MODELLING THE RAINFALL INTERCEPTION PROCESS AS PART OF A DYNAMIC WATER BALANCE APPROACH TO IRRIGATION SCHEDULING.

by

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GLASGOW

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٤٧ وَهُوَ الَّذِي أَرْسَلَ الرِّيَاحَ بُشْرًا بَيْنَ

يَدَيْ رَحْمَتِهِ وَأَنْزَلْنَا مِنَ السَّمَاءِ مَاءً طَهُورًا ٤٨ لِنُحْيِيَ

بِهِ بَلْدَةً مَيْتًا وَنُسْقِيَهُ مِمَّا خَلَقْنَا أَنْعَامًا وَأَنَاسِيَّ كَثِيرًا

It is He who drives the winds as harbingers of His mercy, and sends down pure water from the sky, so that He may give life to dead lands and quench the thirst of man and beast.

QURAN 25,47-48

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ABSTRACT

The hydrological process of rainfall interception by vegetation is fully described. Two models are used to simulate the interception loss. A Linear Regression Model expresses the relationship between interception and gross rainfall in linear terms. Its use is thus limited to site-specific seasonal or annual determinations of interception loss. The Deterministic Model calculates the water balance of a vegetation canopy, during the rainfall event, on a continuous basis. This model takes into account such dynamic variables as rainfall duration and intensity, canopy density and meteorological factors controlling evaporation and transpiration. An example is used to illustrate the model. Interception is seen to increase in response to reduced rainfall intensity and increasing potential evaporation.

Irrigation scheduling is achieved through a dynamic soil water balance model. Daily meteorological and crop-characteristic variables are inputs to the model. The evaporative and transpiratory losses are calculated each day and the cumulative loss indicates the date at which the soil water content reaches wilting point. The amount of water needed to wet the soil back to field capacity is thus the desired irrigation water.

The processes of evaporation and transpiration from the soil are treated separately and are discussed in full. The model is applied to an example to illustrate its potential and versatility.

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CHAPTER 1

INTRODUCTION

In a world beset by ever increasing populations, malnutrition, hunger and famines, an even greater emphasis on the proper management of the world's resources is essential to meet the ever growing demands.

Water is an essential element of life, but it is a finite resource which, if properly managed, can be exploited to man's full benefit. The problem in many parts of the world is the lack of or the inadequate supply of usable water. Up to now, man's efforts have been directed mainly towards delaying the processes of the hydrological cycle by collection, storage, regulation, distribution and treatment prior to returning the water back to the cycle. However, increasing demands on a limited and often unpredictable resource have necessitated the search for an ever increasing efficiency in the management of those parts of the hydrological cycle under man's control or influence.

In the effort to maximise the beneficial use of water and minimise water losses, hydrological processes which had been considered too minor to be included in the water balance, are now important areas in the drive for more effective water use. One such area is the water lost due to interception by vegetation, especially in relation to sprinkler irrigation of crops where a sizeable proportion of the applied water never reaches the soil and is evaporated straight off the vegetation canopy. In areas of low water availability such a loss may prove costly in that too much water may have to be applied to achieve the correct effective irrigation, or too little water reaches the soil, in which case the plants experience stress and crop yield is reduced.

The process of the interception of precipitation, whether natural or artificial, by the vegetation is described in Chapter 2. Also discussed is a mathematical model used to simulate the interception of rainfall on a continuous hourly basis. An example is used to illustrate the model's applications and potentials.

The rest of the thesis is concerned with the problems and controls of the amount of water used for irrigation. Chapter 3 outlines the theories and provides mathematical functions to describe the soil and water relationships. Chapter 4 discusses the relationship between plants and soil-water with particular emphasis on the rate of water uptake by the plant roots. Chapter 5 describes the process of evaporation from the point of view of the necessary energy inputs to evaporate water from open surfaces.

Chapter 6 discusses the development of a model to evaluate the water balance of a cultivated soil on a continuous daily basis. Mathematical relationships are presented for the evaporation from a cultivated soil and also for the transpiration process. These two processes are evaluated separately in the model.

The dynamic water balance model is applied to an example in Chapter 7, to illustrate its potential as an aid to irrigation scheduling by calculating the dates and amounts of water to be applied to a field of crops. In the example used, rainfall was assumed to be zero which is highly unlikely in field grown crops. However the model can be readily modified to include the effect of rainfall on the soil water balance.

The biggest potential of the dynamic water balance model is in its application to situations such as glasshouses where all meteorogical variables can be measured and or controlled to ensure proper irrigation scheduling leading to increased crop yield and more efficient use of water.

Fortran computer programmes for both the Deterministic Interception Model and the Irrigation Scheduling Model including the input and output variables, are presented in Appendix 1 and 2 respectively.

CHAPTER 2

THE INTERCEPTION PROCESS

2.1 INTRODUCTION.

Vegetation, through the surface area provided by the leaves and stems, can retain natural precipitation or water applied by sprinkler irrigation. The vegetation canopy provides a finite storage capacity which when exceeded drainage of water to the ground will occur. Throughout the interception process, evaporation from the canopy storage also takes place.

A proportion of the precipitation will reach the ground without touching the canopy surface. This proportion of "free throughfall" along with the drainage from the saturated canopy constitute the overall throughfall (T), or the net precipitation (Pn). The interception loss is thus the difference between gross precipitation (P) and net precipitation (Pn). This loss of water can seriously influence the water management of a site. Zinke (1967) reports interception losses of between 20 and 40% in coniferous trees and between 10 and 20% in hardwoods from annual rainfall on a forest in the USA. Blake (1975) found these figures to be 33% and 27% respectively for studies in New Zealand.

This difference in interception loss between coniferous and deciduous trees can be attributed to the shape of the leaves. In broad leafed deciduous trees, the droplets of precipitation have the opportunity to join together and form large droplets which then fall to the ground. This opportunity does not exist in coniferous trees to the same extent. Another more obvious explanation is that conifers keep their leaves throughout the year whereas deciduous trees do not.

Waggoner et al (1969), from studies carried out on a crop of corn, found the evaporative losses from the wetted crop to be at least twice that of the dry canopy.

These figures only serve to illustrate the importance of the interception process on the water balance of a catchment. Interception represents a loss prior to the water entering the catchment land surface processes. This may be desirable as in the case of flood attenuation or undesirable when a relatively high proportion of precipitation or overhead irrigation is lost from the soil and plant to the atmosphere.

2.2 MODELLING THE INTERCEPTION PROCESS.

2.2.1 Linear Regression Model.

The linear regression model expresses the relation between interception loss and gross rainfall as a function of the form:

$$I = a.P + b \qquad \text{Eq. 2.1}$$

where I is the interception loss, P is the gross rainfall on the canopy, and a and b are linear regression coefficients.

Such empirical regression equations require experimental data for the particular site and rely upon accurate measurements of gross rainfall and throughfall. Gross rainfall can be measured using standard rain gauges placed at canopy height or in clearings at ground level. The type of gauges used for measuring throughfall are not standardised and are open to improvisation, however the most efficient samplers of throughfall are trough gauges. Stemflow (S) can be measured by narrow collars connected to the tree trunks and the down flowing water diverted to measuring containers. A study of the number of gauges required to achieve accuracy is presented by Helvey and Patric (1966).

The water balance of the interception process can be expressed as:

$$I = P - T - S \qquad \text{Eq. 2.2}$$

where:

- I is the interception loss,
- P is the gross rainfall,
- T is the throughfall,
- S is the stemflow.

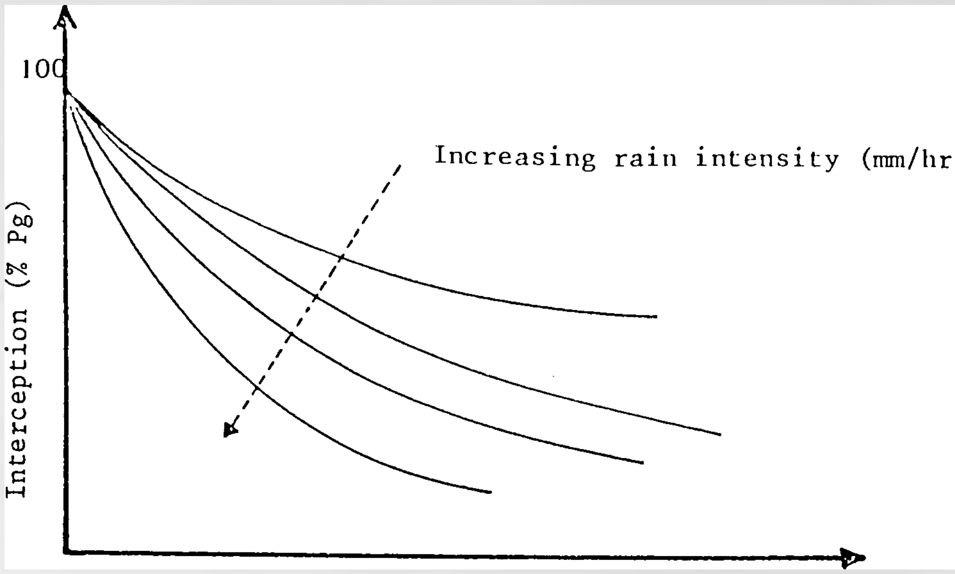
Many experiments on the interception process have been carried out on forests around the world. From studies in hardwood forests of the Eastern United States, Helvey and Patric (1965) concluded that two regression equations, one for the growing season and one for the dormant season, adequately describe the interception losses from all hardwood forests in that region (Table 2.1). Balke (1975) has also derived linear regression equations for several vegetation species in New Zealand (Appendix I.2).

These types of relationships do not take into account the effects of rainfall intensity and duration. Blake (1975) has shown the influence of rainfall intensity on interception to be as in Fig. 2.1.

TABLE 2.1: Equations for calculating seasonal interception losses in the Eastern Hardwood regions of the USA.

Function	Growing Season	Dormant Season
Throughfall	$\Sigma T = 0.901(P) - 0.031(n)^{*}$	$\Sigma T = 0.914(P) - 0.015(n)$
Stemflow	$\Sigma S = 0.041(P) - 0.005(n)$	$\Sigma S = 0.062(P) - 0.005(n)$
Net Rainfall	$\Sigma R = 0.917(P) - 0.036(n)$	$\Sigma R = 0.941(P) - 0.020(n)$
Interception Loss	$\Sigma I = 0.083(P) + 0.036(n)$	$\Sigma I = 0.059(P) + 0.020(n)$

* n is the number of storms per season.



Gross Precipitation (Pg,mm)

Fig. 2.1 Influence of rainfall intensity on interception.

Linear regression models are limited in use as they are site specific and can only be extrapolated to similar vegetative and climatic environments. These models are best suited for estimating total seasonal interception losses and as they ignore such continuous variables as rainfall intensity, duration, evaporation and canopy density, their use in the continuous simulation of interception loss on a diurnal basis is very limited.

2.2.2 Deterministic Model.

A deterministic interception model uses inputs of precipitation and the meteorological variables controlling evaporation, to calculate the water balance of a vegetation canopy on a continuous basis. The model, developed by Rutter et al (1971), uses hourly meteorological data to simulate the interception process due to individual storms. The model has been further applied by Gash and Morton (1978); Calder (1977) and extended by Rutter et al (1975, 1977).

The model considers the vegetation canopy to have a storage capacity (S). Precipitation, in the form of rainfall, adds water to this storage whereas evaporation and drainage remove the water. Interception is that component of the water balance which is lost from the canopy storage by evaporation. A detailed conceptual framework of the model is presented in Fig. 2.2.

Stemflow constitutes only a very small proportion of the rainfall reaching the ground from the canopy and as there is a direct relation between stemflow and trunk diameter, when the model is applied to short vegetation and annual crops, stemflow becomes negligible and throughfall and net rainfall are taken to be the same.

(a) Water Balance:

Let P, T and E be rates of rainfall, throughfall and evaporation repsectively and ΣP, ΣT and ΣE are their totals in a given time. The interception loss in a storm (from the time when rain falls on the dry canopy to when the canopy is dry again) is given by:

$$I = \Sigma E = \Sigma P - \Sigma T \qquad \text{Eq. 2.3}$$

If (p) is the proportion of rain which falls to the ground without striking the canopy, then the water balance of the canopy for any time in a rainfall event can be expressed as:

$$(1 - p).\Sigma P = \Sigma D + \Sigma E \pm \Delta C \qquad \text{Eq. 2.4}$$

where ΣD is the amount of drainage from the canopy, and ΔC is the change in the amount of water (C) stored on the canopy.

Therefore, total throughfall from the canopy is:

$$\Sigma T = p.\Sigma P + \Sigma D \qquad \text{Eq. 2.5}$$

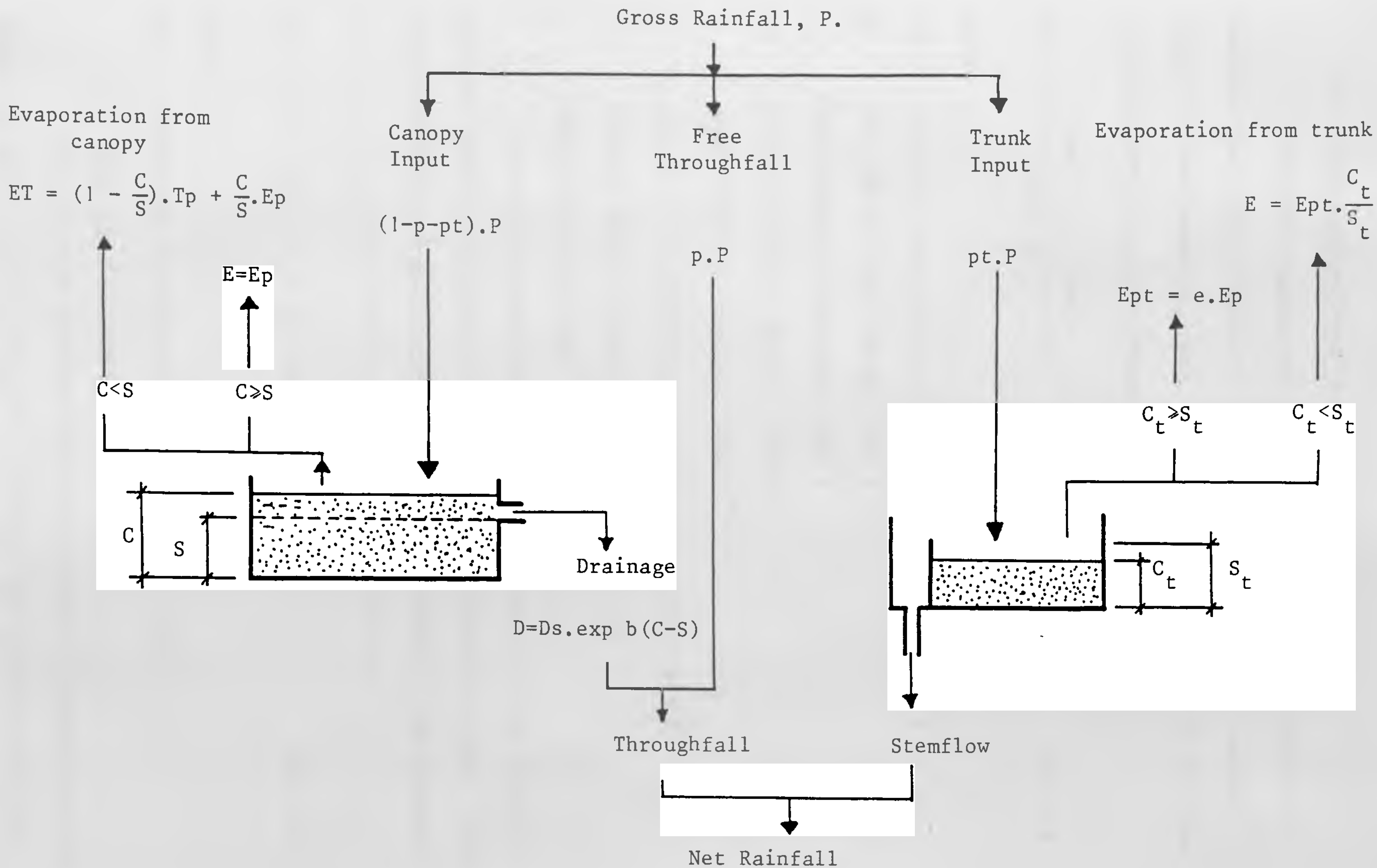


Fig. 2.2 The conceptual framework of the Rutter Model (Gash and Morton, 1978).

(b) Evaporation From Canopy:

When the amount of water on the canopy (C) equals or exceeds the storage capacity (S), evaporation from the canopy occurs at the potential rate. The potential evaporation (Ep) can be calculated using the Penman-Monteith equation:

$$Ep = \frac{\Delta . Rn + \rho . Cp . \ \delta e / r_a}{\lambda(\Delta + \gamma)} \qquad \text{Eq. 2.6}$$

where

Cp = specific heat of air at a constant pressure ($JKg^{-1}K^{-1}$)

Rn = net radiational energy (Wm^{-2})

r_a = aerodynamic resistance (Sm^{-1})

δe = vapour pressure deficit (mbar)

γ = psychrometric constant (mbar K^{-1})

Δ = slope of saturated vapour pressure curve (mbar K^{-1})

λ = latent heat of vaporization of water (JKg^{-1})

ρ = density of air (Kgm^{-3})

When the amount of water on the canopy is less than the storage capacity (ie C<S), the canopy is only partially wet. Thus evaporation and transpiration occur simultaneously. The evaporation from a partially wet plant surface is given by:

$$ET = (1 - \frac{C}{S}) . T_p + \frac{C}{S} . Ep \qquad \text{Eq. 2.7}$$

where

Tp = potential transpiration from unwetted plant..

(c) Drainage From Canopy:

The rate of drainage from the canopy (D) depends upon the amount of water on the canopy(C). Rutter (1971) by plotting lnD versus C, found this relationship to be linear (Fig. 2.3). Note that these values were estimated from the actual observations of rainfall (P) and throughfall (T) for a number of storms. The slope of the line (b) can be averaged for the number of storms considered.

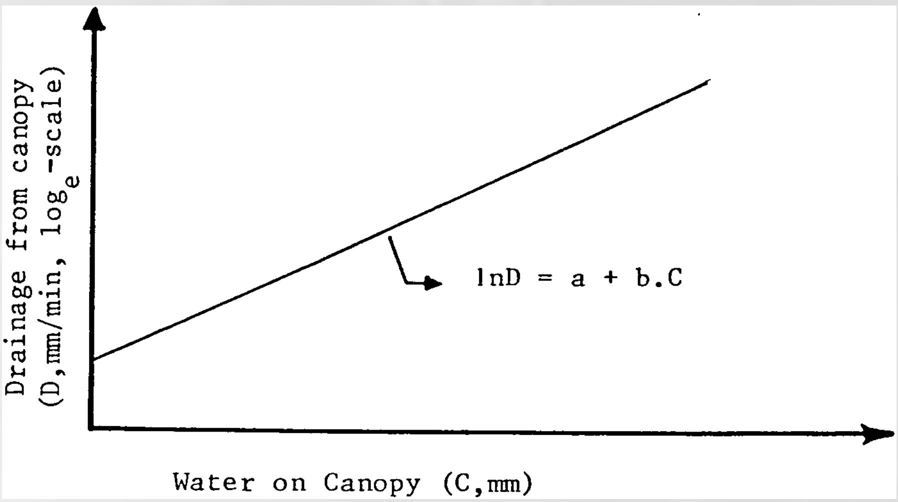


Fig. 2.3 The relation of rate of drainage to amount of water on the canopy.

Thus, the drainage rate (D) from the canopy can be expressed as:

$\ln D = a + b.C$ Eq. 2.8

Let D_S equal the drainage rate when C = S, therefore:

$D = D_S . \exp\ b(C-S)$ mm/min Eq. 2.9

Rutter (1971) found D_S to be 0.002 mm/min for Corsican pine of leaf area per unit ground area, LAI_C. For canopies with different leaf area index (LAI), the value of D_S is equal to $0.002 \times \frac{LAI}{LAI_C}$. However, assuming a linear relation exists between LAI and S:

$D_S = 0.002 \frac{S}{S_C}$ Eq. 2.10

where S_C is the storage capacity of Corsican pine as expressed by

Rutter (1971) and found to be 1.05mm.

Therefore:

$$D_S = 1.9 \times 10^{-3} . S \qquad \text{Eq. 2.11}$$

substituting this expression in Eq. 2.9:

$$D = 1.9 \times 10^{-3} . S. \exp \; b(C-S) \qquad \text{Eq. 2.12}$$

Note that the above equation for the rate of drainage from a canopy allows a small but finite drainage rate when C = 0. Since this is an impossibility, a general assumption is made that drainage from the canopy is zero when C<S.

(d) Canopy Storage Capacity:

Canopy storage capacity (S) or canopy saturation value can be defined as the depth of water on the projected area covered by a plant, which can be detained on the plant surface in still air. It can also be defined as the amount of water required to wet all the canopy surfaces before the occurrence of drainage and which is lost to the atmosphere by evaporation.

The storage capacity is dependent upon several physical characteristics of the canopy such as shape and texture of leaves, dimensions and shape of canopy. Wind also plays an important part in the storage capacity of a canopy. Water that is not drained naturally by gravity can be 'shaken' off the tree, thus lowering the storage capacity.

The storage capacity cannot be regarded as the absolute amount of water on the canopy since the water stored on the canopy (C) can exceed storage capacity. However, the storage capacity gives an indication of when drainage is expected to occur.

Many studies of interception losses in forests have provided values of storage capacity for different tree species. Some are reported by Rutter (1975) and are presented in Table 2.2. Also included are values of S for a number of herbaceous plants. It must be pointed out that these values of storage capacity were determined without reference to the canopy structure and particularly the leaf area index. However some studies have differentiated between the values of S for summer (in leaf) and winter (leafless).

In herbaceous plants, the relationship between S and LAI becomes more important since storage capacity of the vegetation is constantly changing due to the growth of the plant. Very few studies have attempted to relate S to LAI for plants, however this relationship has been expressed as a linear function. Examples of such expressions for small trees and herbaceous plants are given in Table 2.3.

(e) Proportion of Free Throughfall:

The proportion of free throughfall (p) is that part of the precipitation which falls through the canopy without striking the canopy surfaces. The shape and density of the canopy, as quantified by the LAI has a direct bearing on the value of p. This relationship has been shown to be linear (Zinke 1967).

TABLE 2.2 Interception Storage Capacities.

Vegetation		S, mm
Coniferous forest		
Pinus sylvestris		1.6
Picea abies		1.5
Pseudotsuga menziesii		2.1
Pinus nigra		1.0
Deciduous forest		
Carpinus betulus	Summer	1.0
	Winter	0.6
Old quercus robor	Summer	1.0
Coppice	Winter	0.4
Ericaceous		
Callona volgaris		2.0
Herbaceous		
Zea mais		0.4-0.7
Mixed grasses and legumes		1.0-1.2
Lolium perenne, 10cm high		0.5
48cm high		2.8
Molinia caerulea		0.7
Pteridium aquilinum		0.9

TABLE 2.3 Linear relationship between storage capacity and Leaf Area Index (LAI)

Vegetation	Linear Expression	Source
Rye Grass	S= -0.0011+0.0024 LAI	Meriam (1961)
Corn (Zea mais)	S=0.07+0.12 LAI	Wangati (1972)
Pinus radiata	S=0.125+(0.065±0.012) LAI	Aston (1979)
Acacia longifolia	S=0.038+(0.065±0.017) LAI	-do-
Eucalyptus viminalis	S=0.018+(0.035±0.017)LAI	-do-
E. maculata	S=0.073+(0.032±0.006) LAI	-do-
E. dives	S=0.028+(0.059±0.014) LAI	-do-
E. mannifera (maculosa)	S=0.04+(0.067±0.014) LAI	-do-
E. cinerea	S=0.052+(0.086±0.032) LAI	-do-
E. pauciflora	S=0.072+(0.178±0.031) LAI	

2.3 AN EXAMPLE OF A DETERMINISTIC MODEL.

For a fully developed crop of corn (Zea mais) assume:

$p = 0.75$

$S = 0.6$mm

let drainage coefficient, $b = 2.5$

Further, let potential transpiration (T_p) be constant at 0.1mm/hr. For a rainfall event of 4 hours duration, the hourly rainfall (P.mm) and the hourly potential evaporation (Ep.mm) are as in Table 2.4:

TABLE 2.4 Rainfall and potential evaporation for a four-hour rainfall event.

Time (hr)	1	2	3	4	5
Rainfall (P.mm)	1.50	2.50	1.00	0.50	0.00
Potential Evaporation (Ep.mm)	0.25	0.25	0.50	1.00	1.50

Assuming that the above variables are uniform throughout the hour, the model operates by considering the water balance of the canopy every 6 minutes. A Fortran computer programme (Appendix I.1) was used to simulate the interception (ET), water on the canopy (C), drainage (D) and throughfall (THF), (Appendix I.2). The results were then plotted using the computer programme in Appendix I.5 and are presented in Fig. 2.4

Total interception was calculated as $\Sigma ET = 1.326$mm, and total rainfall was 5.5mm.

Thus:

$$\text{Interception loss} = \frac{100 \times \Sigma ET}{\Sigma P}$$

$$= \frac{1.326 \times 100}{5.5} = 24\%$$

It can be seen that the interception loss will play an important role in the water balance of the cultivated field.

Referring to Fig. 2.4, it is evident that maximum interception occurs when rainfall intensity is low and potential evaporation high.

The throughfall (THF) is the effective rain which reaches the ground. In considering the soil water balance of a cultivated field, whether supplied by overhead irrigation or natural rainfall, the effective rain may be considerably (mainly in economic consequences) less than the applied water.

The above conclusion is also true in relation to large scale catchment concerns where interception loss by the vegetation may effect the accurate operation of schemes such as flood attenuation, reservoir water storage and hydroelectric power stations.

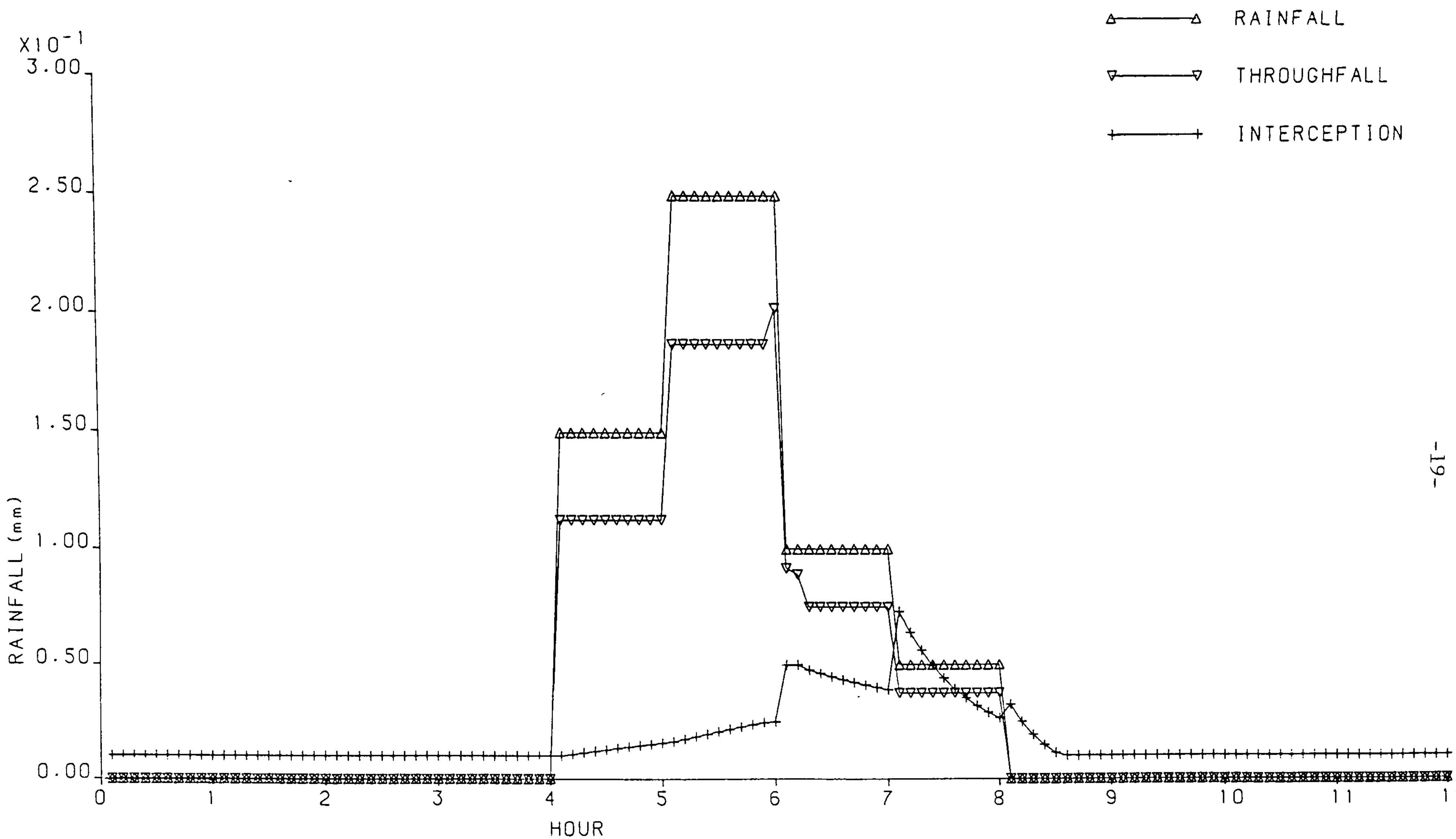


Fig. 2.4 Simulation of rainfall, throughfall and interception throughout the rainfall event.

CHAPTER 3

SOIL AND WATER RELATIONSHIP

3.1 INTRODUCTION.

In the plant-soil-atmosphere environment the soil not only acts as an anchorage medium for the plant but also as a storage reservoir for the minerals and nutrients so necessary for plant growth. One of the most important properties of soil is its ability to store water and release it to the transpiring plants. This water can also dissolve and make available the various minerals present in the soil.

3.2 SOIL WATER CONTENT.

The proportion of water in the soil medium can be expressed either in terms of mass of water or the volume of water:

$$W = \frac{M_w}{M_s} \qquad \text{Eq. 3.1}$$

$$\theta = \frac{V_w}{V_b} = \frac{V_w}{(V_s + V_w + V_a)} \qquad \text{Eq. 3.2}$$

where:

W = proportion (by mass) of water content

M_w = mass of water

M_s = mass of dry soil

and

θ = volumetric water content

V_w = volume of water

V_b = bulk soil volume

V_s, V_w, V_a = volumes of soil, water and air respectively.

In irrigation terms, it is often useful to express the water content of a depth of soil (dt) in terms of the ratio of the volume of water per unit area of land, i.e. a depth of water (dw). Thus:

$$dw = \theta . dt \qquad \text{Eq. 3.3}$$

3.3 SOIL WATER POTENTIAL.

The potential energy of water is the most important property of the soil. The difference in the potential energy of water between two points is the driving force for the movement of water. In the plant-soil water relationship, it is the difference between the water potentials of the plant and the soil which cause the water to move from a higher potential in the soil to a lower potential in the plant.

The potential energy of soil water is generally expressed relative to that of pure water, at atmospheric pressure, at the same temperature as that of soil water and at a constant elevation. Since within the soil, forces such as adsorption, capillary, osmotic and pressure act to lower the water potential, the soil water potential is expressed negatively relative to the standard. The units of soil water potential can be expressed in terms of energy per unit mass (joules per kilogram), energy per unit volume (bars, atmospheres or cm H_2O) or energy per unit weight (bars or Cm H_2O).

Soil water potential is the sum of component potentials and can be expressed as:

$$\psi = \pi + \tau + P + G \qquad \text{Eq. 3.4}$$

where

π = osmotic potential

τ = matric potential

P = pressure potential

G = gravitational potential

(a) Osmotic Potential:

This is as a result of the solute level present in the water which effect the energy status and the movement of water across permeable membranes such as root cells in plants. Osmotic potential can be express as:

$$\pi = -R.T.C. \qquad \text{Eq. 3.5}$$

where:

C = molar concentration

R = gas constant (8.315 J/K/mol)

T = temperature (K)

(b) Matric Potential:

Water absorbed onto the soil particles and held by capillary between particles, combine to produce a matric suction (potential), as in Fig. 3.1:

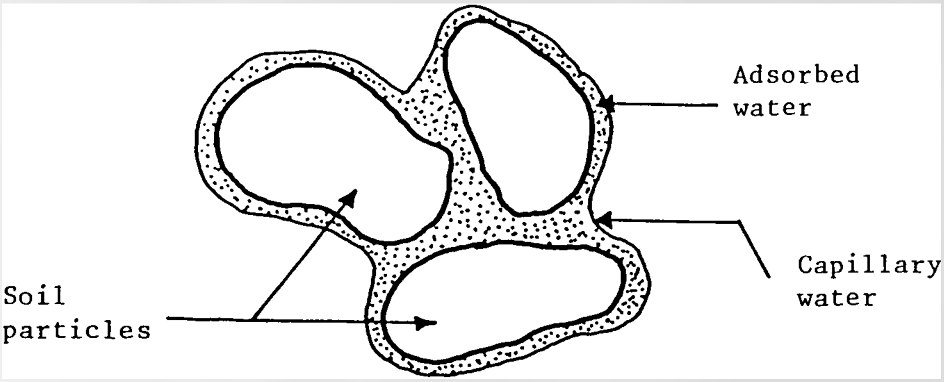


Fig. 3.1 Attractive forces in soils causing matrix suction.

It is thus evident that the matric potential of a soil is dependent on the pore size distribution. The relationship between pore diameter (D μm) and matric potential can be expressed as:

$$\tau = \frac{-2.9 \times 10^{2}}{D} \quad \text{J/kg} \qquad \text{Eq. 3.6}$$

The matric potential of soils represent the main restrictive force acting against water uptake by plants. Matric potential is influenced strongly by the soil texture. Clayey soils retain more water and with stronger suction force, whereas sandy soils have larger particle sizes and thus less surface area to allow strong hydrogen bonding to exert strong suction forces on the soil water. Such soil-moisture characteristic curves are illustrated in Fig. 3.2:

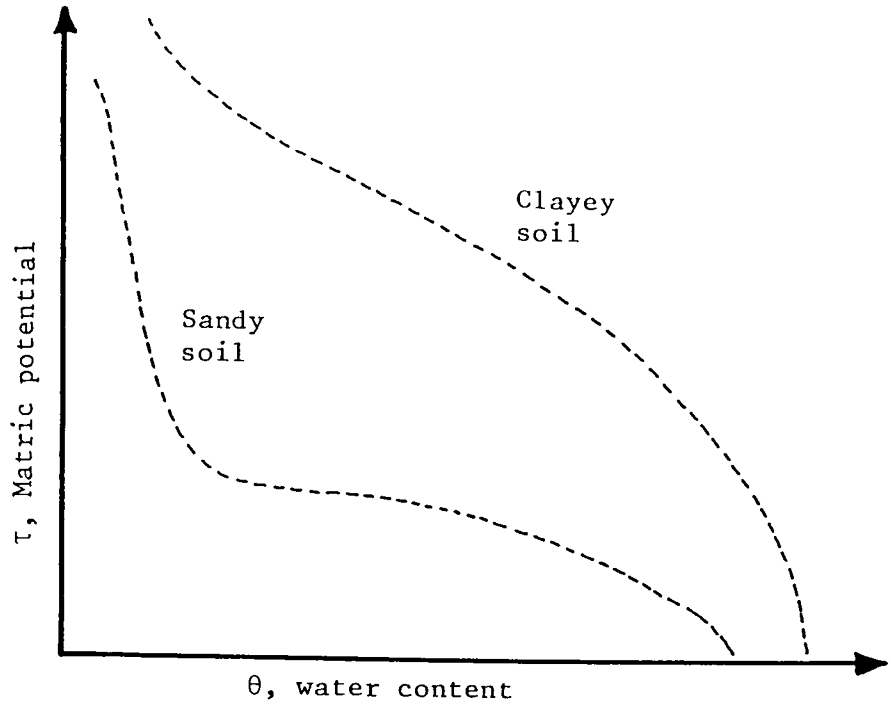


Fig. 3.2 Soil-moisture characteristic curves.

Several mathematical models have been proposed to describe the characteristic curves.

Visser (1966) derived the empirical relationship:

$$\tau = a(f - \theta)^b/\theta^c \qquad \text{Eq. 3.7}$$

where:

τ = matric potential

f = porosity

θ = volumetric water content

a, b, c = constant.

Gardner et al (1970) proposed the relation:

$$\tau = -a\,\theta^{-b} \qquad \text{Eq. 3.8}$$

The use of these equations is limited due to the difficulty in determining the constants. However some empirical relationships in the form of Eq.3.8 have been reported (Milthorpe and Moorby 1979):

Heavy clay $\tau = 3.45 \times 10^{-2}\ \theta^{-8.2}$ Eq. 3.9

Clay loam $\tau = -2.19 \times 10^{-2}\ \theta^{-4.8}$ Eq. 3.10

where:

τ = matric potential J/kg

θ = water content g/g soil

It is often the case that pressure potential (P) and gravitational potential (G), are negligible since in most irrigation practices the soil water is not at a hydrostatic pressure greater than atmospheric pressure and since gravitational potential is dependent only on relative elevation above an arbitrary datum thus it can be set to positive or zero. Since neither P nor G play a vital role in the uptake of water by plants, they can be neglected and the soil water potential can be considered to be the sum of matric and osmotic potentials. However, osmotic potential is always negative and it is assumed that its change in magnitude is not large enough to effect the availability of soil water to plants, especially in an idealised environment where water is the only limiting factor in plant growth.

It can therefore be assumed that the soil water potential can be solely described by the matric potential, i.e.

$\psi = \tau$ Eq. 3.11

Zur and Jones (1981) report the soil water potential to water content relationship for two types of soils. These are presented in Table 3.1

TABLE 3.1 Soil water potential and volumetric water content relationship of two types of soils.

Volumetric water content, θ	Soil water potential, ψ (bar)	Unsaturated hydraulic conductivity K cm/h
	Arredondo Fine Sand	
0.02	-17.425	1.00×10^{-10}
0.03	-12.473	5.16×10^{-8}
0.04	-7.575	8.32×10^{-7}
0.05	-2.678	4.35×10^{-6}
0.06	-0.260	1.25×10^{-4}
0.07	-0.185	1.99×10^{-3}
0.08	-0.103	8.68×10^{-3}
0.09	-0.094	2.59×10^{-2}
0.10	-0.087	5.61×10^{-2}
0.11	-0.079	1.01×10^{-1}
0.12	-0.061	1.67×10^{-1}
0.13	-0.058	2.63×10^{-1}
0.14	-0.055	3.93×10^{-1}
0.15	-0.053	5.61×10^{-1}
	Netofa Sand	
0.23	-19.36	3.0×10^{-6}
0.25	-14.52	3.0×10^{-5}
0.27	-9.78	6.0×10^{-5}
0.29	-8.23	9.0×10^{-5}
0.31	-5.81	5.0×10^{-4}
0.33	-3.87	8.0×10^{-4}
0.35	-1.94	1.0×10^{-3}
0.37	-1.06	4.0×10^{-3}
0.39	-0.87	1.0×10^{-2}
0.41	-0.58	4.0×10^{-2}
0.43	-0.19	1.0×10^{-1}
0.45	-0.09	1.0×10^{-1}

3.4 FLOW OF WATER IN SOILS.

Flow of water in saturated soils is a well defined process. The driving force is the existence of a positive pressure gradient which causes water to move through the saturated pores in the soil. Darcy's law states that the flux of water (q) is proportional to the hydraulic gradient (H/L), and denoted by Eq. 3.12:

$$q = K_s \cdot \frac{H}{L} \qquad \text{Eq. 3.12}$$

where;

K_s = saturated hydraulic conductivity cm/d

H = head of water above sample cm

L = length of soil sample cm

q = flux or volume of water flowing through a unit cross-sectional area per unit time.

However, since allowing a soil to be kept at saturation is contrary to irrigation practice, the flow of water in saturated soils, as characterised by the saturated hydraulic conductivity, is of little practical use. Since all effort is made to prevent the saturation of soils and allow air entrainment for the continuation of plant growth and prevention of salt accumulation, it is therefore necessary to have a knowledge of the flow of water through unsaturated soils. This is best defined by measuring the unsaturated hydraulic conductivity (K) of the soil. This is further complicated by the constantly changing water content of the soil. Various empirical relationships, relating K to matric potential ψ and volumetric water content θ, are presented below:

$$K = a\,\psi^{n} \qquad \text{Eq.3.13a}$$

$$K = a/(b+\psi^{n}) \qquad \text{Eq.3.13b}$$

$$K = K_s/|1+(\psi/\psi_c)^{m}| \qquad \text{Eq.3.13c}$$

$$K = a.\theta^{m} \qquad \text{Eq.3.13d}$$

$$K = K_s(\theta/f)^{m} \qquad \text{Eq.3.13e}$$

where a,b,n, m are constants and K_s is saturated hydraulic conductivity (Hillel 1980).

Some numerical values for the above relationships are given for two types of soils in Table 3.1. Fig.3.3 also shows such a relationship for a sandy loam soil as reported by Rowse and Stone (1978). Methods of measuring the unsaturated hydraulic conductivity of soils, both in the laboratory and in the field, are outlined by Hillel (1980).

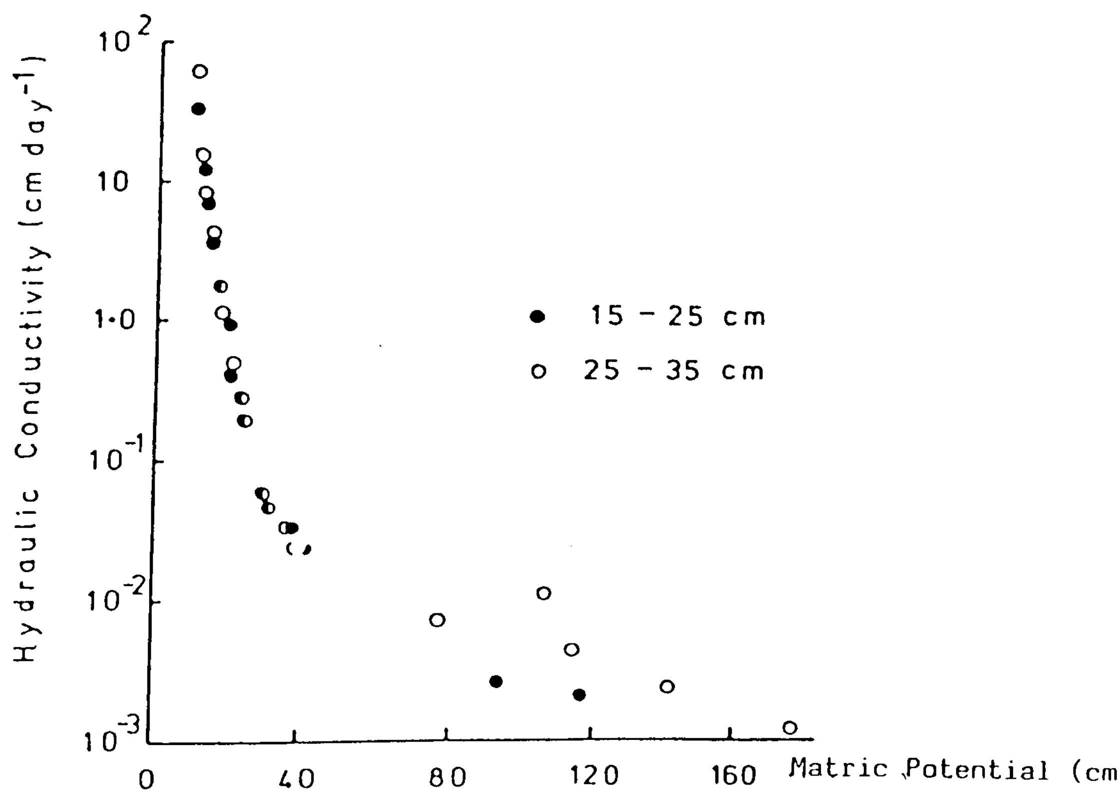


Fig.3.3 Matric potential-unsaturated hydraulic conductivity relationship at two depths of a sandy loam soil profile. (from Rowse and Stone 1978).

CHAPTER 4

PLANT AND SOIL-WATER RELATIONSHIP

4.1 INTRODUCTION.

Plants derive their nutrients from the soil by absorbing the mineral-rich soil water. Minerals such as N, P, K, Ca and Mg are essential to plant growth. Water also acts as a means by which the minerals in the root zone are replenished by the percolation of rain and the capillary rise of ground water, to replace those lost by evapotranspiration.

It is vital that a balance between water contents and air content be met to prevent anaerobic conditions arising in the soil. This can be done by ensuring an efficient drainage system to remove excess water from below the root zone.

4.2 TRANSPORT OF WATER IN PLANTS.

Water is transported through the plant due to the existence of a potential gradient between the roots and the leaves. Water evaporated from the leaf cells causes a drop in water potential. The potential gradient that forms between the leaves and the root is the principle cause of flow. Water is transported upwards to the leaves by the xylem. The xylem is a membrane acting like a pipe network, collecting water from the source at the root tips and transporting it through the shoots, to branch off and supply the demand at the leaves. The rate of movement of water through the plant is primarily controlled by the xylem resistance which for non-woody plants has been reported as a constant value of magnitude 36 bar.s/cm^3 (Meidner and Sheriff 1976).

4.3 THE FUNCTION OF PLANT ROOTS.

Apart from providing the plant with an anchorage, the root system also responds to the changes in the water and mineral contents of the soil by spreading and extending deeper to tap new grounds.

Water is absorbed due to decreasing water potential gradients from soil to roots. The causes of this gradient are twofold. One is terms 'active absorption', which is as a result of the concentration of solutes in the plant xylem thus creating a differential cosmotic pressure; and the other is terms 'passive absorption' and is controlled by the rate of water loss from the shoots. As water evaporates from the leaves, the reduction of water potential in the leaf cells causes water to move into them from the xylem. This results in a reduction of potential in the xylem, which is then transmitted through the xylem network down to the roots. The reduction of potential in the root xylem produces a gradient along which water moves from the root surface across the root wall tissues and into the xylem.

The flow of water from the soil to a unit length of a single cylindrical root of radius R at any one time is given by (Milthorpe and Moorby 1979):

$$Q = 4\pi K_s.(\psi_s - \psi_r)/\ln (D_s^2/R^2) \qquad \text{Eq.4.1}$$

where:

K_s = unsaturated hydraulic conductivity cm/s

ψ_s = water potential in the soil at distance D_s. bars.

ψ_r = water potential at the root surface, bars.

D_s = half the distance between neighbouring roots

= $1/(\pi R_v)^{0.5}$ where R_v in root concentration. cm.

Integrating Eq.4.1 to include all the roots at a concentration R_v in a soil layer of depth ΔZ and of unit area, Zur and Jones (1981) wrote:

$$V = \frac{\psi_r - \psi_s}{R_s + R_r} \quad cm^3/s \qquad \text{Eq.4.2}$$

where V is the volume of water transferred to the roots per unit land area per unit time in the layer ΔZ. R_s and R_r are the resistances to water flow in the boundary between soil and root, and that inside the roots respectively.

It is thus apparent that the total flux of water from a soil layer to the roots of a plant is controlled by the product of the potential gradient and a conductance term. The soil conductance is a function of root geometry and soil hydraulic conductivity.

Gardner (1960) expressed the resistance to water flow from a soil layer to the roots in bar.s/cm^3 as:

$$R_s = \frac{\ln(R_{cyl}/R_{root})}{2.\pi.K_s.R_v.V_s} \qquad \text{Eq.4.3}$$

where:

R_{cyl} = radius of soil cylinder through which water is moving (cm), assumed to be one half the distance between adjacent roots.

= $1/\pi.R_v)^{0.5}$

R_v = rooting density (concentration) cm/cm^3

R_{root} = radius of root cm.

V_s = volume of the soil layer per plant cm^3

Rearranging Eq.4.3 and considering a unit land area:

$$R_s = \frac{\ln(\pi.R_v)^{0.5} + \ln(R_{root})}{2.\pi.K_s.R_v.\Delta Z} \quad \text{bar. s/cm}^3 \qquad \text{Eq.4.4}$$

The resistance to flow of water inside the root is defined by Taylor and Klepper (1978) as:

$$R_r = \frac{1}{K_r.R_v.\Delta Z} \quad \text{bar.s/cm}^3 \qquad \text{Eq.4.5}$$

where:

K_r = root conductivity $cm^3/cm/bar/s$

= 0.93×10^{-8} (Taylor and Klepper 1975)

The driving force for water uptake by roots is the potential gradient between the soil and root. Fig. 4.1 illustrates the gradients necessary to achieve various rates of water uptake in a sandy loamsoil.

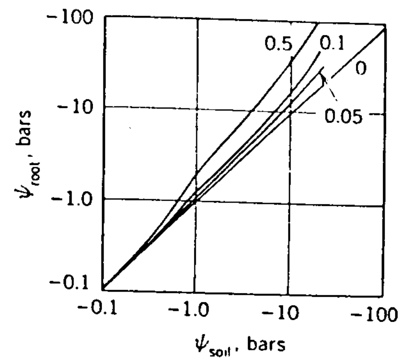


Fig. 4.1 Root-soil water potential gradients required to cause uptake rate of 0, 0.05, 0.1 and 0.5 ml/cm of root length per day in a Pachappa sandy loam (Gardner 1960).

4.4 WATER DEFICIT AND PLANT GROWTH.

Water in the soil is only available to the plant through a certain range of soil water content. This availability depends mainly on soil water potential and its hydraulic conductivity. The maximum and minimum soil water contents between which water is available to the plant are termed 'field capacity' and 'wilting percentage' respectively. These two parameters are different for each soil type. The practice of irrigation is aimed at maintaining the soil water content between field capacity and wilting percentage. An efficient drainage system ensures the soil does not remain above field capacity and an adequate control of irrigation scheduling guarantees that the soil water content will not fall below the wilting percentage.

The transpiration rate, as expressed in Eq.4.2, only relates to the average daily value. In reality, transpiration fluctuates diurnally in response to the fluctuations in atmospheric temperature. The rapid drop in water potential in the plant leaves, in direct response to maximum daily temperature, manifests itself in temporary wilting or loss of turgor (of which water potential is an indication). However, as the temperature drops there is a recovery in plant turgor. Although important in terms of plant growth and yield, temporary wilting, due to its nature, is not easily controllable.

From the evidence presented, it can therefore be justifiable to assume that the rate of transpiration is controlled by the rate of water uptake of the roots and not the rate at which water is evaporated from the leaves. It is generally accepted that the minimum soil water potential at which plants can extract water from the soil is -15 bars. By ensuring that the soil water potential does not fall below this limit, permanent wilting of the plant can be avoided.

CHAPTER 5

EVAPORATION

5.1 INTRODUCTION.

Evaporation is the process of the change of state of water molecules from liquid to gas, owing to an energy input known as the latent heat of vaporisation. The source of the energy required to convert water into water vapour is the radiation emitted by the sun.

Other terrestrial factors such as wind, relative humidity and temperature also play vital roles in the evaporation process. When water evaporates from a surface a boundary layer is produced between the moist surface and the air surrounding it. This boundary layer eventually becomes saturated with water vapour and to enable further evaporation from the wet surface, the saturated boundary layer must be removed and replaced by dryer air. Thus the wind contributes to creating the right conditions for continual evaporation.

The air replacing the saturated boundary layer must have a lower relative humidity to result in an increase in the evaporation rate. Increasing the air humidity produces a lower rate of evaporation since the water vapour absorption by the surrounding air becomes more difficult. It must be noted also that as the air temperature rises, its capacity to absorb water vapour also increases. Thus air and ground temperatures are important factors in the evaporation process.

5.2 SOLAR RADIATION.

Not all the short wave radiation aimed at the planet earth is utilized in the evaporation process. Only a proportion (R_C) of the radiation arriving at the earth's atmosphere (R_A), reaches the earth's surface. Clouds and dust particles in the atmosphere help to reflect part of the radiation. This proportion depends on the latitude, season of the year, time of day and degree of cloudiness. An empirical relationship between R_C and R_A has been derived by Penman (1948):

$$R_C = R_A(a + b.\frac{n}{N}) \quad \text{mm/d} \qquad \text{Eq.5.1}$$

where:

n/N = ratio of actual to possible hours of sunshine (for N see Table 5.1)

a and b = geographical constants. For Southern England 0.18 and 0.55 respectively.

Values of R_A vary with latitude and season of the year. A tabulated set of values is presented in Table 5.2.

The earth absorbs only a certain proportion of R_C. This proportion is dependent upon the reflectivity or albedo (r) of the earth surface. Table 5.3 shows typical values of r for various surfaces and several soil types.

If R_I is the net amount of radiation absorbed by the earth, then the relationship between R_I and R_C can be expressed as:

$$R_I = R_C (1 - r) \text{ mm/d} \qquad \text{Eq.5.2}$$

However, the earth reflects some of R_I as long-wave radiation. This proportion (R_B) is expressed empirically by Penman (1948) as:

$$R_B = \sigma . T_a^4 . (0.56 - 0.09\sqrt{e}) \cdot (0.10 + 0.90.\frac{n}{N}) \text{ mm/d} \qquad \text{Eq.5.3}$$

where:

σ = Stefan-Boltzman constant 5.67×10^{-8} $W/m^2/K^{-4}$

(multiply by 0.034 to convert to mm/K)

T_a = absolute earth temperature, ^oK

e = actual vapour pressure of air, mm Hg

The radiation energy remaining in the earth (R_n) is the net energy available for evaporating water. Thus:

$$R_n = R_I - R_B \text{ mm/d} \qquad \text{Eq.5.4}$$

To calculate R_n from the above equations, daily measurements of temperature ,vapour pressure and sunshine hours are required.

Penman (1948) then derived an expression for evaporation from open water surfaces:

$$E_p = \frac{\frac{S}{\gamma} . R_n + E_a}{\left(\frac{S}{\gamma} + 1\right)} \text{ mm/d} \qquad \text{Eq.5.5}$$

where:

S = slope of saturation vapour pressure curve at temperature t^oC.

γ = Psychrometer constant 0.485.

R_n = net radiation energy for evaporation (equivalent mm/d of water).

E_a = evaporation at the hypothetical case of equal air and water temperature, mm/d.

E_a can be expressed empircally as:

$$E_a = 0.35 \ (0.50 + \frac{U_2}{100}) \cdot (e_s - e) \quad \text{mm/d} \qquad \text{Eq.5.6}$$

where:

U_2 = mean wind speed at 2m above surface, miles/d

e_s = saturation vapour pressure at temperature $t^{o}C$, mmHg

e = actual vapour pressure of air, mmHg

The equation developed by Penman applies to evaporation from open water surfaces and can be termed 'potential evaporation'. Ritchie (1972) applied Eq.5.5 to the case of evaporation from a cultivated soil. It was assumed that the terms containing the vapour pressure deficit and the wind function, are negligible. This was justified by considering that the protection provided by the canopy lowers wind speed and vapour pressure deficit at the ground level. Also, only a proportion (τ) of the net radiation reaches the soil through the crop canopy. This proportion is dependent on the canopy density (expressed in terms of LAI). Thus, applying the above assumptions to Eq.5.5, Ritchie obtained:

$$E = \tau . R_n \frac{S}{S + \gamma} \quad \text{mm/d} \qquad \text{Eq.5.7}$$

Table 5.1: **Mean Daily Duration of Maximum Possible Sunshine Hours (*N*)**

(United Nations (FAO) (1977) *Crop Water Requirements*; and Ministry of Agriculture, Fisheries and Food (1967) *Potential Transpiration*.

North Lats. South Lats.		Jan. July	Feb. Aug.	Mar. Sept.	Apr. Oct.	May Nov.	June Dec.	July Jan.	Aug. Feb.	Sept. Mar.	Oct. Apr.	Nov. May	Dec. June
	60	6.7	9.0	11.7	14.5	17.1	18.6	17.9	15.5	12.9	10.1	7.5	5.9
	58	7.2	9.3	11.7	14.3	16.6	17.9	17.3	15.3	12.8	10.3	7.9	6.5
	56	7.6	9.5	11.7	14.1	16.2	17.4	16.9	15.0	12.7	10.4	8.3	7.0
	54	7.9	9.7	11.7	13.9	15.9	16.9	16.5	14.8	12.7	10.5	8.5	7.4
	52	8.3	9.9	11.8	13.8	15.6	16.5	16.1	14.6	12.7	10.6	8.8	7.8
	50	8.5	10.0	11.8	13.7	15.3	16.3	15.9	14.4	12.6	10.7	9.0	8.1
	48	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
	46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
	44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
	42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.1	9.8	9.1
	40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
	35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
	30	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	11.5	10.6	10.2
	25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
	20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
	15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
	10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
	5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
Equator	0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

Table 5.2: R_a Expressed in Equivalent Evaporation (mm day^{-1})

(Reproduced from J.S.G. McCulloch (1965) *E. African Agric. Forest. J.*, xxx (3) 286–295

	Lat.	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
	NORTHERN HEMISPHERE												
	60	1.4	3.6	7.0	11.1	14.6	16.4	15.6	12.6	8.5	4.7	2.0	0.9
	50	3.7	6.0	9.2	12.7	15.5	16.6	16.1	13.7	10.4	7.1	4.4	3.1
	40	6.2	8.4	11.1	13.8	15.9	16.7	16.3	14.7	12.1	9.3	6.8	5.6
	30	8.1	10.5	12.8	14.7	16.1	16.5	16.2	15.2	13.5	11.2	9.1	7.9
	20	10.8	12.4	14.0	15.2	15.7	15.8	15.8	15.4	14.4	12.9	11.3	10.4
	10	12.8	13.9	14.8	15.2	15.0	14.8	14.9	15.0	14.8	14.2	13.1	12.5
Equator	0	14.6	15.0	15.2	14.7	13.9	13.4	13.6	14.3	14.9	15.0	14.6	14.3
	10	15.9	15.7	15.1	13.9	12.5	11.7	12.0	13.1	14.4	15.4	15.7	15.8
	20	16.8	16.0	14.5	12.5	10.7	9.7	10.1	11.6	13.6	15.3	16.4	16.9
	30	17.2	15.8	13.5	10.9	8.6	7.5	7.9	9.7	12.3	14.8	16.7	17.5
	40	17.3	15.1	12.2	8.9	6.4	5.2	5.6	7.6	10.7	13.8	16.5	17.8
	50	16.9	14.1	10.4	6.7	4.1	2.9	3.4	5.4	8.7	12.5	16.0	17.6
	60	16.5	12.6	8.3	4.3	1.8	0.9	1.3	3.1	6.5	10.8	15.1	17.5
	SOUTHERN HEMISPHERE												

TABLE 5.3 Albedo values of soils.

(compiled by Linacre 1969)

Soil	Albedo		
	Dry soil	Unknown Wetness	Moist Soil
Sand	0.18		0.09
Black mould	0.14		0.08
Ploughed field	0.20-0.29	0.12-0.20	
Black soil	0.14	0.10-0.15	0.07
Grey soil	0.25-0.30		0.10-0.12
Loam	0.23		0.16
Soil	0.16		0.06
Dark soil		0.05-0.15	
Grey soil	0.20-0.39		0.10-0.20
Sandy	0.25-0.45	0.15-0.40	
Raw Humus		0.15	
Brown soil	0.16		
Dark clay	0.16		0.02-0.08
Dark cultivated			0.07-0.10
Latosol	0.13		0.08
Organic sand			0.06
Red soil			0.11
Dark brown clay	0.17		0.11

CHAPTER 6

DEVELOPMENT OF THE MODEL

6.1 INTRODUCTION.

The model is developed by considering the daily water losses from the soil root zone owing to evaporation and transpiration. It is assumed that the soil is initially at field capacity and that the water content is reduced each day until a minimum allowable soil water level, the wilting point, is reached. The model then calculates the amount of water necessary to bring the soil back to field capacity.

6.2 SOIL WATER BALANCE.

It is assumed that the soil is uniform and that it is divided into three equal layers containing the depth of the roots. The thickness of the layers is related to the depth of the roots and since root growth extends the rooting depth, the thickness of the soil layers must also increase. This relationship can be expressed as (defined by Hanks and Hill 1980):

$$D = DM/(1 + \exp(6-(12(T + 14)/RD)))\ \text{cm} \qquad \text{Eq.6.1}$$

where:

RD = date of maximum root growth (90 days for corn)

DM = maximum depth of root zone (180cm for corn)

T = time in days since planting.

Note that in the above equation 14 days have been allowed for the emergence of the plant.

Bearing in mind that transpiration occurs at different rates from each soil layer (due to decreasing root density with depth) and that evaporation is assumed to occur from the top 500mm of the soil only, the daily water loss from each compartment or soil layer can be calculated (see Fig. 6.1).

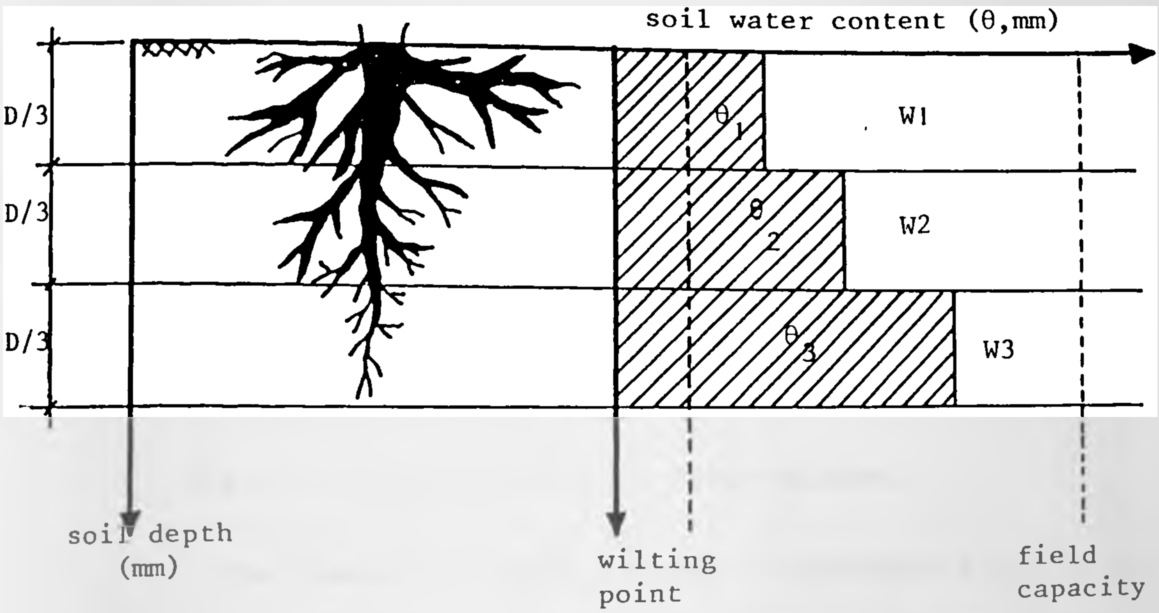


Fig. 6.1 Illustration of soil layers and water balance within the rooting zone.

The model thus keeps an up-to-date measure of the soil moisture contents of each layer and when the average of the three layers reaches a critical value (wilting point), the amount of water needed to bring each layer back to field capacity is thus obtained. This represents the irrigation requirement for the soil.

A more accurate account of the irrigation requirement may be obtained if hourly measurements of transpiration and evaporation were available. Assuming that the rate of flow of water into the first compartment to be equal to the infiltration rate of the soil (INFR), the amount retained in the layer to bring it to field capacity can be calculated. The excess is the flux into the second compartment and so on. This method was first used by Van Keulen (1975) for an infiltration model to calculate the effect of applied irrigation water and or natural precipitation upon the soil water balance of a cultivated soil.

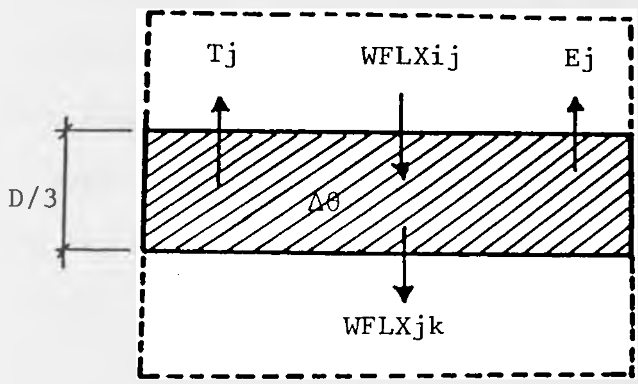


Fig. 6.2 Soil compartment water balance.

The compartment water balance is represented in Fig. 6.2. As an example, consider the second compartment. The water balance equation is thus:

$$WFLX_{23} = WFLX_{12} - \Delta\theta - E_2 - T_2 \qquad \text{Eq.6.2}$$

where:

WFLX = water flux, mm

E = evaporation, mm

T = transpiration, mm

Δθ = amount of water retained, mm.

and:

$$\Delta\theta = W_2 = (SWFC - SWCS) \cdot (D/3) \qquad \text{Eq.6.3}$$

where:

W_2 = water needed to wet second layer to field capacity, mm.

SWFC = soil field capacity, mm.

SWCS = initial soil water content of second layer, mm.

D = depth of rooting zone, mm.

A setback to achieving an accurate measure, by the above method, of the infiltration process of rainfall or irrigation and its subsequent use in the model is the lack of economically obtainable hourly measurements of evaporation, transpiration and other atmospheric variables such as solar radiation, temperature and vapour pressure. For this reason the present model sufficies with the calculation of the volume of water necessary to return the soil to field capacity after a controlled drying cycle.

6.3 EVAPORATION FROM THE SOIL.

Evaporation from the soil is assumed to occur in two stages (Ritchie 1972). These are the constant (E_1) and falling (E_2) evaporation rates. The constant rate occurs when the soil is wet and evaporation is at the potential rate, given by:

$$E_1 = \tau . |S/(S + \gamma)| . Rn \quad \text{mm/d.} \qquad \text{Eq.6.4}$$

where:

τ = ratio of net radiation reaching the soil (Rns) to the net radiation above the canopy (Rn)

S = slope of saturation vapour pressure curve at a weighted average temperature $(3\ T_{max} + T_{min})/4$.

γ = psychrometric constant.

Rn = daily net radiation, mm/d.

Ritchie (1972) and Rosenthal et al (1977) have shown that τ is a function of leaf area index, LAI; and can be expressed as:

$$\tau = \exp|(-0.389 \times LAI) + 0.15| \qquad \text{Eq.6.5}$$

Evaporation continues at the potential rate until the cumulative water loss from the soil reaches a critical value (U,mm), after which evaporation occurs at the falling rate and is expressed as:

$$E_2 = C.t^{\frac{1}{2}} - C.(t - 1)^{\frac{1}{2}} \text{ mm/d} \qquad \text{Eq.6.6}$$

where:

C = constant depending on soil hydraulic properties $mm/d^{\frac{1}{2}}$

t = time since initiation of the falling rate stage.

Typical values of U and C are presented in Table 6.1 for several soils.

Assuming that the groundwater plays no part in this soil profile, the evaporation from the soil may be considered to occur from the top 500mm of the soil. The dynamic nature of the rooting depth adds a complication in that initially all three soil layers are within the 500mm evaporation depth. At this stage, evaporation from each soil layer is only a proportion of the total evporation. This may be expressed as:

$$E = \frac{D \times E}{3 \times 500} \text{ mm for } D \leqslant 500\text{mm} \qquad \text{Eq.6.7}$$

When the rooting depth D, exceeds 500mm, all the evaporation is associated with the first layer and evaporation from the second and third layers are zero.

TABLE 6.1 Values of U, C, field capacity (FC) and wilting percentage (WP) for several soil types. (Ritchie 1972 and Kanemasu et al 1976)

Soil Type	U mm	C $mm/d^{\frac{1}{2}}$	FC mm	WP mm
Carurle sand	5.0	1.68	82	45
Florence stony loam	5.8	2.89	521	342
Manter fine sandy loam	9.0	2.41	230	115
Mansic silty clay loam	9.2	3.53	334	158
Muir silty clay loam	10.2	3.27	546	289
Harney (Hays) silt loam	11.2	3.36	468	261
Harney (Minneola) silt loam	12.6	3.53	560	240
Lancaster clay loam	16.5	3.73	544	263
Adelanto clay loam	12.0	5.08	-	-
Yolo loam	9.0	4.04	-	-
Houston black clay	6.0	3.50	-	-
Plainfield sand	6.0	3.34	-	-

6.4 TRANSPIRATION.

The transpiration rate is taken to be equal to the rate of water uptake by the plant roots and is expressed similar to Eq.4.2:

$$V = \frac{\psi_r - \psi_s}{R_s + R_r} \quad mm/d \qquad \text{Eq.6.8}$$

The unsaturated hydraulic conductivity of the soil (K) can be related to the soil water content (θ, g/g soil). For a clay loam soil, Wilson and Gelhar (1980), report this relationship to be:

$$K = 1.68 \exp (3.58 \times \theta) \quad mm/d \qquad \text{Eq.6.9}$$

The soil water potential, ψ_s, of a clay loam soil varies with the soil water content, θ , by the expression derived from Milthorpe and Moorby (1979):

$$\psi_s = 8.5 \times 10^{-3}(\theta^{-6.0}) \text{ bars} \qquad \text{Eq.6.10}$$

where:

θ = soil water content'cm^3 water/cm^3 soil.

The rooting density is a major factor in the process of water removal from the soil, yet practically no experimental data is available on the variation of rooting density R_V, with time or stage of growth. R_V is expressed as the total length of root per unit volume of soil and has units of cm/cm^3. It is assumed that rooting density increases exponentially with time and that the maximum density corresponds with the date of maximum root depth, RD. Owing to the lack of real data on the root density development, an assumption must be made on the shape of the exponential curve. This can then be modified to best suit the model. It is further assumed that the concentration of roots in the first layer is five times greater than the second layer and ten times greater than the third. This is based on the fact that anything up to 85% of the roots are distributed in the top one third of the soil (Milthorpe and Moorby, 1979).

The mean root radius can either be estimated for the whole rooting depth, or for each soil layer, this parameter can be entered into the model separately. However, in this case it is assumed that the overall mean root radius R root equals 0.015 cm (similar to Zur and Jones 1981).

The root water potential ψ_r, is a function of the leaf water potential ψ_L, and of the xylem resistance to water flow. This relationship is expressed by Zur and Jones (1981) as:

$$\psi_r = \psi_L - Q_p \cdot R_x - j.(D/3) \text{ bars} \qquad \text{Eq.6.11}$$

where:

$$Q_p = 2.3 \times 10^{-6} \times R_V \times (D/3) \text{ cm}^3/\text{s} \qquad \text{Eq.6.11a}$$

QP is the rate of flow of water into the roots, and the above expression assumes a total water flux to the plant of 0.1 ml/cm root/day (Gardner 1960).

Also:

R_X = 36 bar.s/cm^3 (xylem resistance for non-woody plants. Meidner & Sheriff 1976) Eq.6.11b

ψ_L = 15 bars (This is at the critical point when plant uses water from the roots (Cowan 1965). Eq.6.11c

j = layer number from top to bottom .

D = depth of each soil layer, converted to pressure units, bars.

(1 bar $\equiv 2 \times 10^{-3}$ cm)

6.5 MODEL DESCRIPTION.

The model, as can be seen from the flow diagram (Fig.6.3), operates by considering the water balance of each of three soil layers separately on a continuous daily basis. Input parameters required to operate the programme are two-fold. One is the set of parameters variable for each soil layer and the other is the set of values constant for all layers. These parameters are:

I) Per layer, per day:

a) j = layer number i.e. 1, 2, 3.

b) R_{root} = mean root radius (mm) - may assume constant

c) R_V = rooting density (cm/cm^3) - assumed values due to lack of any applicable data.

d) θ = mean soil water content (mm) - calculated for each layer at the end of the previous day.

II) Per day:

a) LAI = leaf area index - measured daily or from records.

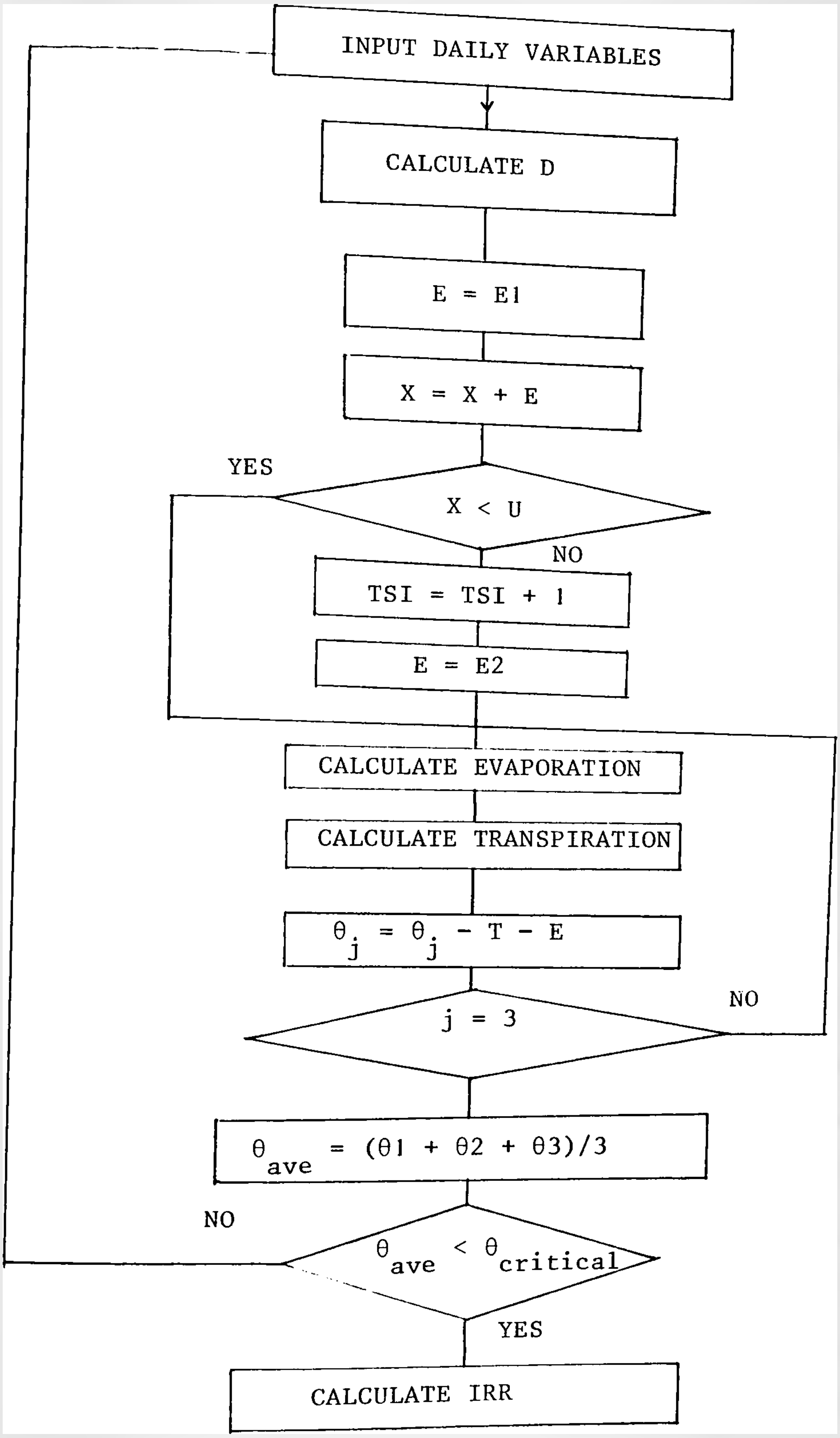
b) S = slope of saturation vapour pressure.

c) R_n = net radiation.

d) T = days since initiation of model.

The model calculates the daily water losses due to evaporation and transpiration for each soil layer and outputs the reduced soil water content. If at the end of the day, the average of the three soil water contents is still above the critical level (wilting point) then the cycle is repeated for the following day until such time as the average soil water content in the whole rooting depth is below the critical level. At this point, the water contents of each layer having been determined, the model then calculates, for each layer, the amount of water required to bring it back to field capacity. The sum for the three layers is thus the total irrigation requirement.

Fig. 6.3 Flow diagram of the water balance model.



CHAPTER 7

APPLICATION OF THE MODEL

7.1 INTRODUCTION.

The example used to operate the model only acts to illustrate the models potential. The meteorological variables and the crop growth characteristics used in the example are not those of an actual case, but were chosen from several sources and are real only in range and magnitude.

7.2 INPUT VARIABLES.

Daily meteorological input data were generated using the data of Wangati (1972) and are presented in tabulated form in Appendix II. The variation of leaf area index (LAI) is that of Wangati (1972), measured for a crop of maize. Rooting density, although being a major factor in water uptake, has rarely been studied and its relationship with growth stage is little known. However, for the purpose of simulating the model, a relationship such as that depicted in Fig. 7.4 is used. The shape of the curve is only an assumption but the magnitude and range of values are compatible with those reported by Milthorpe and Moorby (1979) for similar crops. Further, it was assumed that the rooting density curve (Fig. 7.4) applies to the first layer of soil and that the rooting densities of the second and third layers are respectively one fifth and one tenth of the first layer (Appendix II).

Rooting depth was assumed to vary with time as expressed in Eq.6.1. Hanks and Hill (1980) reported a maximum depth of rooting of 180cm for corn attained after 90 days of growth. This daily variation is represented in Fig. 7.5

7.3 OUTPUT FROM THE MODEL.

The water balance of the cultivated soil is illustrated in Fig. 7.1. The soil water is depleted gradually from the time of planting until such time that the soil water content falls below the wilting percentage, when irrigation is applied to restore soil water content to field capacity. For the example used to illustrate the model, three irrigation stages are required. Table 7.1 lists the calculated output from the model and determines the date and amount of irrigation as follows:

On day 80, required irrigation = 144.69mm

On day 99, required irrigation = 146.10mm

On day 119,required irrigation = 144.32mm.

It can be seen that the last irrigation date is one day before harvesting and thus can be justifiably ignored.

Since the model differentiates between the evaporation and transpiration functions, these two parameters, as simulated by the model, are presented in Fig. 7.2 and Fig. 7.3 respectively. The sudden jumps in the transpiration rate in Fig. 7.2 correspond to irrigation applied on days 80, 99 and 119 of the growth stage. This sudden rise in transpiration is expected since the function used in the model is highly dependent on the soil water content.

7.4 VALIDATION OF THE MODEL.

A comparison of the actual transpiration rate as measured by the model, and that of potential evapotranspiration, as measured by the Penman method, is shown in Fig. 7.6. It can be seen that in the latter stages of growth, particularly after the irrigation is applied, the actual transpiration rate simulated by the model is many times that of the potential rate. It is thus evident that the transpiration function used to operate the model over-estimates the transpiration rate. This can also be verified by considering the overall water balance for the whole of the growth period. This is summarised below:

Initial available soil water	=	+80.00mm
Applied irrigation water, (1)	=	+144.69mm
(2)	=	+146.10mm
(3)	=	+144.32mm
Total evaporation from soil	=	-44.80mm
Total transpiration from soil	=	-755.90mm
Thus: Overall water balance	=	-285.59mm

From the above summation it can be seen that more water is lost from the soil than is actually available. Clearly this is an impossibility which can be attributed to overestimation of the transpiration rate. One plausible cause of overestimation can be seen from Fig. 7.2 where at the time of irrigation the transpiration rate rises very rapidly to magnitudes seven times that of the rate before irrigation.

This total overestimation (about 30%) of the transpiration rate seems to arise from an unintentional assumption built into the model, whereby upon restoration of field capacity to the soil, the plant roots uptake water at a rapid rate thus producing excessive rates of transpiration.

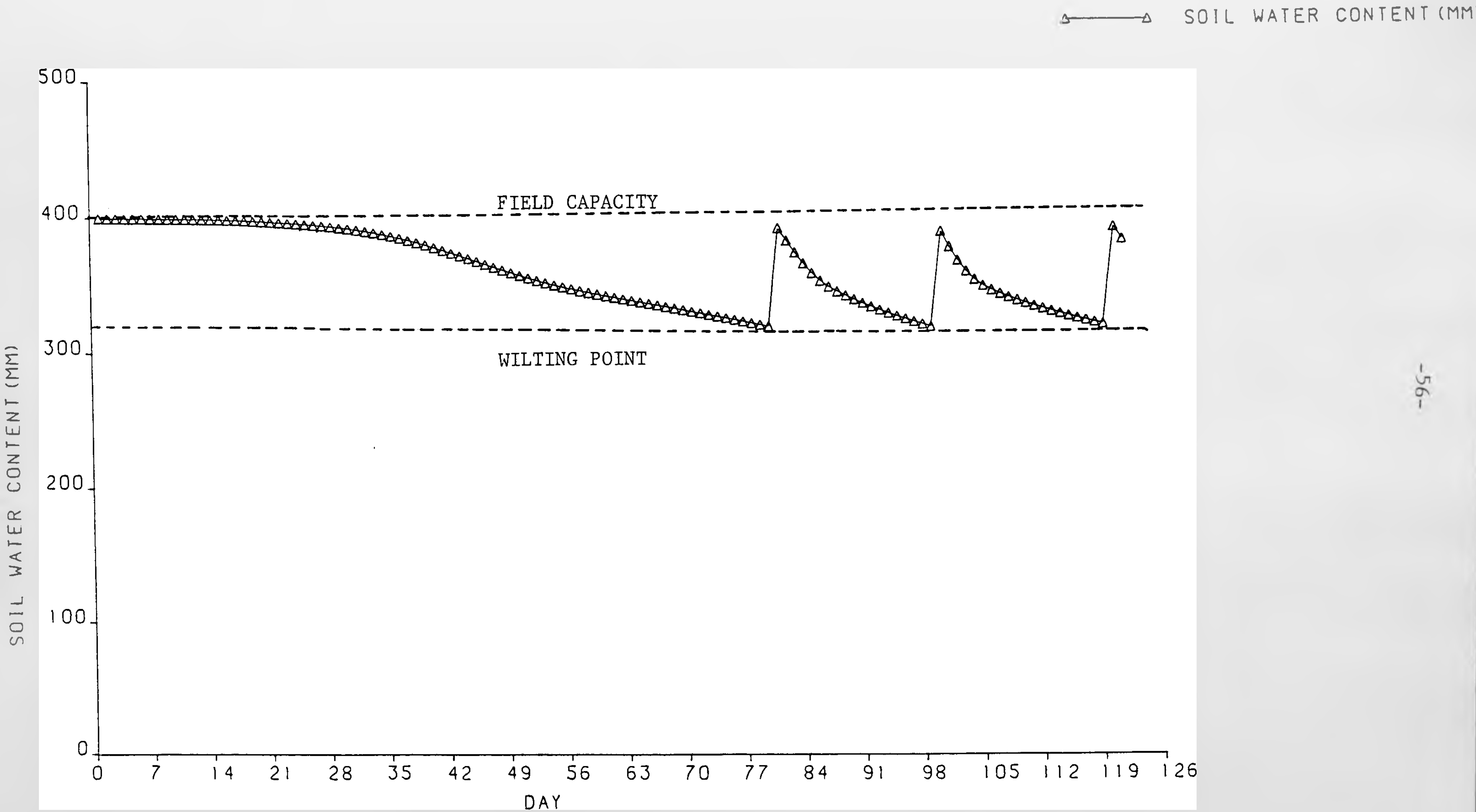


Fig. 7.1 Soil water balance throughout the growth period.

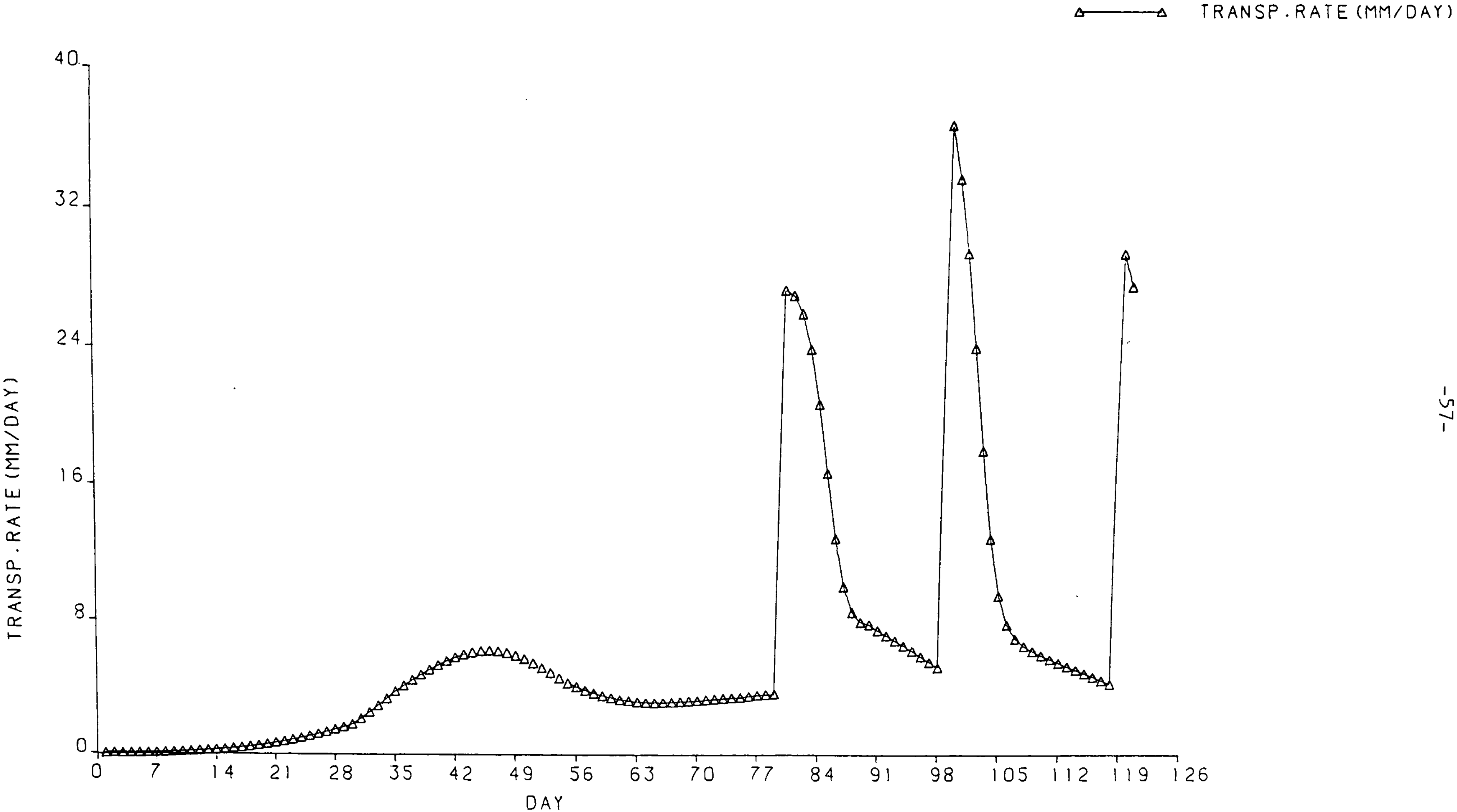


Fig. 7.2 Simulated daily transpiration rate.

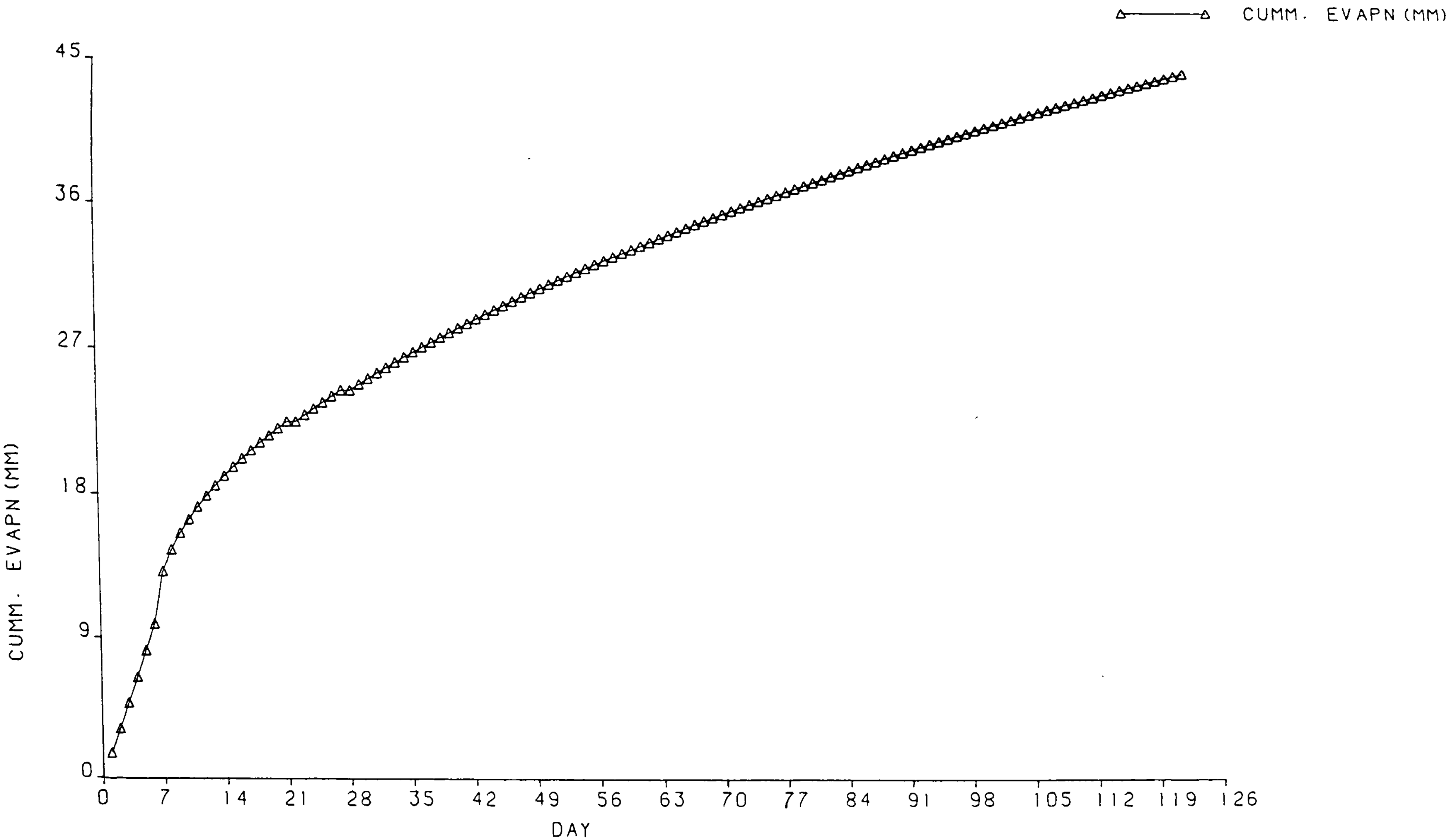


Fig. 7.3 Simulated cumulative soil evaporation.

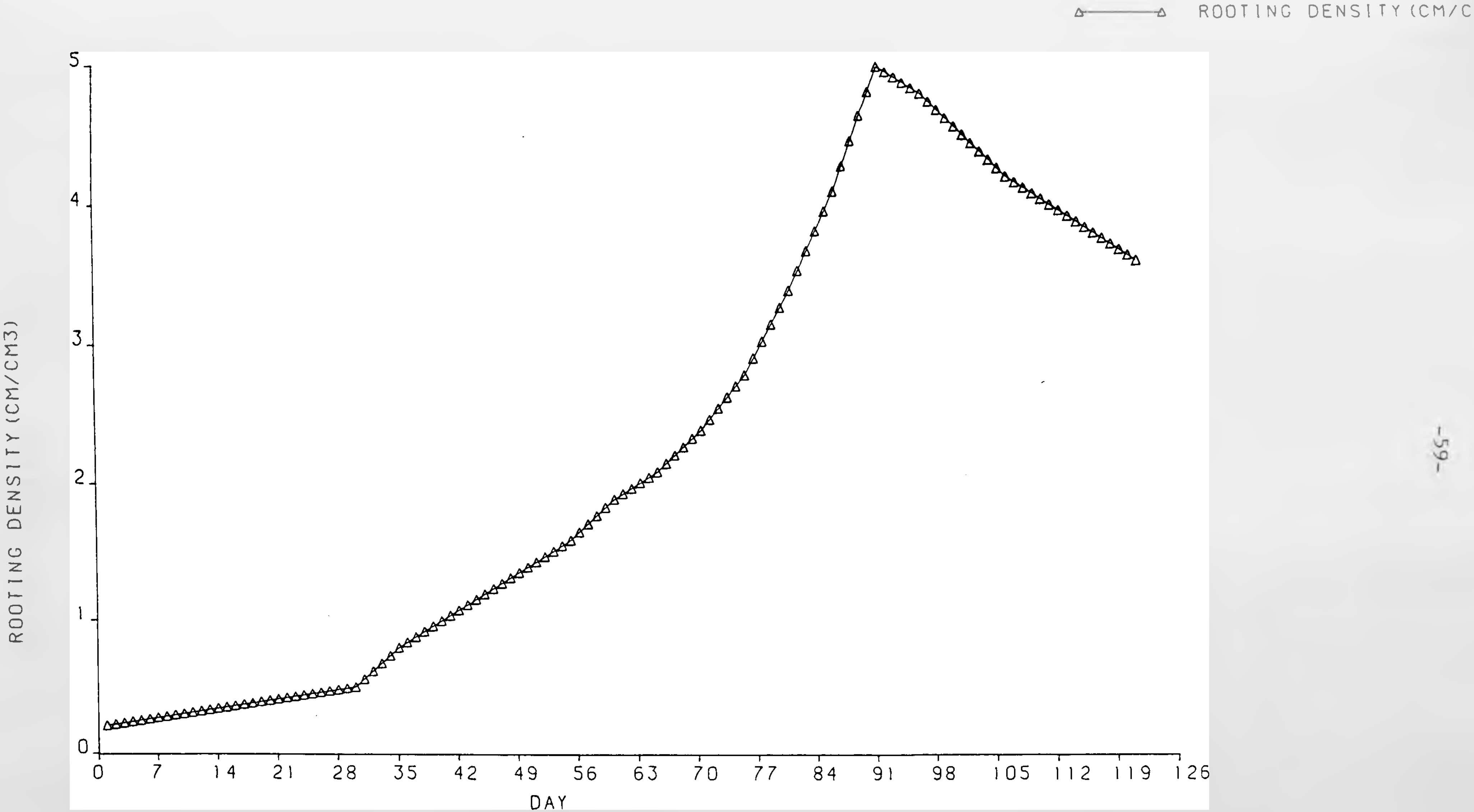


Fig. 7.4 Rooting density of the first layer.

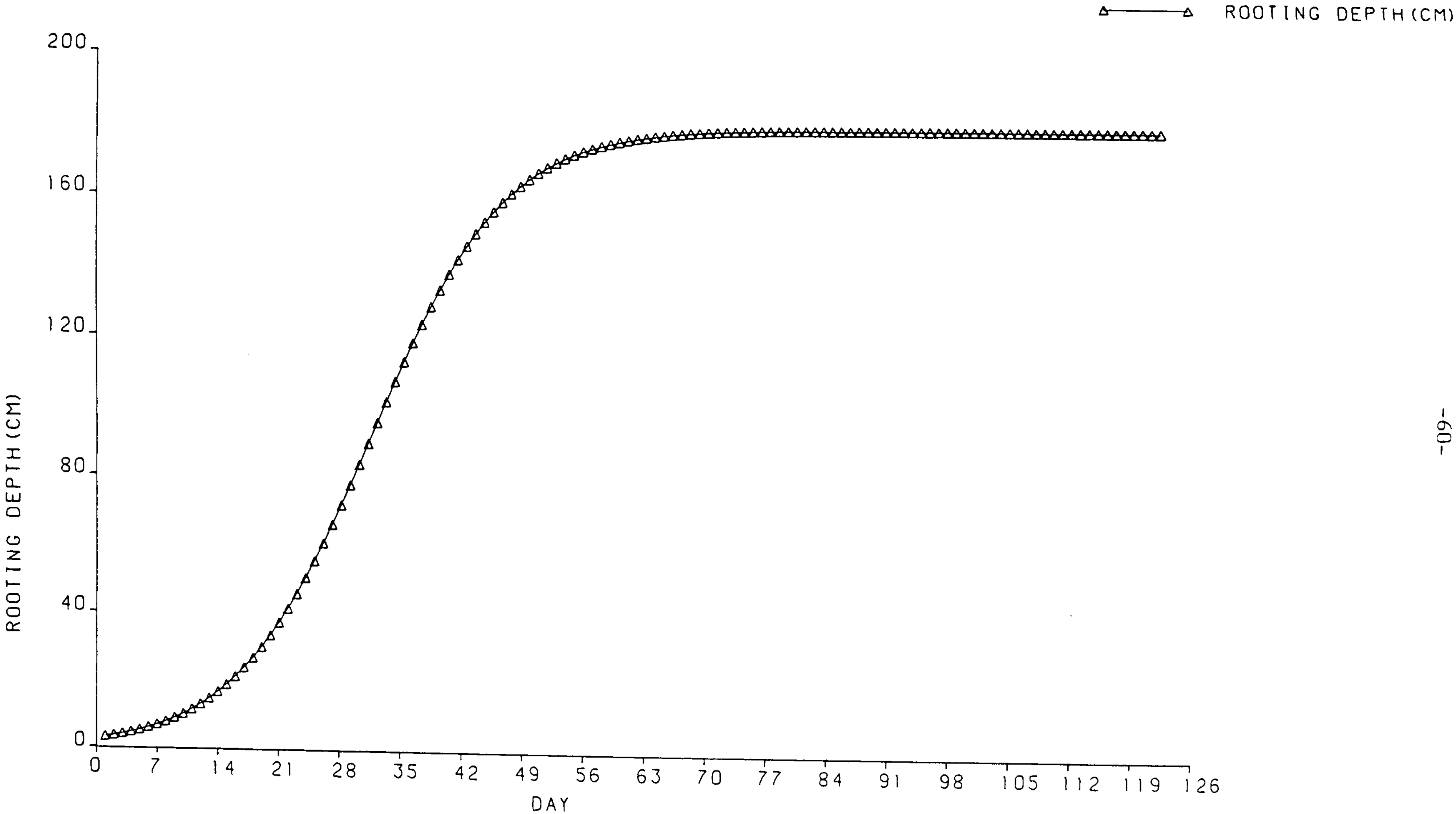


Fig. 7.5   Variation of rooting depth with growth.

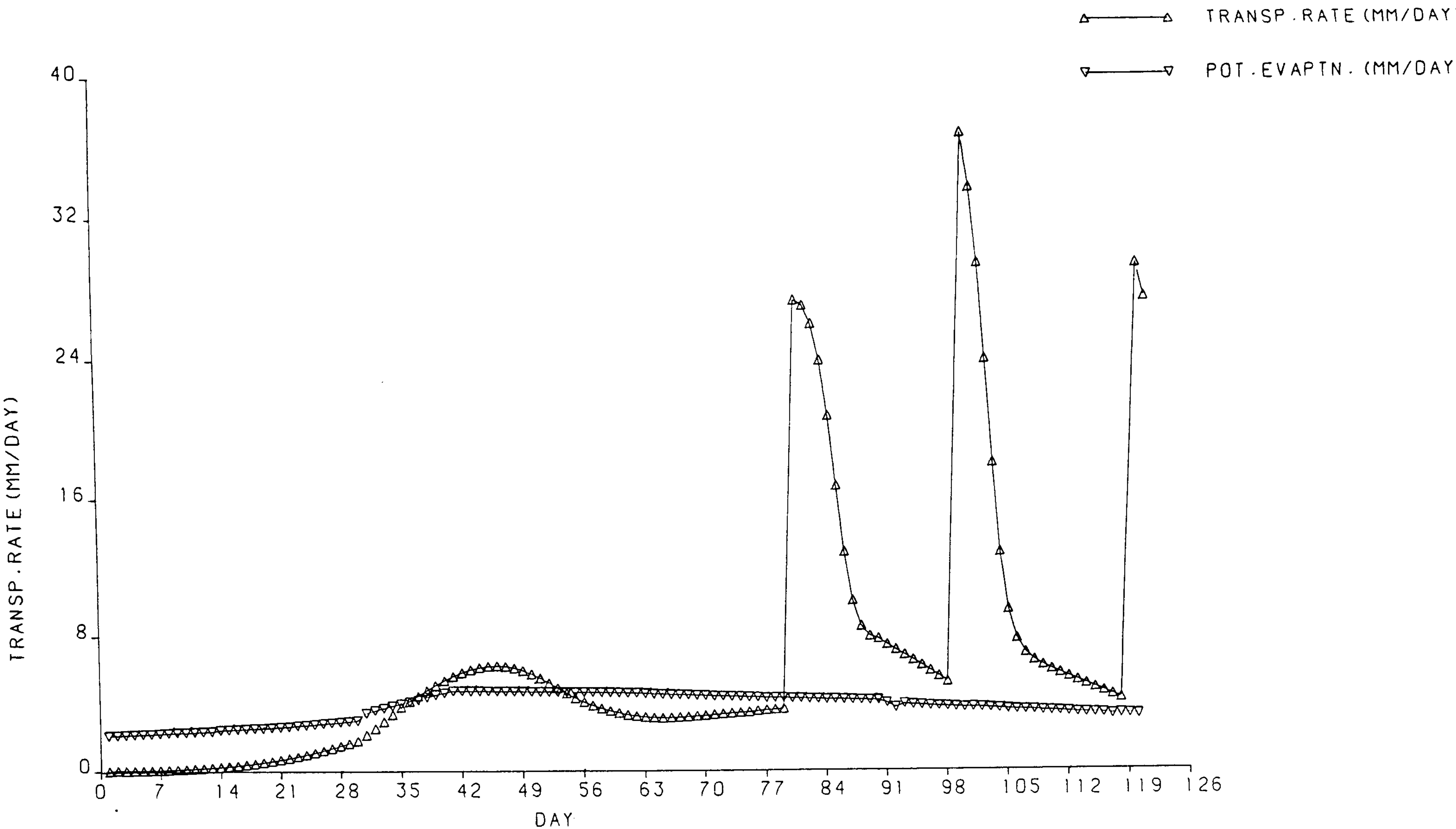


Fig. 7.6 Comparison of simulated transpiration rate with Penman's potential evapotranspiration.

TABLE 7.1

CALCULATED VALUES OF SOIL WATER CONTENTS OF EACH LAYER AND THE OVERALL AVERAGE SOIL WATER CONTENT FOR EACH DAY INCLUDING THE REQUIRED IRRIGATION AMOUNT [IRR(MM)] :

(I)	SWC(I,1)	SWC(I,2)	SWC(I,3)	ASWC(I)
1	399.9424	399.9613	399.9637	399.9558
2	399.8749	399.9163	399.9214	399.9042
3	399.7958	399.8540	399.8724	399.8441
4	399.7027	399.8026	399.8151	399.7735
5	399.5938	399.7315	399.7487	399.6913
6	399.4672	399.6495	399.6722	399.5963
7	399.2476	399.4826	399.5120	399.4141
8	399.0977	399.3948	399.4319	399.3081
9	398.9436	399.3135	399.3597	399.2056
10	398.7764	399.2318	399.2838	399.0990
11	398.5910	399.1466	399.2160	398.9845
12	398.3832	399.0558	399.1398	398.8596
13	398.1487	398.9576	399.0587	398.7217
14	397.8833	398.8506	398.9715	398.5685
15	397.5822	398.7332	398.8772	398.3976
16	397.2404	398.6040	398.7747	398.2064
17	396.8526	398.4614	398.6628	397.9923
18	396.4129	398.3037	398.5405	397.7523
19	395.9151	398.1292	398.4066	397.4836
20	395.3526	397.9362	398.2601	397.1830
21	394.7184	397.7227	398.0996	396.8469
22	394.0056	397.4870	397.9241	396.4723
23	393.2066	397.2272	397.7323	396.0554
24	392.0558	397.0738	397.6556	395.5951
25	390.8249	396.9015	397.5694	395.0986
26	389.5064	396.7090	397.4731	394.5629
27	388.0936	396.4947	397.3660	393.9848
28	386.5804	396.2574	397.2473	393.3617
29	384.9616	395.9959	397.1165	392.6913
30	383.2328	395.7090	396.9729	391.9716
31	381.2427	395.3651	396.8008	391.1362
32	378.9731	394.9596	396.5977	390.1768
33	376.4084	394.4879	396.3615	389.0860
34	373.5373	393.9461	396.0900	387.8578
35	370.3530	393.3306	395.7814	386.4884
36	366.9286	392.6544	395.4420	385.0083
37	363.2716	391.9163	395.0714	383.4198
38	359.3944	391.1154	394.6688	381.7262
39	355.3146	390.2514	394.2339	379.9333
40	351.0549	389.3243	393.7658	378.0487
41	346.6437	388.3344	393.2673	376.0818
42	342.1149	387.2823	392.7356	374.0443
43	337.5081	386.1690	392.1721	371.9497
44	332.8681	384.9956	391.5770	369.8136

45	328.2448	383.7635	390.9508	367.6531
46	323.6917	382.4743	390.2941	365.4867
47	319.2650	381.1295	389.6075	363.3340
48	315.0214	379.7310	388.8915	361.2146
49	311.0154	378.2805	388.1468	359.1476
50	307.2961	376.7802	387.3741	357.1501
51	303.9045	375.2319	386.5739	355.2368
52	300.8702	373.6378	385.7471	353.4184
53	298.2091	371.9998	384.8941	351.7010
54	295.9227	370.3203	384.0157	350.0862
55	293.9987	368.6011	383.1125	348.5708
56	292.3962	366.8233	382.1737	347.1311
57	291.0941	364.9895	381.2002	345.7613
58	290.0617	363.1023	380.1924	344.4521
59	289.2631	361.1648	379.1511	343.1930
60	288.6604	359.1801	378.0769	341.9724
61	288.2191	357.1721	376.9818	340.7910
62	287.9025	355.1334	375.8665	339.6342
63	287.6803	353.0874	374.7316	338.4998
64	287.5283	351.0266	373.5777	337.3776
65	287.4276	348.9542	372.4053	336.2624
66	287.3651	346.8537	371.2040	335.1409
67	287.3300	344.7292	369.9745	334.0113
68	287.3140	342.5852	368.7177	332.8723
69	287.3110	340.4262	367.4344	331.7239
70	287.3166	338.2569	366.1254	330.5663
71	287.3293	336.0647	364.7807	329.3916
72	287.3463	333.8560	363.4015	328.2013
73	287.3655	331.6376	361.9890	326.9974
74	287.3857	329.4164	360.5445	325.7822
75	287.4058	327.1999	359.0693	324.5583
76	287.4287	324.9648	357.5438	323.3125
77	287.4525	322.7224	355.9702	322.0484
78	287.4758	320.4841	354.3507	320.7702
79	287.4982	318.2617	352.6877	319.4825
W1=67.38911	W2=48.96162		W3=28.34032	IRR=144.6911
80	378.7681	395.8063	397.9126	390.8290
81	358.0376	391.4854	395.7501	381.7577
82	338.5438	387.0464	393.5144	373.0348
83	321.2802	382.4994	391.2074	364.9956
84	307.3666	377.8561	388.8313	358.0180
85	297.6165	373.1298	386.3883	352.3782
86	291.8873	368.2901	383.8575	348.0116
87	289.1814	363.3568	381.2421	344.5935
88	288.1442	358.3527	378.5459	341.6809
89	287.8132	353.3030	375.7729	338.9630
90	287.7276	348.2367	372.9276	336.2973
91	287.7058	343.3998	370.1386	333.7481
92	287.6995	338.7997	367.4066	331.3019
93	287.6970	334.4424	364.7319	328.9571
94	287.6955	330.3326	362.1153	326.7145
95	287.6942	326.4732	359.5571	324.5749
96	287.6919	322.8305	357.0682	322.5469
97	287.6894	319.5508	354.6486	320.6295
98	287.6867	316.4781	352.2980	318.8210
W1=67.37907	W2=50.10649		W3=28.61744	IRR=146.1030
99	371.5859	394.3688	397.1969	387.7172
100	346.0460	388.8914	394.4500	376.4625

101	324.5292	383.5717	391.7595	366.6201
102	308.2144	378.4132	389.1252	358.5843
103	297.6205	373.4193	386.5471	352.5290
104	291.9296	368.5934	384.0254	348.1828
105	289.3604	363.9384	381.5597	344.9529
106	288.3158	359.4355	379.1385	342.2966
107	287.9115	355.0886	376.7618	339.9206
108	287.7562	350.9013	374.4298	337.6958
109	287.6956	346.8769	372.1427	335.5717
110	287.6709	343.0182	369.9005	333.5299
111	287.6600	339.3275	367.7032	331.5636
112	287.6545	335.8064	365.5509	329.6706
113	287.6510	332.4558	363.4437	327.8502
114	287.6483	329.2759	361.3814	326.1019
115	287.6459	326.2661	359.3641	324.4254
116	287.6436	323.4250	357.3917	322.8201
117	287.6413	320.7504	355.4640	321.2852
118	287.6389	318.2392	353.5809	319.8197
W1=67.41602		W2=49.05601	W3=27.85118	IRR=144.3232
119	377.2892	395.5040	397.7621	390.1852
120	356.3395	391.1079	395.5611	381.0028

CHAPTER 8

CONCLUSIONS AND SUGGESTIONS

The process of interception is not a major factor in the hydrological cycle, yet its understanding helps to clarify the consequences of man's manipulation of nature in such fields as afforestation, deforestion, artificial storage of water and specific irrigation practices.

The linear regression model of interception described is only suitable for seasonal or annual determinations of interception loss, whereas the deterministic model is infinitely more versatile in that the interception loss due to individual rainfall events can be evaluated. The latter model also incorporates such variables as foliage density (leaf area index), rainfall intensity and duration and potential evaporation and transpiration.

The greatest potential of the deterministic model is in the field of sprinkler irrigation where most variables are measurable or controllable, enabling accurate measurement of the gross amounts and rates of application of water to achieve desirable effective irrigation. An example is used to illustrate the continuous water balance held throughout a rainfall event. Interception loss is seen to increase in response to decreasing rainfall intensity and increasing potential evaporation.

The universal drive for more effective use of water in agriculture has meant that greater emphasis must be placed upon the measurement and prediction of irrigation demands. Scheduling irrigation is a complex amalgamation of natural processes which can only be measured or controlled and at best, partially predicted.

The dynamic water balance model proposed for scheduling irrigation acts by manipulating the daily inputs of meteorological and crop-characteristic variables and calculating evaporation and transpiration as separate functions.

The model was applied to an example in which owing to lack of any real data, many of the input variables were chosen arbitrarily but their magnitudes were kept within comparable conditions. Three irrigation dates and amounts were predicted with the last irrigation falling one day before harvest day in which case it was irgnored.

The overall water balance for the whole growth period showed an overestimation (by about 30%) of the transpiration function, giving rise to the impossible condition where more water is lost from the soil than is actually available. This inaccuracy seems to point to an unintentional assumption built into the model in that upon application of water to the dry soil, the plant roots are capable of rapid uptake of water indicating sudden increases of seven or eight fold in the transpiration rate. This assumption, although seemingly logical, is not true in practice. Plant roots in a dry soil do not respond to wetting of the soil by rapid rises in the rate of water uptake. This rate is limited by the plant turgor and xylem conductance. Since the incorporation of these conditions is outwith the limit of this thesis, it is recommended that further research is to be undertaken in the aforementioned field.

The greatest potential of this irrigation scheduling model is in its use in greenhouses where many of the meteorological variables can be readily controlled and measured, allowing accurate prediction of the dates and amounts of irrigation.

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APPENDIX I

```
      DIMENSION A(120),G(120)
      OPEN(UNIT=1,FILE='POTEVAP.DAT',STATUS='OLD')
      OPEN(UNIT=2,FILE='RAINFALL.DAT',STATUS='OLD')
      OPEN(UNIT=3,FILE='RESULT.DAT',STATUS='NEW',CARRIAGECONTROL='LIST')
      PT=0.75
      S=0.6
      B=2.5
      TP=0.01
      N=50
      C=0
      X=0
      DO 140 I=1,N
      READ(1,80) A(I)
80    FORMAT(F5.3)
      READ(2,90) G(I)
90    FORMAT(F5.3)
      IF(C.GT.S) GO TO 110
      IF(C.EQ.0.0) GO TO 100
      E=((1-(C/S))*TP)+((C/S)*A(I))
      GO TO 105
100   E=TP
105   D=0
      GO TO 120
110   E=A(I)
      D=0.0019*S*EXP(B*(C/S))
120   C=((1-PT)*G(I))-E-D
      X=X+C
      C=X
      THF=D+(PT*G(I))
      WRITE(3,130)G(I),E,C,D,THF
130   FORMAT(10X,5(F6.4,5X))
      IF(C.LE.0.0) GO TO 150
140   CONTINUE
150   STOP
      END
```

RAIN. DAT.

0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.1500	0.1500	0.1500	0.1500	0.1500	0.1500	0.1500	0.1500	0.1500	0.1500
0.2500	0.2500	0.2500	0.2500	0.2500	0.2500	0.2500	0.2500	0.2500	0.2500
0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000
0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

EVAPTN. DAT.

0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
0.0100	0.0107	0.0114	0.0120	0.0126	0.0133	0.0139	0.0145	0.0150	0.0156
0.0162	0.0173	0.0184	0.0195	0.0206	0.0217	0.0227	0.0237	0.0246	0.0250
0.0500	0.0500	0.0477	0.0462	0.0447	0.0434	0.0422	0.0411	0.0400	0.0390
0.0731	0.0640	0.0563	0.0497	0.0441	0.0394	0.0354	0.0319	0.0290	0.0265
0.0325	0.0249	0.0191	0.0146	0.0112	0.0100	0.0100	0.0100	0.0100	0.0100
0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100
0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100

THF. DAT.

0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.1125	0.1125	0.1125	0.1125	0.1125	0.1125	0.1125	0.1125	0.1125	0.1125
0.1875	0.1875	0.1875	0.1875	0.1875	0.1375	0.1875	0.1875	0.1875	0.2028
0.0918	0.0891	0.0750	0.0750	0.0750	0.0750	0.0750	0.0750	0.0750	0.0750
0.0375	0.0375	0.0375	0.0375	0.0375	0.0375	0.0375	0.0375	0.0375	0.0375
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TABLE 2

Linear regression equations comparing throughfall, stemflow and interception with gross precipitation for selected New Zealand vegetation communities

Common name (see Fig. 2)	Dominant Botanical name	Site	Reference	Characteristic	Equation	n	r	F
Kauri forest	*Agathis australis*	Trounson Park		Interception	$V = 0{\cdot}43\ P_g + 1{\cdot}0$	10	0·877	—
				Throughfall	$T_f = 0{\cdot}60\ P_g - 3{\cdot}71$	23	0·971	—
				Stemflow	$S_f = 0{\cdot}04\ P_g - 0{\cdot}15$	5	0·938	—
Kauri Understorey				Stemflow	$S_f = 0{\cdot}04\ P_g - 0{\cdot}45$	6	0·693	—
Manuka scrub	*Leptospermum scoparium*	Puketurua		Interception	$V = 0{\cdot}18\ P_g + 1{\cdot}19$	39	0·877	171·0
				Throughfall	$T_f = 0{\cdot}44\ P_g - 0{\cdot}10$	40	0·973	—
				Stemflow	$S_f = 0{\cdot}38\ P_g - 0{\cdot}01$	40	0·971	—
Manuka scrub	*Leptospermum scoparium*	Taita	Aldridge and Jackson 1968	Interception	$V = 0{\cdot}26\ P_g - 1{\cdot}52$	—	—	—
				Throughfall	$T_f = 0{\cdot}45\ P_g - 0{\cdot}25$	—	0·990	—
				Stemflow	$S_f = 0{\cdot}32\ P_g - 1{\cdot}39$	—	0·960	—
Pine 1948 forest	*Pinus radiata*	Whakarewarewa		Interception	$V = 0{\cdot}20\ P_g + 0{\cdot}94$	183	0·801	577·0
				Throughfall	$T_f = 0{\cdot}71\ P_g - 0{\cdot}66$	186	0·988	—
				Stemflow	$S_f = 0{\cdot}07\ P_g - 0{\cdot}19$	181	0·948	—
Pine 1968 forest	*Pinus radiata*	Whakarewarewa		Interception	$V = 0{\cdot}23\ P_g + 0{\cdot}05$	25	0·893	147·0
				Throughfall	$T_f = 0{\cdot}84\ P_g - 3{\cdot}21$	26	0·984	—
				Stemflow	$S_f = 0{\cdot}17\ P_g - 0{\cdot}52$	25	0·950	—
Pine	*Pinus radiata*	Silverstream	Fahey 1964	Interception (used Whaka 1948 S_f)	$V = 0{\cdot}31\ P_g + 1{\cdot}25$	—	—	—
				Throughfall	$T_f = 0{\cdot}63\ P_g - 1{\cdot}11$	—	—	—

Common name (see Fig. 2)	Dominant Botanical name	Site	Reference	Characteristic	Equation	n	r	F
Five finger scrub	*Neopanax arboreum*	Otutira		Interception	$V = 0{\cdot}14\,P_g + 0{\cdot}66$	36	0·857	75·0
				Throughfall	$T_f = 0{\cdot}47\,P_g + 0{\cdot}09$	35	0·989	—
				Stemflow	$S_f = 0{\cdot}30\,P_g - 0{\cdot}56$	36	0·969	—
Gorse scrub	*Ulex europeaus*	Moutere		Interception	$V = 0{\cdot}33\,P_g + 2{\cdot}57$	19	0·971	18·0
				Throughfall	$T_f = 0{\cdot}59\,P_g - 1{\cdot}88$	50	0·990	—
				Stemflow	$S_f = 0{\cdot}07\,P_g - 0{\cdot}28$	29	0·929	—
Gorse scrub	*Ulex europeaus*	Taita	Aldridge 1968	Interception (used Moutere S_f)	$V = 0{\cdot}64\,P_g + 0{\cdot}95$	39	—	—
				Throughfall	$T_f = 0{\cdot}23\,P_g - 0{\cdot}05$	39	0·970	—
Kamahi scrub	*Weinmannia racemosa*	Taita	Jackson 1973	Interception	$V = 0{\cdot}20\,P_g + 0{\cdot}81$	141	0·900	—
				Throughfall	$T_f = 0{\cdot}48\,P_g + 0{\cdot}07$	141	0·990	—
				Stemflow	$S_f = 0{\cdot}32\,P_g - 0{\cdot}89$	141	0·980	—
Hard beech forest	*Nothofagus truncata*	Taita	Aldridge and Jackson 1973	Interception	$V = 0{\cdot}39\,P_g + 0{\cdot}0$	11	—	—
				Throughfall	$T_f = 0{\cdot}53\,P_g - 0{\cdot}71$	86	—	—
				Stemflow	$S_f = 0{\cdot}18\,P_g - 0{\cdot}33$	73	—	—
Mountain beech forest	*Nothofagus solandri var. cliffortiodes*	Camp Stream	Rowe 1975	Interception	$V = 0{\cdot}29\,P_g + 1{\cdot}90$	88	—	1205·0
				Throughfall	$T_f = 0{\cdot}69\,P_g - 1{\cdot}90$	88	—	—

APPENDIX II

LIST OF SYMBOLS

AAVP	=	Actual air vapour pressure (mmHg).
ALBD	=	Albedo (reflectivity).
AN	=	Actual number of sunshine hours per day.
ASWC	=	Average soil water content (mm).
C	=	Constant depending on soil hydraulic properties.
CSWC	=	Critical soil water content (W.P.)(mm).
D	=	Depth of plant roots (cm).
DM	=	Maximum rooting depth (cm).
E	=	Loss of water due to evaporation (mm/d).
IRR	=	Total irrigation requirement (mm).
j	=	Soil layer number.
K	=	Unsaturated soil hydraulic conductivity.
LAI	=	Leaf area index.
LPOT	=	Leaf water potential.
PN	=	Possible number of sunshine hours.
PSYC	=	Psychrometer constant.
QP	=	Total water flux to plant root.
R	=	Mean root radius (cm).
RA	=	Radiation reaching earth's atmosphere (mmH_2O).
RB	=	Net radiation reflected by earth (mmH_2O).
RD	=	Date to maximum rooting (day).
RI	=	Net radiation absorbed by earth (mmH_2O).

RPOT = Root water potential.

RR = Resistance to flow in the root.

RS = Resistance to flow in the soil.

RV = Rooting density (cm/cm^3).

RX = Xylem resistance.

S = Slope of saturation vapour pressure curve.

SBC = Stefan-Boltzman constant.

SE = Soil layer evaporation.

SPOT = Soil water potential.

SWC = Soil water content (mm).

SWFC = Soil water field capacity (F.C.)(mmH_2O).

T = Time since emergence of plant (days).

TA = Absolute temperature (^oK).

TEMP = Mean daily temperature (^oC).

TRNP = Loss of water due to transpiration (mm/d).

TSI = Time since last irrigation (days).

TTRNP = Total plant transpiration.

U = Constant, critical soil water loss by evaporation (mm).

```
-------------------------------------------------------
A DYNAMIC WATER BALANCE PROGRAMME FOR IRRIGATION
SCHEDULING :
-------------------------------------------------------
      DIMENSION SWC(0:120,3)
      DIMENSION RV(120,3),SE(120,3),TRNP(120,3)
      DIMENSION T(120),LAI(120),TEMP(120),AAVP(120)
      DIMENSION S(120),ASWC(120)
      DIMENSION AN(120),PN(120),RA(120),D(120),E(120),TTRNP(120)
      DATA DM,RD,U,C,CSWC/180.0,90.0,10.2,3.27,320.0/
      DATA SWFC,PSYC,ALBD,SBC/400.0,0.485,0.165,5.67E-08/
      DATA X,TSI,N/0.0,0.0,1/
      REAL K
      REAL LPOT
      REAL IRR
      OPEN(UNIT=10,FILE='METEO.DAT',STATUS='OLD')
      OPEN(UNIT=20,FILE='SWC.FOR',STATUS='NEW')
      OPEN(UNIT=30,FILE='ROOT.DAT',STATUS='OLD')
      OPEN(UNIT=40,FILE='EVAPT.FOR',STATUS='NEW')
      SWC(0,1)=SWFC
      SWC(0,2)=SWFC
      SWC(0,3)=SWFC
10    DO 40 I=1,120
      READ(10,*)T(I),LAI(I),TEMP(I),AAVP(I),S(I),AN(I),PN(I),RA(I)
      RI=RA(I)*(1-ALBD)*(0.16+(0.62*(AN(I)/PN(I))))
      TA=TEMP(I)+273
      Z=(0.10+(0.90*(AN(I)/PN(I))))
      RB=(SBC*0.0344)*(TA**4.0)*(0.56-(0.09*(AAVP(I)**0.5)))*Z
      RN=RI-RB
      D(I)=DM/(1+EXP(6-(12*(T(I)+14)/RD)))
      E(I)=(S(I)/(S(I)+PSYC))*RN*EXP((-0.389*LAI(I))+0.15)
      X=X+E(I)
      IF(X.LT.U) GO TO 15
      TSI=TSI+1
      E(I)=(C*(TSI**0.5))-(C*(TSI-1)**0.5)
15    READ(30,*) (RV(I,J),J=1,3)
20    DO 30 J=1,3
      R=0.015
      K=1.68*EXP(3.58*(SWC(I-1,J)/1000))
      K=K*(1.157E-06)
      Y=ALOG(SQRT(3.14*RV(I,J)))+ALOG(0.015)
      RS=Y/(2*3.14*K*RV(I,J)*(D(I)/3))
      RR=1/(0.93E-08*RV(I,J)*(D(I)/3))
      LPOT=15
      RX=36
      QP=2.3E-06*RV(I,J)*(D(I)/3)
      RPOT=LPOT-(QP*RX)-(J*(D(I)/(3*1000)))
      SPOT=85E-04*((SWC(I-1,J)/1000)**-6)
      TRNP(I,J)=(RPOT-SPOT)/(RS+RR)
      TRNP(I,J)=TRNP(I,J)*8.64E05
      IF(D(I).LE.50.0) GO TO 24
      IF (J.EQ.1) GO TO 26
      IF (J.EQ.2) GO TO 22
      IF (J.EQ.3) GO TO 22
22    SE(I,J)=0.0
      GO TO 28
```

```
24     SE(I,J)=(10*D(I)*E(I))/(3*500)
       GO TO 28
26     SE(I,J)=E(I)
28     CONTINUE
       SWC(I,J)=SWC((I-1),J)-TRNP(I,J)-SE(I,J)
30     CONTINUE
       TTRNP(I)=TRNP(I,1)+TRNP(I,2)+TRNP(I,3)
       ASWC(I)=(SWC(I,1)+SWC(I,2)+SWC(I,3))/3
       WRITE(40,*)I,D(I),E(I),TTRNP(I)
       WRITE(20,*)I,(SWC(I,J),J=1,3),ASWC(I)
       IF(ASWC(I).LT.CSWC) GO TO 50
       GO TO 40
50     W1=(SWFC-SWC(I,1))*(10*D(I)/(3*1000))
       W2=(SWFC-SWC(I,2))*(10*D(I)/(3*1000))
       W3=(SWFC-SWC(I,3))*(10*D(I)/(3*1000))
       IRR=W1+W2+W3
       WRITE(20,*) W1,W2,W3,  IRR
       SWC(I,1)=SWFC
       SWC(I,2)=SWFC
       SWC(I,3)=SWFC
40     CONTINUE
       STOP
       END
```

CALCULATED DATA OF ROOT DEPTH,EVAPORATION
AND TRANSPIRATION:

(I)	D(I)	E(I)	TTRNP(I)
1	3.237518	1.575119	3.0619042E-02
2	3.689822	1.602632	3.6553103E-02
3	4.203813	1.628068	4.3530423E-02
4	4.787459	1.671634	5.1719159E-02
5	5.449624	1.699521	6.1311293E-02
6	6.200136	1.713628	7.2525486E-02
7	7.049829	3.270000	8.5609555E-02
8	8.010604	1.354478	0.1008251
9	9.095428	1.039328	0.1185238
10	10.31835	0.8761940	0.1390436
11	11.69445	0.7719426	0.1627729
12	13.23975	0.6978889	0.1901399
13	14.97108	0.6417751	0.2216104
14	16.90587	0.5973501	0.2576863
15	19.06181	0.5610437	0.2989005
16	21.45653	0.5306473	0.3458110
17	24.10702	0.5047159	0.3989899
18	27.02911	0.4822483	0.4590112
19	30.23669	0.4625406	0.5264325
20	33.74096	0.4450674	0.6017757
21	37.54953	0.4294357	0.6855016
22	41.66554	0.4153442	0.7779834
23	46.08675	0.4025555	0.8794754
24	50.80481	0.3908787	0.9900851
25	55.80458	0.3801661	1.109211
26	61.06386	0.3702850	1.237027
27	66.55316	0.3611374	1.373042
28	72.23621	0.3526373	1.516539
29	78.07060	0.3447094	1.666575
30	84.00887	0.3372936	1.821994
31	90.00000	0.3303375	2.175674
32	95.99112	0.3237934	2.554491
33	101.9294	0.3176231	2.954935
34	107.7638	0.3117962	3.372588
35	113.4468	0.3062763	3.802145
36	118.9361	0.3010387	4.138937
37	124.1954	0.2960606	4.469784
38	129.1952	0.2913246	4.789293
39	133.9132	0.2868061	5.091808
40	138.3345	0.2824917	5.371465
41	142.4505	0.2783699	5.622249
42	146.2590	0.2744198	5.838107
43	149.7633	0.2706337	6.013061
44	152.9709	0.2669983	6.141423
45	155.8930	0.2635098	6.218075
46	158.5435	0.2601528	6.238878
47	160.9382	0.2569218	6.201165
48	163.0941	0.2538052	6.104323

49	165.0289	0.2508011	5.950380
50	166.7603	0.2479038	5.744439
51	168.3056	0.2450981	5.494856
52	169.6816	0.2423935	5.212959
53	170.9046	0.2397728	4.912254
54	171.9894	0.2372322	4.607183
55	172.9502	0.2347755	4.311607
56	173.7999	0.2323914	4.086536
57	174.5504	0.2300797	3.879493
58	175.2125	0.2278347	3.699484
59	175.7962	0.2256546	3.551780
60	176.3102	0.2235355	3.438060
61	176.7625	0.2214737	3.322845
62	177.1602	0.2194710	3.251133
63	177.5098	0.2175179	3.185582
64	177.8169	0.2156200	3.151070
65	178.0865	0.2137680	3.131824
66	178.3231	0.2119656	3.152334
67	178.5307	0.2102051	3.178772
68	178.7128	0.2084885	3.208297
69	178.8725	0.2068157	3.238551
70	179.0125	0.2051792	3.267593
71	179.1351	0.2035828	3.320560
72	179.2427	0.2020245	3.368852
73	179.3368	0.2004948	3.411185
74	179.4193	0.1990089	3.446538
75	179.4916	0.1975479	3.474087
76	179.5549	0.1961231	3.541390
77	179.6104	0.1947269	3.597506
78	179.6589	0.1933594	3.641100
79	179.7014	0.1920223	3.671121
80	179.7386	0.1907139	27.32227
81	179.7712	0.1894283	27.02439
82	179.7997	0.1881676	25.98045
83	179.8247	0.1869335	23.93072
84	179.8466	0.1857224	20.74723
85	179.8657	0.1845379	16.73478
86	179.8825	0.1833763	12.91636
87	179.8971	0.1822300	10.07224
88	179.9100	0.1811104	8.556540
89	179.9212	0.1800060	7.973577
90	179.9310	0.1789284	7.818299
91	179.9396	0.1778641	7.469794
92	179.9472	0.1768246	7.161672

93	179.9538	0.1757965	6.858577
94	179.9595	0.1747894	6.553214
95	179.9646	0.1737976	6.245143
96	179.9690	0.1728249	5.910993
97	179.9729	0.1718712	5.580072
98	179.9762	0.1709251	5.254938
99	179.9792	0.1700001	36.67841
100	179.9818	0.1690884	33.59497
101	179.9841	0.1681919	29.35893
102	179.9861	0.1673069	23.94035
103	179.9878	0.1664391	17.99941
104	179.9893	0.1655846	12.87300
105	179.9907	0.1647377	9.525074
106	179.9918	0.1639137	7.804840
107	179.9929	0.1630898	6.964809
108	179.9937	0.1622887	6.512211
109	179.9945	0.1614952	6.210658
110	179.9952	0.1607132	5.964859
111	179.9958	0.1599426	5.738937
112	179.9963	0.1591797	5.519773
113	179.9968	0.1584320	5.302931
114	179.9972	0.1576920	5.087145
115	179.9975	0.1569672	4.872529
116	179.9978	0.1562500	4.659595
117	179.9981	0.1555367	4.449064
118	179.9984	0.1548386	4.241713
119	179.9986	0.1541519	29.29052
120	179.9987	0.1534691	27.39333

DAILY METEOROLOGICAL INPUT DATA:

T	LAI	TEMP	AAVP	S	AN	PN	RA
1	0.02	20.4	11.60	1.13	1.15	12.0	14.3
2	0.04	20.4	11.59	1.13	1.25	12.0	14.3
3	0.06	20.5	11.58	1.16	1.30	12.0	14.3
4	0.08	20.6	11.58	1.20	1.40	12.0	14.3
5	0.10	20.6	11.57	1.20	1.50	12.0	14.3
6	0.13	20.6	11.57	1.20	1.55	12.0	14.3
7	0.16	20.7	11.56	1.23	1.65	12.0	14.3
8	0.19	20.8	11.56	1.26	1.75	12.0	14.3
9	0.22	20.8	11.55	1.26	1.85	12.0	14.3
10	0.25	20.8	11.55	1.26	1.90	12.0	14.3
11	0.30	20.9	11.54	1.30	2.00	12.0	14.3
12	0.35	20.9	11.54	1.30	2.10	12.0	14.3
13	0.40	20.9	11.53	1.30	2.15	12.0	14.3
14	0.45	21.0	11.53	1.15	2.25	12.0	14.3
15	0.50	21.0	11.53	1.15	2.35	12.0	14.3
16	0.57	21.1	11.54	1.15	2.40	12.0	14.3
17	0.64	21.1	11.56	1.15	2.50	12.0	14.3
18	0.71	21.2	11.57	1.16	2.60	12.0	14.3
19	0.78	21.2	11.59	1.16	2.65	12.0	14.3
20	0.85	21.3	11.60	1.17	2.75	12.0	14.3
21	0.93	21.4	11.62	1.17	2.85	12.0	14.3
22	1.01	21.5	11.63	1.18	2.90	12.0	14.3
23	1.09	21.8	11.65	1.18	3.00	12.0	14.3
24	1.17	21.9	11.66	1.19	3.10	12.0	14.3
25	1.25	22.1	11.68	1.19	3.15	12.0	14.3
26	1.36	22.3	11.69	1.20	3.25	12.0	14.3
27	1.47	22.5	11.71	1.22	3.35	12.0	14.3
28	1.58	22.7	11.72	1.23	3.40	12.0	14.3
29	1.69	22.9	11.74	1.25	3.50	12.0	14.3
30	1.80	23.1	11.75	1.26	3.60	12.0	14.3
31	1.91	23.2	11.70	1.26	3.65	12.0	14.9
32	2.02	23.4	11.65	1.27	4.15	12.0	14.9
33	2.13	23.5	11.60	1.28	4.70	12.0	14.9
34	2.24	23.7	11.55	1.28	5.15	12.0	14.9
35	2.35	23.8	11.51	1.29	5.65	12.0	14.9
36	2.44	24.0	11.46	1.30	6.15	12.0	14.9
37	2.53	24.0	11.42	1.30	6.65	12.0	14.9
38	2.62	24.2	11.38	1.32	7.15	12.0	14.9
39	2.71	24.4	11.38	1.33	7.65	12.0	14.9
40	2.80	24.6	11.37	1.34	8.00	12.0	14.9
41	2.88	24.7	11.35	1.35	8.50	12.0	14.9
42	2.96	24.9	11.34	1.36	8.30	12.0	14.9
43	3.04	25.0	11.32	1.38	8.20	12.0	14.9
44	3.12	25.1	11.31	1.39	8.15	12.0	14.9
45	3.20	25.1	11.30	1.39	8.05	12.0	14.9
46	3.26	25.2	11.30	1.40	7.95	12.0	14.9
47	3.32	25.3	11.29	1.41	7.90	12.0	14.9
48	3.38	25.4	11.28	1.42	7.80	12.0	14.9
49	3.44	25.5	11.27	1.43	7.70	12.0	14.9
50	3.50	25.5	11.27	1.43	7.60	12.0	14.9
51	3.52	25.6	11.26	1.44	7.55	12.0	14.9
52	3.54	25.6	11.25	1.44	7.45	12.0	14.9

53	3.56	25.7	11.24	1.45	7.35	12.0	14.9
54	3.58	25.8	11.24	1.46	7.25	12.0	14.9
55	3.60	25.9	11.23	1.47	7.20	12.0	14.9
56	3.63	26.0	11.22	1.48	7.10	12.0	14.9
57	3.66	26.1	11.21	1.49	7.00	12.0	14.9
58	3.69	26.1	11.20	1.49	6.95	12.0	14.9
59	3.72	26.2	11.20	1.50	6.85	12.0	14.9
60	3.75	26.3	11.19	1.51	6.75	12.0	14.9
61	3.76	26.3	11.75	1.51	6.70	12.0	15.0
62	3.77	26.2	11.68	1.50	6.70	12.0	15.0
63	3.78	26.2	11.94	1.50	6.65	12.0	15.0
64	3.79	26.1	12.22	1.49	6.65	12.0	15.0
65	3.80	26.1	12.46	1.49	6.60	12.0	15.0
66	3.82	26.1	12.77	1.49	6.60	12.0	15.0
67	3.84	26.1	13.03	1.49	6.65	12.0	15.0
68	3.86	26.0	13.05	1.48	6.65	12.0	15.0
69	3.88	26.0	13.07	1.48	6.55	12.0	15.0
70	3.90	26.0	13.08	1.48	6.50	12.0	15.0
71	3.92	25.9	13.11	1.47	6.50	12.0	15.0
72	3.94	25.9	13.12	1.47	6.45	12.0	15.0
73	3.96	25.8	13.14	1.46	6.45	12.0	15.0
74	3.98	25.8	13.16	1.46	6.40	12.0	15.0
75	4.00	25.7	13.21	1.45	6.40	12.0	15.0
76	3.96	25.7	13.23	1.45	6.35	12.0	15.0
77	3.92	25.6	13.50	1.44	6.35	12.0	15.0
78	3.88	25.6	13.27	1.44	6.30	12.0	15.0
79	3.84	25.6	13.29	1.44	6.30	12.0	15.0
80	3.80	25.5	13.31	1.43	6.25	12.0	15.0
81	3.79	25.5	13.34	1.43	6.25	12.0	15.0
82	3.78	25.4	13.36	1.42	6.20	12.0	15.0
83	3.77	25.4	13.39	1.42	6.20	12.0	15.0
84	3.76	25.3	13.41	1.41	6.15	12.0	15.0
85	3.75	25.3	13.43	1.41	6.15	12.0	15.0
86	3.72	25.3	13.44	1.41	6.10	12.0	15.0
87	3.69	25.2	13.47	1.40	6.10	12.0	15.0
88	3.66	25.2	13.49	1.40	6.05	12.0	15.0
89	3.63	25.1	13.52	1.39	6.05	12.0	15.0
90	3.60	25.2	13.54	1.40	6.00	12.0	15.0
91	3.58	25.1	13.64	1.39	6.00	12.0	14.6
92	3.56	25.0	13.72	1.38	5.95	12.0	14.6
93	3.54	24.9	13.83	1.36	5.95	12.0	14.6
94	3.52	24.7	13.93	1.35	5.90	12.0	14.6
95	3.50	24.6	14.02	1.34	5.90	12.0	14.6
96	3.44	24.5	14.13	1.34	5.85	12.0	14.6
97	3.38	24.4	14.20	1.33	5.85	12.0	14.6
98	3.32	24.4	14.30	1.33	5.80	12.0	14.6

99	3.26	24.3	14.40	1.32	5.80	12.0	14.6
100	3.20	24.2	14.43	1.32	5.75	12.0	14.6
101	3.11	24.4	14.60	1.33	5.75	12.0	14.6
102	3.02	24.3	14.70	1.32	5.75	12.0	14.6
103	2.93	24.2	14.79	1.32	5.70	12.0	14.6
104	2.84	24.1	14.90	1.31	5.70	12.0	14.6
105	2.75	24.0	14.99	1.30	5.70	12.0	14.6
106	2.60	23.8	14.95	1.29	5.65	12.0	14.6
107	2.45	23.7	14.88	1.29	5.65	12.0	14.6
108	2.30	23.6	14.82	1.28	5.65	12.0	14.6
109	2.15	23.4	14.76	1.27	5.60	12.0	14.6
110	2.00	23.3	14.71	1.27	5.60	12.0	14.6
111	1.80	23.2	14.69	1.26	5.55	12.0	14.6
112	1.60	23.0	14.58	1.25	5.55	12.0	14.6
113	1.40	22.8	14.55	1.24	5.50	12.0	14.6
114	1.20	22.7	14.50	1.23	5.50	12.0	14.6
115	1.00	22.6	14.44	1.22	5.45	12.0	14.6
116	0.80	22.5	14.39	1.22	5.45	12.0	14.6
117	0.60	22.2	14.32	1.20	5.40	12.0	14.6
118	0.40	22.4	14.29	1.21	5.40	12.0	14.6
119	0.20	22.3	14.20	1.21	5.35	12.0	14.6
120	0.00	22.1	14.17	1.19	5.35	12.0	14.6

ROOTING DENSITY(CM/CM3) FOR THREE LAYERS:

RV(1)	RV(2)	RV(3)
0.21	0.042	0.021
0.22	0.044	0.022
0.23	0.046	0.023
0.24	0.048	0.024
0.25	0.050	0.025
0.26	0.052	0.026
0.27	0.054	0.027
0.28	0.056	0.028
0.29	0.058	0.029
0.30	0.060	0.030
0.31	0.062	0.031
0.32	0.064	0.032
0.33	0.066	0.033
0.34	0.068	0.034
0.35	0.070	0.035
0.36	0.072	0.036
0.37	0.074	0.037
0.38	0.076	0.038
0.39	0.078	0.039
0.40	0.080	0.040
0.41	0.082	0.041
0.42	0.084	0.042
0.43	0.086	0.043
0.44	0.088	0.044
0.45	0.090	0.045
0.46	0.092	0.046
0.47	0.094	0.047
0.48	0.096	0.048
0.49	0.098	0.049
0.50	0.100	0.050
0.56	0.112	0.056
0.62	0.124	0.062
0.68	0.136	0.068
0.74	0.148	0.074
0.80	0.160	0.080
0.84	0.168	0.084
0.88	0.176	0.088
0.92	0.184	0.092
0.96	0.192	0.096
1.00	0.200	0.100
1.04	0.208	0.104
1.08	0.216	0.108
1.12	0.224	0.112
1.16	0.232	0.116
1.20	0.240	0.120
1.24	0.248	0.124
1.28	0.256	0.128
1.32	0.264	0.132
1.36	0.272	0.136
1.40	0.280	0.140
1.44	0.288	0.144
1.48	0.296	0.148
1.52	0.304	0.152
1.56	0.312	0.156
1.60	0.320	0.160
1.66	0.332	0.166
1.72	0.344	0.172

1.78	0.356	0.178
1.84	0.368	0.184
1.90	0.380	0.190
1.94	0.388	0.194
1.98	0.398	0.198
2.02	0.404	0.202
2.06	0.412	0.206
2.10	0.420	0.210
2.16	0.432	0.216
2.22	0.444	0.222
2.28	0.456	0.228
2.34	0.468	0.234
2.40	0.480	0.240
2.48	0.496	0.248
2.56	0.512	0.256
2.64	0.528	0.264
2.72	0.544	0.272
2.80	0.560	0.280
2.92	0.584	0.292
3.04	0.608	0.304
3.16	0.632	0.316
3.28	0.656	0.328
3.40	0.680	0.340
3.54	0.708	0.354
3.68	0.736	0.368
3.82	0.764	0.382
3.96	0.792	0.396
4.10	0.820	0.410
4.28	0.856	0.428
4.46	0.892	0.446
4.64	0.928	0.464
4.82	0.964	0.482
5.00	1.000	0.500
4.96	0.992	0.496
4.92	0.984	0.492
4.88	0.976	0.488
4.84	0.968	0.484
4.80	0.960	0.480
4.74	0.948	0.474
4.68	0.936	0.468
4.62	0.924	0.462
4.56	0.912	0.456
4.50	0.900	0.450
4.44	0.888	0.444
4.38	0.876	0.438
4.32	0.864	0.432
4.26	0.852	0.426
4.20	0.840	0.420
4.16	0.832	0.416
4.12	0.824	0.412
4.08	0.816	0.408
4.04	0.808	0.404
4.00	0.800	0.400
3.96	0.792	0.396
3.92	0.784	0.392
3.88	0.776	0.388
3.84	0.768	0.384
3.80	0.760	0.380
3.76	0.752	0.376
3.72	0.744	0.372
3.68	0.736	0.368
3.64	0.728	0.364
3.60	0.720	0.360

CUMMULATIVE EVAPORATION (CUMEVAP) DATA:

1.575119 3.177751 4.805819 6.477458 8.176974 9.890602 13.160602
14.51508 15.55440 16.43060 17.20250 17.90040 18.54220 19.139560
19.7006 20.2312 20.7360 21.21821 21.6808 22.1258 22.55520 22.5553
22.97060 23.37315 23.76403 24.144195 24.51448 24.51448 24.875617
25.228254 25.572963 25.910256 26.240593 26.5642386 26.882009
27.193805 27.500081 27.801119 28.097179 28.388503 28.675309
28.957800 29.236169 29.510588 29.781221 30.048219 30.311728
30.57188 30.828801 31.082606 31.333407 31.58131 31.826408 32.068801
32.308573 32.545805 32.78058 33.012971 33.24305 33.470884 33.696538
33.920073 34.141546 34.361077 34.578594 34.794214 35.007982 35.2199
35.430152 35.63864 35.845455 36.050634 36.254216 36.45624 36.656734
36.855742 37.053289 37.249412 37.444138 37.637497 37.829519
38.020232 38.209660 38.397827 38.58476 38.770482 38.955019 39.13839
39.320625 39.501735 39.681741 39.860669 40.038533 40.215357
40.391153 40.565942 40.739739 40.912563 41.084434 41.255359
41.425359 41.59447 41.762638 41.929944 42.096383 42.261964
42.426701 42.590638 42.753727 42.916015 43.07751 43.238223
43.398165 43.557344 43.715776 43.873468 44.030435 44.186685
44.342221 44.497059 44.65121 44.804679

DAILY AVERAGE SOIL WATER CONTENT [ASWC(I)] DATA:

399.9558	399.9042	399.8441	399.7735	399.6913	399.5963	399.4141
399.3081	399.2056	399.0990	398.9845	398.8596	398.7217	398.5685
398.3976	398.2064	397.9923	397.7523	397.4836	397.1830	396.8469
396.4723	396.0554	395.5951	395.0986	394.5629	393.9848	393.3617
392.6913	391.9716	391.1362	390.1768	389.0860	387.8578	386.4884
385.0083	383.4198	381.7262	379.9333	378.0487	376.0818	374.0443
371.9497	369.8136	367.6531	365.4867	363.3340	361.2146	359.1476
357.1501	355.2368	353.4184	351.7010	350.0862	348.5708	347.1311
345.7613	344.4521	343.1930	341.9724	340.7910	339.6342	338.4998
337.3776	336.2624	335.1409	334.0113	332.8723	331.7239	330.5663
329.3916	328.2013	326.9974	325.7822	324.5583	323.3125	322.0484
320.7702	319.4825	390.8290	381.7577	373.0348	364.9956	358.0180
352.3782	348.0116	344.5935	341.6809	338.9630	336.2973	333.7481
331.3019	328.9571	326.7145	324.5749	322.5469	320.6296	318.8210
387.7172	376.4625	366.6201	358.5843	352.5290	348.1828	344.9529
342.2966	339.9206	337.6958	335.5717	333.5299	331.5636	329.6796
327.8502	326.1019	324.4254	322.8201	321.2852	319.8197	390.1852
381.0028						

DAILY TRANSPIRATION RATE (MM):

0.0362	0.0655	0.0435	0.0517	0.0613	0.0725	0.0856	0.1008	0.1185
0.1390	0.1628	0.1901	0.2216	0.2577	0.2989	0.3458	0.3989	0.4590
0.5264	0.6018	0.6855	0.7779	0.8795	0.9900	1.1092	1.2370	1.3730
1.5165	1.6666	1.8220	2.1756	2.5545	2.9550	3.3725	3.8021	4.1389
4.4697	4.7893	5.0918	5.3714	5.6222	5.8381	6.0130	6.1414	6.2180
6.2389	6.2011	6.1043	5.9504	5.7444	5.4948	5.2129	4.9122	4.6071
4.3116	4.0865	3.8795	3.6995	3.5517	3.4380	3.3228	3.2511	3.1856
3.1510	3.1318	3.1523	3.1787	3.2082	3.2386	3.2676	3.3206	3.3688
3.4111	3.4465	3.4740	3.5414	3.5975	3.6411	3.6711	27.322	27.024
25.980	23.930	20.747	16.735	12.916	10.072	8.5565	7.9736	7.8183
7.4698	7.1616	6.8585	6.5532	6.2451	5.9110	5.5800	5.2550	36.678
33.595	29.359	23.940	17.999	12.873	9.5250	7.8048	6.9648	6.5122
6.2107	5.9648	5.7390	5.5197	5.3030	5.0871	4.8725	4.6600	4.4500
4.2417	29.290	27.393						

```
C       POTENTIAL EVAPOTRANSPIRATION :
C
        DIMENSION T(120),LAI(120),TEMP(120),AAVP(120)
        DIMENSION AN(120),PN(120),RA(120),SAVP(120),S(120)
        DIMENSION RI(120),RB(120),RN(120),EA(120),PE(120)
        OPEN (UNIT=10,FILE='METEO.DAT',STATUS='OLD')
        OPEN (UNIT=70,FILE='SAVP.DAT',STATUS='OLD')
        OPEN(UNIT=80,FILE='PENM.DAT',STATUS='NEW')
10      DO 40 I=1,120
        READ (70,*)SAVP(I)
        READ(10,*)T(I),LAI(I),TEMP(I),AAVP(I),S(I),AN(I),PN(I),RA(I)
        RI(I)=RA(I)*0.75*(0.16+(0.62*(AN(I)/PN(I))))
        TA=TEMP(I)+273
        Z=(0.1+(0.9*(AN(I)/PN(I))))
        RB(I)=1.95E-09*(TA**4)*(0.56-(0.09*(AAVP(I)**0.5)))*Z
        RN(I)=RI(I)-RB(I)
        IF(I.LE.30)GOTO 15
        IF(I.LE.60)GOTO 16
        IF(I.LE.90)GOTO 17
        IF(I.LE.120)GOTO 18
15      U=45.6
        GO TO 30
16      U=76.8
        GO TO 30
17      U=76.8
        GO TO 30
18      U=72.0
30      EA(I)=0.35*(1+(U/100))*(SAVP(I)-AAVP(I))
        PE(I)=((S(I)/0.485)*RN(I)+EA(I))/((S(I)/0.485)+1)
        WRITE(80,*)T(I),SAVP(I),EA(I),RI(I),RB(I),RN(I),PE(I)
40      CONTINUE
        STOP
        END
[EOB]
```

CALCULATED DAILY POTENTIAL EVAPOTRANSPIRATION:

2.144	2.165	2.183	2.209	2.230	2.240	2.268	2.296	2.317	2.327
2.353	2.373	2.384	2.460	2.480	2.504	2.522	2.553	2.560	2.593
2.625	2.648	2.714	2.745	2.786	2.838	2.878	2.919	2.960	3.009
3.446	3.593	3.730	3.870	3.994	4.122	4.230	4.382	4.522	4.631
4.748	4.743	4.734	4.740	4.719	4.711	4.720	4.714	4.707	4.686
4.691	4.671	4.665	4.660	4.661	4.667	4.660	4.650	4.641	4.633
4.620	4.611	4.586	4.555	4.529	4.503	4.504	4.489	4.464	4.452
4.422	4.410	4.394	4.381	4.361	4.343	4.311	4.317	4.316	4.286
4.284	4.255	4.253	4.222	4.220	4.208	4.185	4.171	4.154	4.156
3.984	3.717	3.925	3.867	3.345	3.804	3.780	3.759	3.731	3.697
3.721	3.692	3.652	3.525	3.582	3.551	3.538	3.526	3.482	3.467
3.438	3.409	3.362	3.351	3.329	3.311	3.249	3.292	3.271	3.236