	3.773						
13.	0.23	0.12	0.133	3.640						
14.	0.12	0.07	0.093	4.047	0.50		0.550	0.750	0.900	2.200
15.	0.24	0.12	0.144	3.903						
16.	0.29	0.20	0.173	3.370						
17.	0.10	0.12	0.036	3.694						
18.	0.20	0.13	0.136	4.358	0.80					
19.	0.06	0.06	0.054	4.624	0.32					
20.	0.11	0.08	0.057	4.587	0.02					
21.	0.22	0.16	0.111	4.476						
22.	0.12	0.10	0.060	4.416						
23.	0.24	0.19	0.157	4.259						
24.	0.20	0.13	0.142	4.117						
25.	0.28	0.19	0.148	3.969						
26.	0.05	0.10	0.095	3.934						
27.	0.22	0.18	0.136	4.248	0.75					
28.	0.20	0.17	0.158	4.090						
29.	0.18	0.17	0.118	3.972						
30.	0.16	0.11	0.040	3.932						
31.	0.12	0.10	0.063	3.869						
Total	5.05	4.37	3.418							
Avg.	0.18	0.14	0.110							

*Clock stopped.

Table 7. Soil moisture balance table - 1957 (continued)

June

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Meaured soil moisture 0-12	12-24	24-36	0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.14	0.07	0.056	3.813						
2.	0.17	0.06	0.055	4.068	0.31					
3.	0.07	0.04	0.020	4.098	0.05		0.80	0.43	0.95	2.18
4.	0.02	0.01	0.018	4.630	0.55					
5.	0.00	0.01	0.018	4.684	0.72					
6.	0.04	0.02	0.082	4.682	0.08					
7.	0.20	0.13	0.153	4.539	0.01					
8.	0.13	0.13	0.116	5.439	1.07					
9.	0.00	0.16	0.010	5.439	0.01					
10.	*	0.11	0.060	5.433						
11.	*	0.08	0.063	5.370						
12.	*	0.10	0.126	5.244						
13.	*	0.10	0.151	5.683	0.59					
14.	0.18	0.10	0.156	5.547	0.02					
15.	0.22	0.13	0.178	5.369						
16.	0.16	0.14	0.138	5.231						
17.	0.08	0.10	0.080	5.211	0.06					
18.	0.17	0.16	0.149	5.062						
19.	0.28	0.25	0.168	4.894						
20.	0.23	0.18	0.178	4.716						
21.	0.14	0.12	0.119	4.597						
22.	0.16	0.08	0.087	4.560	0.05					
23.	0.13	0.07	0.116	4.554	0.11					
24.	0.06	0.02	0.054	4.560	0.06					
25.	0.08	0.05	0.035	4.605	0.08					
26.	0.07	0.04	0.118	4.657	0.17					
27.	0.11	0.04	0.080	4.587	0.01					
28.	0.08	0.11	0.060	4.580	0.53		0.75	0.90	1.05	2.70
29.	0.19	0.17	0.195	4.385						
30.	0.16	0.10	0.107	4.278						
31.										
Total	3.27	2.88	2.974							
Avg.	0.13	0.096	0.099							

*Clock stopped.

Table 7. Soil moisture balance table - 1957 (continued)

July

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	Measured soil moisture 12-24	Measured soil moisture 24-36	Measured soil moisture 0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.29	0.16	0.179	4.099						
2.	0.18	0.16	0.144	3.955						
3.	0.22	0.24	0.172	3.783						
4.	0.23	0.20	0.160	3.767						
5.	0.23	0.22	0.156	3.611						
6.	0.29	0.20	0.179	3.432						
7.	0.26	0.22	0.190	3.413						
8.	0.17	0.18	0.120	3.293						
9.	0.14	0.08	0.063	3.600	0.37					
10.	0.24	0.14	0.188	3.412						
11.	0.20	0.16	0.172	3.240						
12.	0.22	0.30	0.178	3.062						
13.	0.24	0.16	0.080	2.982						
14.	0.25	0.18	0.198	2.784						
15.	0.13	0.12	0.118	2.666						
16.	0.24	0.18	0.164	2.502						
17.	0.10	0.06	0.043	4.589	2.13					
18.	0.02	0.06	0.030	4.569	0.01					
19.	0.16	0.10	0.139	4.430						
20.	0.16	0.11	0.129	4.301			1.80	0.70	0.95	3.45
21.	0.18	0.12	0.149	4.152						
22.	0.20	0.19	0.178	3.974						
23.	0.10	0.10	0.092	3.962	0.08					
24.	0.07	0.07	0.060	4.012	0.11					
25.	0.26	0.17	0.157	3.855						
26.	0.13	0.14	0.081	3.774						
27.	0.12	0.13	0.088	3.719	0.33					
28.	0.16	0.12	0.141	3.598	0.02					
29.	0.13	*	0.132	3.466						
30.	0.14	*	0.107	3.359						
31.	0.24	*	0.133	3.226						
Total	5.70	4.27	4.120							
Avg.	0.18	0.15	0.133							

*Clock stopped.

Table 7. Soil moisture balance table - 1957 (continued)

August

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	Measured soil moisture 12-24	Measured soil moisture 24-36	Measured soil moisture 0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.07	*	0.090	3.136						
2.	0.18	*	0.162	2.974						
3.	0.19	0.16	0.147	2.827						
4.	0.08	0.06	0.044	2.783	0.30					
5.	0.22	0.18	0.159	2.624						
6.	0.18	0.20	0.148	2.476						
7.	0.20	0.18	0.149	2.327						
8.	0.16	0.12	0.138	2.189						
9.	0.19	0.16	0.159	2.030						
10.	0.32	0.22	0.131	1.899						
11.	0.19	0.16	0.077	1.822						
12.	0.18	0.12	0.132	1.690						
13.	0.18	0.13	0.105	1.625	0.04		0.00	0.05	0.70	0.75
14.	0.14	0.12	0.074	1.571	0.02					
15.	0.07	0.04	0.057	1.804	0.29					
16.	0.29	0.17	0.152	1.652						
17.	0.13	0.14	0.021	1.651	0.02					
18.	0.02	0.04	0.010	1.891	0.25					
19.	0.01	0.01	0.020	1.901	0.03					
20.	0.14	0.11	0.130	1.771						
21.	0.14	0.12	0.116	1.655						
22.	0.24	0.18	0.125	1.530						
23.	0.17	0.14	0.137	1.393						
24.	0.16	0.12	0.030	1.363						
25.	0.08	0.06	0.010	1.353						
26.	0.18	0.11	0.066	1.287						
27.	0.22	0.13	0.142	1.145						
28.	0.24	0.14	0.147	0.998						
29.	0.18	0.12	0.148	0.850						
30.	0.28	0.17	0.159	0.691						
31.	0.26	0.16	0.133	0.558						
Total	5.29	3.77	3.318	3.318						
Avg.	0.17	0.13	0.107	0.107						

*Clock stopped.

Table 7. Soil moisture balance table - 1957 (continued)

September

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	Measured soil moisture 12-24	Measured soil moisture 24-36	Measured soil moisture 0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.26	0.16	0.137	0.421						
2.	0.11	0.11	0.093	0.498	0.17					
3.	0.10	0.10	0.064	0.434						
4.	0.19	0.17	0.107	0.327						
5.	0.25	0.17	0.135	0.192						
6.	0.12	0.10	0.055	0.907	0.77		0.00	0.10	0.95	1.05
7.	0.01	0.01	0.064	0.883	0.04					
8.	0.06	0.05	0.007	1.126	0.25					
9.	0.01	0.01	0.012	1.249	0.18					
10.	0.00	0.02	0.051	1.753	0.51					
11.	0.10	0.05	0.080	1.813	0.14					
12.	0.12	0.02	0.121	1.792	0.01					
13.	0.16	0.11	0.111	1.781	0.10					
14.	0.01	0.00	0.057	2.134	0.41					
15.	0.12	0.06	0.106	2.028						
16.	0.01	0.04	0.005	3.803	1.78					
17.	0.00	0.00	0.005	4.888	1.09					
18.	0.00	0.00	0.003	5.585	0.70					
19.	0.00	0.00	0.007	5.638	0.06					
20.	0.01	0.05	0.030	5.638	0.03		2.60	1.65	1.50	5.75
21.	0.12	0.05	0.106	5.552	0.02					
22.	0.16	0.10	0.107		0.01					
23.	0.07	0.05	0.008							
24.	0.14	0.12	0.101							
25.	0.11	0.11	0.090							
26.	0.10	0.08	0.056							
27.	0.14	0.12	0.010		0.10					
28.	0.07	0.08	0.003		2.01					
29.	0.00	0.00	0.000		0.15					
30.	0.01	0.00	0.001							
31.										
Total	2.56	1.93	1.732							
Avg.	0.09	0.06	0.058							

Table 8. Soil moisture balance table - 1958

April

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	12-24	24-36	0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.17	0.12	0.080							
2.	0.05	0.06	0.037	6.700	0.09					
3.	0.13	0.04	0.080	6.620			2.800	1.950	1.950	6.700
4.	0.02	0.04	0.002	6.868	0.25					
5.	0.01	0.00	0.002	6.866						
6.	0.14	0.07	0.086	7.000	0.74	0.520				
7.	0.07	0.11	0.012	6.998	0.01					
8.	0.13	0.16	0.106	6.892						
9.	0.22	0.12	0.072	6.820						
10.	0.06	0.06	0.022	7.000	0.21	0.008	2.750	1.925	1.950	6.625
11.	0.00	0.01	0.030	7.000	0.09	0.060				
12.	0.12	0.12	0.054	6.946						
13.	0.18	0.10	0.096	6.850						
14.	0.12	0.11	0.100	6.750						
15.	0.06	0.04	0.009	6.821	0.08					
16.	0.16	0.06	0.060	6.781	0.02					
17.	0.18	0.10	0.129	6.652						
18.	0.20	0.12	0.131	6.651						
19.	0.14	0.11	0.112	6.409						
20.	0.20	0.17	0.093	6.316						
21.	0.11	0.07	0.076	6.310	0.07					
22.	0.04	0.04	0.047	7.000	1.35	0.613	2.050	1.450	1.550	5.050
23.	0.14	0.07	0.136	6.844	0.02					
24.	0.11	0.06	0.053	6.791						
25.	0.12	0.08	0.040	6.751						
26.	0.10	0.08	0.013	6.818	0.08					
27.	0.00	0.00	0.007	6.911	0.10					
28.	0.01	0.00	0.022	7.000	0.56	0.464				
29.	0.02	*	0.011	7.000	0.04	0.029				
30.	0.10	0.07	0.042	6.958						
31.										
Total	3.11	2.19	1.760							
Avg.	0.11	0.08	0.059							

*Clock stopped.

Table 8. Soil moisture balance table - 1958 (continued)

May

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	Measured soil moisture 12-24	Measured soil moisture 24-36	Measured soil moisture 0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.00	0.00	0.008	7.000	0.28	0.230				
2.	0.00	0.00	0.009	7.000	0.48	0.471				
3.	0.07	0.05	0.099	6.941	0.04					
4.	0.17	0.10	0.128	6.832	0.01					
5.	0.00	0.07	0.031	7.000	1.67	1.462				
6.	0.01	0.08	0.009	7.000	0.51	0.420				
7.	0.00	0.02	0.007	7.000	0.34	0.270				
8.	0.18	0.11	0.132	6.898	0.03					
9.	0.14	0.11	0.088	7.000	0.50	0.310				
10.	0.00	0.00	0.016	7.000	0.07	0.054				
11.	0.05	0.00	0.065	6.935						
12.	0.17	0.07	0.116	6.819						
13.	0.29	0.18	0.151	6.668						
14.	0.18	0.13	0.149	6.519						
15.	0.17	0.10	0.051	6.468						
16.	0.17	0.11	0.122	6.346						
17.	0.10	0.05	0.086	6.490	0.23					
18.	0.14	0.10	0.144	6.376	0.03					
19.	0.01	0.02	0.044	6.562	0.23					
20.	0.12	0.06	0.093	6.559	0.09		2.450	1.500	1.525	5.475
21.	0.29	0.19	0.156	6.433	0.03					
22.	0.20	0.20	0.153	6.290	0.01					
23.	0.08	0.01	0.045	6.715	0.47					
24.	0.06	0.02	0.012	6.733	0.03					
25.	0.02	0.01	0.017	6.846	0.13					
26.	0.11	0.10	0.150	6.696						
27.	0.17	0.13	0.127	6.569						
28.	0.11	0.10	0.087	6.562	0.08					
29.	0.22	0.18	0.165	6.397						
30.	0.13	0.13	0.153	6.244						
31.	0.17	0.12	0.122	6.122						
Total	3.53	2.55	2.753							
Avg.	0.11	0.08	0.088							

Table 8. Soil moisture balance table - 1958 (continued)

June

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	12-24	24-36	0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.13	0.10	0.121	6.531	0.53		2.100	1.400	1.700	5.200
2.	0.11	0.11	0.105	6.436	0.01					
3.	0.16	0.14	0.068	6.368						
4.	0.18	0.12	0.113	6.255						
5.	0.17	0.14	0.137	6.118						
6.	0.19	0.16	0.151	5.967						
7.	0.22	0.18	0.129	5.838						
8.	0.18	0.17	0.124	5.714						
9.	0.14	0.11	0.146	5.898	0.33					
10.	0.17	0.12	0.177	5.811	0.09					
11.	0.23	0.14	0.177	5.744	0.11					
12.	0.14	0.11	0.172	5.592	0.02					
13.	0.18	0.19	0.143	5.459	0.03					
14.	0.06	0.08	0.150	5.489	0.16					
15.	0.08	0.11	0.077	5.862	0.45		1.200	1.300	1.550	4.050
16.	0.26	0.22	0.150	5.712						
17.	0.24	0.18	0.178	5.534						
18.	0.19	0.19	0.160	5.374						
19.	0.18	0.11	0.125	5.399	0.15					
20.	0.16	0.08	0.148	5.451	0.20					
21.	0.14	0.12	0.098	5.353						
22.	0.13	0.17	0.067	5.336	0.05					
23.	0.10	0.04	0.080	5.456	0.20					
24.	0.12	0.11	0.113	5.343						
25.	0.23	0.22	0.169	5.174						
26.	0.04	0.07	0.093	5.161	0.08					
27.	0.14	0.13	0.144	5.017						
28.	0.14	0.12	0.145	4.872						
29.	0.20	0.17	0.174	4.698						
30.	0.14	0.16	0.169	4.529						
31.										
Total	4.75	4.07	4.003							
Avg.	0.16	0.14	0.133							

Table 8. Soil moisture balance table - 1958 (continued)

July

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	12-24	24-36	0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.22	0.18	0.190	4.339						
2.	0.23	0.18	0.171	4.168						
3.	0.23	0.17	0.172	3.996						
4.	0.23	0.23	0.137	3.859						
5.	0.16	0.12	0.069	3.870	0.08					
6.	0.18	0.16	0.103	3.767						
7.	0.11	0.14	0.146	3.621			0.150	0.200	0.350	0.700
8.	0.06	0.12	0.051	3.740	0.17					
9.	0.02	0.04	0.031	3.789	0.08					
10.	0.04	0.07	0.095	3.914	0.22					
11.	0.07	0.11	0.137	3.787	0.22					
12.	0.11	0.10	0.107	3.690	0.01					
13.	0.10	0.10	0.074	3.636	0.02					
14.	0.07	0.07	0.075	3.581	0.02					
15.	0.20	0.18	0.183	3.398						
16.	0.23	0.19	0.160	3.238						
17.	0.11	0.07	0.055	3.453	0.20					
18.	0.11	0.12	0.089	3.434	0.07					
19.	0.24	0.22	0.166	3.268						
20.	0.14	0.11	0.076	3.192						
21.	0.04	0.11	0.022	3.170						
22.	0.06	0.08	0.088	3.152	0.07					
23.	0.11	0.12	0.096	3.056						
24.	0.08	0.07	0.093	3.133	0.17					
25.	0.18	0.18	0.163	2.970			0.350	0.450	0.850	1.650
26.	0.12	0.11	0.113	2.857						
27.	0.13	0.10	0.111	3.746	1.00					
28.	0.14	0.13	0.160	3.616	0.03					
29.	0.24	0.22	0.195	3.461	0.04					
30.	0.22	0.19	0.179	3.282						
31.	0.18	0.16	0.155	3.327	0.20					
Total	4.36	4.15	3.662							
Avg.	0.14	0.13	0.118							

Table 8. Soil moisture balance table - 1958 (continued)

August

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	12-24	24-36	0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.18	0.13	0.183	3.194	0.05					
2.	0.14	0.11	0.065	3.279	0.15					
3.	0.01	0.01	0.045	3.814	0.58					
4.	0.14	0.16	0.171	3.663	0.02					
5.	0.20	0.16	0.149	3.514						
6.	0.22	0.17	0.169	3.345						
7.	0.14	0.16	0.116	3.229						
8.	0.13	0.17	0.093	3.136			0.600	0.550	0.450	2.100
9.	0.24	0.17	0.158	2.978						
10.	0.24	0.24	0.172	2.806						
11.	0.18	0.16	0.172	2.634						
12.	0.08	0.08	0.089	2.595	0.05					
13.	0.02	0.05	0.048	2.717	0.17					
14.	0.02	0.02	0.061	2.966	0.31					
15.	0.11	0.12	0.136	2.850	0.02					
16.	0.12	0.14	0.114	2.736						
17.	0.22	0.20	0.127	2.609						
18.	0.18	0.20	0.162	2.447						
19.	0.18	0.18	0.147	2.300						
20.	0.18	0.13	0.125	2.175						
21.	0.19	0.17	0.123	2.052						
22.	0.20	0.16	0.100	1.952						
23.	0.12	0.12	0.015	1.937						
24.	0.06	0.06	0.025	2.192	0.28					
25.	0.05	0.02	0.026	1.937	0.47					
26.	0.16	0.13	0.125	2.511						
27.	0.18	0.17	0.128	2.383						
28.	0.16	0.13	0.130	2.253						
29.	0.16	0.12	0.135	2.118						
30.	0.17	0.14	0.141	1.977						
31.	0.19	0.14	0.082	1.895						
Total	4.57	4.12	3.532							
Avg.	0.15	0.13	0.114							

Table 8. Soil moisture balance table - 1958 (continued)

September

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	Measured soil moisture 12-24	Measured soil moisture 24-36	Measured soil moisture 0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.29	0.30	0.174	1.721						
2.	0.11	0.14	0.120	1.601						
3.	0.18	0.16	0.115	1.486			0.075	0.100	0.250	0.425
4.	0.20	0.16	0.130	1.356						
5.	0.18	0.16	0.110	1.246						
6.	0.22	0.22	0.136	1.110						
7.	0.22	0.19	0.092	1.078	0.06					
8.	0.20	0.23	0.127	0.951						
9.	0.14	0.16	0.107	0.844						
10.	0.19	0.19	0.085	0.759						
11.	0.18	0.13	0.113	0.646						
12.	0.08	0.14	0.035	0.611						
13.	0.18	0.11	0.088	0.523						
14.	0.20	0.18	0.105	0.418						
15.	0.11	0.12	0.121	0.297						
16.	0.13	0.12	0.095	0.202						
17.	0.12	0.08	0.095	0.767	0.66					
18.	0.10	0.14	0.030	0.747	0.01					
19.	0.08	0.11	0.058	0.689						
20.	0.01	0.01	0.004	1.185	0.50					
21.	0.04	0.01	0.045	1.710	0.57					
22.	0.07	0.07	0.097	1.613			1.250	0.150	0.350	1.750
23.	0.10	0.08	0.065	1.548						
24.	0.13	0.10	0.085	1.463						
25.	0.11	0.12	0.104	1.359						
26.	0.12	0.06	0.075	1.284						
27.	0.17	0.16	0.076	1.208						
28.	0.19	0.19	0.096	1.112						
29.	0.08	0.10	0.057	1.055						
30.	0.01	0.02	0.002	1.183	0.13					
31.										
Total	4.14	3.96	2.642							
Avg.	0.14	0.13	0.088							

Table 9. Soil moisture balance table - 1959

April

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	Measured soil moisture 12-24	Measured soil moisture 24-36	Measured soil moisture 0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.										
2.										
3.										
4.										
5.										
6.	0.16	0.12	0.093	5.800			2.450	1.650	1.700	5.800
7.	0.13	0.12	0.100	5.700						
8.	0.19	0.17	0.117	5.583						
9.	0.18	0.10	0.107	5.476						
10.	0.06	0.04	0.007	5.569	0.10					
11.	0.01	0.04	0.016	5.618	0.65					
12.	0.02	0.05	0.002	6.696	1.08					
13.	0.00	0.07	0.002	6.694						
14.	0.17	0.08	0.085	6.609						
15.	0.14	0.10	0.118	6.491						
16.	0.16	0.12	0.121	6.370						
17.	0.14	0.12	0.135	6.235						
18.	0.06	0.06	0.050	6.345	0.16					
19.	0.01	0.00	0.042	6.823	0.52					
20.	0.07	0.01	0.092	6.791	0.06					
21.	0.05	0.10	0.041	7.000	0.32	0.070				
22.	0.00	0.00	0.007	7.000	0.66	0.653				
23.	0.06	0.02	0.084	6.976	0.06					
24.	0.14	0.12	0.116	6.860						
25.	0.16	0.12	0.106	6.754						
26.	0.18	0.20	0.112	6.642						
27.	0.08	0.10	0.023	6.619						
28.	0.05	0.04	0.060	6.609	0.05					
29.	0.16	0.12	0.119	6.490						
30.	0.19	0.14	0.122	6.398	0.03					
31.										
Total	2.57	2.16	1.917							
Avg.	0.09	0.07	0.064							

Table 9. Soil moisture balance table - 1959 (continued)

May

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	12-24	24-36	0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.11	0.07	0.122	6.296	0.02					
2.	0.22	0.13	0.151	6.145						
3.	0.24	0.16	0.150	5.995						
4.	0.10	0.06	0.096	6.399	0.50					
5.	0.18	0.14	0.148	6.251						
6.	0.23	0.17	0.146	6.105						
7.	0.25	0.19	0.163	5.942			2.200	1.675	1.800	5.675
8.	0.24	0.23	0.158	5.784						
9.	0.17	0.18	0.041	5.743						
10.	0.12	0.08	0.030	5.713						
11.	0.19	0.12	0.162	5.551						
12.	0.17	0.11	0.128	5.603	0.18					
13.	0.08	0.04	0.040	6.553	0.99					
14.	0.16	0.24	0.075	6.478						
15.	0.12	0.18	0.088	6.390			1.925	1.350	1.775	5.050
16.	0.12	0.12	0.115	6.257						
17.	*	0.08	0.096	6.179						
18.	0.05	0.02	0.058	6.121	0.05					
19.	0.23	0.12	0.173	5.948						
20.	0.14	0.07	0.087	5.861	0.15					
21.	0.05	0.04	0.102	5.759			1.550	1.050	1.225	3.825
22.	0.12	0.08	0.119	5.640						
23.	0.24	0.19	0.162	5.478						
24.	0.26	0.22	0.182	5.296						
25.	0.16	0.17	0.037	5.259			0.950	0.300	1.100	2.350
26.	0.04	0.02	0.013	5.326	0.08					
27.	0.10	0.05	0.060	5.276	0.01					
28.	0.12	0.07	0.097	5.179						
29.	*	0.11	0.118	5.061						
30.	*	0.06	0.029	5.382	0.35					
31.	*	0.07	0.020	5.362						
Total	4.21	3.59	3.166							
Avg.	0.16	0.12	0.102							

*Clock stopped.

Table 9. Soil moisture balance table - 1959 (continued)

June

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	12-24	24-36	0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.01	0.01	0.048	5.884	0.57					
2.	0.07	0.06	0.044	6.320	0.48					
3.	0.19	0.16	0.134	6.186						
4.	0.24	0.18	0.166	6.020						
5.	0.18	0.16	0.155	5.865						
6.	0.18	0.14	0.142	5.723						
7.	0.20	0.16	0.173	5.550						
8.	0.22	0.17	0.174	5.376						
9.	0.23	0.18	0.150	5.226						
10.	0.20	0.19	0.147	5.079						
11.	0.19	0.17	0.180	4.899						
12.	0.19	0.17	0.155	4.744						
13.	0.34	0.32	0.176	4.568			0.525	0.925	1.550	3.000
14.	0.31	0.30	0.160	4.408						
15.	0.32	0.24	0.150	4.258						
16.	0.23	0.22	0.128	4.130						
17.	0.18	0.17	0.114	4.016						
18.	0.14	0.13	0.089	3.927						
19.	0.24	0.19	0.148	3.779						
20.	0.25	0.19	0.170	3.601						
21.	0.20	0.16	0.168	3.433						
22.	0.24	0.20	0.176	3.257						
23.	0.16	0.08	0.048	3.919	0.71					
24.	0.02	0.06	0.019	3.910	0.01					
25.	0.08	0.11	0.090	3.820						
26.	0.23	0.17	0.150	3.670						
27.	0.19	0.16	0.083	3.587						
28.	0.25	0.22	0.190	3.397						
29.	0.28	0.22	0.201	3.196						
30.	0.26	0.19	0.201	2.995						
31.										
Total	6.02	5.09	4.129							
Avg.	0.20	0.17	0.138							

Table 9. Soil moisture balance table - 1959 (continued)

July

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	12-24	24-36	0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.24	0.22	0.146	2.849						
2.	0.22	0.23	0.076	2.773						
3.	0.25	0.22	0.149	2.624						
4.	0.29	0.25	0.173	2.451						
5.	0.23	0.23	0.166	2.285						
6.	0.13	0.11	0.107	2.178			0.000	0.200	0.700	0.900
7.	0.34	0.28	0.181	1.997						
8.	0.34	0.26	0.168	1.829						
9.	0.20	0.16	0.057	1.772						
10.	0.25	0.17	0.140	1.632						
11.	0.17	0.17	0.061	1.571						
12.	0.12	0.13	0.124	1.447						
13.	0.16	0.18	0.085	1.362						
14.	0.12	0.07	0.091	1.359	0.88					
15.	0.13	0.11	0.061	1.298						
16.	0.25	0.16	0.147	1.151						
17.	0.14	0.16	0.082	1.069						
18.	0.12	0.10	0.123	0.996	0.05					
19.	0.17	0.12	0.147	0.849						
20.	0.13	0.16	0.122	0.727						
21.	0.05	0.07	0.034	0.703	0.01					
22.	0.05	0.06	0.058	1.135	0.49					
23.	0.14	0.08	0.173	0.972	0.01					
24.	0.14	0.18	0.158	0.864	0.05					
25.	0.05	0.05	0.048	0.836	0.02					
26.	0.11	0.11	0.092	0.744						
27.	0.02	0.08	0.057	1.087	0.40					
28.	0.07	0.08	0.080	1.427	0.42		0.600	0.300	0.900	1.800
29.	0.02	0.11	0.078	1.040						
30.	0.10	0.10	0.080	1.587	0.24					
31.	0.06	0.04	0.090	1.717	0.22					
Total	4.81	4.50	3.354							
Avg.	0.16	0.14	0.108							

Table 9. Soil moisture balance table - 1959 (continued)

August

Date	Pan evaporation Class A	Pan evaporation Class B	E_t	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	12-24	24-36	0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.12	0.12	0.139	1.608	0.03					
2.	0.22	0.20	0.165	1.443						
3.	0.12	0.10	0.087	1.556	0.20					
4.	0.00	0.00	0.015	3.451	1.91					
5.	0.19	0.14	0.163	3.298	0.01					
6.	0.17	0.13	0.128	3.170						
7.	0.12	0.12	0.093	3.077			1.600	0.900	0.950	3.450
8.	0.12	0.10	0.102	2.975						
9.	0.18	0.16	0.102	2.873						
10.	0.17	0.17	0.138	2.735						
11.	0.18	0.16	0.146	2.589						
12.	0.19	0.16	0.150	2.439						
13.	0.19	0.17	0.139	2.300						
14.	0.20	0.16	0.142	2.158						
15.	0.19	0.17	0.143	2.015	0.04					
16.	0.19	0.14	0.122	1.933	0.38					
17.	0.12	0.10	0.140	2.173						
18.	0.05	0.10	0.099	2.074	0.73					
19.	0.13	0.12	0.094	2.710						
20.	0.17	0.13	0.154	2.556						
21.	0.17	0.16	0.148	2.408						
22.	0.18	0.16	0.168	2.240						
23.	0.18	0.14	0.167	2.073						
24.	0.10	0.08	0.102	2.071						
25.	0.16	0.14	0.123	1.948						
26.	0.16	0.16	0.110	1.838						
27.	0.07	0.11	0.051	1.787						
28.	0.08	0.10	0.110	1.697	0.02					
29.	0.00	0.01	0.031	1.821	0.18					
30.	0.06	0.07	0.055	2.316	0.03					
31.	0.01	0.00	0.015		0.51					
Total	4.19	3.78	3.541							
Avg.	0.14	0.12	0.114							

Table 9. Soil moisture balance table - 1959 (continued)

September

Date	Pan evaporation Class A	Pan evaporation Class B	Et	Soil moisture balance	Rain-fall	Surface runoff	Measured soil moisture 0-12	Measured soil moisture 12-24	Measured soil moisture 24-36	Measured soil moisture 0-36
	in/day	in/day	in/day	in	in	in	in	in	in	in
1.	0.00	0.00	0.041	3.543						
2.	0.10	0.11	0.126	3.449	1.27					
3.	0.13	0.10	0.135	3.314	0.03		1.950	0.750	1.125	3.825
4.	0.17	0.16	0.123	3.191						
5.	0.16	0.16	0.100	3.091						
6.	0.01	0.04	0.047	3.044	0.05					
7.	0.07	0.06	0.082	2.962	0.20					
8.	0.07	0.08	0.109	2.853						
9.	0.14	0.13	0.118	2.735						
10.	0.13	0.13	0.100	2.635						
11.	0.11	0.16	0.051	2.584						
12.	0.12	0.12	0.104	2.480						
13.	0.13	0.14	0.090	2.390						
14.	0.07	0.10	0.070	2.320						
15.	0.07	0.08	0.052	2.268						
16.	0.14	0.10	0.098	2.170						
17.	0.02	0.07	0.007	2.163						
18.	0.17	0.13	0.100	2.063						
19.	0.11	0.12	0.089	1.974						
20.	0.12	0.10	0.091	1.883						
21.	0.05	0.08	0.090	1.993						
22.	0.13	0.10	0.103	1.690						
23.	0.13	0.12	0.105	1.585			0.275	0.500	0.800	1.575
24.	0.12	0.10	0.111	1.474						
25.	0.17	0.13	0.110	1.364						
26.	0.14	0.14	0.105	1.259						
27.	0.10	0.08	0.044	1.215						
28.	0.08	0.08	0.086	1.129						
29.	0.01	0.01	0.010	3.459	2.34					
30.	0.01	0.00	0.007	6.262	2.81					
31.										
Total	2.98	2.93	2.504							
Avg.	0.10	0.10	0.083							

PREDICTION OF SOIL MOISTURE FROM SELECTED CLIMATIC DATA

by

Andrew Chia-Shing Chang

ABSTRACT

Climatic variables have been used to calculate evapotranspiration loss by many researchers. Evapotranspiration formulas have been developed for local use in predicting soil moisture in many parts of the United States. The objective of this study was to develop a method to estimate soil moisture in Virginia using data collected by the Agricultural Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

The first step in the study was to determine the relationship between soil moisture loss and pan evaporation. This relationship was found on a seasonal cumulated basis. For shorter periods, the results were poor. No workable relation could be found that would satisfactorily estimate soil moisture from any of these procedures.

A soil moisture accounting system based on the soil moisture balance principle was then devised in which daily evapotranspiration loss was calculated by Van Bavel's nomogram method. Daily soil moisture values were estimated by this system. The estimated soil moisture and measured soil moisture were compared by the student t-test for paired observations. The results of the statistical analysis indicated it could be used to estimate soil moisture in local conditions. Finally, the correlation between daily evapotranspiration and pan evaporation was determined. A high correlation was found.

The problem encountered in analyzing the data available for this study indicated the need for a detailed, statistically controlled experiment. Hence an experimental design has been formulated that, hopefully, will allow an accurate, systematic investigation and evaluation of the problem.