THE ESTIMATION OF EVAPOTRANSPIRATION
FOR THREE SURFACES

THE ESTIMATION OF EVAPOTRANSPIRATION FOR THREE SURFACES USING A SIMPLIFIED SOIL MOISTURE BUDGET EQUATION

By

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SCOPE AND CONTENTS:

Evapotranspiration, an important physiological and geophysical process, was estimated using a simplified water balance equation and soil moisture measurements made by a neutron probe. For three surfaces (grass, orchard and wheat) considerable spatial variation in soil moisture was found. Deep seepage errors were demonstrated to be negligible except for one measurement period. Similar trends in measured evapotranspiration were shown by all three crop types throughout the season, even though rates were less than potential. A statistical analysis was used to establish the number of sampling points necessary to achieve an acceptable maximum error in evaporation estimates.

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CHAPTER ONE

INTRODUCTION

Evaporation, as defined by Thornthwaite and Hare (1965) is "both a physiological and geophysical process of immense significance". Physiologically it is evaporation which draws the transpirational stream of water through the plant, thus supplying it with the necessities of life; and geophysically, evaporation consumes a considerable proportion of the available solar energy at the earth's surface. This combination of evaporation from plants (part of the transpiration process) and evaporation from the soil is known as evapotranspiration. As this is a factor of obvious importance in many fields of research, it must be either measured or estimated. Since it is very difficult to divide evapotranspiration into its two components (Fritchen and Shaw, 1961) for micro-meteorological purposes it is considered as one process. Hence, in this study the terms "evapotranspiration", "evaporation" and "water loss to the atmosphere" are synonymous.

The main problem dealt with in this study was that of calculating evapotranspiration by the soil moisture method for three vegetation types (grass, wheat and orchard). This was carried out on Caledon sandy loam, and the three rates of evaporation were compared. Associated with this, soil moisture was measured and the nature of variation of water content in the Caledon sandy loam was examined. A third problem was to calculate the number of soil moisture sampling points necessary to reduce the error of the estimate of evapotranspiration at any site to an acceptable maximum.

The neutron attenuation method was used to measure soil moisture. Since this is an accurate method of measuring water content repeatedly at several fixed sites and depths it was possible to analyse in detail, for the first time, the spatial variability which causes error in soil moisture measurements. Use of the neutron probe also allowed a calculation of the number of sampling points necessary to reduce errors due to variability in soil moisture to acceptable levels.

The results of the study have shown the errors inherent in the use of the simplified moisture budget equation to estimate evapotranspiration. In spite of this, however, the most important contribution of this study is that it has shown evapotranspiration to be more a function of energy and water supply than of vegetation type.

CHAPTER TWO

THEORETICAL BACKGROUND.

A. The water budget and soil moisture measurement.

The change in stored soil moisture (ΔSM) over any time interval depends on the inputs of water to a soil column from precipitation (P), lateral movement (+L) and capillary rise (+G) and the losses due to run-off (R), lateral movement (-L) deep seepage (-G) and evapotranspiration (E_T).

This can be expressed as

$$\Delta SM = P - R - \Delta G - \Delta L - E_T, \qquad (1)$$

where ΔL gives the net loss of soil water due to lateral flow and ΔG the net loss due to vertical flow out of the column. Soil moisture can be measured directly, and hence the temporal change in storage can be calculated. Methods of doing this are documented by Cope and Trickett (1965). The method of soil moisture measurement used in this study was the neutron attenuation technique.

The measurement of soil moisture using radioactive methods has become increasingly popular since it was introduced in the late 1940's and early 1950's (Holmes, 1956; Lane et al, 1953; Spinks et al,1951). When a source of fast neutrons bombards a moderating material the neutrons are slowed by elastic collision. Some return to the emitting source where they are monitored. The rate of the slow neutron return is proportional to this concentration of the moderating material (Van Bavel, 1963). Since hydrogen in soil moisture is a very good moderator of fast neutrons the density of the slow neutron cloud can be directly related to the soil moisture content by volume. Other neutron moderators in the soil are regarded as constant and are accounted for by calibrating the instruments for each individual soil type. Instruments using these principles have been developed and are commercially available.

The neutron probe has many advantages over other methods of measuring soil moisture (Van Bavel, 1956). It is the fastest method, the soil is not changed or damaged once the access tubes are in place, and measurements can be repeated at the same location counteracting the effects of spatial variation in the soil. The access tubes are placed flush with the ground and therefore offer very little chance for damage, while allowing normal agricultural activities to take place without disturbance. The substantial penetration of the neutrons gives an average picture of a larger volume of soil and, as a result, a higher degree of accuracy than that obtained by other means of direct soil moisture measurement. Some of the disadvantages of the instrument are the need to calibrate it for each soil, its weight and awkwardness, the necessity to have two instruments (one for depth and one for the surface) and interface effects. It is necessary to have both a depth probe and a surface gauge, since the depth probe is not accurate within 15 cm of the surface due to neutron escape through the earth-air interface. Interface effects are also found where there are wet and dry layers in the soil (Lawless et al, 1963). The depth probe in this case will record an average soil moisture which integrates between the wet and dry layers, and the derived profile will show a smooth change in soil moisture rather than a sudden break. These errors will tend to cancel each other out as long as measurements are made on both sides of the interface.

The variation in soil moisture within a soil depends largely on its texture and structure. A homogenous soil will show less variation than one which contains patches of different materials. Inhomogeneities in the soil constituents will be reflected by differences in gravitational and capillary flow. Since texture and structure are basic characteristics of a given soil type, they will remain constant throughout the growing season providing there is no disturbance to the soil. Consequently one would expect the spatial variation in soil moisture to remain constant through time, especially if the soil profile is well established or developing very slowly. The only factor in eq. (1) which does not behave in this manner is precipitation which will vary randomly in time and space. This, however, will be insignificant over small flat areas such as those studied (see analysis of error - Appendix II) unless there is shading of the ground by trees.

B. Evapotranspiration.

There have been many attempts to measure, estimate and predict evapotranspiration with varying degrees of sophistication. In 1965, Thornthwaite and Hare summarised work up to that time, and Penman, Angus and Van Bavel (1967) and Tanner (1967) presented a comprehensive review of the "microclimatic factors affecting evaporation and transpiration" and the various methods of measurement.

The method chosen for calculating evapotranspiration uses the water balance equation (1) solving for E_T:

$$E_T = P - \Delta G - \Delta L - \Delta SM - R. \tag{2}$$

This method was discussed by Bowman and King (1965), who measured ΔSM, assumed ΔL and R to be negligible and estimated ΔG by covering a control plot with plastic (thus making $E_T = 0$).

In the present study ΔL was also assumed to be negligible because of the coarse nature of the soil. This was also the reason for assuming no runoff, and in fact, none was observed. Bowman and King found that deep percolation on loam soils with gravelly parent materials (which one would expect to have rapid percolation) was actually a maximum of 0.36 cm per month, which would give a small monthly error if ignored. Since there was no more recent information on this factor at the time, eq. (2) was simplified to

$$E_T = P - \Delta SM. \tag{3}$$

The importance of this method is that accurate measurements of water loss to the atmosphere can be obtained rapidly and simply, merely by measuring soil moisture and precipitation. This means that it is not dependent on intricate instrumentation and is therefore more useful for long term measurement. Greater accuracy can be obtained when necessary by measuring the other terms in eq. (2).

Measured evapotranspiration was compared with potential and actual evapotranspiration calculated by other methods. These methods included the net radiational equivalent of evapotranspiration R_n/L where R_n is net radiation and L is the latent heat of vaporization, the Penman combination model and the Thornthwaite mean temperature method.

In the first of these methods R_n/L represents the maximum amount of evaporation possible with a non-limiting water supply when none of the available energy is used to heat the soil or the air and there is no advective heat input. The Penman model for potential evaporation was tested at Simcoe in the summer of 1967 (McCaughey, 1968) and found to predict both hourly and daily evaporative loss to an accuracy of 5%. This applied to both cloudy and cloudy bright days under conditions of potential evapotranspiration and used measured net radiation and an improved wind function. The Penman formula used for this study was:

$$E_T = \frac{\Delta/\gamma\ (R_n - G) + Ea}{\Delta/\gamma + 1} \qquad (4)$$

where

$$E_a = f\ (u)\ (e_d - e_a) \qquad (5)$$

and

$$f(u) = u.\ 1.2 \left[k^{-1} \ln\left\{(z + z_o)/z_o\right\}\right]^{-2} \qquad (6)$$

Δ = the slope of the saturation vapour pressure - air temperature curve

γ = c_p/L where c_p = specific heat of air at constant pressure

= $0.66°C^{-1}m^{-1}$

G = soil heat flux

e_d = saturation vapour pressure at wet bulb temperature

e_a = vapour pressure at air temperature

u = wind speed

k = von Karman's constant

z = height of anemometer (60 cm)

z_o = a crop roughness parameter of 0.7 cm for grass (Priestley, 1959). The wind function (eq. 6) is that of Businger (1956). The Thornthwaite method for computing potential evapotranspiration and the water balance is described by Thornthwaite and Mather (1957). This method of estimation is based on empirically found relationships between potential evapotranspiration and mean daily temperature. Tables are used to find the potential evaporation corresponding to a given mean daily temperature. This is adjusted for day-length, and then used in other tables to find the amount of water retained in the soil. These tables are constructed so that less water can be evaporated under given PE conditions at lower soil moisture levels. "Actual storage change" is then calculated and this can be compared to that measured by the neutron probe. By substituting "actual storage change" for ΔSM in eq. (3) "actual evapotranspiration" can be calculated.

It is important to note that the R_n/L and Penman methods assume potential evapotranspiration. That is, evaporation is not limited by water supply and occurs from a complete, green vegetation cover. This is not true for the Thornthwaite estimate, which uses soil water storage to modify "potential" evaporation to "actual". Hence under limited water supply one would expect the R_n/L and Penman methods to overestimate actual evapotranspiration.

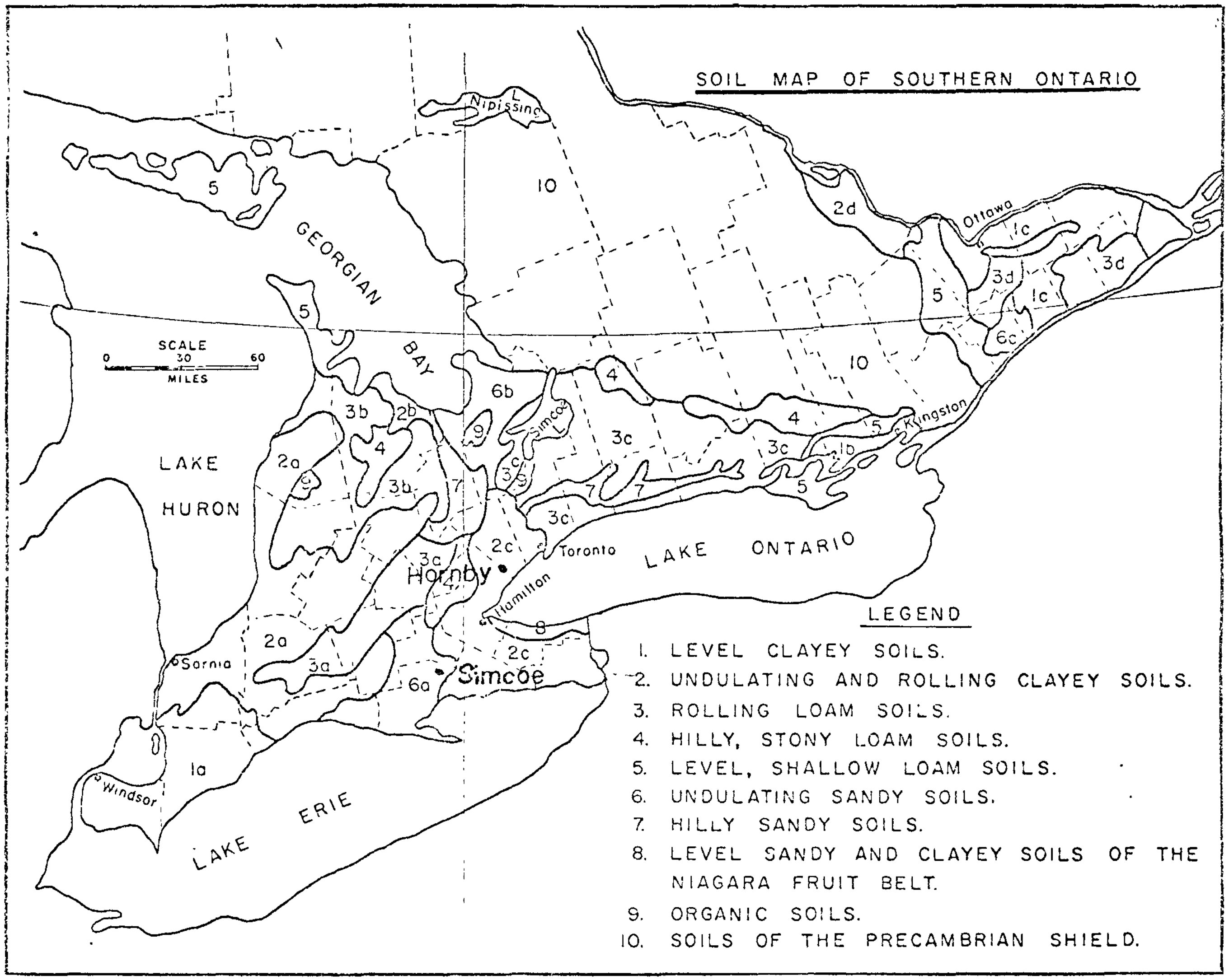


Figure I

After Webber and Hoffman, 1967

CHAPTER THREE

EXPERIMENTAL METHODS

A. General Description

The experimental sites were located at the Ontario Horticultural Experiment Station, near Simcoe, Ontario. This farm is part of a mixed farming area located on loam soils. Fig. 1 shows the location of the farm in relation to Southern Ontario, and the distribution of the main soil types in the area.

B. Site Description

On the soil map of the farm (Fig. 2) one can see the three sites used for this study. Each was on Caledon sandy loam, which has a dark brown sandy loam surface about seven inches thick, underlain in turn by brown sandy loam and a reddish brown loam eight inches and five to seven inches thick respectively. Beneath these horizons is a fine to medium calcareous gravel.

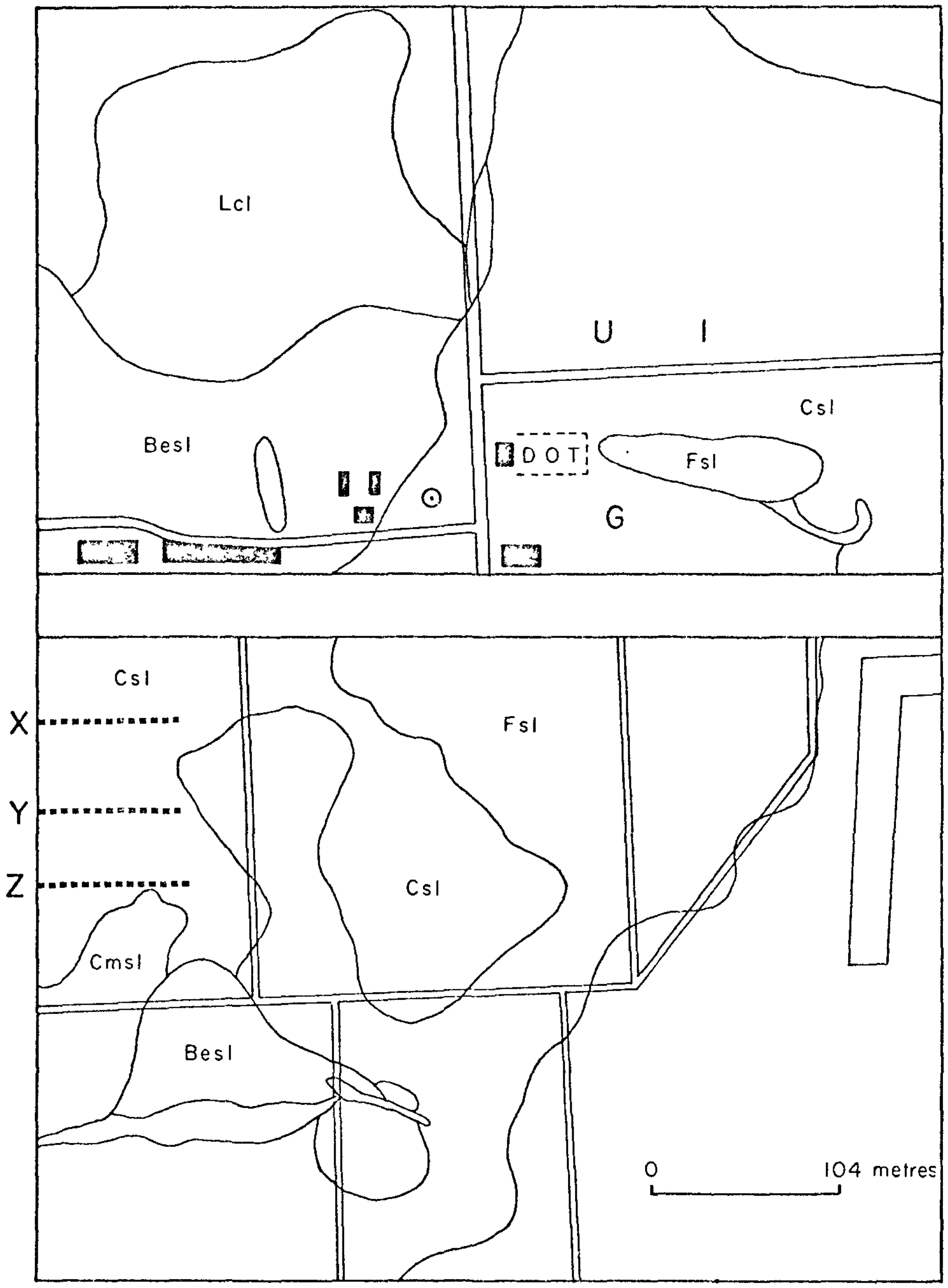
1. Grass Plot.

The position of the grass grid is shown in Fig. 2. The plot was situated in a grass lawn which was cut regularly throughout the growing season. The grass remained in the vegetative phase during the measuring period, and rooting depth was at least 60 cm although the main body of the roots was above the 30 cm depth.

One of the purposes of the study on the grass plot was to measure variation between sampling points. Thin-walled seamless steel access tubes were installed to a depth of 90 cm. These were shorter

Figure 2

SOIL MAP OF EXPERIMENT FARM



Legend for Figure 2

▨	Building
D O.T.	Meteorological Observation Station
⊙	Field calibration site
G	Grass plot
U	Unirrigated orchard site
I	Irrigated orchard site
X	Rows of access tubes in wheatfield
Y	
Z	
Besl	Berrien sandy loam
Ll	Lincoln loam
Wasl	Wauseon sandy loam
Bdsl	Brady sandy loam
Csl	Caledon sandy loam
Lcl	Lincoln clay loam
Fsl	Fox sandy loam
Cmsl	Camilla sandy loam

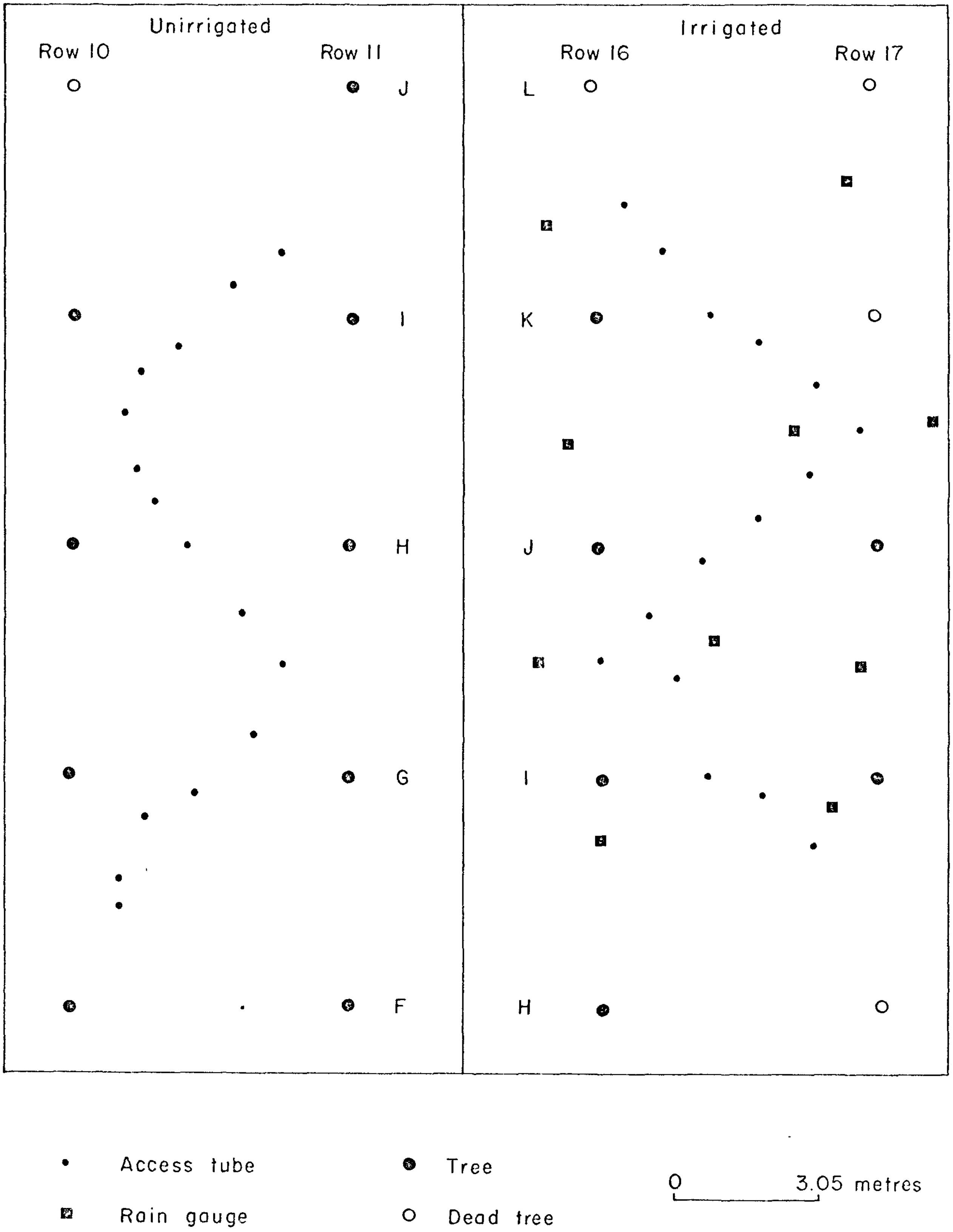
than those installed in the orchard and wheat field since the area of interest lay in the upper layers of soil where moisture variation was greatest. Measurement time at each tube was thus reduced, and this enabled a larger areal sample to be taken at any one time. The sampling points were located in a five by five grid of twenty-five tubes, each tube positioned 1.2 m from its nearest neighbour. The access tubes in all plots were inserted by driving them into the ground and augering the soil out of the tubes. This method gave the closest fit between the tube and the soil. Because of its stoney nature some air spaces along the sides of the tube were inevitable, but these should have remained constant throughout the season, and while giving slight error to the soil moisture calculations would not be likely to affect the derived evaporation since the error in soil moisture should be constant. The inserted tubes were sealed at the bottom with rubber stoppers and corked at the top to prevent the penetration of soil moisture or rain. It is vital to ensure that tubes are correctly installed and are water-tight. In this study water penetrated the tubes after a heavy rainstorm and necessitated a break in measurement while the tubes were pumped dry and the depth probe repaired.

2. Orchard Site. The locations of the two sampling sites in the orchard are shown in Fig. 2, while Fig. 3 demonstrates the arrangement of the tubes at these sites. The tubes were inserted to a depth of 150 cm using the "drive and auger" method described above. They were also stoppered in a similar manner to the grass grid.

Horticultural experiments in the orchard (which was composed

Figure 3

ARRANGEMENT OF ACCESS TUBES IN THE ORCHARD



of several different types of soft fruit tree, especially peach) involved the use of irrigation in the eastern portion. Tubes were therefore situated in both irrigated and non-irrigated zones in order to compare results. Unfortunately, only one irrigation was necessary between the end of May and the middle of August so that only the last set of measurements refer to irrigated conditions. However, the eastern site is called "irrigated" to avoid confusion.

The arbitrary zig-zag pattern shown in Fig. 3 was chosen to include different root density and canopy cover characteristics. These factors might be expected to give rise to variations in soil moisture withdrawal and precipitation receipt, and this procedure was designed to give a generalised picture of moisture conditions within the orchard. This could also have been achieved by a random distribution of tubes in the same area, but it was decided that measurements should not be made too near to the trees since the organic matter in the mulches used there would affect the calibration of the probe. The peach trees were spaced 6.1 m apart in the north-south direction, and 7.3 m apart in the east-west direction. The tubes were inserted before the trees came into leaf and some trees were subsequently found to be dying. These were removed during the season and they are marked in Fig. 3. The trees were approximately 3 m high, with roots radiating to at least 3 m in depth. A complete cover of grass (growing at times to over 30 cm long and rooting to at least 60 cm) covered the soil surface. This was kept in the vegetative phase by mowing. The fruit were developing during the measuring period and were nearly ripe on August 12, the last day of measurement.

3. Wheatfield. The location of the three rows of tubes is shown in Fig. 2. Three rows were used for replication and to test conditions throughout the field. In the southern section of the field the upper horizons of sandy loam became thin and the lower parts of the tubes were in clay. The effects of this are discussed in the next chapter. The tubes were inserted and stoppered, as in the grass grid, to a depth of 150 cm and were placed at the western edge of the field and at intervals of 0.3, 1, 2.5, 5, 10.5, 21, 42.5 and 75 m from that edge. This arrangement was designed to correspond with a wind and temperature advection study which was expected to run simultaneously. However, this latter study did not take place.

To prevent the wheat from being trampled more than necessary, paths were made ten feet to the south of each row of tubes. The probe was then carried along the rows and the measurements were recorded by the ratemeter mounted on a specially designed wheelbarrow which was moved along the path from site to site. This kept damage to the crop at a minimum at the measuring sites. A smooth area was prepared adjacent to the path at each tube, on which surface moisture readings were taken.

The roots of the wheat penetrated at least 75 cm in depth. A summary of the development of the crop through the measuring season is given in Table 1.

C. Data Collection.

In order to calculate evapotranspiration it was necessary first to calculate soil moisture change from successive soil moisture measure-

TABLE I

DEVELOPMENT OF WHEAT DURING EXPERIMENTAL PERIOD

DATE	OBSERVATION
June 6	Wheat ears still encased in leaves.
June 14	Anthers, still green, appearing.
June 20	Pollination taking place.
June 26	Crop bent by strong wind and over 3 in. rain.
July 7	Crop recovered, ears beginning to fill out.
July 25	Ears almost ripe, stems and leaves yellowing and drying.
July 30	Crop harvested.

ments, and to measure precipitation. The method of soil moisture measurement has already been described. The instruments used in this study were the Nuclear Chicago model 5901 I/M Combination Moisture-Density Gauge and model 5806 Subsurface Moisture Probe. The source of fast neutrons in the surface gauge is a 4 millicurie Radium - beryllium pellet with a half life of 1620 years. The depth probe source is an 80 millicurie Americium-241/beryllium pellet with a 475 year half life. A sensor of lithium-chloride is located near the source to count the number of slow neutrons returning per unit time. The two measurement devices were calibrated for Caledon sandy loam. The methods and results of calibration are presented in Appendix I. Measurements were made over different lengths of time (due to weather conditions and instrument repair problems) averaging about ten days. Sub-surface measurements were taken at 15 cm intervals starting at a depth of 18 cm. Measurements closer to the surface would have been affected by the air/soil interface effects discussed previously. This measurement interval was considered close enough to give a good average moisture value for the soil between each depth and to allow some overlap of "spheres of influence".

Surface measurements were made at the same time as the depth measurements. However, at the beginning of the season there were no surface measurements due to a malfunctioning instrument. Surface readings were not taken in the orchard since there were no suitable flat areas of bare soil. A prepared area would have been atypical and would not have given useful results. Surface gauge readings were taken on the grass plot, where the grass was much shorter and better contact could be made between the gauge and the soil. However, even these results are suspect since the contact between gauge and soil was not smooth and probably included many air gaps. The presence of grass would also affect the moisture reading because of the water and other hydrogenous matter in the plants.

The precipitation data used in eq. 3 were obtained from the Department of Transport Meteorological Branch station situated on the farm and marked in Fig. 2. Precipitation was also measured by Casella 6 in. diameter rain gauges in the irrigated orchard. Originally these instruments were intended for measurement of amounts of irrigation water applied to the site but they were also used to analyse the spatial variation of rainfall for the analysis of error (Appendix II). Pan evaporation, wet and dry bulb temperatures and wind data were also collected from the meteorological station for use in the calculation of evaporation by the Penman and Thornthwaite methods and for other comparisons. Hourly totals of net radiation for the calculation of potential evapotranspiration (R_n/L) and Penman evaporation were obtained from the Department of Transport for the meteorological station at Hornby (for location see Fig. 1). This station was considered near enough to Simcoe to give representative net radiation totals, especially for weekly to ten day periods.

D. Data Analysis.

Conversion of neutron counts to soil moisture was accomplished using the calibration curves derived in Appendix I. Variations in soil moisture were analysed spatially and in profile to examine the possibility of lateral or gravity flow.

The total soil moisture in a column of soil equal in depth to the length of an access tube was calculated for each sampling point. Averages were found for each area under consideration. Total soil moisture for each tube was calculated first by using only the depth probe measurements (and extrapolating to the surface) and secondly by using surface probe data (where available) to calculate the soil moisture of the top 10 cm. Results of the calculations of water loss to the atmosphere using both sets of data are discussed in the next chapter.

Calculated evapotranspiration was compared with potential evaporation from a Class A open pan, and water loss calculated from R_n/L. This latter (ignoring advection effects) should give the maximum possible evaporation under non-limited water supply over a given period of time. The Thornthwaite and Penman methods of calculating evapotranspiration were also used to compare with measured evaporation. It was hoped that these would reveal any large anomalies and give an indication of whether any deep seepage had occurred.

The measured evapotranspiration from the three different crop surfaces was examined and compared, to determine whether, in fact, it would be similar for all three, since each was growing in the same soil and experiencing the same climatic conditions.

The evaporation data for the grass was analysed statistically to ascertain the minimum number of tubes to be used in order to be certain (at a given significance level) that the true mean evapotranspiration would fall within a given deviation from the sample mean.

CHAPTER FOUR

RESULTS

A. Soil Moisture.

1. Grass Plot. Figure 4 shows the mean soil moisture profiles for the eight days on which soil moisture was measured. Surface probe measurements are included for the six days on which they were made. These show how the surface moisture can differ from that measured at 18 cm and underline the dangers of using measurements extrapolated from the 18 cm depth to calculate surface moisture. However, the error inherent in this is made smaller when calculating evapotranspiration over a period between soil moisture measurements, since the surface soil moisture fluctuates both above and below that of the lower depths during the measuring period. The errors in measurement therefore, may tend to cancel each other out. The grass evapotranspiration results were used to test the significance of differences caused by calculating soil moisture from depth probe measurements only, and using the surface moisture meter to calculate the moisture content of the first 10 cm. Table 2 gives the deviation of E_T, calculated from depth probe results only, from E_T calculated from depth probe and surface gauge results. These reached a maximum of 11.0% during the period after heavy rains (July 2-11). Figure 4 shows that the greatest overestimation by the depth probe of surface soil moisture occurred on July 11. However, the absolute mean error incurred by this method of estimation was 6.8%. This is fairly low in view of the disadvantages

Figure 4

MEAN SOIL MOISTURE PROFILES – GRASS

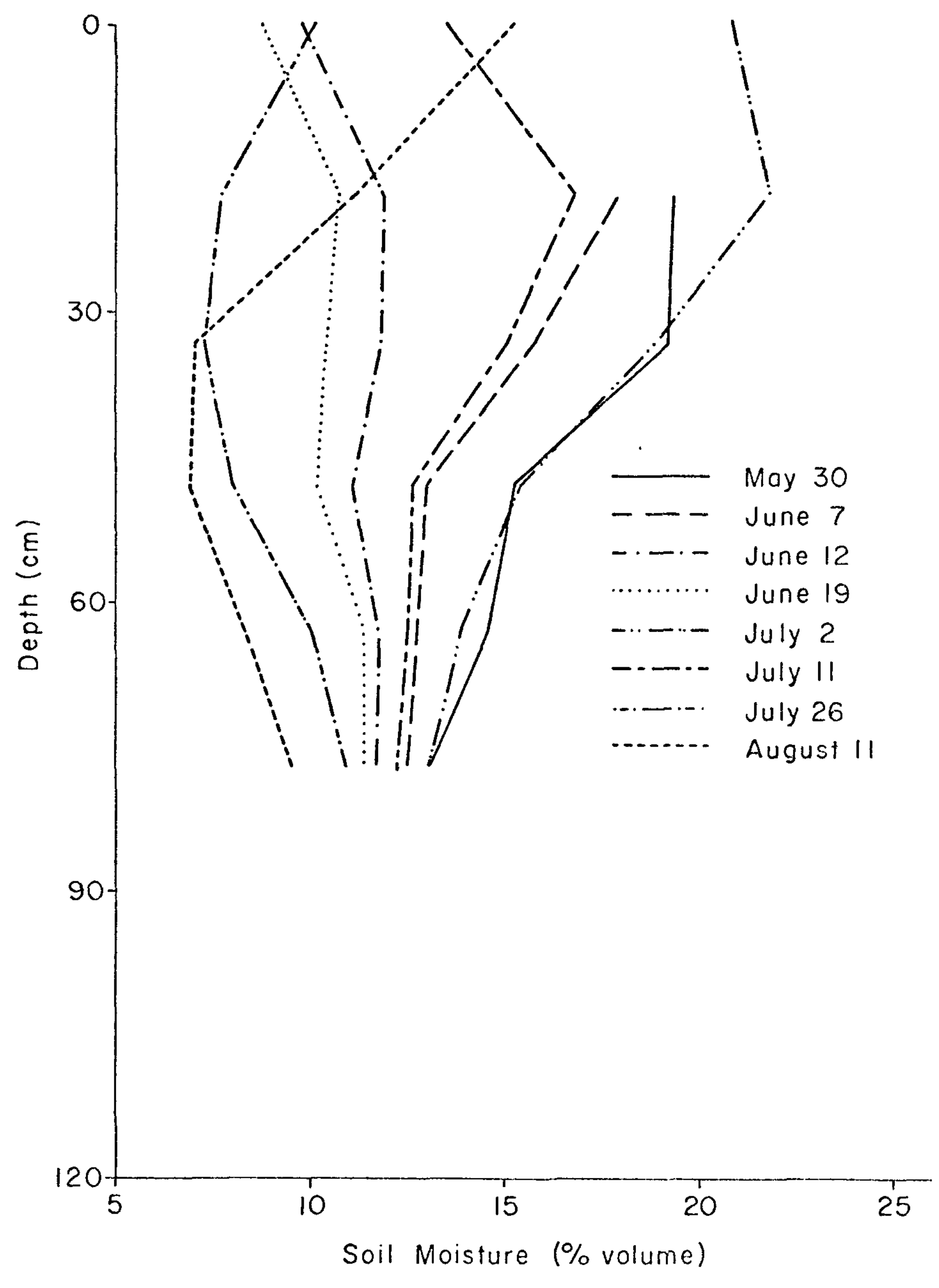


TABLE 2

COMPARISON OF EVAPOTRANSPIRATION RESULTS CALCULATED FROM DEPTH PROBE AND SURFACE GAUGE DATA (SET) AND DEPTH PROBE DATA ONLY (ET).

Date	Mean SET (cm)	Mean ET (cm)	Difference (cm)	% SET
June 12 - 18	1.630	1.576	+ .054	+ 3.3
June 19 - July 2	6.185	6.832	- .647	- 10.5
July 2 - 11	4.434	3.949	+ 4.85	+ 11.0
July 11 - 26	5.824	5.940	- .116	- 2.0
July 26 - Aug. 11	4.706	5.051	- .345	- 7.3

TABLE 3

GRASS GRID - MEAN SOIL MOISTURE

Date	Mean soil moisture (cm)	Standard deviation (cm)
May 30	13.2	1.6
June 7	11.7	1.6
June 12	9.4	1.4
June 19	8.7	1.4
July 2	13.6	1.7
July 11	11.3	1.5
July 26	7.0	1.1
August 11	7.1	0.9

of the surface probe measurements. These are firstly, that only 16 measurements were taken each time and these were averaged to apply to the nearest sampling point. Secondly there was poor contact between soil and meter since a bare, smooth surface was not used. Thirdly the grass cover between the gauge and the soil presented a large mass of neutron moderating material which was interpreted as soil moisture. Lastly the calibration curve for the surface gauge had a large standard error of the estimate and was not considered to be as accurate as that of the depth probe (see Appendix I). Because the surface gauge results were considered unreliable and since the errors involved in estimating them from depth probe data were small, the further analysis of evapotranspiration was performed on soil moistures calculated solely from the depth probe measurements.

Mean total soil moistures for the 90 cm soil columns are shown in Table 3. Quite clearly the deviation from the mean varies with the amount of water in the soil. Thus when the soil was wet, for example on July 2 after a very heavy rainfall, the spatial variation in soil moisture was greater than when it was dry (for example August 11). This shows that a certain amount of lateral water flow must have taken place along the wetness gradients since the soil moisture tended to less variability as it dried out. This would be expected since the amount of precipitation received would vary from point to point on the grid, and the soil moisture immediately after a rain would depend on minor drainage features and interception by plants and roots. As the soil dried out, the moisture it contained would tend to reach equilibrium and these spatial variations would decrease.

The seasonal variation in the soil moisture profiles (Fig. 4) shows two drying cycles. On May 30, the soil moisture at the 33 cm and 63 cm depths was at its observed maximum following 1.66 cm of rain during the previous three days. Moisture was then gradually lost, either by seepage or evapotranspiration until the middle of June. By this time the gradients of soil moisture were reversed in the lower layers and only slight in the upper layers, indicating that there was very little seepage at that time (Van Bavel et al, 1968). On July 2 measurements showed the increase in soil moisture due to the extreme rainfall of June 25-29 (11.9 cm). Although there were two days in which the profile could drain after the rain stopped, the top soil layers were still much wetter than they had been on May 30. Below the 33 cm depth the May 30 and July 2 profiles are very similar indicating that the lower layers were probably saturated and the water in the upper layers was unable to drain away, Throughout July the profile again gradually changed shape, although in August a rainfall of 4.06 cm raised the content of the upper layers while the lower layers continued to dry out. The gradient on August 11 indicates that drainage was taking place in the upper layer, but not in the lower ones. Probably the water was being used to recharge the lower horizons which had been depleted during a very dry July, and a good deal of it was being intercepted by the roots of the grass. From the gradients of the lower layers it can be seen that deep seepage only took place after heavy rainfall when the soil was full to capacity. At other times the profiles indicate that an upward movement of water was taking place.

2. Orchard. Fig. 5 is a composite graph incorporating measured profiles from the "unirrigated" and "irrigated" parts of the orchard. On the two days when measurement of soil moisture was completed at both sites on the same day the soil moistures were tested to ascertain whether they belonged to the same population. The null hypothesis (Freund, 1967) that the means and standard deviations of soil moisture at both plots were equal was tested, using a t test. The null hypothesis could not be rejected on June 17 and it was concluded that the two samples belonged to the same population. On August 12, 12 days after the application of irrigation water the means were significantly different although the standard deviations were not. This long term effect of irrigation indicates that deep seepage could not have been of great importance. The positive results from the June 17 test validate the technique of including data from both plots in Fig. 5.

Some similarities in range of soil moisture can be seen between these profiles and those in the grass plot. However, the orchard profiles show larger gradients in the upper layers than do those of the grass. The curvature of the profiles remains the same throughout the season. In every case the soil moisture decreases with depth giving a gradient which permits percolation, although in the lower layers this is very slight and may be of no consequence.

Table 4 gives the average available soil moisture for each measurement period, and the standard deviations for all measurement points in the unirrigated orchard. A seasonal shift similar to grass is evident with the amount of spatial variation depending on the amount of soil moisture, but in this case the actual standard deviations are

Figure 5

MEAN SOIL MOISTURE PROFILES – ORCHARD

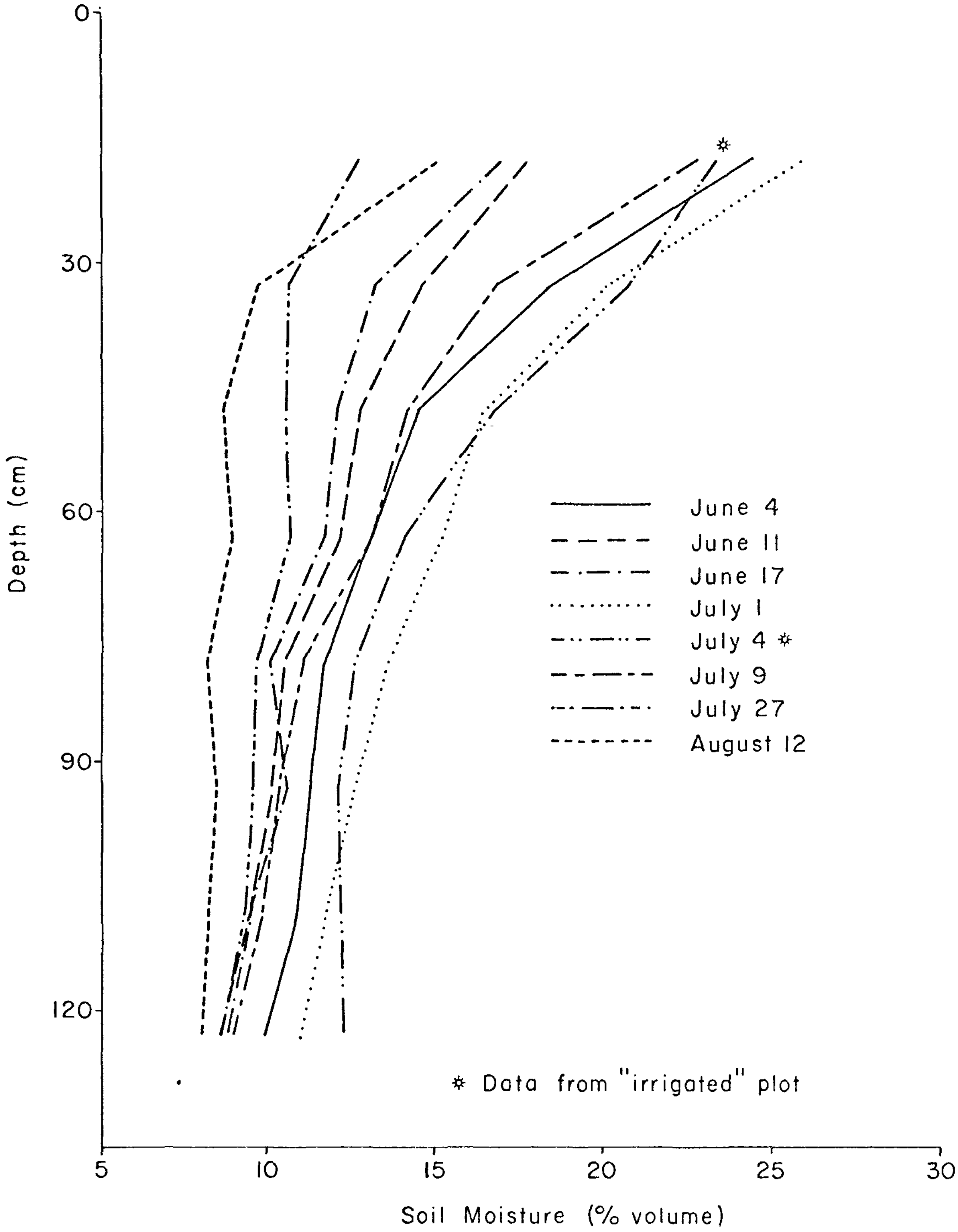


TABLE 4

ORCHARD - MEAN SOIL MOISTURE

Date	Mean soil moisture (cm)	Standard deviation (cm)
June 4	17.8	3.1
June 11	15.3	2.9
June 17	14.7	2.6
July 1	20.3	3.5
July 9	17.7	3.2
July 27	12.8	2.4
August 12	12.0	2.0

TABLE 5

DEPTH OF CLAY IN WHEATFIELD (cm)

Tube	Row X	Row Y	Row Z
1	-	113	83
2	-	113	83
3	-	113	68
4	-	128	83
5	-	-	83
6	-	-	83
7	-	128	68
8	-	113	68
9	-	113	128

much higher than those of the grass plot. This is expected in an orchard where there is a less uniform precipitation receipt at the surface due to the shading and funnelling effects of the trees.

The seasonal variation of the profiles is also similar to that of the grass, with depletion during the first part of June, recharge at the end of that month, depletion through July, and a recharge of the upper layers in early August. By using measurements from the irrigated plot, which were available for July 4, it is possible to trace in more detail the drainage after the June 25-29 storm. On July 1, the profile retained its normal shape, but the soil moisture content was much higher than at any other time except July 4. By this date water had drained from the top 30 cm layer to the next 15 cm layer beneath and from the 50-100 cm layer into the layers below. This is the only direct evidence (apart from that of the profile gradients) to show that there was deep seepage, although indirect evidence will be presented later in this chapter. By July 9 the soil had regained its characteristic profile, an indication of the rapidity with which the drainage of a very large quantity of water was accomplished. In summary, when there is a very high rainfall (an extreme for this area and season) there is a rapid drainage until the surface layers fall below the 25% soil moisture level. After this percolation, if any, is very slow.

3. Wheat. Analysis of the soil moisture in the wheatfield was complicated by the layer of clay, which was below the terminal depth of measurement at the northern end of the field, but which rose to within 68 cm of the surface at the southern end. It was noted, with one exception, that when the neutron count was over 20,000 cpm the probe

was in clay, the distribution of which had been established by the original tube borings and verified when the tubes were removed. Table 5 gives the depths at which the neutron count rose above 20,000 cpm and shows the variation in depth of clay from tube to tube and row to row. This count indicator was used to divide the data into loam and clay sections which were averaged separately to show the variation between June 6 and July 30 (Figs. 6 and 7). The profiles show quite clearly that the temporal variation of soil moisture at the 123 cm depth is less than 2.3% by volume in the sandy loam and less than 1.5% in the clay during that period. In fact, the lower layers show a decrease in soil moisture throughout July, in spite of the heavy rainfall experienced at the end of June. Since this rainfall had such a profound effect on the water content of the upper layers on July 7, one might expect this effect to appear later in the lower layers. This did not occur, although there was evidence of a slight increase in the moisture content of the clay on July 7. As shown in the orchard, the seepage was so rapid that the profile had time to readjust before the next measurements were taken.

Towards the end of the growing season there was a sharp drop in the moisture content of both the sandy loam and the clay layer. This corresponded to a hot dry period and could be due to excessive drying of the root zone and subsequent withdrawal of water (required by the ripening crop) from below. This is borne out by the soil moisture measurements at the 123 cm level which also dropped at the end of the season when moistures in the upper layers were at their lowest. Fig. 7 emphasises how similar the profiles were in the clay

Figure 6

MEAN SOIL MOISTURE PROFILES-WHEAT
(sandy loam)

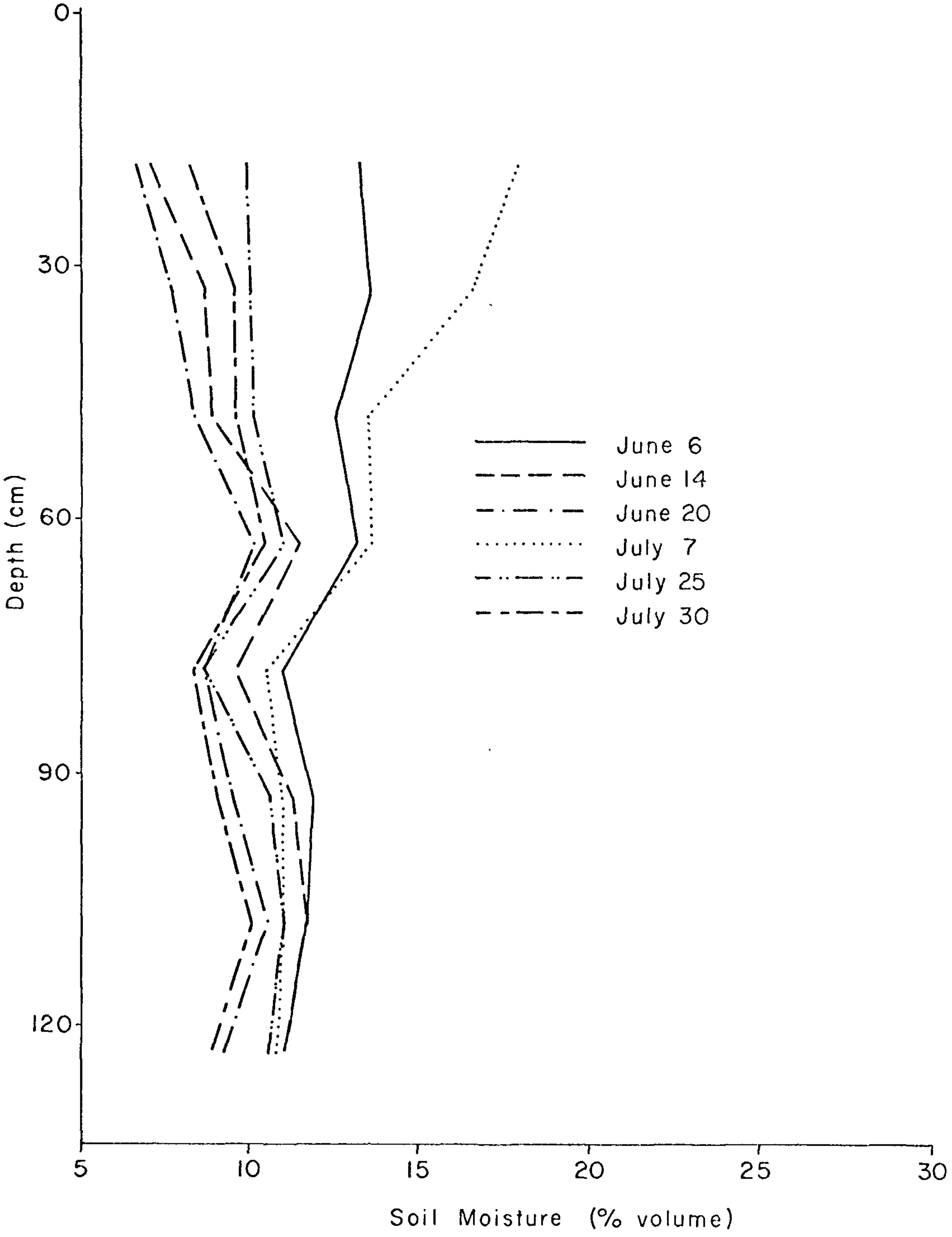
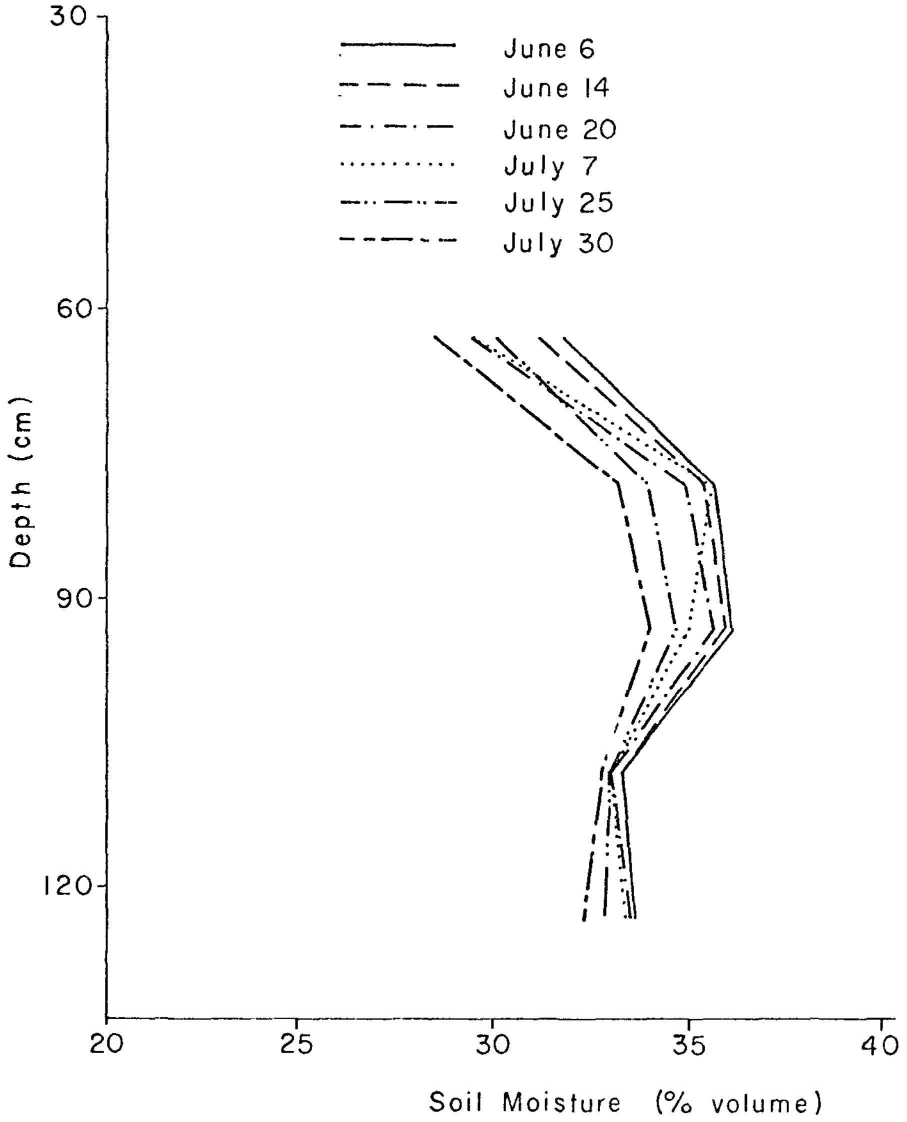


Figure 7

MEAN SOIL MOISTURE PROFILES - WHEAT
(clay)



throughout the measuring period. Since the clay was of an extremely heavy type it is doubtful whether there was much vertical extraction. By the end of July, however, there was a drop in soil moisture content (although of less than 5%) presumably as tension above the clay rose and withdrew the water. Evidence of recharge is seen in the July 7 profile, especially between 60-90 cm. One reason for the curved shape of the profiles in the clay might be that this deposit was only about 80 cm thick and that below 123 cm there was sand or loam. The interface effects would cause a lowering of the neutron count at the top edge of the clay and again at 123 cm.

The wheat field sandy loam profiles are generally at a lower soil moisture than the orchard ones especially in the top 60 cm. This can be attributed to extraction of moisture from the soil by the wheat roots in the area, and the drying out of the bare soil surface between the rows of wheat. In the orchard, the surface was kept damp by the thick cover of grass while moisture extraction proceeded in a more even manner throughout the profile.

4. Comparison of three surfaces. Comparison of the profiles below 60 cm for the orchard and non-clay wheat show a similarity which is to be expected since the two soils are of the same type. Hence, any subsequent comparisons between the water losses of the clay and non-clay areas and any conclusions about deep seepage, can be applied to the orchard and hence to the grass plot. The latter shows similarities in its upper layers to the orchard, although there is not sufficient depth to compare them below 80 cm.

Attention has been focussed upon the problem of deep seepage by Van Bavel et al (1968a, 1968b). Their data indicate that up to 16 days after irrigation a measurable downward flux occurs at 170 cm in a clay loam. The calculation of evaporation from the simplified water balance equation is criticised because of the importance of percolation. This problem would obviously be greater in a situation where the soil is kept moist either by irrigation or high rainfall and the time taken for percolation to cease or become negligible would also depend on the permeability of the soil. In the case of this study, rainfall occurred at scattered intervals and, except for the "irrigated" orchard, no attempt was made to keep the soil moist. Evidence has already been presented to show that percolation took place very rapidly after a heavy rainstorm. Errors in the calculation of evapotranspiration resulting from this deep seepage would be confined to the period including the storm. This is borne out in the following section by comparison with other methods of estimating evapotranspiration and by a comparison of evaporation calculated for the separate rows of samples in the wheatfield.

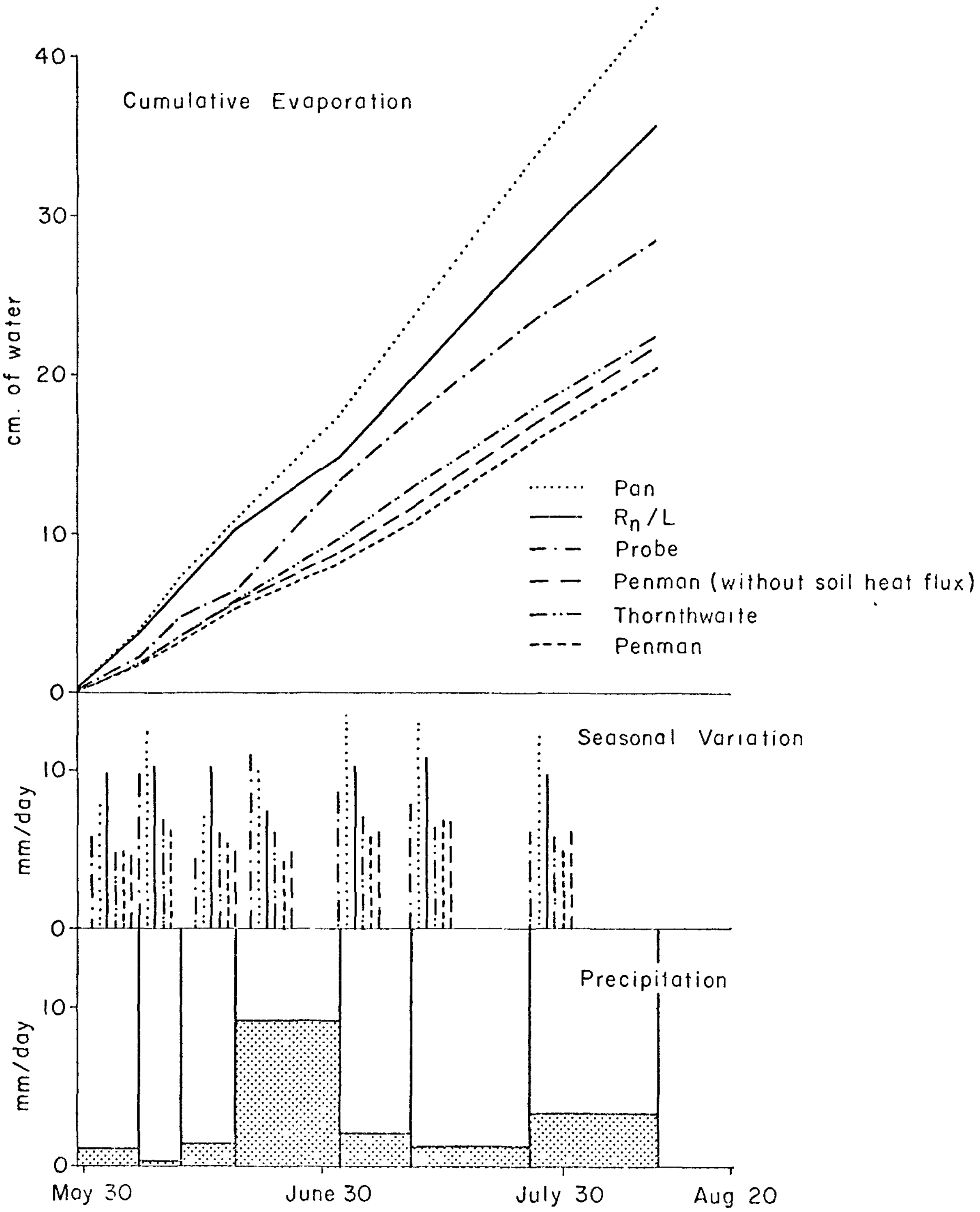
B. Evapotranspiration.

1. Grass grid.

Figure 8 is a composite graph comparing measured evapotranspiration with potential and actual evaporation. The seasonal variation of measured evaporation is shown in the middle section, where it can be seen to reach a peak during the very wet period June 19 - July 2 and then to decrease throughout July and the beginning of August. This resulted from decreased soil moisture storage which lowered the

Figure 8

PRECIPITATION AND EVAPORATION – GRASS



availability of water to the evaporating surfaces. The reliability of results for the period June 19 - July 2 is suspect since calculated probe evapotranspiration exceeds all other calculations including the water loss from an open pan, and R_n/L. During this period, actual evapotranspiration probably equalled the potential, since there was an abundant water supply. It is unlikely, however, that it would exceed evaporation from an open water surface. This is further evidence of deep seepage during this period. Using R_n/L as a measure of potential evaporation, approximately 1.7 mm of water per day were lost over this 13 day period. This would have occurred in the latter half of the period (after June 25) during and after the major rain storm.

The graph of cumulative evapotranspiration shows two interesting features. First, the pan and R_n/L tend to overestimate actual evapotranspiration as would be expected since neither of these parameters is affected by a limited water supply. A second feature is the underestimation of both the Thornthwaite and Penman models. The Penman estimation gives a lower evaporation than the Thornthwaite even though the former is supposed to be a measure of potential evaporation. The Penman estimate was also calculated without the soil heat flux term (which was estimated as 5% of the net radiation (Penman et al, 1967)). This brought the estimate only slightly closer to actual evapotranspiration. The Penman and Thornthwaite estimates run close to each other during July as well as running parallel to actual evapotranspiration. It is the data for June 19 - July 1 which starts the divergence between the estimates and which is then perpetuated by the cumulative nature of the graph. This is shown in the middle section of Fig. 8 where measured evapotranspiration can be seen to be similar to the Thornthwaite and Penman calculations except during the wet period. Towards the end of the measuring season, actual evapotranspiration becomes increasingly comparable to the Thornthwaite and Penman calculations. This may be due to the averaging effects of longer priod measurement, since during the earlier part of the season, when short measuring periods were used the actual water loss to the atmosphere fluctuated above and below that calculated by the Thornthwaite and Penman methods.

Table 6 gives the results of regression analyses between measured evapotranspiration and calculated evaporation.

These were run first (a) for all data. The correlation coefficients were not significant for Penman and R_n/L and they were quite low with Pan data (due to the differences in radiation balance between an open pan and a vegetated surface). The data for the period including the storm of June 25-29 (when there was considerable water loss by percolation) were removed and the regressions were run again (b). In this case all correlation coefficients were significant to the 99% level, while the best estimate was that of Penman (without soil heat flux) closely followed by that of Thornthwaite. A t test (Stanley, 1963) showed that the slopes of both Penman estimates and that of Thornthwaite were not significantly different from 1:1 at the 5% level whilst the R_n/L and Pan estimates deviated significantly from this line. This indicates that during this particular experimental period

TABLE 6

RESULTS OF LINEAR REGRESSION OF CALCULATED ON MEASURED EVAPOTRANSPIRATION FOR THE GRASS PLOT

Independent Variable	Intercept	Slope	Correlation Coefficient	% Explanation	Standard Error of Estimate
Pan a	0.6	0.6	0.78	60.5	1.2
b	0.3	0.5	0.95	89.9	0.5
Thornthwaite a	-0.2	1.3	0.88	77.2	0.9
b	-0.0	1.2	0.95	91.9	0.5
Penman a	1.1	1.0	0.70 *	49.2	1.3
b	0.5	1.1	0.94	88.2	0.5
Penman - a	0.8	1.1	0.76	58.5	1.2
Soil Heat Flux b	0.4	1.0	0.95	90.7	0.5
R_n/L a	0.8	0.6	0.69 *	47.2	1.3
b	0.1	0.7	0.92	84.3	0.6

* Not significant at the 95% confidence level.

a Including all data.

b Suspect data removed.

both the Penman and Thornthwaite methods are suitable for the prediction of actual evapotranspiration for a grass surface.

2. Orchard. Figure 9 shows much the same patterns as Fig. 8, but in this case the actual evaporation was always lower than that shown by the open pan or R_n/L. Again the Thornthwaite estimate is low especially during the wet period when deep seepage loss occurred. In this case the evapotranspiration assumed a fairly constant rate throughout the season, with only one large fluctuation at the end of June due to heavy rainfall. In comparison to wheat and grass, all the correlations with orchard data presented in Table 7 are significant due primarily to a larger data input. The results in part (b) are again better than in part (a). In all cases the slope came closer to the 1:1 ratio and the intercept to zero. The correlation coefficient was raised and the standard error lowered. The t test showed that only the Thornthwaite slope was not significantly different from 1:1 at the 95% level.

3. Wheatfield. Figure 10 shows a similar pattern to 8 and 9, with the Thornthwaite method underestimating and the Pan and R_n/L data overestimating actual evapotranspiration. In general R_n/L exceeds measured evapotranspiration by more than 1 mm/day. During the period of heavy rainfall (measuring period June 20 - July 7) measured evapotranspiration was greater than R_n/L by 0.6 mm/day. This high rate of evapotranspiration is suspicious during a period when potential evaporation was low and is therefore attributed to seepage loss from the measurement zone. From July 25 to 30 the measured daily water

Figure 9

PRECIPITATION AND EVAPORATION - ORCHARD

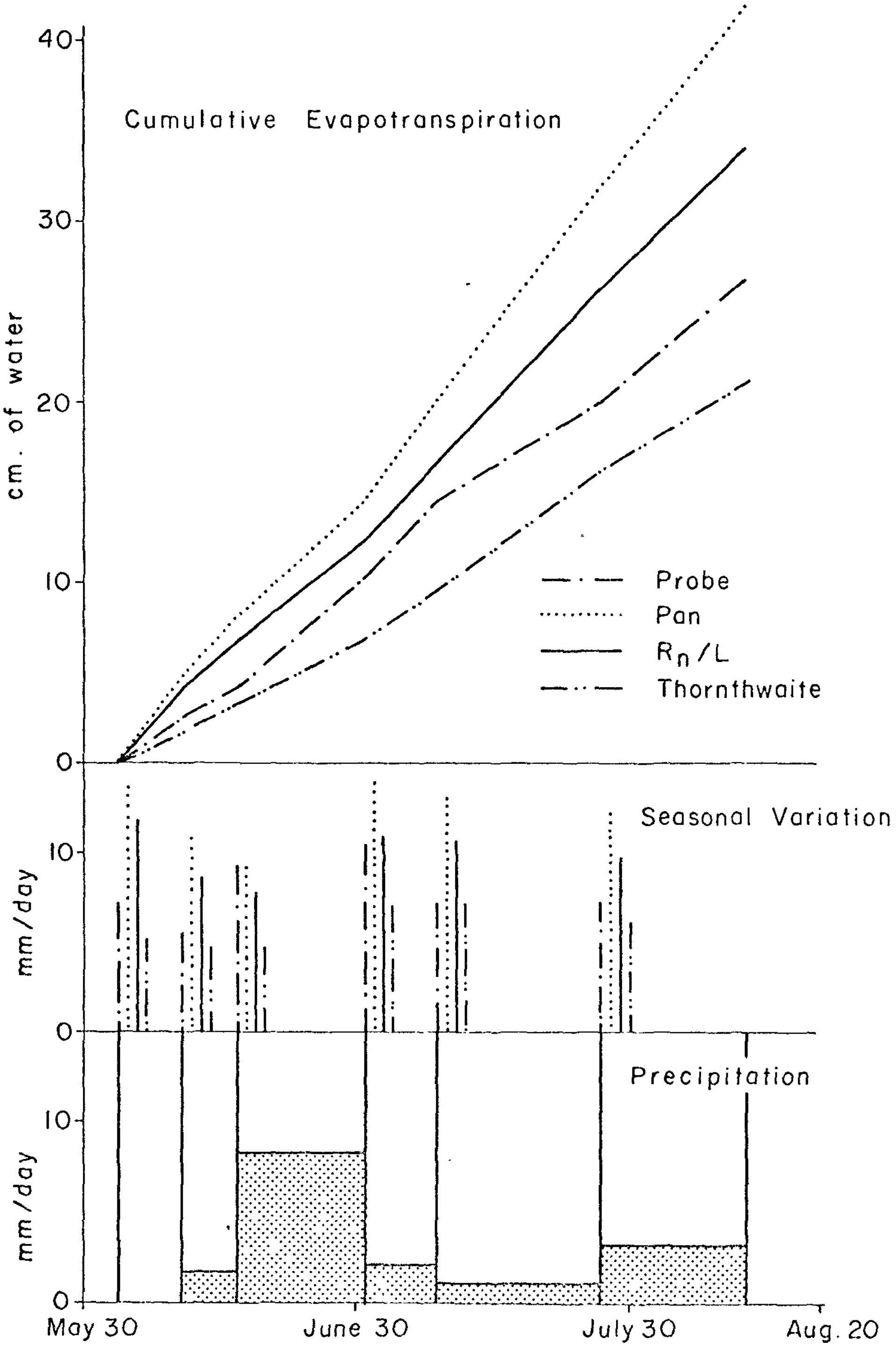


TABLE 7

RESULTS OF LINEAR REGRESSIONS OF CALCULATED ON MEASURED EVAPOTRANSPIRATION FOR THE ORCHARD

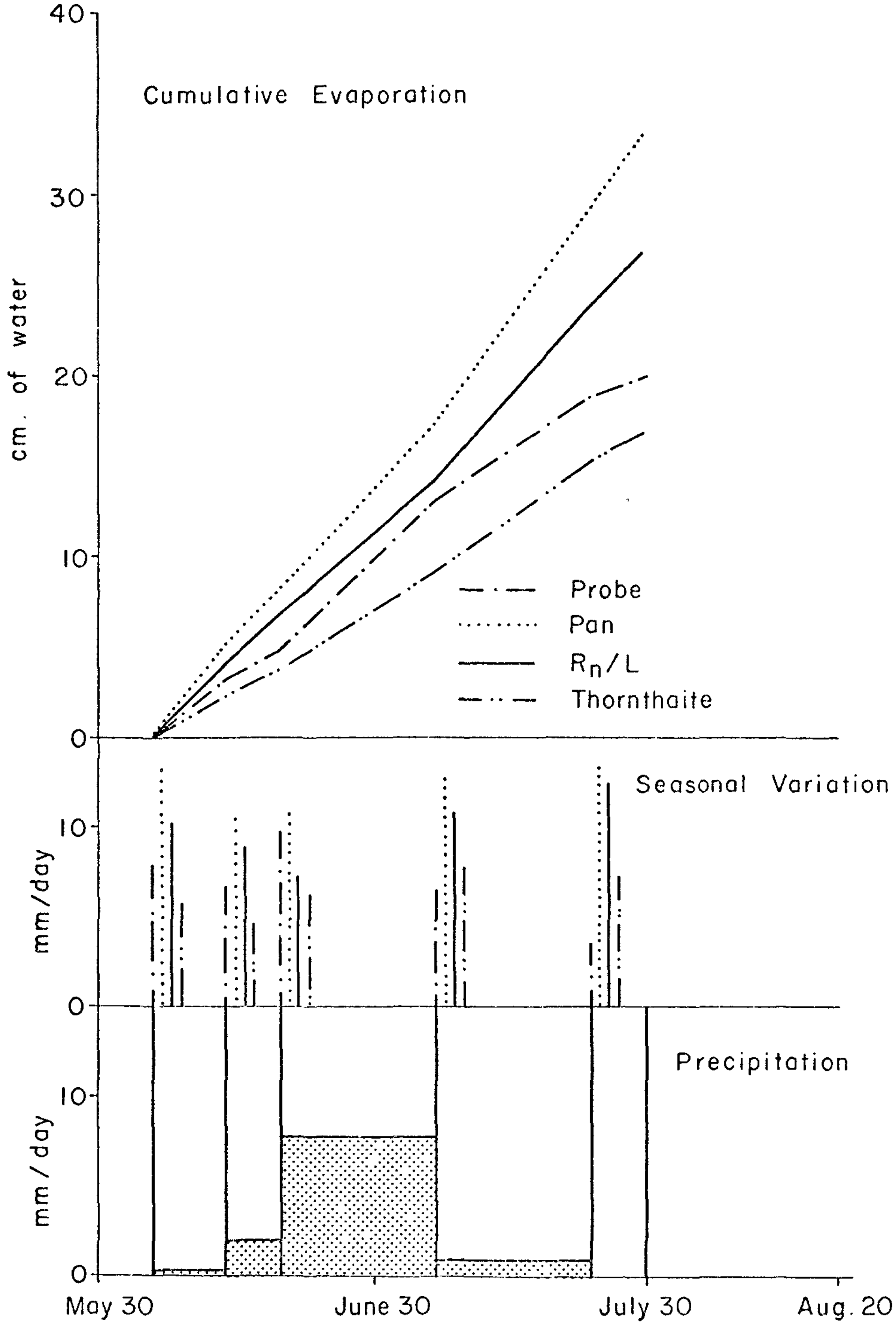
Independent Variable		Intercept	Slope	Correlation Coefficient	% Explanation	Standard Error of the Estimate
Pan	a	0.6	0.5	0.86	73.7	0.9
	b	0.1	0.6	0.97	94.2	0.4
Thornthwaite	a	1.2	0.9	0.88	76.9	0.9
	b	0.9	0.9	0.97	93.9	0.5
R_n/L	a	0.6	0.7	0.86	74.6	0.9
	b	0.2	0.7	0.96	91.6	0.5

a Including all data.

b Suspect data removed.

Figure 10

PRECIPITATION AND EVAPORATION – WHEAT



loss was at its lowest in spite of the fact that the pan evaporation was at its highest for the season. This appears to have been caused by the ripening of the wheat and accompanying decrease in transpiration, since no similar drop in evapotranspiration was noted for the grass plot and orchard during this period.

Table 8 shows the mean evapotranspiration for all measurement sites for each period and individually for rows X, Y and Z. As noted previously the tubes of Row X were situated entirely in sandy loam, while for all sites in Row Z the tubes were partly located in clay. Roy Y had some of each kind. One would expect the measured water loss in Row X to be higher than in the parts of the field with a layer of clay because of the additional influence of deep percolation through the sandy soil. However, this did not always prove to be the case. During the period of extremely high precipitation, Row Z showed a slightly higher water loss to the atmosphere than the other rows or the mean for the field (11%). In the last measuring period Row Z again showed a higher evapo transpiration than X (96%). This was a hot dry period when the sandy loam was quite dry. The clay acted as a reservoir from which the water moved upwards through the soil (see Fig. 7). However, the overall trends are demonstrated cumulatively in Fig. 11. Evaporation from Row X is cumulatively higher throughout the season than from both Y and Z. The latter two fluctuate slightly above and below each other.

Results of the regressions between measured and estimated water loss to the atmosphere are presented in Table 9.

TABLE 8

EVAPOTRANSPIRATION IN WHEAT (cm)

Period	Field Mean	Row X Mean	Row Y Mean	Row Z Mean
June 6 - 13	3.12	3.76	2.94	2.66
June 14 - 19	1.87	2.12	1.81	1.69
June 20 - July 6	8.17	8.07	7.45	8.98
July 7 - 24	5.76	6.15	6.25	4.86
July 24 - Aug. 3	0.89	0.60	0.89	1.18

TABLE 9

RESULTS OF LINEAR REGRESSION OF CALCULATED ON MEASURED EVAPOTRANSPIRATION FOR THE WHEAT

Independent Variable		Intercept	Slope	Correlation Coefficient	% Explanation	Standard Error of the Estimate
Pan	a	-0.5	0.7	0.84 *	70.0	1.5
	b	-0.1	0.5	0.95 *	89.8	0.6
Thornthwaite	a	-0.0	1.2	0.89	79.7	1.2
	b	0.4	0.9	0.95 *	89.5	0.6
R_n/L	a	-0.5	0.8	0.83 *	68.5	1.5
	b	-0.1	0.6	0.94 *	89.0	0.6

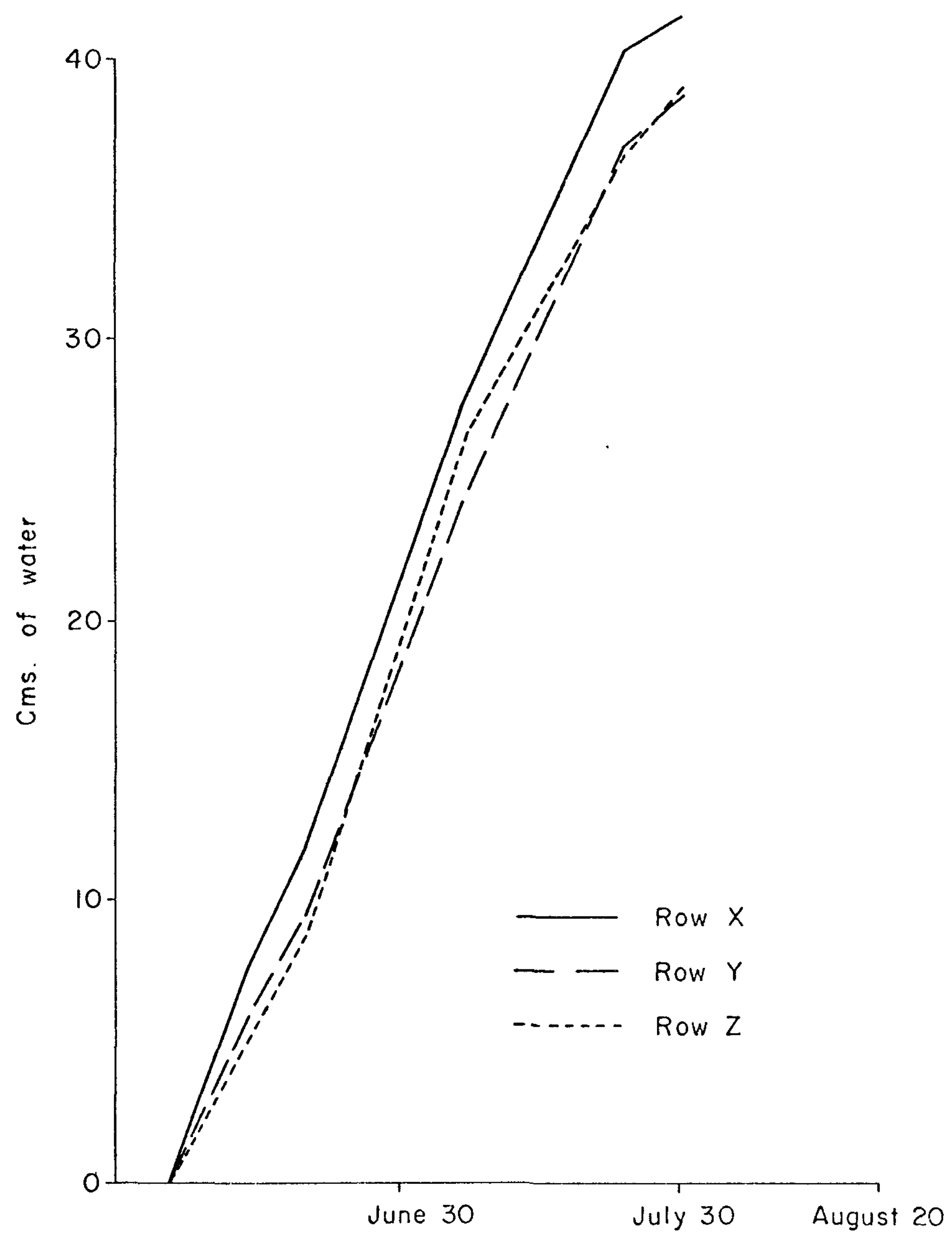
* Not significant at the 95% confidence level.

a Including all data.

b Suspect data removed.

Figure 11

CUMULATIVE MEASURED EVAPOTRANSPIRATION FOR INDIVIDUAL ROWS OF SAMPLING POINTS IN THE WHEAT FIELD



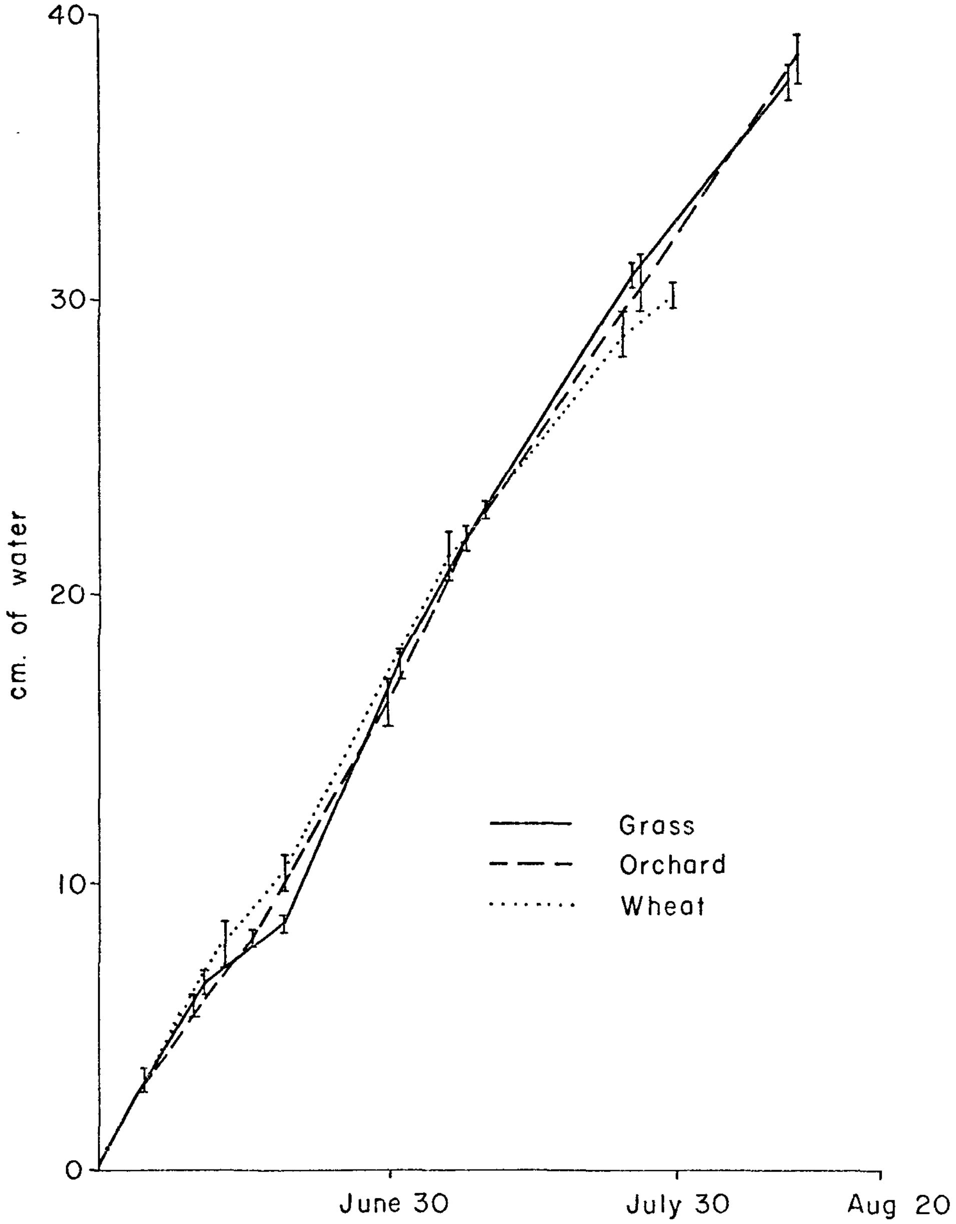
Note that only the Thornthwaite method had a significant linear relation with measured evapotranspiration, and this prediction was only valid when all the data were used, since the number of data points was increased and hence the value of correlation coefficient necessary to be significant was decreased. Because the lack of data limits the use of conventional techniques, few valid statistical inferences can be drawn from Table 9. However, comparison may be made with Tables 6 and 7 which show the same trends. Rejection of the suspect data improves the relationship between measured evapotranspiration and all forms of calculated evaporation, while the Thornthwaite estimate gives the best prediction, has an intercept closest to zero and a slope approximating the 1:1 ratio.

4. Comparison of three surfaces. While it is definite that percolation of a large quantity of water took place after the storm of June 25-29, there is no way of knowing how much drainage occurred at other times. One reason why the cumulative measured evaporation was higher than the Thornthwaite or Penman evaporation estimates could have been deep-seepage loss. However, although there is probably an overestimate of actual evapotranspiration, this is most likely an error which is similar in all three vegetation types. This is borne out by their similar soil moisture profiles. If one postulates this, then comparisons between the evaporation from the different vegetation types is valid.

Cumulative evapotranspiration for grass, orchard and wheat, adjusted to start on the same day has been plotted in Fig. 12. It shows that evaporation was continuing at much the same rate throughout

Figure 12

CUMULATIVE MEASURED EVAPOTRANSPIRATION FOR THREE SURFACES



the season (except after the ripening of the wheat) and that the evapotranspiration from the three different vegetation types was the same. This explains the similar soil moisture profiles for the three surface types. These results support the hypothesis put forward by Thornthwaite and Hare (1965) and Penman, Angus and Van Bavel (1967) that given non-limiting soil moisture conditions and a similar radiation balance, evapotranspiration from complete, green crop covers will be similar regardless of species. In this case, even when water supply is limiting it is the same for all three surfaces on a seasonal basis.

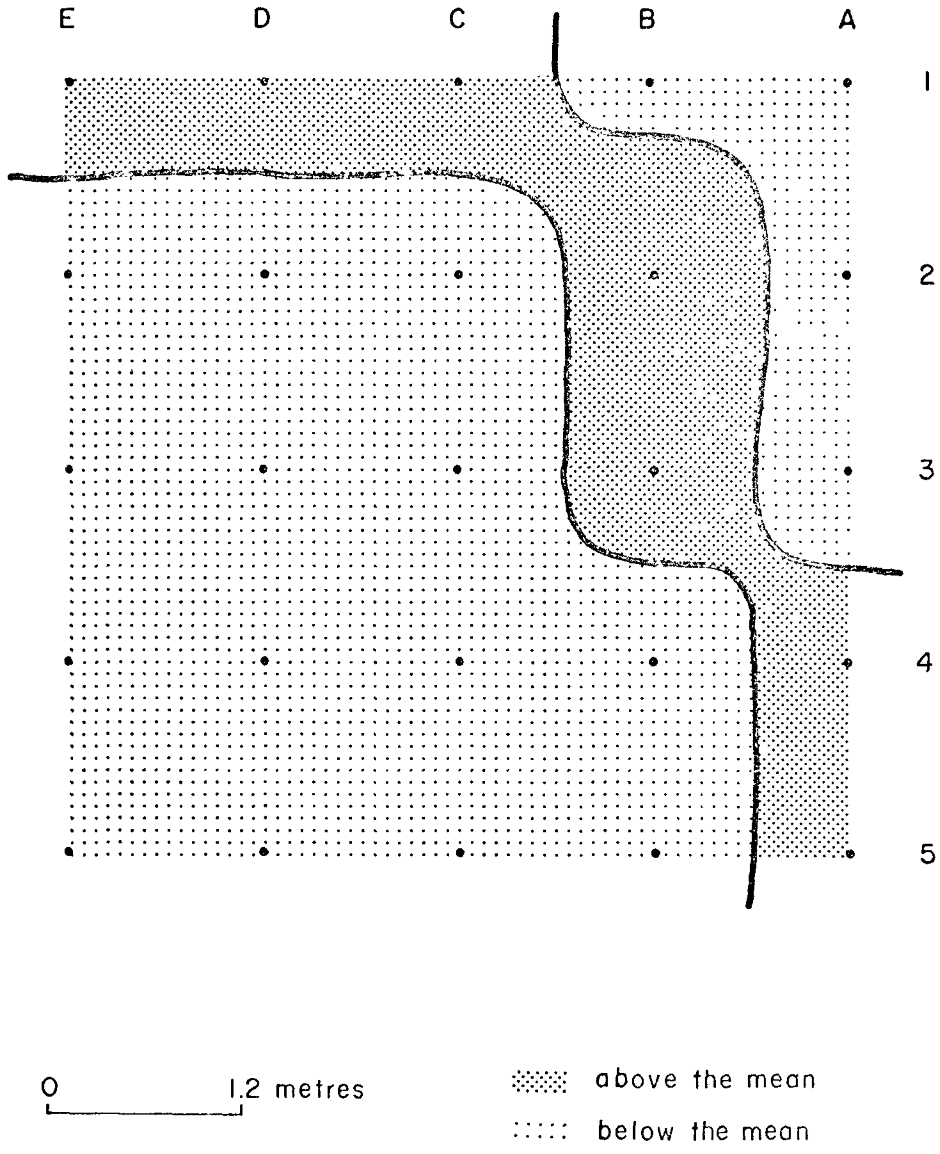
Fig. 12 also gives the standard deviations for each point. It shows that in some cases the three lines are significantly different, but the differences are quite small. These could be attributed to a number of factors including differences in the structure and metabolism of the plants, slight variations in energy balances or advection effects due to different surface roughness, but might equally be due to experimental error.

C. Statistical Analysis of the Spatial Variation in Soil Moisture on the Grass Plot.

A two colour analysis (Anderson, 1969) of the variation of soil moisture in the grass plot when applied to the first seven cases showed the pattern illustrated in Fig. 13. This pattern remained virtually constant throughout the season and was attributed to variations in the soil. However, although the soil moisture pattern remained constant it was postulated that the evapotranspiration calculated at the various tubes would not necessarily have a similar pattern. This

Figure 13

GENERAL PATTERN OF SOIL MOISTURE VARIATION ABOVE AND BELOW THE MEAN IN THE GRASS PLOT



was tested by a two colour contiguity test (Anderson, 1965) performed on the seven evapotranspiration calculations. In four of the seven cases the spatial variation in evapotranspiration was found to be random at the 95% significance level. Because there were more points above the mean than below it, the results were inconclusive in the other three cases.

For the purposes of determining the number of tubes necessary to give a given standard error of the mean at a given significance level the distribution was assumed to be random and standard normal. The results of the tests to find the necessary number of tubes are shown in Tables 10 and 11. Table 10 gives the number of tubes necessary to confine an error of the estimate of the mean to 10% and 5% at the 99 and 95% significance levels. This number was calculated separately for each measurement period since the evapotranspiration varied with the length of the period. Disregarding period 7 for reasons stated below, the minimum number of tubes at the different levels of significance would be at the 99% level, 15 and 58 for an error of 10% and 5% respectively, and at the 95% level 9 and 34 for a similar error (Freund, 1967).

The larger number of tubes necessary for period 7 in both Table 10 and 11 may be due to chance. However, the soil moisture pattern shown in Fig. 14 changed for the last measuring period. This means that whereas in the first six periods soil moisture changes were similar for all tubes, during the last one for unknown reasons soil moisture change varied within the grid, giving a greater variation in measured evapotranspiration and hence a larger standard deviation.

TABLE 10

NUMBER OF TUBES NECESSARY TO LIMIT THE ERROR OF THE ESTIMATE OF THE MEAN TO A GIVEN %

Period	Error = 99% Confidence Level 10%	99% Confidence Level 5%	95% Confidence Level 10%	95% Confidence Level 5% of the mean
1	12	48	7	28
2	15	58	9	34
3	7	26	4	16
4	8	29	5	17
5	9	33	5	20
6	7	26	4	15
7	24	94	14	55

TABLE 11

NUMBER OF TUBES NECESSARY TO LIMIT THE ERROR OF THE ESTIMATE OF THE MEAN TO A GIVEN AMOUNT

Period	No. of days	99% Confidence Level			95% Confidence Level		
		1mm	2mm	3mm	1mm	2mm	3mm
1	8	66	17	8	40	10	5
2	5	89	23	10	51	13	6
3	7	40	10	5	24	6	3
4	13	339	85	38	199	50	22
5	9	128	32	15	74	19	7
6	15	223	56	25	128	33	15
7	16	596	149	67	346	87	39

This is atypical, but from the present data there is a 12.5% chance of this occurring.

Table 11 shows the number of tubes necessary to reduce the error of the estimate of the mean to 1, 2 and 3 mm at the 99 and 95% levels of significance. Since this statistic is based on the standard deviations of each set of evaporation calculations it too becomes larger as the length of measuring period increases. Obviously with a larger mean of evapotranspiration, it will be necessary to use a greater number of tubes to insure that the error of the estimate falls within a certain value. With the percentage value of Table 10 this is not the case, since the size of error increases with the size of the mean. Similarly for the sample mean to be within 1 sample standard deviation of the true population mean, 4, 6 and 7 tubes are needed at the 95, 98 and 99% confidence limits respectively.

The standard deviation becomes smaller as the measuring period is reduced, as does the mean. However, the coefficient of variation also decreases with the length of the measuring period so a shorter period will produce smaller errors. Table 11 clearly indicates that in order to use a small number of tubes, the measuring period must be limited to nine days at the most.

CHAPTER FIVE

SUMMARY AND CONCLUSIONS

A. Soil Moisture Patterns.

There was much spatial variation on all three plots because of the varied nature of the soil. The pattern of variation remained fairly constant throughout the season in the grass grid. The variability was greater in the orchard because of the uneven distribution of precipitation (due to shading) and of absorption by roots, and in the wheatfield because of the presence of a clay layer at the southern end of the field.

The soil moisture profiles at all three sites varied substantially with time, especially near the surface where the greatest inputs and losses of water took place. Deep seepage loss was shown to be large during heavy rainfall periods, and was probably always a process influencing the soil water budget during wet periods when gradients of soil moisture indicated downward movement of water. However, seepage was considered negligible during dry spells when the soil moisture gradients were reversed.

B. Evapotranspiration.

Similar trends in measured evapotranspiration were shown by all three crop types throughout the season. This was due to similar radiation, energy and water balances, and similar soil characteristics. Slight differences between the three were attributed to the effects of differences in the structure and morphology of the plants, to the effects of differences in local microclimate such as advection effects, and to instrumental error.

For all three surfaces the measured evapotranspiration was, as expected, less than potential evaporation (in this case pan evaporation and PE calculated by R_n/L), but more than that estimated by the Thornthwaite actual evapotranspiration method, and in the case of grass by the Penman method. The underestimation of these two methods was probably the result of deep seepage, leading to higher measured water loss.

C. Effect of Spatial Variability on the Measurement of Evapotranspiration.

It was shown, from the measurement grid in the grass plot, that for mean measured evapotranspiration to be within one standard deviation of the true mean 4, 6 and 7 tubes were needed at the 95, 98 and 99% confidence limits respectively. Similarly, to limit the error of estimate of mean evapotranspiration for any one period to 3 mm at the 99% confidence level it is necessary to use at least 15 tubes, and to limit the measuring period to a maximum of 9 days.

D. Further Work.

This work could be furthered in several ways. Firstly a more detailed study should be carried out. This would include the determination of deep seepage loss, using hydraulic head and capillarity measurements, more soil moisture measurements taken at more frequent and more regular intervals, and a closer monitoring of other climatic factors. This would lead to a better knowledge of this particular soil and its water holding characteristics, would give more data and therefore assist statistical analysis, and might be a more rigorous test of new and existing evapotranspiration models. Evapotranspiration should be measured from other crops on the same soil and on other soil types to test the hypothesis that evapotranspiration depends more on the energy and water balances than on vegetation type. After sufficient attention has been paid to the improvement of the instrumentation to make it reliable over longer periods, a more widespread study could be carried out to develop a general water balance model applicable to large areas such as drainage basins or river systems.

APPENDIX I

Calibration of Nuclear Chicago model 5901 I/M Combination Moisture-Density Gauge (serial number 51) and model 5806 Subsurface Moisture Probe (serial number 228).

Calibration of the instruments was done in the laboratory and in the field during the summer of 1968. This provided a cross-check on the two methods of calibration since there was some controversy in the literature about which of the two is the best method (Sartz and Curtis, 1961; Van Bavel et al, 1961).

A. Experimental Method.

1. Laboratory. Caledon sandy loam from the field site was thoroughly soaked with demineralised water. This was used to fill a box 0.8 m^3 in volume. The weight of the wet soil was obtained by weighing each bucket load of soil before it was tipped into the box. The soil was well trampled in order to approximate field conditions.

A neutron probe access tube of standard type was placed in the centre of the box and neutron counts were obtained with the depth probe at 5 cm intervals in the tube. Count rates taken between 30 and 60 cm from the surface were considered to be representative of the soil moisture of the whole sample since these were not affected by earth/air or earth/floor interface effects. Eight readings around the central tube were taken with the surface gauge. The average surface count was taken to be representative of that particular soil moisture. After readings of neutron counts were taken the soil was removed from the box and spread on the floor to dry. During this process the humidity was kept low and the temperature high to assist evaporation. The soil was also turned over at intervals to speed the drying process and to keep its moisture content homogenous.

The above process was repeated several times. On the last occasion sixty samples were taken to determine the soil moisture content by weight and hence the weight of dry soil in 0.8 m^3. From this the percentage of soil moisture by volume was calculated for each run. The calibration points were plotted and analysed statistically with the points supplied by the manufacturer (only in the case of the depth probe) and from the field experiment.

2. Field. A 90 cm access tube was inserted into grass covered Caledon sandy loam at the field site by the "drive and auger" method described in Chapter Three. A neutron count was obtained with the depth probe at 45 cm, this being well below the zone of air/soil interface effects. Six volumetric soil samples were taken around the tube. They were 15 cm long from depth 37.5 cm to 52.5 cm and of known volume. This process was repeated three times, the soil being wetted by a sprinkler between each measurement. The calibration points obtained were used as outlined above.

The surface gauge was calibrated on bare Caledon sandy loam. For each neutron count obtained, a 20 cm volumetric sample was taken from the actual measurement point, dried and weighed to give soil moisture content by volume. The soil was wetted to obtain the higher points on the calibration curve and each count was duplicated to reduce experimental error. Since the manufacturer's calibration did not correspond to the data derived from the laboratory and field calibrations it was omitted from the calculation.

B. Results.

The results of the depth probe calibration are plotted in Fig. 14 and those of the surface moisture gauge in Fig. 15. The dry bulk density of the soil averaged from all the volumetric samples taken was 2.0g cm^{-3}. The statistical analysis of the calibration data is summarised in Table 12.

C. Conclusions.

The calibration of the depth probe is satisfactory, showing a high degree of explanation and a close correspondence between the manufacturer's, the laboratory and the field calibrations for this particular soil.

The surface probe calibration shows a far greater scatter about the regression line. There are several factors to account for this. Firstly, there may have been an error in reading the count rates or weighing the soils during the field calibration. Secondly, the field method used gives equal weight to the soil moisture in all parts of the volumetric core taken for analysis, whereas the moisture of the layers nearer the surface will affect the count rate more than those farther away. Hence if there was a sharp change in soil moisture within a core (as there may have been during wetting) this would have given a lower soil moisture when dried and weighed than that measured by the surface gauge. This would account for the divergence of the field and

Figure 14

DEPTH PROBE CALIBRATION

Model 5810
Serial Number 51
Operating voltage 1125

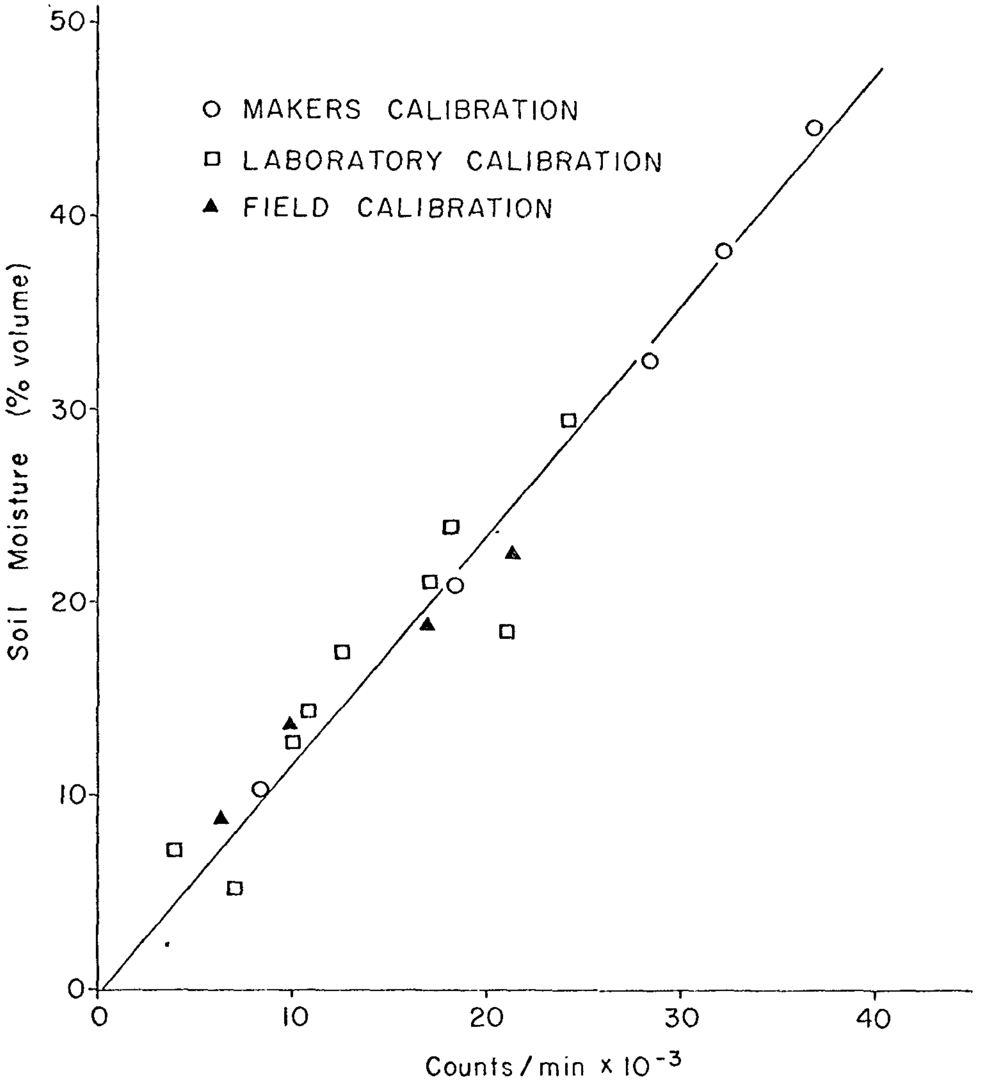


Figure 15

SURFACE MOISTURE GAUGE CALIBRATION

Model	5901
Serial Number	228
Operating voltage	1300

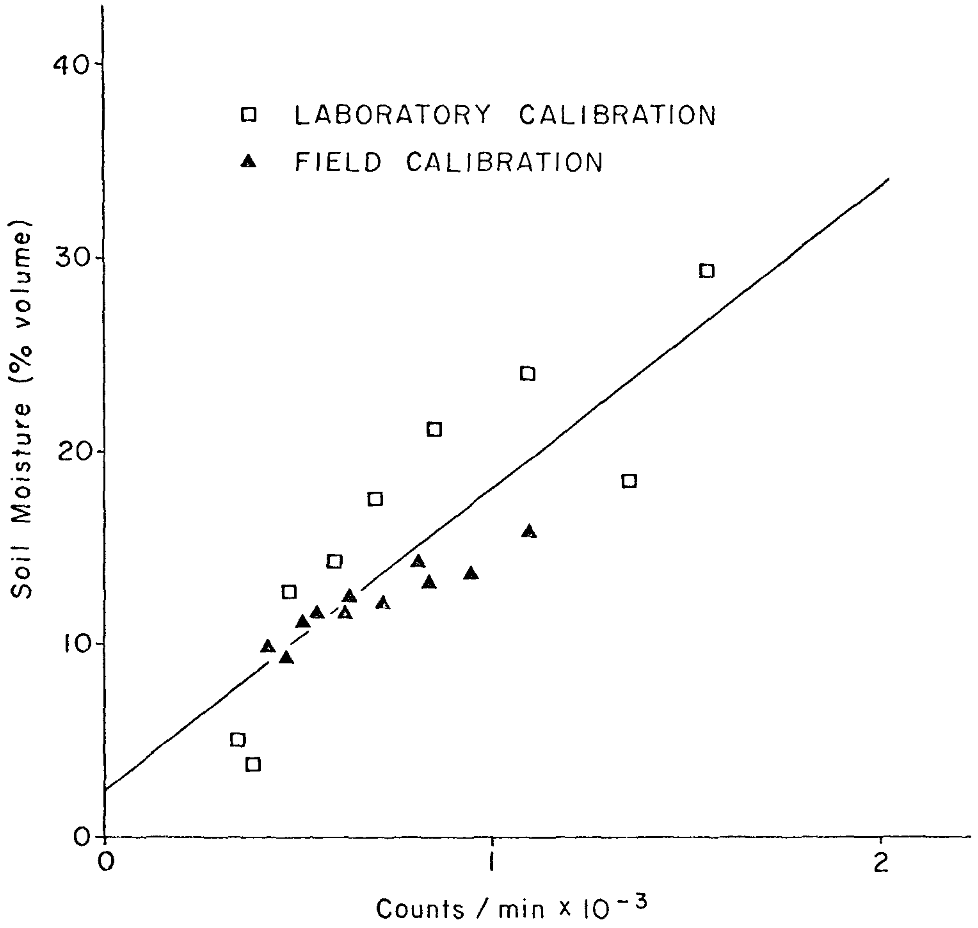


TABLE 12

CALIBRATION RESULTS

	Depth probe	Surface gauge
Intercept	-0.48	2.34
Slope	$1.19\text{x}10^{-3}$	$0.02\text{x}10^{-3}$
Correlation coefficient	0.97	0.86
Variability account for	94.9%	73.5%
Standard error of the estimate	2.40	3.01

laboratory calibrations at higher soil moistures as seen in Fig. 15. A third reason for the difference between the field and laboratory calibrations is that Caledon sandy loam has a dark brown humus rich A horizon. For the laboratory calibration this was thoroughly mixed with the lower layers, but in the field this humus would be in contact with the surface gauge. The hydrogenous nature of the humus would tend to raise the neutron count.

APPENDIX II

ANALYSIS OF ERROR

The error in the calculation of evapotranspiration is a function of the error in the measurement and calculation of evapotranspiration, and the error in the assumptions used in that calculation.

$$\epsilon_{ET} = f\left(\epsilon_{ET(M)} , \epsilon_{ET(A)} \right) \qquad \text{(i)}$$

The error in the calculation and measurement of E_T is a function of the error in the measurement of precipitation and soil moisture change.

$$\epsilon_{ET(M)} = f\left(\epsilon_{P} , \epsilon_{\Delta SM} \right) \qquad \text{(ii)}$$

The error in soil moisture change is a function of the error in soil moisture measurement at time 1 and time 2.

$$\epsilon_{\Delta SM} = f\left(\epsilon_{SMT1} , \epsilon_{SMT2} \right) \qquad \text{(iii)}$$

The overall error in soil moisture measurement at any one time is a function of the error at each measurement depth.

$$\epsilon_{SMTN} = f\left(\epsilon_{SM1} , \epsilon_{SM2} \cdots\cdots \epsilon_{SM8} \right) \qquad \text{(iv)}$$

Dealing with (iv) first, the error in a point soil moisture measurement is twice the standard error of the slope of the calibration curve.

$$\epsilon_{SMN} = SE_b \times 2 = 0{\cdot}15 \quad (\%\ \text{S.M. by vol.}) \qquad \text{(v)}$$

Let a typical low soil moisture be 7% soil moisture by volume.

Let a typical high soil moisture be 20% soil moisture by volume.

Then:

$$\text{largest } \epsilon_{SMN} = 2\%$$

$$\text{smallest } \epsilon_{SMN} = 1\%$$

Let the error in precipitation be 3% (Oliver, 1959).

Let the error in the assumptions used for the calculation of evapotranspiration be 20%. (Deep seepage; Rouse, 1970)

A. Calculation of error for measurements only.

1. Largest error

$$\epsilon^2_{SMTN} = 8 \times 2^2$$

$$\epsilon^2_{\Delta SM} = 16 \times 2^2$$

$$\epsilon^2_{ET(M)} = 3^2 + 16 \times 2^2$$

$$\epsilon_{ET(M)} = 8.5\%$$

2. Smallest error

$$\epsilon^2_{SMTN} = 8 \times 1^2$$

$$\epsilon^2_{\Delta SM} = 16 \times 1^2$$

$$\epsilon^2_{ET(M)} = 3^2 + 16 \times 1^2$$

$$\epsilon_{ET(M)} = 5\%$$

B. Calculation of error for measurements and assumptions.

1. Largest error.

$$\epsilon_{ET} = \sqrt{8.5^2 + 20^2}$$

$$= \sqrt{73 + 400}$$

$$= \sqrt{473}$$

$$= 21.7\%$$

2. Smallest error.

$$\epsilon_{ET} = \sqrt{5^2 + 20^2}$$

$$= \sqrt{425}$$

$$= 20.6\%$$

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