Improved Method of Estimating Crop Consumptive Use and Distribution of Soil Water in Irrigated Soil Profiles

by

Sameir Al-Khafaf
Graduate Research Assistant

Peter J. Wierenga
Professor of Soil Physics

Boyce C. Williams
Professor of Soil Science

Completion Report
Project 3109-208
January, 1979

New Mexico Water Resources Research Institute
in cooperation with
Department of Agronomy
New Mexico State University
Las Cruces, New Mexico 88001

The work upon which this publication is based was supported in part by funds provided through the New Mexico Water Resources Research Institute by the State of New Mexico through state appropriations and by the United States Department of Interior, Office of Water Research and Technology, as authorized under the Water Research and Development Act of 1978.

The purpose of WRRI technical reports is to provide a timely outlet for research results obtained on projects supported in whole or in part by the Institute. Through these reports we are promoting the free exchange of information and ideas and hope to stimulate thoughtful discussion and action which may lead to resolution of water problems. The WRRI, through peer review of draft reports, attempts to substantiate the accuracy of information contained in its reports but the views expressed are those of the author(s) and do not necessarily reflect those of the WRRI or its reviewers.

ABSTRACT

Field-embedded lysimeter tests were conducted to determine soil and plant evaporation from a trickle-irrigated cotton field located in the lower Rio Grande basin of New Mexico. Soil evaporation was determined gravemetrically (1-10 cm) and with embedded containers. Evapotranspiration was determined from changes in soil water content, from the depths of applied irrigation water, and the volume of drainage water. The transpiration and soil evaporation were correlated with leaf area index, soil water, and potential evaporation estimated by Penman equations. Empirical equations describing the effect of these parameters on transpiration and soil evaporation agreed very well with the results of Ritchie, obtained under dryland farming of central Texas. It was also found that transpiration did not decrease below potential level until about 60% of the available soil water was depleted.

A method was developed to determine the distribution of cotton roots with depth and time in field soils. The method consisted of soaking soil and roots removed from the field in a solution containing 40 g/l sodium hexametaphosphate in a 1:5 soil solution ratio. The density of the resulting soil suspension is increased to 1.5 g/cm^3 by added dry 78% pure $CaCl_2$ in a ratio of 1 g $CaCl_2$ to 2 g soil suspension. Roots float to the surface and are skimmed from the surface with a fine wire strainer. By subsequent washing in tap water, roots and organic debris may be further separated. The method was used to determine the distribution of fine roots (mean diameter 0.25 mm) and total root mass for field-grown cotton at various times and depths. The method was found to be inexpensive and efficient.

A computer simulation model was developed to compute changes in water content with depth and time in a layered soil. The model uses the hydraulic properties of the soil, climatological data, and root distribution as determined in the field. Computed water contents compared well with water contents measured in the embedded lysimeters planted with cotton and irrigated over a 70-day period. The model was further tested by varying the hydraulic conductivity versus water content relationship and the root distribution with depth. These changes appeared to have less effect on predicted water-contents in comparison with observed water distributions than did modifying evapotranspiration rates. It appears that water uptake by cotton roots at any particular point in the soil profile was found to be a function of the root mass at that point and the depth below the soil surface. The results of this study show that water-content profiles in a given soil with an actively growing crop are to a large extent determined by the external evaporation demand rather than by the hydraulic properties of the soil.

TABLE OF CONTENTS

Page

LIST OF TABLES viii

LIST OF FIGURES xii

LIST OF SYMBOLS USED xvi

CHAPTER

1 INTRODUCTION 1

2 LITERATURE REVIEW 3

2.1 Estimation of evapotranspiration from climatological data when soil water is not limiting . . . 3

Aerodynamic methods 3

Energy balance methods 3

Combination methods 5

Empirical methods 6

Pan evaporation methods 9

Crop coefficient 9

2.2 Transpiration and soil evaporation when soil water is non-limiting and when it is limiting 10

Transpiration when soil water is non-limiting 10

Transpiration when soil water is limiting . 12

2.3 Model for computing infiltration and redistribution of water in soil with water uptake by roots . . 17

General flow equation 17

Water uptake by roots 19

(1) Microscopic approach 20

(2) Macroscopic approach 21

Page

3 THEORETICAL 24

3.1 Equations and Boundary and Initial Conditions . 24

3.2 Computer Model 26

3.3 Simplified Computer Model 40

4 METHODS AND MATERIALS 48

4.1 Location 48

4.2 Lysimeters 48

4.3 Soil Measurements 52

Soil water content 52

Pressure potential-water content relationship 55

Hydraulic conductivity-water content relationship 55

4.4 Climatic Measurements 56

4.5 Plant Measurements 57

Leaf area 57

Plant pressure potential 57

Plant dry weight 58

Estimation of root mass 58

4.6 Field Test 61

4.7 Treatments 61

5 RESULTS AND DISCUSSION 62

5.1 Cotton Growth and Development 62

Leaf area and leaf dry weight 62

Root growth 67

Page

5.2 Potential Evaporation 79

5.3 Evapotranspiration 84

Evapotranspiration data from lysimeters . . 84

Soil evaporation. 85

Transpiration 93

Effect of soil water on transpiration . . . 94

Actual ET versus potential evaporation . . . 96

5.4 Simulation 103

5.3 Sensitivity of the model 130

Hydraulic conductivity 130

Root mass distribution 133

Potential evaporation 133

6 SUMMARY AND CONCLUSIONS 139

BIBLIOGRAPHY 143

APPENDIX A Root-mass distributions as a function of time and depth for different treatments 151

APPENDIX B Climatic parameters and potential evaporation data for 1975 and 1976 158

APPENDIX C Evapotranspiration data of different treatments for 1975 and 1976 192

LIST OF TABLES

TABLE		PAGE
1	CSMP program for simulation of root water uptake, infiltration and drainage in layered soil.	29
2	CSMP program for simulation of root water uptake, infiltration and drainage in layered soil using simplified model.	43
3	Texture and some chemical properties of the soil profile of the Glendale clay loam from the lysimeters . .	51
4	Leaf-, stem-, and total dry weights, and leaf area index (LAI) for cotton (wet and dry treatments), 1975.	65
5	Leaf-, stem-, and total dry weights, and leaf area index (LAI) for cotton (wet and dry treatments), 1976.	66
6	Dry weight distribution of fine and suberized roots as a function of time and depth, dry weight of leaf and stem, and root/shoot ratio. Samples taken from the embedded containers 1976.	70
7	Mean and standard deviation of fine and suberized roots. Samples were taken August 23, 1976, from the last container.	71
8	Dry weight of different parts of the cotton plant. Field samples (1976)	75
9	The rate of potential evaporation (Eo) calculated using different equations compared to the rate of Eo calculated by the Penman equation.	83
10	Soil water content, pressure potential, hydraulic conductivity and diffusivity of the Glendale clay loam in the lysimeters.	109
11	Soil water content, pressure potential, hydraulic conductivity, and diffusivity of the sandy loam 60-150 cm in the lysimeters	111
12	Evapotranspiration (ET), total water in profile and drainage predicted by simulation and simplified models.	129

TABLE PAGE

13 Effect of change in hydraulic conductivity on computed values of evapotranspiration, total water in profile and drainage (71 days). Simulation model. . . 129

14 Effect of different types of root mass distribution on soil evaporation, transpiration, total water in profile and drainage (71 days). Simulation model. . . 135

15 Effect of change in potential evaporation on soil evaporation, transpiration, total water in profile and drainage (71 days). Simulation model. 135

Appendix A

16 Dry weights of fine and suberized roots in two-dimensional distribution. Field plot sample, wet, trickle-irrigated, single row. August 16, 1976. . . . 151

17 Dry weights of fine and suberized roots in two-dimensional distribution. Field plot sample, wet, trickle-irrigated, single row. August 10, 1976. . . . 152

18 Dry weights of fine and suberized roots in two-dimensional distribution. Field plot sample, wet, trickle-irrigated, double row. August 17, 1976. . . . 153

19 Dry weights of fine and suberized roots in two-dimensional distribution. Field plot sample, wet, trickle-irrigated, double row. August 20, 1976. . . . 154

20 Dry weight of fine and suberized roots in two-dimensional distribution. Field plot sample, wet, furrow-irrigated, single row. August 18, 1976. . . . 155

21 Dry weights of the fine and suberized roots in two-dimensional distribution. Field plot sample, wet, furrow-irrigated, single row. August 13, 1976. . . . 156

22 Dry weights of fine and suberized roots in two-dimensional distribution. Field plot sample, dry, trickle-irrigated, single row. August 3, 1976. . . . 157

Appendix B

23 CSMP program to calculate potential evaporation using different equations for 1975. 166

TABLE PAGE

24 CSMP program to calculate potential evaporation using different equations for 1976 175

25 Cumulative potential evaporation calculated using different equations for south central New Mexico in 1975 184

26 Cumulative potential evaporation calculated using different equations for south central New Mexico in 1976 188

Appendix C

27 Potential evaporation (Eo), irrigation or rain (q), evapotranspiration (ET), soil evaporation (Es), and leaf area index (LAI) of each irrigation interval for different treatments 192

28 Soil water in 100 cm of soil (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for wet treatment lysimeter 1, 1976 . 193

29 Soil water in 100 cm of soil (SW), irrigation or rain (a), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for wet treatment lysimeter 2, 1976 . 194

30 Soil water in 100 cm of soil (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for wet treatment lysimeter 3, 1976 . 195

31 Soil water in 100 cm of soil (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for wet treatment lysimeter 4, 1976 . 196

32 Soil water in 100 cm of soil (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for dry treatment lysimeter 6, 1976 . 197

33 Soil water in 100 cm of soil (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for dry treatment lysimeter 7, 1976 . 198

TABLE PAGE

34 Soil water in 100 cm of soil (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for dry treatment lysimeter 8, 1976. . . 199

35 Soil water in 100 cm of soil (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for dry treatment lysimeter 9, 1976 200

LIST OF FIGURES

FIGURE		PAGE
1	Relative soil evaporation and transpiration versus leaf area index (adapted from Ritchie, 1972).	13
2	Models proposed to describe the relation between the ratio of transpiration (Ep) to potential transpiration (Epo) and soil water content. a. Veihmeyer and Hendrickson (1955); b. Penman (1949); c. Thornwaite and Mathers (1955); d. Havens (1956); e. Pierce (1958); and f. Bahrani and Taylor (1961). (Adapted from Tanner, 1967).	15
3	Ratio of evapotranspiration (ET) to potential evaporation (Eo) versus soil water content as influenced by the evaporative demands (Shaw, 1963).	16
4	Schematic diagram of the flow of water through soil-plant-atmosphere system, simulation model.	28
5	Schematic diagram of the flow of water through soil-plant-atmosphere system, simplified model.	42
6	Experimental plot at New Mexico State University Plant Science Research Center.	49
7	Schematic diagram of the lysimeter installation . . .	50
8	The calibration curve presented by solid line was used in the present investigation.	54
9	The relationship between leaf area index, leaf dry weight and time after emergence for cotton, 1976. . .	63
10	The relationship between leaf area index and leaf dry weight for cotton in 1975 and 1976	65
11	Root distribution as a function of time and depth for cotton grown in the embedded containers.	68
12	The relationship between dry weight of the fine root and leaf area index for cotton grown in the embedded containers in 1976.	69
13	Root mass distribution of cotton grown in the field outside the containers and irrigated by trickle irrigation in 1976.	73

FIGURE PAGE

14 Water content distribution of the field irrigated using trickle irrigation system. 74

15 Root mass distribution of single and double row cotton, irrigated by trickle irrigation 77

16 Root mass distribution of cotton irrigated by trickle and furrow irrigation. 78

17 Cumulative potential evaporation calculated by different methods for the period of April through September 1975. 81

18 Cumulative potential evaporation calculated by different methods for the period of April through September 1976. 82

19 Average cumulative evapotranspiration and soil evaporation as measured with lysimeter in the wet treatment during 1975 and 1976. 86

20 Average cumulative evapotranspiration and soil evaporation as measured with lysimeters in the dry treatment during 1975 and 1976. 87

21 Changes in total amount of water held in two bare lysimeters, as measured with a neutron probe during the growing season of 1976 88

22 The relationship between soil evaporation (Es) and time after irrigation. 89

23 The relationship between the ratio of soil evaporation during one day after irrigation (Eso) to potential evaporation (Eo) and leaf area index (LAI). . . . 92

24 The relationship between the ratio of transpiration during one day after irrigation (Epo) to potential evaporation (Eo) and leaf area index 95

25 The relationship between the ratio of transpiration (Ep) to potential transpiration (Epo) and fraction of available water remaining in a lysimeter 97

26 The ratio of actual transpiration (ET) over computed potential evaporation (Eo) as a fraction of time after emergence. 99

FIGURE PAGE

27 Comparison between measured and computed evapotranspiration and soil evaporation for wet treatment in 1976 101

28 Comparison between measured and computed evapotranspiration and soil evaporation for dry treatment in 1976 102

29 Comparison between measured evapotranspiration (ET) and soil evaporation (Es) reported by Ritchie (1972) and computed ET and Es for Ritchie's condition using the empirical relationship developed in this study . . 104

30 The relationship between the pressure potential and water content of Glendale clay loam. 105

31 The relationship between the pressure potential and water content of sandy loam used with lysimeter (60-150 cm 106

32 The relationships between hydraulic conductivity and water content for soils used in this study 108

33 The relationship between root distribution coefficient (RDC = $\frac{RETA/Ep}{RDF}$) versus root depth. RETA is Wierenga root water uptake, Ep is transpiration and RDF is fraction of the root mass 114

34a Comparison between measured and simulated water content profiles for the wet treatment lysimeter 1 in 1976 115

34b Comparison between measured and simulated water content profiles for the wet treatment lysimeter 2 in 1976 116

35a Comparison between measured and simulated water content profiles for the dry treatment lysimeter 6 in 1976 117

35b Comparison between measured and simulated water content profiles for the dry treatment lysimeter 9 in 1976 118

36 Variation in measured water content profile of four lysimeters for the wet treatment in 1976 120

FIGURE PAGE

37 Variation in measured water content-profile of four lysimeters for dry treatment in 1976 122

38 Comparison between measured and simulated water-content values at 30 and 90 cm during the months of July and August for wet treatment 1976. 125

39 Comparison between measured and simulated water-content values at 30 and 90 cm during the months of July and August for dry treatment 1976. 126

40 Comparison between measured and calculated total amount of water in 100 cm of soils for wet treatment in 1976. 127

41 Comparison between the calculated water-content profiles using the simulation model and the simplified model. 128

42 Water-content distribution computed with three different hydraulic conductivity versus water content relationships 131

43 Schematic root distributions used in the simulation model. 134

44 Water-content distribution computed with three different values of potential evaporation. 137

LIST OF SYMBOLS USED

Symbol	Explanation	Units
A	Heat flux to the air	cal cm^{-2} day^{-1}
Bv	Turbulent transfer coefficient	g cm^{-2} day^{-1} mb^{-1}
CR	Count ratio of the neutron probe	- - - -
Cp	Specific heat of the air at constant pressure	cal g^{-1} $^{o}C^{-1}$
D	Soil water diffusivity	cm^2 day^{-1}
Dr	Drainage water	cm day^{-1}
E	Water vapor flux	cal cm^{-2} day^{-1}
ET	Evapotranspiration	cm day^{-1}
Eo	Potential evaporation	cm day^{-1}
Ep	Transpiration	cm day^{-1}
Es	Soil evaporation	cm day^{-1}
Epo	Potential transpiration	cm day^{-1}
Eso	Potential soil evaporation	cm day^{-1}
E_{pan}	Evaporation from the pan	cm day^{-1}
FAW	Fraction of available soil water	cm^3 cm^{-3}
G	Soil heat flux	cal cm^{-2} day^{-1}
H	Hydraulic potential	cm
H_{root}	Effective root pressure potential	cm
K_c	Crop coefficient	- - - -
K(θ)	Hydraulic conductivity	cm day^{-1}
K_A	Eddy transfer coefficient for heat	cm^2 day^{-1}

Symbol	Explanation	Units
a	Coefficient for soil evaporation depends on soil properties	- - -
a_1	Root radius	cm
b	Coefficient for soil evaporation depends on soil properties	- - -
e	Actual vapor pressure	mb
e_s	Saturation vapor pressure	mb
q	Rain or irrigation	cm
q_a	Specific humidity	- - -
r	Radial distance	cm
s	Osmotic potential	cm
t	Time	day
z	Depth below soil surface	cm
z_1	Depth of the root zone	cm
π	Pi	
τ	Momentum flux	cal cm^{-2} day^{-1}
ρ	Air density	g cm^{-3}
Δ	Slope of saturation vapor pressure versus temperature at the air temperature	mb $^{\circ}\mathrm{C}^{-1}$
γ	Psychrometric constant	mb $^{\circ}\mathrm{C}^{-1}$
γ_1	Euler's constant	0.57722
α	Proportionality constant	$1.35 \pm .10$

Symbol	Explanation	Units
K_M	Eddy transfer coefficient for momentum	$cm^2\ day^{-1}$
K_V	Eddy transfer coefficient for water vapor	$cm^2\ day^{-1}$
K_p	Pan coefficient	- - -
L	Latent heat of vaporization	$cal\ cm^{-3}$
LAI	Leaf area index	- - -
LDW	Leaf dry weight	$kg\ m^{-2}$
P	Atmospheric pressure	mb
RC	Root coefficient	0.05
RH	Relative humidity	- - -
Rn	Net radiation	$cal\ cm^{-2}\ day^{-1}$
Rs	Solar radiation	$cal\ cm^{-2}\ day^{-1}$
RCC	Root mass distribution	$g\ g^{-1}$
RDC	Root distribution coefficient	- - -
RDF	Root fraction coefficient	$g\ g^{-1}$
RET	Root extraction term	$1\ day^{-1}$
RETA	Wierenga root extraction term	$1\ day^{-1}$
RRES	Root resistance	- - -
T	Average temperature	^oC
U_2	Wind speed	$km\ day^{-1}$
Z	Elevation above the soil surface at which weather parameters are measured	cm
Z_o	Roughness length	cm

Symbol	Explanation	Units
α_1	Coefficient depends on hydraulic properties of the soil - soil evaporation	- - -
α_2	Coefficient depends on hydraulic properties of the soil - hydraulic conductivity	- - -
κ	Von Karmen coefficient	0.41
ψ	Pressure potential	cm of H_2O
ψ_r	Root pressure potential	cm
β	Coefficient depends on hydraulic properties of the soil - hydraulic conductivity	- - -
ε	Ratio of molecular weight of water to air	0.622
θ	Volumetric water content	cm cm^{-3}
θ_r	Residual water content	cm cm^{-3}
θ_s	Saturation water content	cm cm^{-3}

1. INTRODUCTION

Evapotranspiration data from agricultural crops have become increasingly important in planning and managing irrigation, and in water resources allocation. During the past 30 years, a number of procedures have been developed to estimate water use by well-watered crops from climatological data. Most of these procedures do not take into account the soil water status and the nature and condition of the crops. Other investigators, however, consider the soil to be the major factor controlling water use by crops.

In recent investigations, evapotranspiration is considered to be a dynamic process in which the soil, the plant, and the atmosphere form a single system for water movement. Thus, evapotranspiration is the result of the interactions of these components and cannot be characterized by any single component.

If the effects of plant cover and soil water on transpiration and soil evaporation are known, then transpiration and soil evaporation can be estimated with reasonable accuracy from climatological data.

The objectives of this study were:

1) To develop empirical relationships for estimating transpiration and soil evaporation as influenced by leaf area index, soil water, and evaporation demand under limiting and non-limiting soil water regimes.

2) To test these empirical relationships for the conditions of southern New Mexico.

3) To develop and test a model for computing water content as a function of depth and time in layered soils including plant water uptake and soil surface evaporation.

2. LITERATURE REVIEW

The literature review consists of three parts:

2.1 Estimation of evapotranspiration from climatological data when soil water is not limiting.

2.2 Transpiration and soil evaporation when soil water is non-limiting, and when it is limiting.

2.3 Models for computing infiltration, redistribution, and water uptake by roots in soil.

2.1 Estimation of Evapotranspiration from Climatological Data when Soil Water Is not Limiting

The methods for measuring evapotranspiration and evaporation from a free water surface using climatological data are generally classified as follows: (1) aerodynamic or mass transfer, (2) energy balance, (3) combination, (4) empirical, and (5) pan evaporation.

Aerodynamic methods. This technique measures actual evapotranspiration and is used less often than other methods. It is based on the assumption of similarity of the transport mechanisms of momentum (τ), heat (A), and water vapor (E) (Rosenberg, Hart and Brown, 1968). This assumption is questionable. The instrumentation is partially developed and very expensive.

The three flux equations are

$$\tau = \rho K_M \frac{\delta \overline{U}_2}{\delta Z} \qquad (1)$$

$$A = -\rho C_p K_A \frac{\delta T}{\delta Z} \qquad (2)$$

$$E = -\rho K_V \frac{\delta q_a}{\delta Z} \qquad (3)$$

where U_2 is wind speed, T is temperature, and q_a is specific humidity. The bar indicates average value. Z is the height at which the measurements are made. The assumption that the momentum, heat, and vapor transfer coefficients, e.g., K_M, K_H, and K_V, respectively, are equal will hold only under conditions of neutral stability at sunrise and sunset (Rosenberg, Hart and Brown, 1968).

Energy balance methods. The basic equation is

$$Rn = LET + G + A \qquad (4)$$

where

Rn is net radiation (cal/cm^2/day)

L is latent heat of vaporization of water (cal/cm^3) or (cal/g)

ET is evapotranspiration (cm/day)

G is soil heat flux (cal/cm^2/day)

A is sensible heat flux to the air (cal/cm^2/day).

Rn and ET are easily measured with currently available instruments, but A is not easily measured. The energy balance techniques for measuring evaporation generally yield satisfactory results in humid regions (Rosenberg, Hart and Brown, 1968).

Aerodynamic and energy balance techniques measure actual evapotranspiration. The original equations have undergone many refinements. For more detail see Rosenberg, Hart, and Brown (1968) and Jensen (1973).

Combination methods. The aerodynamic and energy balance methods are combined to produce an equation to calculate potential evaporation. These methods utilize climatological measurements taken at only a single height. Penman (1948) presented an equation to measure potential evaporation. In Penman (1963), the equation was slightly modified and presented as

$$E_o = \frac{\Delta Rn + \gamma Ea}{\Delta + \gamma} \tag{5}$$

$$Ea = 15.36\ (1.0 + 0.0062U_2)(e_s - e) \tag{6}$$

where

E_o is potential evaporation (cm/day)

Ea is an aerodynamic component

Δ is slope of the saturation vapor pressure vs. temperature curve at the air temperature (mb $^{o}C^{-1}$)

Rn is net radiation, expressed (ly day^{-1}) or (cal cm^{-2} day^{-1}); ly = cal cm^{-2}.

To convert Rn from cal cm^{-2} day^{-1} to cm day^{-1}, Rn is divided by L.

L is latent heat of vaporization (cal g^{-1})

U_2 is wind speed (km/day) at a height of 2 m

e_s is saturation vapor pressure (mb)

e is actual vapor pressure (mb)

γ is a psychrometric constant (mb $^{o}C^{-1}$)

$$\gamma = \frac{C_p P}{0.622L} \tag{7}$$

where

C_p is specific heat of air (cal g^{-1} $^{o}C^{-1}$)

P is atmospheric pressure (mb).

Another combination equation widely used is Van Bavel's equation (1966). This equation is based on the earlier work of Penman:

$$E_o = \frac{[\Delta/\gamma]Rn + LBv(e_s - e)}{\Delta/\gamma + 1} \qquad (8)$$

$$Bv = \frac{\rho\varepsilon\kappa^2}{P} \cdot \frac{U_2}{[\ln(Z/Zo)]^2} \qquad (9)$$

where

Bv is turbulent transfer coefficient (g cm^{-2} day^{-1} mb^{-1})

ρ is density of air (g cm^{-3})

κ is Von Karman coefficient (0.41)

Z is elevation above surface at which variables are measured (cm)

Zo is roughness length (cm).

The combination methods overestimate potential evaporation in coastal climates (Jensen, 1973). The advantage of combination equations when compared to aerodynamic or energy balance methods are their greater simplicity.

Empirical methods. Many empirical equations have been developed for estimating potential evaporation. These methods relate evaporation to one or more micrometeorological parameters. Most of the equations are reliable for the location where they were developed, but may not be applicable when used for locations with different climatic conditions. A few of the more prominent are briefly discussed below.

Jensen-Haise (1963): Jensen and Haise presented a method for estimating Eo based on solar radiation and mean air temperature. It was recommended for use on a five-day basis. Their equations are as follows:

$$Eo = C_T (T - Tx)\ Rs \tag{10}$$

$$C_T = \frac{1}{C_1 + C_2 \cdot CH} \tag{11}$$

$$CH = \frac{50\ mb}{(e_2 - e_1)} \tag{12}$$

where e_2 and e_1 are saturation vapor pressure at mean maximum and mean minimum temperatures, respectively, for the warmest month of the year in the area.

$$C_2 = 13^{o}F \text{ or } 7.6^{o}C$$

$$C_1 = 68^{o}F - (3.6^{o}F \times \text{elev. in ft}/1000) \tag{13}$$

$$C_1 = 38 - (2^{o}C \times \text{elev. in m}/305) \tag{14}$$

$$Tx = 27.5^{o}F - (0.25\ (e_2 - e_1) - \text{elev. in ft}/1000) \tag{15}$$

$$Tx = -2.5^{o}C - (0.14(e_2 - e_1) - \text{elev. in m}/550) \tag{16}$$

T is average air temperature.

Christiansen and Hargreaves (1969): Christiansen and Hargreaves developed equations to compute Eo using multiple correlation methods. The equations were derived for clipped ryegrass (8-15 cm). The equations were recommended for use on a monthly basis.

Christiansen and Hargreaves -- correlation with pan evaporation:

$$Eo = 0.755 E_{pan} C_t C_w C_h \tag{17}$$

$$C_t = 0.670 + 0.476(T/To) - 0.146(T/To)^2 \qquad (18)$$

where T is the average air temperature, ^oF, and To = 68^oF or:

$$C_t = 0.862 + 0.179(T/To) - 0.041(T/To)^2 \qquad (19)$$

where T is the average air temperature, ^oC, and To = 20^oC.

$$C_w = 1.189 - 0.240(U_2/U_o) + 0.51(U_2/U_o)^2 \qquad (20)$$

where U_2 is wind speed at 2 m above the ground in miles/day or km/hr and U_o = 100 miles/day or 6.7 km/hr.

$$C_h = 0.499 + 0.629(RH/RH_o) - 0.119(RH/RH_o)^2 \qquad (21)$$

where RH is percent relative humidity and RH_o = 60.0 percent.

Christiansen and Hargreaves--correlation with solar radiation:

$$Eo = 0.429RsC_{tt}C_{ww}C_{hh} \qquad (22)$$

$$C_{tt} = 0.174 + 0.428(T/T_o) + 0.398(T/T_o)^2 \qquad (23)$$

where T is the mean air temperature, ^oF, and $T_o = 68^oC$.

$$C_{tt} = 0.463 + 0.425(T/T_o) + 0.112(T/T_o)^2 \qquad (24)$$

where T is the mean air temperature, ^oC, and $T_o = 20^oC$.

$$C_{ww} = 0.672 + 0.406(U_2/U_o) - 0.780(U_2/U_o)^2 \qquad (25)$$

where U_2 is the mean wind velocity at 2 m above ground level, and U_o = 100 miles/day or 6.7 km/hr, and Rs is solar radiation (mm/day).

$$C_{hh} = 1.035 + 0.429(RH/RH_o)^2 - 0.275(RH/RH_o)^3 \qquad (26)$$

where RH and RH_o are defined as above.

Priestley-Taylor (1972): Priestley and Taylor presented an equation to calculate potential evaporation on a daily basis, using net radiation:

$$Eo = \alpha(\frac{\Delta}{\Delta + \gamma}) \cdot Rn \qquad (27)$$

where

Rn is net radiation expressed (cm/day)

α is a proportionality constant equal to 1.35 ± 0.10

Δ and γ are defined as in equation (6).

Pan evaporation methods. In the past twenty years an extensive amount of research has been done on the use of pan evaporation data to estimate Eo using simple linear correlation (Pruitt and Jensen, 1955; Campbell et al., 1959; Stanhill, 1961, 1962; Fuchs and Stanhill, 1963; Jensen, 1973):

$$Eo = K_p \cdot E_{pan} \qquad (28)$$

where the value of K_p is a function of the type of pan involved, the environment of the pan as influenced by the area immediately around the pan, and the climate. The pan coefficient (K_p) must be determined experimentally.

Crop coefficient. Combination, empirical and pan evaporation methods are used to estimate evaporation from a free water surface.

Evapotranspiration (ET) is calculated from evaporation from a free water surface (Eo) using a crop coefficient (K_c) as follows:

$$ET = Eo \cdot K_c \tag{29}$$

The crop coefficient must be determined experimentally for each different location and for different crops. While serving a useful purpose in some areas, this approach lacks general adaptation since the crop coefficient varies not only with crop species, but also with season, growing conditions, and cultural practices.

2.2 Transpiration and Soil Evaporation when Soil Water Is Non-limiting and when It Is Limiting

Transpiration when soil water is non-limiting: Several models have been suggested to estimate transpiration and soil evaporation directly from climatological data, using a crop coefficient based on stage of plant development. In one such approach (Ritchie, 1972), leaf area index is used as an index of plant development. This approach was also used by Tanner and Jury (1976) and Kanemasu, Stone and Powers (1976).

In his model, Ritchie (1972) developed empirical relationships to compute transpiration and soil evaporation. In these relationships transpiration and soil evaporation are computed separately when water is not a limiting factor for plant evaporation. Transpiration is calculated from the potential evaporation with a stage of growth correction according to the leaf area index:

$$Epo = Eo(-0.21 + 0.70LAI^{\frac{1}{2}}) \qquad (30)$$

$$\text{when } (0.1 \leq LAI \leq 2.7)$$

$$Epo = Eo \qquad (31)$$

$$\text{when } (2.7 \leq LAI \leq 3.0)$$

where

Epo is potential transpiration (mm/day)

Eo is potential evaporation (mm/day)

LAI is leaf area index, the ratio of measured leaf area surface to ground surface area (Watson, 1947).

Following Philip (1957), soil evaporation is assumed to occur in two stages: (1) the constant rate stage when evaporation is controlled by energy supply, and (2) the falling rate stage when water movement is controlled by soil hydraulic properties.

Soil evaporation at the constant rate stage was calculated using the following equation:

$$Eso = \frac{\Delta}{\Delta + \gamma} Rn \cdot e^{(-0.40LAI)} \qquad (32)$$

where Eso is potential soil evaporation when water is not limiting.

During the falling rate stage when soil water becomes a limiting factor, Ritchie used Black's (Black et al., 1969) relationship to calculate soil evaporation (Es) as follows:

$$Es = \alpha_1 t^{\frac{1}{2}} \qquad (33)$$

where α_1 depends on the hydraulic properties of the soil and is determined experimentally, and t is time in days after irrigation.

Figure (1) shows the relationship of transpiration or soil evaporation versus leaf area index under nonlimiting soil water conditions. Data were obtained from Ritchie (1972). The sum of plant transpiration and soil evaporation under nonlimiting soil water conditions is called maximum evapotranspiration (ETo), which should approximately be equal to the potential evaporation (Eo) calculated with the Penman equation under conditions of no advection (Ritchie, 1972). Figure (1) also compares ETo with Eo. It shows that ETo is less than Eo when LAI is less than 1.0, and greater than Eo when LAI exceeds the value of 1.0 as indicated by the shaded area.

Some of the limitations of Ritchie's model are: Equation (32) was developed by correlating the net radiation at the soil surface below the crop canopy with LAI. Early in the season when the plants are small, if wind and vapor pressure are not considered, soil evaporation may be underestimated. Equation (33) was derived from experimental data for bare soil without plant cover. Using the same equation for soil with a crop will cause some error in the estimation of soil evaporation.

Transpiration when soil water is limiting. Several theories have been proposed to relate transpiration to available soil water where available soil water is defined as the water held in the soil between the field capacity and wilting point (Veihmeyer and Hendrickson, 1927). Field capacity is the water content of a soil following irrigation or heavy rainfall after drainage has become very slow. It is also defined as a soil pressure potential between -0.1 and -0.3 bars. Permanent

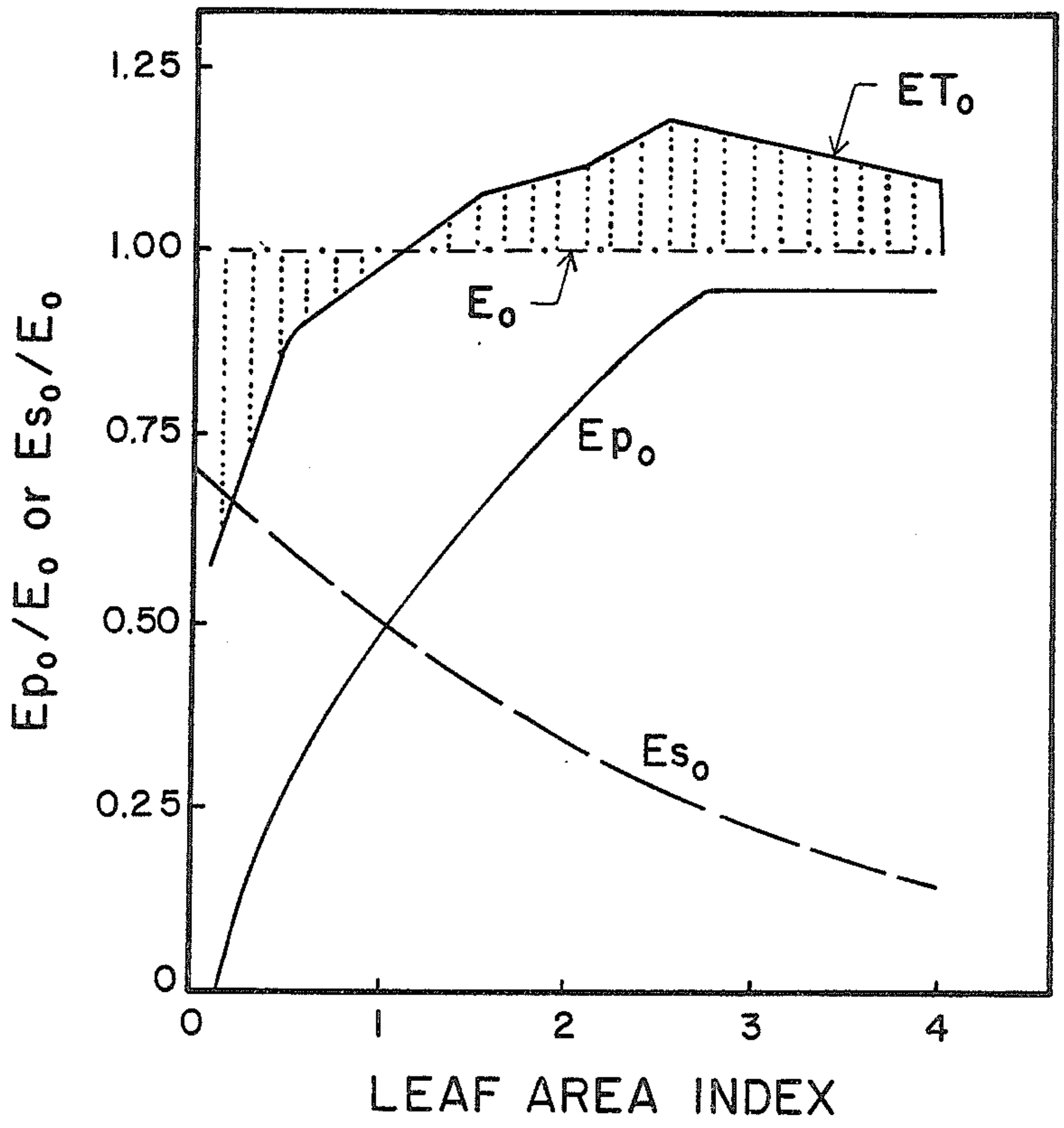

Figure 1. Relative soil evaporation and transpiration versus leaf area index (adapted from Ritchie, 1972).

wilting point is the range of soil pressure potential over which the rate of water supply to the plant is not great enough to prevent wilting, or when soil pressure potential is approximately -15 bars (Veihmeyer and Hendrickson, 1931). There is no general agreement on the functional relationship between soil water and evapotranspiration. Figure (2) illustrates a number of theories that have been suggested. These are (a) the ratio of transpiration (Ep) to potential transpiration (Epo) is unity in the range of available soil water (Veihmeyer and Hendrickson, 1955; Glover and Forsgate, 1964); (b) the ratio of Ep/Epo is unity in three-fourths of the available soil water range and then decreases sharply (Penman, 1949); (c) the ratio of Ep/Epo decreases linearly from the upper to the lower limits of the available soil water range (Thornwaite and Mather, 1955; Halstead, 1954; Wu, 1967); (d) same as (c) but oven-dryness is used as the lower limit of the available water (Havens, 1956); (e) the relationship between the ratio of Ep/Epo and soil water is curvilinear (West and Perkman, 1953; Butler and Prescott, 1955; Eagleman and Decker, 1956; Pierce, 1958; Knoerr, 1961).

Holmes (1961), Denmead and Shaw (1962), Shaw (1963), Holmes and Robertson (1963), Zahner (1967), and others have tried to explain why the curves in Fig. (3) all have a different shape. One of the main reasons is that the relationship of the ratio of Ep/Epo versus soil water is affected by different intensities of evaporative demand (see Fig. (3)) and by the physical properties of the soil.

Recent work by Ritchie, Burnett and Henderson (1972), using a weighing lysimeter, has shown that for cotton (*Gossypium hirsutum* and grain sorghum (*Sorghum bicolor* L.) about 80% of the available soil

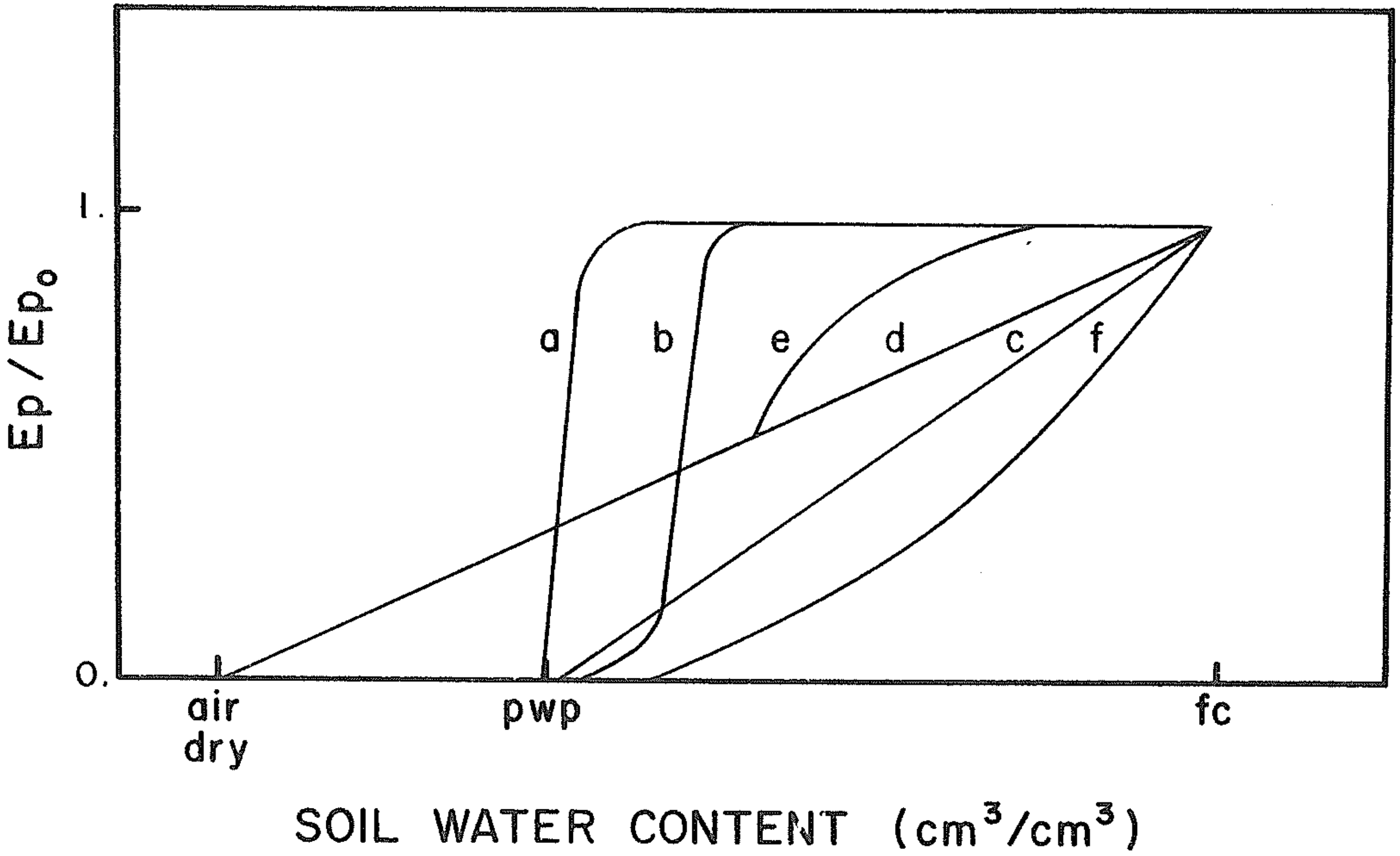

Figure 2. Models proposed to describe the relation between the ratio of transpiration (Ep) to potential transpiration (Epo) and soil water content. a. Veihmeyer and Hendrickson (1955); b. Penman (1949); c. Thornwaite and Mathers (1955); d. Havens (1956); e. Pierce (1958); and f. Bahrani and Taylor (1961). (Adapted from Tanner (1967)).

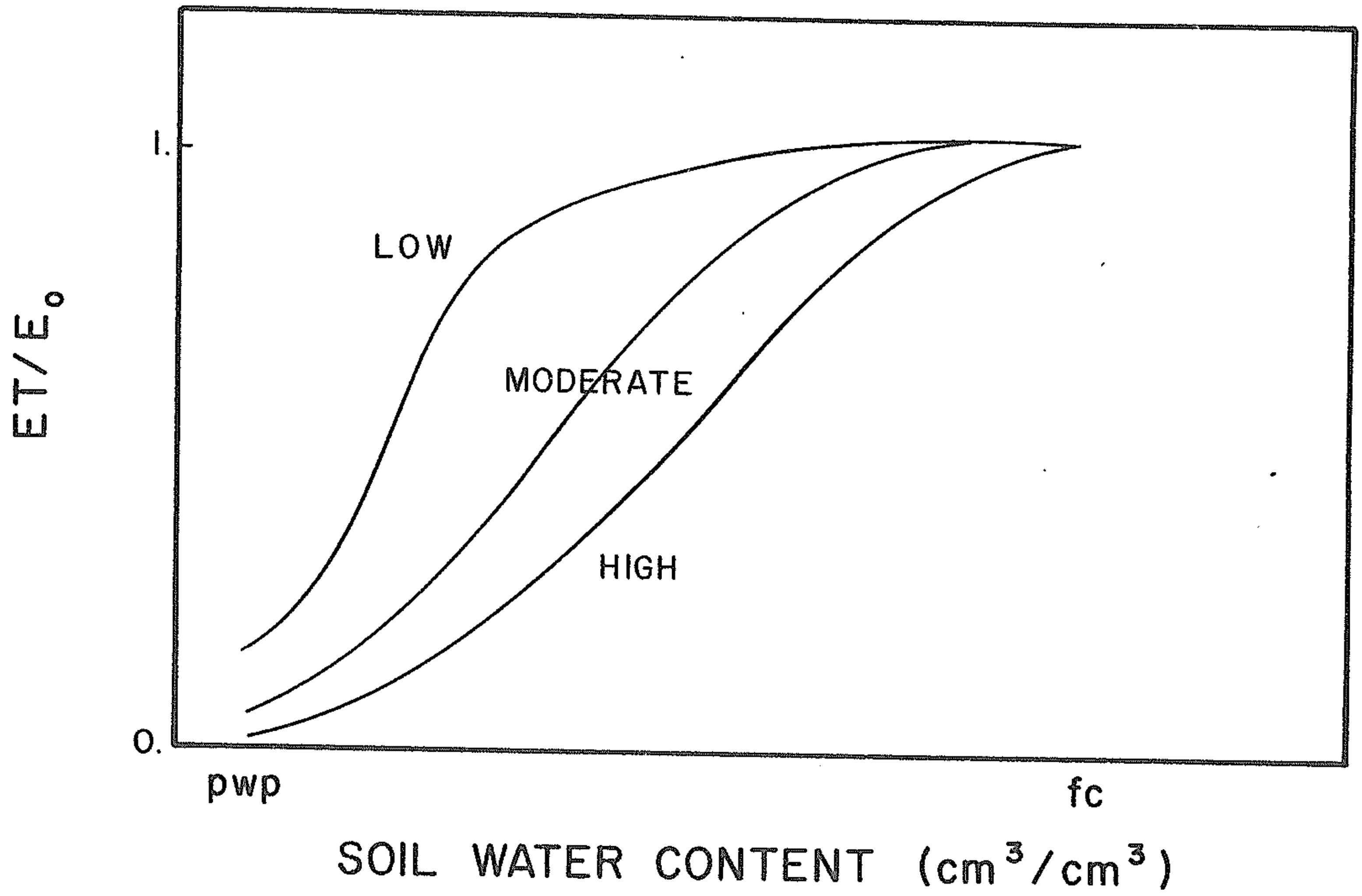

Figure 3. Ratio of evapotranspiration (ET) to potential evaporation (Eo) versus soil water content as influenced by the evaporative demands (Shaw, 1963).

water from a deep soil profile can be used before the ratio of Ep/Epo drops below unity. Similar results were reported by van Bavel (1967) for alfalfa. Ritchie (1973), comparing the results of Denmead and Shaw (1962) and Ritchie et al. (1972), explains that the amount of the removable soil water did not influence the transpiration rate nearly as much as reported by Denmead and Shaw. Ritchie's explanations about the lack of agreement between his results and the results reported by Denmead and Shaw are: (1) Root system differences--the experimental technique used by Denmead and Shaw resulted in a higher root density than would be expected for a field plant-root system. The average volume of the soil in the containers used by Denmead and Shaw was about 1/12 that of the field soil volume with rooting depth to 120 cm. (2) In field studies there can be considerable upward flow of water into the root zone, which cannot be ignored as a source of water contributing to evaporation from field-grown plants.

2.3 Models for Computing Infiltration and Redistribution of Water in Soil with Water Uptake by Roots

General Flow Equation: The general equation for water flow in soil in one dimension without the root extraction term (Hanks, Klute and Bresler, 1969) is:

$$\frac{\delta \Theta}{\delta t} = \frac{\delta}{\delta z}\left[K(\theta)\ \frac{\delta H}{\delta z}\right] \qquad (34)$$

where

θ is volumetric water content (cm^3/cm^3)

t is time (days)

z is depth (cm)

K is hydraulic conductivity which is a function of water content (cm/day)

H is hydraulic potential (sum of pressure potential and gravity potential) in cm.

Equation (34) is a nonlinear partial differential equation. There is no analytical solution to the general flow equation for initial and boundary conditions as usually found under field conditions (Dane, 1972). In order to solve equation (34), the pressure head versus water content and the hydraulic conductivity versus water-content relationships must be known.

Numerical solutions have been developed to solve the general flow equation. Klute (1952) presented a solution to the flow equation for horizontal flow using the method of iteration developed by Crank and Henry (1949).

Philip (1955) presented a quasi analytical solution for vertical infiltration of water in soil.

Finite difference techniques were also used extensively to solve equation (34). Hanks and Bowers (1962) presented a solution for infiltration and redistribution of water in soil which also is valid for nonhomogeneous soil with nonuniform initial water contents. Finite difference solutions were further used by Rubin and Steinhardt (1963, 1964), Whisler and Klute (1965), Remson et al. (1965), Rubin (1966), Remson et al. (1967), and Hanks et al. (1969).

In recent years two somewhat different methods were developed to solve Equation (34): (1) the finite element method, and (2) the simulation method. The finite element method is based on the theory of variational calculus (Remson, Hornberger, and Molz, 1971). The simulation approach was first reported by Wierenga and de Wit (1970) in a study of heat movement in soil. Bhuiyan et al. (1971), de Wit and van Keulen (1972), and van Keulen and van Beek (1971) were the first to use the simulation method for describing water movement in soil. CSMP allows digital simulation of continuous processes on large-scale digital computers. Models may be constructed simply and easily from a set of differential equations or from a block diagram representation of the continuous process to be simulated (IBM, 1972). Simplicity of input and output enables the user to concentrate upon the process to be simulated rather than on the internal organization of the program. A comparison between the CSMP method, various finite differences solutions and Philip's solution for one-dimensional infiltration was recently presented by Haverkamp et al. (1977).

Water Uptake by Roots: In order to simulate water uptake from soil with actively growing plants, a root extraction term has to be added to Equation (34). Many models have been developed to describe water uptake by plants (Philip, 1957; Gardner, 1960; Gardner, 1964; Newman, 1969). Most of these models are based on the assumption that water uptake from uniformly moist soil is roughly proportional to the root mass present. Based on this assumption, there are two approaches to describe root water uptake.

(1) Microscopic Approach: In this approach a typical root can be represented by an infinitely long, narrow cylinder of constant radius and water-absorbing characteristics. The soil water movement to the root is radial (Gardner, 1960). The flow equation is:

$$\frac{\delta\theta}{\delta t} = \frac{1}{r}\frac{\delta}{\delta r}\left[rD\frac{\delta\theta}{\delta r}\right] \tag{35}$$

where D is diffusivity and r is radial distance from the axis of the root. Assuming constant flux at the surface, Gardner (1960) solved equation (35) subject to the following initial and boundary conditions:

$$\theta = \theta_o \qquad \psi = \psi_o \qquad t = 0$$

where θ_o and ψ_o are the initial water content and pressure potential of the soil, respectively. Assuming further that:

$$q_1 = 2\pi a_1 K\frac{\delta\psi}{\delta r} = 2\pi a_1 D\frac{\delta\theta}{\delta r} \quad \text{at } r = a_1 \tag{36}$$

where a_1 is the root radius and q_1 is the rate of water uptake by the root expressed as volume of water per unit length of root per unit time, the solution of equations (35) and (36) for constant values of D and K and after a sufficiently long time period is:

$$\psi - \psi_o = \Delta\psi = \frac{q_1}{4\pi K}\left(\ln\frac{4Dt}{r^2} - \gamma_1\right) \tag{37}$$

where γ_1 is Euler's constant = 0.57222... . From this equation, it is possible to calculate the pressure potential gradient that will develop in the soil at a distance $(r - a_1)$ from the root and the pressure potential at the root-to-soil contact zone. Equation (37) is more sensitive to the diffusivity and time factors than to q_1 and K (Gardner, 1960).

The limitations of the microscopic approach are:

1. The diffusivity, D, and hydraulic conductivity, K, of the soil were assumed to be constant (Gardner, 1964), while in actuality they change as soil water content changes.
2. Determination of the correct boundary condition at the root surface is difficult. Most authors have assumed either a constant flux condition (Gardner, 1960) or a constant head condition (Molz et al., 1968). The correct condition would probably be some combination of both, that varied temporally (Molz and Remson, 1970). Moreover, if an attempt is made to realistically treat more than one root at a time, it becomes very difficult to specify the geometry correctly. An added difficulty is measuring the necessary variables with macroscopic instruments.

(2) Macroscopic Approach: In this approach, water uptake is assumed to be the removal of water by the roots as a whole unit without considering explicitly the effect of individual roots. The macroscopic approach is feasible and based upon the original suggestion of Ogata et al. (1960) that vertical divergence of the water flux minus the rate of change of the water content equals the root water uptake (Rose and Sterns, 1967; Whisler et al., 1968; Molz and Remson, 1970, 1971; Molz, 1971; and Nimah and Hanks, 1973a, 1973b; Van Bavel and Ahmed, 1976). An example of the macroscopic approach is the model developed by Nimah and Hanks (1973a). They expanded the general flow equation as follows:

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta z}\left[K(\theta)\ \frac{\delta H}{\delta z}\right] + \mathrm{RET}(z,t) \qquad (38)$$

RET(z,t) is the root extraction term defined as

$$\mathrm{RET}(z,t) = \frac{[H_{root} + (\mathrm{RRES}\cdot z) - \psi(z,t) - s(z,t)]\cdot \mathrm{RDF}(z)\ K(\theta)}{\Delta x\cdot \Delta z} \quad (39)$$

where

H_{root} is the effective water potential at the root surface (cm)

RRES is root resistance, equal to (1 + RC)

RC is a coefficient assumed to be 0.05

ψ is the pressure potential (cm)

s is osmotic potential (cm)

z is the depth from the soil surface (cm)

RDF(z) is the root distribution factor, dimensionless

Δx is the distance between the plant roots and the point in the soil where h(z,t) and s(z,t) are measured. Δx is assumed to be one.

Equations (38) and (39) were solved by Nimah and Hanks (1973a) numerically, using an implicit finite difference scheme similar to the one used by Hanks and Bowers (1962). The values of H_{root} were bounded on the wet end by (H_{root} = 0.0) and on the dry end by (H_{root} = -15 bars). The computation was set up to find the proper falue of H_{root} to satisfy the potential evaporation conditions. Some of Nimah and Hank's assumptions, however, are questionable. First, the root resistances are equal to the soil resistance. Molz (1975) stated that the estimated value for the tissue hydraulic conductivity was much lower than the soil hydraulic conductivity. A model in the form of (ΔH)$\cdot$(RDF)$\cdot$(Kr) would be more applicable to predict root-water uptake where ΔH is potential gradient, RDF is root distribution fraction, and Kr is root tissue permeability (Molz, 1975). Second, transpiration does not always cease at critical soil water potential, i.e. 15 bars. Third, the assumption that the internal plant resistances remain constant in spite of changes in water potential is probably incorrect (Kramer, 1950; Ordin and Gairon, 1961).

The macroscopic approach has significant advantages over the microscopic approach. The geometry for a one-dimensional model is quite simple. The boundary conditions are easy to identify and apply in contrast to those that occur at the root surface in the microscopic treatment. The upper boundary conditions are usually taken at the soil surface; thus evaporation, rainfall, or zero flow conditions can be accounted for. The lower boundary might be an impermeable layer, water table, or an infinite soil profile.

3. THEORETICAL

3.1 Equations and Boundary and Initial Conditions

In the following section a simplified mathematical model based on CSMP is developed for computing water content as a function of depth and time in layered soils including plant water-uptake and soil surface evaporation.

The model is based on the general flow equation with a root extraction term similar to equation (39):

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta z}\left[K(\theta)\frac{\delta H}{\delta z}\right] + \mathrm{RETA}(z,t) \qquad (40)$$

where RETA (z,t) is the root extraction term, here defined as:

$$\mathrm{RETA}(z,t) = \frac{1}{R}(\psi_r - \psi)\cdot\mathrm{RCC}(z) \qquad (41)$$

where ψ_r and ψ are root and soil pressure potentials in cm, RCC(z) is the root mass distribution, and R represents the resistance for water flow through soil around the roots and the resistance in the root itself. Equation (41) is, except for the following simplification, basically similar to equation (39). The root resistance RRES(z), and the hydraulic conductivity $K(\theta)$ in Eq. (39) are combined in a single resistance term R, in equation (41). Also the soil osmotic potential, and the effects of gravity potential on water flow through roots are not singled out in equation (41), as they are in equation (39). Furthermore, no assumptions are made concerning the distance Δx, between the plant roots and the point in soil where h(z,t) and s(z,t) are measured. Nimah and Hanks (1973a) arbitrarily assumed this distance to be one. If the soil water is not limiting for transpiration, then:

$$\mathrm{Epo} = \int_0^z \mathrm{RETA}(z) \cdot dz = \frac{1}{R}(\psi_r - \psi) \cdot \int_0^z \mathrm{RCC}(z) \cdot dz \qquad (42)$$

where Epo is the transpiration when soil water is not limiting. Rearranging Eq. (42)

$$\psi_r = \frac{\mathrm{Epo} \cdot R}{\int_0^z \mathrm{RCC}(z) \cdot dz} + \psi \qquad (43)$$

Substitution of (43) in (41) yields:

$$\mathrm{RETA}(z,t) = \frac{\mathrm{RCC}(z)}{\int_0^z \mathrm{RCC}(z) \cdot dz} \cdot \mathrm{Epo} \qquad (44)$$

We now define RDC(z) as:

$$\mathrm{RDC}(z) = \frac{\mathrm{RCC}(z)}{\int_0^z \mathrm{RCC}(z) \cdot dz} \qquad (45)$$

where RDC(z) is the root distribution coefficient, which varies with root mass and depth. It is the rate of water uptake at any particular depth, with respect to the total water-uptake rate over the soil profile. Substituting equation (45) in equation (44) results in:

$$\mathrm{RETA}(z,t) = \mathrm{Epo}(t) \cdot \mathrm{RDC}(z) \qquad (46)$$

The use of previously developed models has been largely limited because the physics of the process of water flow from soils to roots is very poorly understood, and much research is needed before a rational physically based model of water uptake by roots can be advanced (Feddes et al., 1974). The present model makes no assumption about the root water potential and resistance in the plant. The model is somewhat simpler, and easier to program than the model based on Equation (39).

Equation (41) was solved for the following boundary and initial conditions:

The upper boundary condition is taken at the soil surface. The lower boundary condition is taken as infinite soil depth. The following must be provided to solve the problem:

$$t = 0 \qquad z \geq 0 \qquad \theta(z,0) = \theta_o(z) \tag{46A}$$

and

$$t = 0 \qquad z = 0 \qquad q = \text{rain, irrigation or soil evaporation.}$$

The subscript o denotes initial conditions.

Soil evaporation is estimated at two stages: when the soil is sufficiently moist, soil evaporation is calculated as a function of leaf area index and evaporative demand. As the soil surface becomes drier, soil evaporation is estimated as a function of hydraulic properties of the soil. This will be discussed in detail later.

3.2 Computer Model

Equation (40) with (46) and boundary and initial conditions given in (46A) were solved with CSMP III, a continuous system modeling program (IBM, 1972).

A CSMP program is divided into three parts: (1) initial, (2) dynamic, and (3) terminal.

Each of the three parts is divided into a number of sections. The initial section includes calculations to be performed once. Also included in this section are the evaluation of parameters and initial conditions. The dynamic section includes statements to be executed at each iteration step, and the terminal section is used for the calculations to be done at the end of the run.

Eq. (40) is approximated by a set of differential equations, by dividing the soil profile into a number of equally thick layers. For each of these layers the water flow into and out of these layers is calculated first. These rates are integrated with time and changes in water content added or subtracted from the existing water content. Figure (4) shows a schematic representation of the soil layers, while a listing of the program is given in Table (1).

The following statements are from the dynamic part of the model. The flow of water into layer I is calculated using Darcy's equation:

```
FLUX(I) = (SWT(I) - SWT(I-1))*KOND(I)/TCOM + KOND(I)    (47)
```

where

FLUX(I) is flow into layer I (cm/day)

SWT(I) is pressure potential of layer I (cm)

TCOM(I) is layer thickness of layer I (cm)

KOND(I) is average hydraulic conductivity between the centers of the consecutive soil layers computed as follows:

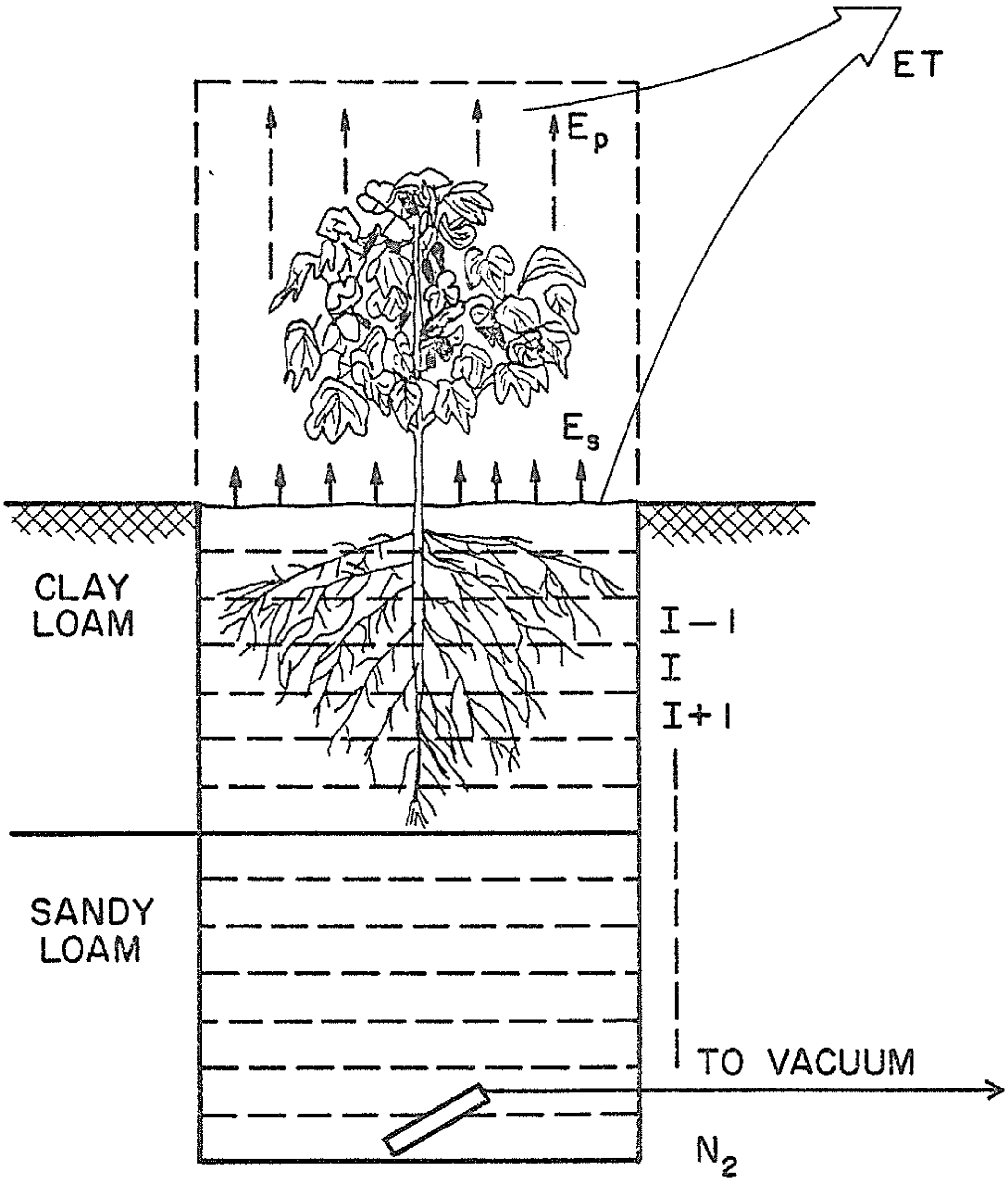

Figure 4. Schematic diagram of the flow of water through soil-plant-atmosphere system, simulation model.

Table 1. CSMP program for simulation of root water uptake, infiltration and drainage in layered soil.

```
// EXEC CSMP3G
TITLE SIMULATION MODEL OF ROOT WATER UPTAKE  IN LAYERED SOILS
********************************************************************************
*      CEO      CUMULATIVE POTENTAIL EVAPORATION,CM                              *
*      CEP     CUMULATIVE TRANSPIRATION,CM                                       *
*      CES     CUMULATIVE SOIL EVAPORAYION,CM                                    *
*      CET     CUMULATIVE EVAPOTRANSPIRATION,CM                                  *
*      CUDRAN  CUMULATIVE DRAINAGE,CM                                            *
*      CUMIN   CUMULATIVE IRRIGATION WATER(FLUX IN),CM                           *
*      COND    HYDRAULIC CONDUCTIVITY ,CM/DAY                                    *
*      DELT    INTEGRATION TIME INTERVAL                                         *
*      DEPTH   DISTANCE FROM SOIL SURFACE TO THE CENTER OF THE SOIL LAYER,CM     *
*      DIF     DIFFUSIVITY,CM2/DAY                                               *
*      DRAIN   DRAINAGE,CM/DAY                                                   *
*      EO      POTENTAIL EVAPORATION ,CM/DAY                                     *
*      EPO     POTENTAIL TRANSPIRATION ,CM/DAY                                   *
*      ES      SOIL EVAPORATION,CM/DAY                                           *
*      ES1     SOIL EVAPORATION AT THE FALLING STAGE ,CM/DAY                     *
*      ESO     POTENTAIL SOIL EVAPORATION ,CM/DAY                                *
*      ET      EVAPOTRANSPIRATION,CM/DAY                                         *
*      FAW     FRACTION OF AVIALABLE SOIL WATER                                  *
*      FCC     FIELD CAPACITY OF CLAY SOILS                                      *
*      FCS     FIELD CAPACITY OF SANDY SOILS                                     *
*      FLUX    FLUX,CM/DAY                                                       *
*      FRD     FRACTION OF ROOT DISTRIBUTION,G/G                                 *
*      KOND    AVERAGE HYDRAULIC CONDUCTIVITY,CM/DAY                             *
*      LAID    LEAF AREA INDEX                                                   *
*      LOSS    WATER BALANCE CHECK                                               *
*      N2      NUMBER OF SOIL  LAYERS                                            *
*      NFLUX   NET FLUX,CM/DAY                                                   *
*      RDC     ROOT DISTRIBUTION COEFFICIENT                                     *
*      RET     ROOT EXTRACTION TERM,CM                                           *
*      SOILF   RATIO OF TRANSPIRATION TO POTENTIAL TRANSPIRATION                 *
*      SWT     PRESSUR POTENTIAL,CM-WATER                                        *
*      T       ACCUMULATIVE TIME TO END OF EACH IRRIGATION CYCLE ,DAY            *
*      TCOM    THICKNESS OF SOIL LAYER,CM                                        *
*      TOVOLW  TOTAL WATER IN PROFILE,CM                                         *
*      VOLW    VOLUME OF WATER IN EACH SOIL LAYER,CM                             *
*      WC      WATER CONTENT ,CM3/CM3                                            *
*      WPC     WILTING POINT OF CALY SOIL                                        *
*      WPS     WILTING POINT OF SANDY SOIL                                       *
********************************************************************************
       STORAGE  FRD(100),WRTIM(100)
/      REAL WC(100),IWC(100),KOND(100),DEPTH(100),RDC(100),DEPT(100)
/      REAL SWT(100), DFLUX(100),VOLW(100),IVOLW(100),FLUX(100),FLRW(100)
/      REAL DIF(100),COND(100),VOLWAT(100),FAW(100),SOIL(100),FET(100)
       FIXED I,NL,N2,J,NL1,K,TT,NL2
       PARAMETER FCC=0.42,FCS=0.115,WPC=0.25,WPS=.06
       PARAMETER FACTOR=0.9,N2=28,TCOM=5.0,T=71,TINIT=0,WCSURF=0.39
       TABLE  WRTIM(1-25)=0.2081,1.,2.,4.,9.,11.,14.,16.,...
      18.,21.,23.,25.,28.,30.,32.,35.,37.,39.,44.,46.,49.,55.,58.,60.,71.
INITIAL
       NOSORT
       K=1
       NIC=0.0
       SFLAST=0.0
       TIM=0.
       DMAX=0.
       CUMIN=0
       CEO=0.0
       TOVOLW=0.
```

Table 1 (cont'd.)

```
      CEP=0.0
      CES=0.0
      CET=0.0
      ITIM=0.0
      CUDRAN=0.0
      TFILEP=0.
      TFLL=0.
      TFL=0.
      NL2=NL+1
      NL=N2
      NL1=NL-1
      STIME=TINIT
      TOTIME=STIME
      FACT=0.5*TCOM*TCOM*FACTOR
      DEPTH(1)=0.5*TCOM
      DO 2 I=2,N2
2     DEPTH(I)=DEPTH(I-1)+TCOM
      CONSUR=AFGEN(CONDTB,WCSURF)
      SWTSUR=AFGEN(SWTTBL,WCSURF)
      DO 3 I=1,N2
      WC(I)=AFGEN(IWCTBL,DEPTH(I))
      VOLW(I)=WC(I)*TCOM
      TOVOLW=TOVOLW+VOLW(I)
      VOLWAT(I)=VOLW(I)
      IF(DEPTH(I).GE.60.) GO TO 18
      SWT(I)=AFGEN(SWTTBL,WC(I))
      COND(I)=AFGEN(CONDTB,WC(I))
      DIF(I)=AFGEN(DIFTBL,WC(I))
      GO TO 27
   18 SWT(I)=AFGEN(SWTTS1,WC(I))
      COND(I)=AFGEN(CONDTS,WC(I))
      DIF(I)=AFGEN(DIFTS1,WC(I))
27    DMAX=AMAX1(DMAX,DIF(I))
      IWC(I)=WC(I)
 3    IVOLW(I)=VOLW(I)
      IVOL1=TOVOLW-VOLW(NL)
      KOND(1)=(CONSUR+COND(1))/2.
      FLUX(1)=AFGEN(SFLUXT,TIM)
      DO 4 I=2,N2
      KOND(I)=(COND(I)+COND(I-1))/2.
      FLUX(I)=(SWT(I)-SWT(I-1))*KOND(I)/TCOM+KOND(I)
 4    CONTINUE
      DO 5 I=1,N2
      NFLUX(I)=FLUX(I)-FLUX(I+1)
      WRITE(6,51) DEPTH(I),WC(I),VOLW(I),SWT(I),COND(I),DIF(I),        ...
      TOVOLW,FLUX(I),NFLUX(I),KOND(I)
51    FORMAT(F6.1,F8.5,3F13.6)
 5    CONTINUE
      FUNCTION LAIDT=     ...
      0.00,0.18,4,0.26,11,0.66,18,0.82,25.,1.69,32,1.9,39,1.98,...
      49,2.52,53,3.17,60.,2.9,71.,2.75
      FUNCTION FRDT,0.1=1,0.54,7,0.25,15,0.21,22,0.16,29,0.16,...
      36,0.16,43,0.16,50.,0.17,100.,0.17
      FUNCTION FRDT,10.=1,0.54,7,0.25,15,0.21,22,0.16,29,0.16,...
      36,0.16,43,0.16,50.,0.17,100.,0.17
      FUNCTION FRDT,10.1= 1,0.32,7,0.34,15,0.26,22,0.18,29,0.17,...
      36,0.18,43,0.17,50.,0.16,100.,0.16
      FUNCTION FRDT,20.0= 1,0.32,7,0.34,15,0.26,22,0.18,29,0.17,...
      36,0.18.43,0.17,50.,0.16,100.,0.16
      FUNCTION FRDT,20.1=1,0.05,7,0.2,15,0.17,22,0.15,29,0.13,...
      36,0.13,43,0.14,50.,0.14,100.,0.14
```

Table 1 (cont'd.)

```
        FUNCTION FRDT,30.0=1,0.05,7,0.2,15,0.17,22,0.15,29,0.13,...
        36,0.13,43,0.14,50.,0.14,100.,0.14
        FUNCTION FRDT ,30.1=1,0.04,7,0.1,15,0.16,22,0.19,29,0.16,...
        36,0.15,43,0.17,50.,0.18,100,0.18
        FUNCTION FRDT ,40.0=1,0.04,7,0.1,15,0.16,22,0.19,29,0.16,...
        36,0.15,43,0.17,50.,0.18,100,0.18
        FUNCTION FRDT,40.1=1,0.04,7,0.04,15,0.15,22,0.19,29,0.2,...
        36,0.17,43,0.19,50,0.18,100,0.16
        FUNCTION FRDT,50.0=1,0.04,7,0.04,15,0.15,22,0.19,29,0.2,...
        36,0.17,43,0.19,50,0.18,100,0.18
        FUNCTION FRDT,50.10=1,0.0,7,0.04,15,0.05,22,0.1,29,0.13,...
        36,0.14,43,0.13,50,0.13,100,0.13
        FUNCTION FRDT,60.00=1,0.0,7,0.04,15,0.05,22,0.1,29,0.13,...
        36,0.14,43,0.13,50,0.13,100,0.13
        FUNCTION FRDT,60.1=1.0,0.0,100.,0.0
        FUNCTION FRDT,200.=1.0,0.0,100.,0.0
FUNCTION SWTTBL=...
.01000,   4799811.00000000,   .02000,  3697943.00000000,...
.03000,   2849025.00000000,   .04000,  2194990.00000000,...
.05000,   1691097.00000000,   .06000,  1302880.00000000,...
.07000,   1003786.43750000,   .08000,   773351.50000000,...
.09000,    595817.12500000,   .10000,   459038.87500000,...
.11000,    353659.37500000,   .12000,   272471.68750000,...
.13000,    209921.87500000,   .14000,   161731.25000000,...
.15000,    124603.50000000,   .16000,    95998.75000000,...
.17000,     73960.81250000,   .18000,    56982.00000000,...
.19000,     43900.96093750,   .20000,    33822.85156250,...
.21000,     26058.33593750,   .22000,    20076.23828125,...
.23000,     15467.44531250,   .24000,    11916.64453125,...
.25000,      9181.00390625,   .26000,     7073.37109375,...
.27000,      5449.57421875,   .28000,     4198.54296875,...
.29000,      3234.70727539,   .30000,     2492.13208008,...
.31000,      1920.02807617,   .32000,     1479.25439453,...
.33000,      1139.66992188,   .34000,      878.04199219,...
.35000,       676.47412109,   .36000,      521.17944336,...
.37000,       401.53515625,   .38000,      309.35693359,...
.39000,       238.33937073,   .40000,      183.62492371,...
.41000,       141.47102356,   .42000,      108.99427795,...
.43000,        83.97306824,   .44000,       64.69581604,...
.45000,        49.84390259,   .46000,       38.40150452,...
.47000,        29.58589172,   .48000,       22.79397583,...
.49000,        17.56127930,   .50000,       13.52983570
FUNCTION SWTTS1=...
.01000,  18033744.00000000,   .02000,  4447069.00000000,...
.03000,   1096634.00000000,   .04000,   270426.75000000,...
.05000,     66686.43750000,   .06000,    16444.67968750,...
.07000,      4055.23779297,   .08000,     1000.00292969,...
.09000,       246.59799194,   .10000,      272.99243164,...
.11000,       252.76101685,   .12000,      234.02886963,...
.13000,       216.69496704,   .14000,      200.62649536,...
.15000,       185.75810242,   .16000,      171.99143982,...
.17000,       159.24517822,   .18000,      147.44352722,...
.19000,       136.51637268,   .20000,      126.39920044,...
.21000,       117.03175354,   .22000,      108.35856628,...
.23000,       100.32901819,   .24000,       92.89273071,...
.25000,        86.00837708,   .26000,       79.63430786,...
.27000,        73.73262024,   .28000,       68.26824951,...
.29000,        63.20390808,   .30000,       58.52450562,...
.31000,        54.18727112,   .32000,       50.17138672,...
.33000,        46.45220129,   .34000,       43.01052856,...
.35000,        39.82304382,   .36000,       36.87173462,...
```

Table 1 (cont'd.)

```
.37000,          5.09412479,    .38000,          0.58396620,...
.39000,          0.06694406,    .40000,          0.00767403,...
.41000,          0.00087771,    .42000,          0.00010085,...
.43000,          0.00001156,    .44000,          0.00000133,...
.45000,          0.00000015,    .46000,          0.00000002,...
.47000,          0.00000000,    .48000,          0.00000000,...
.49000,          0.00000000,    .50000,          0.00000000
FUNCTION CONDTR=...
.01000,          0.00000073,    .02000,          0.00000106,...
.03000,          0.00000154,    .04000,          0.00000225,...
.05000,          0.00000327,    .06000,          0.00000476,...
.07000,          0.00000693,    .08000,          0.00001008,...
.09000,          0.00001468,    .10000,          0.00002137,...
.11000,          0.00003110,    .12000,          0.00004528,...
.13000,          0.00006591,    .14000,          0.00009595,...
.15000,          0.00013968,    .16000,          0.00020333,...
.17000,          0.00029600,    .18000,          0.00043089,...
.19000,          0.00062725,    .20000,          0.00091310,...
.21000,          0.00132922,    .22000,          0.00193497,...
.23000,          0.00281677,    .24000,          0.00410043,...
.25000,          0.00596907,    .26000,          0.00868929,...
.27000,          0.01264916,    .28000,          0.01841362,...
.29000,          0.02680503,    .30000,          0.03902059,...
.31000,          0.05680300,    .32000,          0.08268929,...
.33000,          0.12037235,    .34000,          0.17522836,...
.35000,          0.25508246,    .36000,          0.37132901,...
.37000,          0.54055047,    .38000,          0.78688949,...
.39000,          1.14548874,    .40000,          1.66751385,...
.41000,          2.42742920,    .42000,          3.53365421,...
.43000,          5.14397717,    .44000,          7.43821259,...
.45000,         10.90060711,    .46000,         15.86827946,...
.47000,         23.09983826,    .48000,         33.62698364,...
.49000,         48.95086670,    .50000,         71.25897217
FUNCTION CONDTS=...
.01000,          0.00803174,    .02000,          0.00992445,...
.03000,          0.01226318,    .04000,          0.01515304,...
.05000,          0.01872389,    .06000,          0.02313625,...
.07000,          0.02858835,    .08000,          0.03532533,...
.09000,          0.04364985,    .10000,          0.05393606,...
.11000,          0.06664628,    .12000,          0.08235162,...
.13000,          0.10175806,    .14000,          0.12573779,...
.15000,          0.15536815,    .16000,          0.19198149,...
.17000,          0.23722243,    .18000,          0.29312462,...
.19000,          0.36220050,    .20000,          0.44755417,...
.21000,          0.55302143,    .22000,          0.68334311,...
.23000,          0.84437478,    .24000,          1.04335594,...
.25000,          1.28922558,    .26000,          1.59303665,...
.27000,          1.96844006,    .28000,          2.43230820,...
.29000,          3.00549221,    .30000,          3.71374416,...
.31000,          4.58889675,    .32000,          5.67029381,...
.33000,          7.00651550,    .34000,          8.65762711,...
.35000,         10.69782066,    .36000,         13.21879196,...
.37000,         16.33384705,    .38000,         20.18295288,...
.39000,         24.93913269,    .40000,         30.81617737,...
.41000,         38.07807922,    .42000,         47.05131531,...
.43000,         58.13909912,    .44000,         71.83975220,...
.45000,         88.76907349,    .46000,        109.68774414,...
.47000,        135.53594971,    .48000,        167.47569275,...
.49000,        206.94201660,    .50000,        255.70845032
FUNCTION DIFTBL=...
.01000,         91.11270142,    .02000,        102.18617249,...
```

Table 1 (cont'd.)

```
.03000,          114.60559082,    .04000,          128.53443909,...
.05000,          144.15605164,    .06000,          161.67640686,...
.07000,          181.22591248,    .08000,          203.36392212,...
.09000,          228.08010864,    .10000,          255.80041504,...
.11000,          286.88391602,    .12000,          321.75659180,...
.13000,          360.86206055,    .14000,          404.72045898,...
.15000,          453.90893555,    .16000,          509.07592773,...
.17000,          570.94775391,    .18000,          640.33740234,...
.19000,          718.16235352,    .20000,          805.44604492,...
.21000,          903.33837891,    .22000,         1013.12524414,...
.23000,         1136.25805664,    .24000,         1274.35498047,...
.25000,         1429.23706055,    .26000,         1602.94189453,...
.27000,         1797.75927734,    .28000,         2016.25268555,...
.29000,         2261.30175781,    .30000,         2536.13403320,...
.31000,         2844.37011719,    .32000,         3190.06396484,...
.33000,         3577.77465820,    .34000,         4012.60791016,...
.35000,         4500.28125000,    .36000,         5047.23046875,...
.37000,         5660.66015625,    .38000,         6348.64453125,...
.39000,         7120.22656250,    .40000,         7985.61328125,...
.41000,         8956.14453125,    .42000,        10044.64843750,...
.43000,        11265.39062500,    .44000,        12634.60156250,...
.45000,        14170.00390625,    .46000,        15892.25390625,...
.47000,        17823.82421875,    .48000,        19990.11328125,...
.49000,        22419.38671875,    .50000,        25144.26953125
FUNCTION DIFTS1=...
.01000,    20277920.00000000,     .02000,     6178858.00000000,...
.03000,     1882750.00000000,     .04000,      573690.06250000,...
.05000,      174808.12500000,     .06000,       53265.55859375,...
.07000,       16230.54687500,     .08000,        4945.55468750,...
.09000,        1506.95483398,     .10000,         113.37586975,...
.11000,         129.71092224,     .12000,         148.39942932,...
.13000,         169.78063965,     .14000,         194.24267578,...
.15000,         222.22883606,     .16000,         254.24761963,...
.17000,         290.87915039,     .18000,         332.78857422,...
.19000,         380.73632813,     .20000,         435.59228516,...
.21000,         498.35205078,     .22000,         570.15454102,...
.23000,         652.30078125,     .24000,         746.28515625,...
.25000,         853.80786133,     .26000,         976.82446289,...
.27000,        1117.56396484,     .28000,        1278.58007813,...
.29000,        1462.79858398,     .30000,        1673.55639648,...
.31000,        1914.68017578,     .32000,        2190.54614258,...
.33000,        2506.15698242,     .34000,        2867.24243164,...
.35000,        3280.35009766,     .36000,        3752.97875977,...
.37000,       18022.55468750,     .38000,        2552.88208008,...
.39000,         361.61938477,     .40000,          51.22248840,...
.41000,           7.25562859,     .42000,           1.02775478,...
.43000,           0.14553083,     .44000,           0.02062173,...
.45000,           0.00292106,     .46000,           0.00041377,...
.47000,           0.00005861,     .48000,           0.00000830,...
.49000,           0.00000118,     .50000,           0.00000017
FUNCTION IWCTBL=...
      0.0,0.28,60.,0.28,60.1,0.1,200.,0.1
      FUNCTION  FOT=  ...
      0.0,0.7244,4.,0.7244,5.,0.677,12.,0.6749,13.,0.6303,19.,0.6303,...
      20.,0.5464,26.,0.5464,27.,0.5713,33.,0.5713,34.,0.4721,...
      40.,0.4721,41.,0.4891,47.,0.489,48.,0.523,57.,0.523,58.,0.472,...
      61.,0.471,62.,0.53,71.,0.53,100.,0.53
      FUNCTION TTS=0.0,0.0,1.,0.146,2.,9.1333,3.,18.1792,4.,25.1292,...
      5.,32.2333,6.,39.125,7.,46.1992,8.,56.1,9.,60.1333
      FUNCTION SFLUXT=     ...
      0.0,24.,0.146,24.,0.1461,0.0,9.0,0.0,9.0001,24.,...
```

Table 1 (cont'd.)

```
      9.1333,24.,9.1334,0.0,18.0,0.0,18.0001,24.,...
      18.1792,24.,18.1793,0.0,25.,0.0,25.0001,24.,...
      25.1292,24.,25.1293,0.0,32.,0.0,32.0001,24.,...
      32.2333,24.,32.2334,0.0,39.0,0.0,39.0001,24.,...
      39.125,24.,39.1251,0.0,46.,0.0,46.0001,24.,...
      46.1992,24.,46.1993,0.0,56.,0.0,56.0001,24.,...
      56.1,24.,56.1001,0.0,60.0,0.0,60.00011,24.,...
      60.1333,24.,60.1334,0.0,100.,0.0
      CALL DEBUG(3,0.)
*********                                                         ***********
DYNAMIC
      NOSORT
      IF(TELLER.LT.2.)GO TO 100
      DMAX=0.
      OUDEL=DELT
      DO 8 I=1,NL
      IF(DEPTH(I).GE.60.)  GO TO 19
      SWT(I)=AFGEN(SWTTBL,WC(I))
      COND(I)=AFGEN(CONDTB,WC(I))
      DIF(I)=AFGEN(DIFTBL,WC(I))
      GO TO 28
19    SWT(I)=AFGEN(SWTTS1,WC(I))
      COND(I)=AFGEN(CONDTS,WC(I))
      DIF(I)=AFGEN(DIFTS1,WC(I))
28    DMAX=AMAX1(DMAX,DIF(I))
 8    CONTINUE
      DELT=FACT/DMAX
      IF(DELT.GT.(1.25*OUDEL))DELT=1.25*OUDEL
      FLUX(1)=AFGEN(SFLUXT,TIM)
      SFLUX=FLUX(1)
      IF(SFLUX.GT.0..AND.SFLAST.EQ.0.)NIC=NIC+1.
      T=AFGEN(TTR,NIC)
      IF(TIM.LE.T.AND.(TIM+DELT+0.0002).GT.T) GO TO 333
      GO TO 334
  333 FLUX(1)=FLUX(1)*(T-TIM)/DELT
 334  CONTINUE
      KOND(1)=(CONSUR+COND(1))/2.
      DO 150 I=1,NL
      FRD(I)=TWOVAR(FRDT,TIM,DEPTH(I))
  150 CONTINUE
      LAID=AFGEN(LAIDT,TIM)
      EO=AFGEN(EOT,TIM)
      EPO=EO*(1.-EXP(-0.623*LAID))
      DO 10 I=2,NL
      KOND(I)=(COND(I)+COND(I-1))/2.
      FLUX(I)=(SWT(I)-SWT(I-1))*KOND(I)/TCOM+KOND(I)
      FLMAX=AMAX1(FLMAX,FLUX(I))
 10   CONTINUE
      EP1=0.0
      CPDC=0.0
      DO 1005 I=1,NL
      IF(Z(I).LE.60.)FAW(I)=(WC(I)-WPC)/(FCC-WPC)
      IF(Z(I).GT.60.)FAW(I)=(WC(I)-WPS)/(FCS-WPS)
      IF(FAW(I).GT.1.)FAW(I)=1.
      IF(FAW(I).LT.0.0)FAW(I)=0.
      SOILF(I)=(1.)/(1.+6.2*(EXP(-15.2*FAW(I))))
      DEPT(I)=DEPTH(I)/60.
      IF(DEPT(I).GT.1.)DEPT(I)=1.
      RDC(I)=FRD(I)/2.*2.0*EXP(-1.58*DEPT(I))
      IF(TIM.LT.30.)RDC(I)=FRD(I)/2.
      PET(I)=EPO*SOILF(I)*RDC(I)
```

Table 1 (cont'd.)

```
      EP1=EP1+RET(I)
      CRDC=CRDC+RDC(I)
 1005 CONTINUE
      EP=EP1
      IF(SFLUX.GT.0.AND.SFLAST.EQ.0.) ITIM=0.
      ITIM=ITIM+DELT
      ESO=EO*(EXP(-0.623*LAID))
      ES1=((0.58*ITIM**0.6)-(.58*(ITIM-DELT)**0.6))/DELT
      IF(ESO.GT.0.58) ESO=0.58
      IF(ES1.GT.ESO) ES1=ESO
      IF(ITIM.GT.1.) ES=ES1
      IF(ITIM.LE.1.) ES=ESO
      ET=EP+ES
      CEP=CEP+EP*DELT
      CES=CES+ES*DELT
      CET=CET+ET*DELT
      CEO=CEO+EO*DELT
      DO 11 I=1,NL1
 11   NFLUX(I)=FLUX(I)-FLUX(I+1)-RET(I)
      NFLUX(1)=NFLUX(1)-ES
      NFLUX(NL)=NFLUX(NL1)
      DO 13 I=1,NL
 13   VOLWAT(I)=VOLWAT(I)+NFLUX(I)*DELT
      DO 7 I=1,NL
      WC(I)=VOLWAT(I)/TCOM
      TOVOLW=TOVOLW+WC(I)*TCOM
7     CONTINUE
      TOV1=TOVOLW-WC(NL)*TCOM
      DRAIN=FLUX(N2)
      CUMIN=CUMIN+FLUX(1)*DELT
      CUDRAN=CUDRAN+FLUX(N2)*DELT
      DIFVOL=TOV1-IVOL1+CUDRAN+CET
      LOSS=CUMIN-DIFVOL
      TIM=TIM+DELT
      STIME=TCTIME+TIM
 101  FORMAT(1H ,/,F9.0,2F8.1,6F8.4)
      IF((STIME+2.E-4).GE.WRTIM(K)) GO TO 900
      GO TO 950
 900  WRITE(6,101)TELLER,TIM,STIME,DELT,CUMIN,CUDRAN,TOVOLW,            ...
      DIFVOL,LOSS
      WRITE(6,700) EO,ET,EP,ES,CEO,CET,CEP,CES,CRDC
700   FORMAT(9F11.3)
      DO 107 I=1,NL
      WRITE(6,105)TIM,TELLER,DEPTH(I),WC(I),SWT(I),KOND(I),FLUX(I),...
      RET(I)
105   FORMAT(F10.5,F6.0,F6.2,F8.4,F9.1,4F10.5)
 107  CONTINUE
      K=K+1
 950  CONTINUE
      TEL=TEL+1.
      SFLAST=SFLUX
 100  CONTINUE
      TELLER=TELLER+1.
      TOVOLW=0.
      WC1=WC(1)
      WC2=WC(2)
TERMINAL
      NOSORT
      WRITE(6,101)TELLER,TIM,STIME,DELT,CUMIN,CUDRAN,TOVOLW,            ...
      DIFVOL,LOSS
      DO 108 I=1,NL
```

Table 1 (cont'd.)

```
      WRITE(6,105)TIM,TELLER,DEPTH(I),WC(I),SWT(I),KOND(I),FLUX(I),...
      RET(I)
 108  CONTINUE
      TOTIME=TOTIME+TIM
      TIM=0.
      K=1
      FINISH WC1=0.60,WC2=0.60,TIM=71
METHOD RECT
TIMER FINTIM=90000.,DELT=0.001
END
STOP
ENDJOB
```

$$\mathrm{KOND(I) = (COND(I) + COND(I-1))/2} \quad (48)$$

where

COND(I) is hydraulic conductivity of layer I (cm/day).

RETA(I) is the root extraction term for soil layer I, calculated as:

$$\mathrm{RETA(I) = EP{*}RDC(I)} \quad (49)$$

where EP is transpiration, and RDC(I) is root distribution coefficient of layer I.

The net flux in the first layer was calculated using the law of mass conservation as follows:

$$\mathrm{NFLUX(1) = FLUX(1) - FLUX(2) - RETA(1) - Es} \quad (50)$$

where Es is soil evaporation. The net flux in any given layer is calculated as:

$$\mathrm{NFLUX(I) = FLUX(I) - FLUX(I+1) - RETA(I)} \quad (51)$$

The water volume (VOLWAT) in each soil layer I at t + Δt was calculated as follows:

$$\mathrm{VOLWAT(I) = VOLWAT(I) + NFLUX(I){*}DELT} \quad (52)$$

where DELT is the time step for integration.

Water content (WC) at t + Δt was calculated:

$$\mathrm{WC(I) = VOLWAT(I)/TCOM} \quad (53)$$

The drainage rate at the bottom of the soil profile was set equal to the flux into the lowest layer:

$$\text{DRAIN} = \text{FLUX(N2)} \tag{54}$$

where N2 is the number of layers in the profile.

The water balance in the model is checked by the following:

$$\text{MASSBL} = \text{CUMIN} + \text{IVOLW} - \text{TOVOLW} - \text{CUDRAN} - \text{CET} \tag{55}$$

where TOVOLW is total volume of the soil water at any time, IVOLW is the initial volume of soil water, CUDRAN is cumulative drainage, CET is the cumulative evapotranspiration, CUMIN is cumulative amount of water applied, and MASSBL is mass balance, the value of which should be close to zero.

Input data. One of the most important features of CSMP is the availability of function blocks. Leaf area index, surface flux, evaporation from a water surface as functions of time, and initial water content as a function of depth are entered with function generators:

```
Eo = AFGEN(EOT,TIM)
LAID = AFGEN(LAIDT,TIM)
FLUX(I) = AFGEN(SFLUXT,TIM)
WC(I) = AFGEN(IWCTBL,DEPTH(I))
```

where AFGEN is an arbitrary function generator which allows linear interpolation between consecutive points, TIM is time and DEPTH(I) is distance below the soil surface. EOT, LAIDT, SFLUXT, and IWCTBL are dummy names for function tables entered as pairs of (X,Y):

```
FUNCTION EOT = (0.0, 0.7244), (4.0, 0.7244),...
FUNCTION LAIDT = (0.0, 0.15), (7.0, 0.195),...
FUNCTION SFLUXT = (0.0, 24.0), (0.146, 24.0),...
FUNCTION IWCTBL = (0.0, 0.28), (60.0, 0.28),...
```

Hydraulic conductivity, diffusivity, and pressure potential vary with depth and water content. Fraction of root distribution varies with depth and time. The two variable function generator (y = f(x,z)) was used to enter data as follows:

```
COND(I) = TWOVAR(CONDTB, WC(I), DEPTH(I))
DIF(I) = TWOVAR(DIFTBL, WC(I), DEPTH(I))
SWT(I) = TWOVAR(SWTTBL, WC(I), DEPTH(I))
FRD(I) = TWOVAR(FRDT, TIM, DEPTH(I))
```

where CONDTB, DIFTBL, SWTTBL, and FRDT are dummy names for function tables. The general format of the table is:

FUNCTION CONDTB, $Z_1 = (x_{11}, y_{11}), (x_{12}, y_{12}),\ldots$

FUNCTION CONDTB, $Z_z = (x_{z1}, y_{z1}), (x_{z2}, y_{z2}),\ldots$

Notice that the values of Z must be in an order of algebraically increasing values and that the (x,y) pairs are treated the same as in AFGEN. The use of the TWOVAR function generator consumed more computer time than the use of the AFGEN function generator. Since the soil used in this study consisted of only two layers, hydraulic conductivity, diffusivity, pressure potential, and fraction of root distribution were also entered with the AFGEN function generator for each of the two different soil layers. Computer time was decreased by approximately 40%.

Integration interval (DELT). Integration interval or step size is adjusted according to the maximum diffusivity (DMAX). It is calculated as follows (Haverkamp et al., 1977):

$$\text{DELT} = \text{FACT/DMAX} \qquad (56)$$

where FACT depends on the thickness of each soil layer (TCOM) and on a stability factor (FACTOR):

$$\text{FACTOR} = 0.5{*}\text{TCOM}{*}\text{TCOM}{*}\text{FACTOR} \qquad (57)$$

The program should be stable when FACTOR < 1.0. A value of 0.9 for FACTOR was chosen here.

3.3 Simplified Computer Model

The simulation model described earlier is conceptually pleasing in that it represents the water movement in the soil-plant-atmosphere system. This model and others like it need a large number of input data that are commonly unavailable. It also requires a large amount of computer time. The use of simpler models becomes more desirable when only gross descriptions are required. One such model was presented by Jury et al. (1976). The simplified model is based on the following assumptions: 1) The root zone is divided into four layers, 2) water movement is always downward, 3) rate of water movement is equal to hydraulic conductivity, 4) water uptake is 40%, 30%, 20%, and 10% of the total evapotranspiration requirement removed from each successively deeper quarter of the root zone (Danielson, 1967), 5) available water in any layer at any time is greater than 50%, and 6) crop cover is more than 50% of the ground surface area.

Jury et al. (1976) solved the following equation:

$$L\frac{d\theta_j}{dt} = K(\theta_{j-1}) - K(\theta_j) - RETA_j \qquad (58)$$

$$j = 1,2,3, \text{ and } 4$$

where L is the thickness of each soil layer (¼ of the root zone).

$RETA_j$ is the root extraction term, calculated as follows:

$$\begin{aligned} RETA_{j=1} &= 0.4*Eo \\ RETA_{j=2} &= 0.3*Eo \\ RETA_{j=3} &= 0.2*Eo \\ RETA_{j=4} &= 0.1*Eo \end{aligned} \qquad (59)$$

where Eo is potential evaporation, estimated either from pan evaporation or the Penman equation, as in the previous program.

Figure 5 shows a schematic representation of the soil layers while a listing of the program is given in Table (2).

The flow of water into layer I is calculated by the following:

$$NFLUX(I) = COND(I-1) - COND(I) - RETA(I) \qquad (60)$$

where NFLUX(I) is net flux, COND(I) is hydraulic conductivity, and RETA(I) is the root extraction term, all in cm/day.

The rate of drainage is set equal to the hydraulic conductivity of the bottom layer of the soil profile.

The hydraulic conductivity-water content relationship input data is needed for the model. The upper boundary condition includes

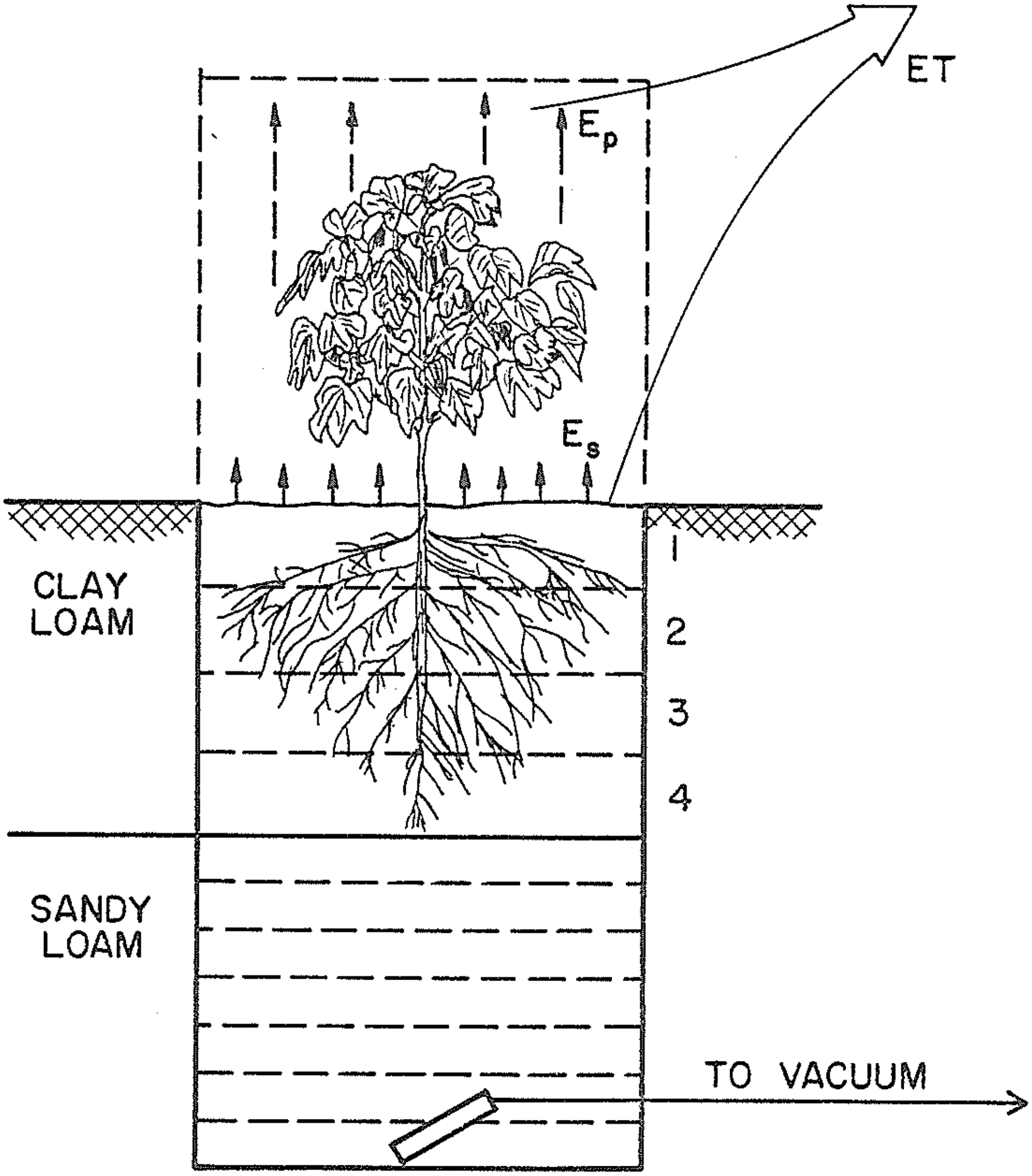

Figure 5. Schematic diagram of the flow of water through soil-plant-atmosphere, simplified model.

Table 2. CSMP program for simulation of root water uptake, infiltration and drainage in layered soil using simplified model.

```
// EXEC CSMP3G
TITLE SIMPLIFIED MODEL FOR WATER UPTAKE AND INFILTERATION
*         SIMULATION OF SIMPLE PROGRAM OF JURY MODEL
*****************************************************************************
*      CEO      CUMULATIVE POTENTAIL EVAPORATION,CM                         *
*      CUDRAN  CUMULATIVE DRAINAGE,CM                                       *
*      CUMIN   CUMULATIVE IRRIGATION WATER(FLUX IN),CM                      *
*      COND    HYDRAULIC CONDUCTIVITY ,CM/DAY                               *
*      DELT    INTEGRATION TIME INTERVAL                                    *
*      DEPTH   DISTANCE FROM SOIL SURFACE TO THE CENTER OF THE SOIL LAYER,CM *
*      EO      POTENTAIL EVAPORATION ,CM/DAY                                *
*      FLUX    FLUX,CM/DAY                                                  *
*      LOSS    WATER BALANCE CHECK                                          *
*      N2      NUMBER OF SOIL  LAYERS                                       *
*      NFLUX   NET FLUX,CM/DAY                                              *
*      T       ACCUMULATIVE TIME TO END OF EACH IRRIGATION CYCLE ,DAY       *
*      TCOM    THICKNESS OF SOIL LAYER,CM                                   *
*      TOVOLW  TOTAL WATER IN PROFILE,CM                                    *
*      VOLW    VOLUME OF WATER IN EACH SOIL LAYER,CM                        *
*      WC      WATER CONTENT ,CM3/CM3                                       *
*****************************************************************************
       STORAGE WRTIM(100)
/      REAL WC(100),IWC(100),DEPTH(100),VOLWAT(100),FLUX(100)
/      REAL COND(100),NFLUX(100),VOLW(100),IVOLW(100),PET(100)
       FIXED I,NL,N2,J,NL1,K,TT,NL2
       PARAMETER FACTOR=0.9,TCOM=15.,TINIT=0.0,N2=8.
       TABLE WRTIM(1-8)=39.,44.,46,49,56,58,60,71
INITIAL
       NOSORT
       K=1
       SFLAST=0.0
       NIC=0.0
       TIM=37.
       CUMIN=0
       CEO=0.0
       TOVOLW=0.
       CUDRAN=0.0
       TELLER=0.
       TELL=0.
       TEL=0.
       NL2=NL+1
       NL=N2
       NL1=NL-1
       STIME=TINIT
       TOTIME=STIME
       DEPTH(1)=0.5*TCOM
       DO 2 I=2,N2
2      DEPTH(I)=DEPTH(I-1)+TCOM
       DO 3 I=1,N2
       WC(I)=AFGEN(IWCTBL,DEPTH(I))
       VOLW(I)=WC(I)*TCOM
       TOVOLW=TOVOLW+VOLW(I)
       VOLWAT(I)=VOLW(I)
       IF(DEPTH(I).GE.60.) GO TO 18
       COND(I)=AFGEN(CONDTB,WC(I))
       GO TO 27
   18  COND(I)=AFGEN(CONDTS,WC(I))
27     IWC(I)=WC(I)
 3     IVOLW(I)=VOLW(I)
       IVOL1=TOVOLW-VOLW(NL)
       FLUX(1)=AFGEN(SFLUXT,TIM)
```

Table 2 (cont'd.)

```
      NFLUX(1)=FLUX(1)-COND(1)
      DO 4 I=2,N2
      NFLUX(I)=COND(I-1)-COND(I)
      WRITE(6,51) DEPTH(I),WC(I),VOLW(I),COND(I),TOVOLW,NFLUX(I)
51    FORMAT(F6.1,F8.5,7F13.6)
 4    CONTINUE
      FUNCTION TTR=0.0,0.0,1.,0.584,2.,9.5332,3.,18.7168,...
      4.,25.5168,5.,32.9332,6.,39.5,7.,46.7968,8.,56.4,9.,60.5332
FUNCTION CONDTB=...
.01000,           0.00000073,    .02000,            0.00000106,...
.03000,           0.00000154,    .04000,            0.00000225,...
.05000,           0.00000327,    .06000,            0.00000476,...
.07000,           0.00000693,    .08000,            0.00001008....
.09000,           0.00001468,    .10000,            0.00002137,...
.11000,           0.00003110,    .12000,            0.00004528,...
.13000,           0.00006591,    .14000,            0.00009595,...
.15000,           0.00013963,    .16000,            0.00020333,...
.17000,           0.00029600,    .18000,            0.00043089,...
.19000,           0.00062725,    .20000,            0.00091310,...
.21000,           0.00132922,    .22000,            0.00193497,...
.23000,           0.00281677,    .24000,            0.00410043,...
.25000,           0.00596907,    .26000,            0.00868929,...
.27000,           0.01264916,    .28000,            0.01841362,...
.29000,           0.02680503,    .30000,            0.03902059,...
.31000,           0.05680300,    .32000,            0.08268929,...
.33000,           0.12037235,    .34000,            0.17522836,...
.35000,           0.25508296,    .36000,            0.37132901,...
.37000,           0.54055047,    .38000,            0.78688949,...
.39000,           1.14548874,    .40000,            1.66751385,...
.41000,           2.42742920,    .42000,            3.53365421,...
.43000,           5.14397717,    .44000,            7.48821259,...
.60,7.48
FUNCTION CONDTS=...
.01000,           0.00803174,    .02000,            0.00992445,...
.03000,           0.01226318,    .04000,            0.01515304,...
.05000,           0.01872389,    .06000,            0.02313625,...
.07000,           0.02858835,    .08000,            0.03532533,...
.09000,           0.04364985,    .10000,            0.05393606,...
.11000,           0.06664628,    .12000,            0.08235162,...
.13000,           0.10175806,    .14000,            0.12573779,...
.15000,           0.15536815,    .16000,            0.19198149,...
.17000,           0.23722243,    .18000,            0.29312462,...
.19000,           0.36220050,    .20000,            0.44755417,...
.21000,           0.55302143,    .22000,            0.68334311,...
.23000,           0.84437478,    .24000,            1.04335594,...
.25000,           1.28922558,    .26000,            1.59303665,...
.27000,           1.96844006,    .28000,            2.43230829,...
.29000,           3.00549221,    .30000,            3.71374416,...
.31000,           4.58889675,    .32000,            5.67029381,...
.33000,           7.00651550,    .34000,            8.65762711,...
.35000,          10.69782066,    .36000,           13.21879196,...
.37000,          16.33384705,    .38000,           20.18295288,...
.39000,          24.93913269,    .40000,           30.81617737,...
.41000,          38.07807922,    .42000,           47.05131531,...
.43000,          58.13909912,    .44000,           71.83975220,...
.60,109.69
FUNCTION IWCTPL=...
      0.,0.27,10.,0.28,15.,0.32,60.,0.32,60.1,0.11,200.,0.10
      FUNCTION  FOT=  ...
      0.0.0.7244,4.,0.7244,5.,0.677,12.,0.6749,13.,0.6303,19.,0.6303,...
      20.,0.5464,26.,0.5464,27.,0.5713,33.,0.5713,34.,0.4721,...
```

Table 2 (cont'd.)

```
      40.,0.4721,41.,0.4891,47.,0.469,48.,0.523,57.,0.523,58.,0.472,...
      61.,0.471,62.,0.53,71.,0.53,100.,0.53
      FUNCTION SFLUXT=    ...
      0.0,6.0,0.584,6.0,0.5841,0.0,8.9998,0.0,8.9999,6.,...
      9.5332,6.0,9.5333,0.0,17.9980,0.0,17.9999,6.,...
      18.7168,6.,18.7169,0.0,24.9900,0,24.9999,6.,...
      25.5168,6.0,25.5169,0.0,31.9500,0.0,31.9999,6.,...
      32.9332,6.,32.9333,0.0,38.9500,0.0,38.9999,6.,...
      39.5,6.,39.5001,0.0,45.9500,0.0,45.9999,6.,...
      46.7968,6.,46.7969,0.0,55.9500,0.0,55.9999,6.,...
      56.4,6.,56.4001,0.0,59.9500,0.0,59.9999,6.,...
      60.5332,6.,60.5333,0.0,100.,0.0
      CALL DEBUG(3,0.)
*********                                                                 ***********
DYNAMIC
      NOSORT
      IF(TELLER.LT.2.)GO TO 100
      DELT=0.100001
      OUDEL=DELT
      DO 8 I=1,NL
      IF(DEPTH(I).GE.60.)  GO TO 19
      COND(I)=AFGEN(CONDTB,WC(I))
      GO TO 8
   19 COND(I)=AFGEN(CONDTS,WC(I))
 8    CONTINUE
      FLUX(1)=AFGEN(SFLUXT,TIM)
      SFLUX=FLUX(1)
      IF(SFLUX.GT.0..AND.SFLAST.EQ.0.)NIC=NIC+1.
      T=AFGEN(TTR,NIC)
      IF(TIM.LE.T.AND.(TIM+DELT+0.0002).GT.T) GO TO 333
      GO TO 334
  333 FLUX(1)=FLUX(1)*(T-TIM)/DELT
 334  CONTINUE
      EO=AFGEN(EOT,TIM)
      RET(1)=EO*0.4
      RET(2)=EO*0.3
      RET(3)=EO*0.2
      RET(4)=EO*0.1
      NFLUX(1)=FLUX(1)-COND(1)-RET(1)
      NFLUX(2)=COND(1)-COND(2)-RET(2)
      NFLUX(3)=COND(2)-COND(3)-RET(3)
      NFLUX(4)=COND(3)-COND(4)-RET(4)
      DO 11 I=5,NL1
11    NFLUX(I)=COND(I-1)-COND(I)
      NFLUX(NL)=NFLUX(NL1)
      DO 13 I=1,NL
 13   VOLWAT(I)=VOLWAT(I)+NFLUX(I)*DELT
      DO 7 I=1,NL
      WC(I)=VOLWAT(I)/TCOM
      TOVOLW=TOVOLW+WC(I)*TCOM
7     CONTINUE
      TOV1=TOVOLW-WC(NL)*TCOM
      DRAIN=COND(N2)
      CUMIN=CUMIN+FLUX(1)*DELT
      CEO=CEO+EO*DELT
      CUDRAN=CUDRAN+COND(N2)*DELT
      DIFVOL=TOV1-IVOL1+CUDRAN+CEO
      LOSS=CUMIN-DIFVOL
      TIM=TIM+DELT
      STIME=TOTIME+TIM
 101  FORMAT(1H ,/,F9.0,2F8.1,6F8.4)
```

Table 2 (cont'd.)

```
        IF((STIME+2.E-4).GE.WRTIM(K)) GO TO 900
        GO TO 950
  900   WRITE(6,101)TELLER,TIM,STIME,DELT,CUMIN,CUDRAN,TOVOLW,          ...
        DIFVOL,LOSS
        WRITE(6,700) EO,CFO
 700    FORMAT(8F11.3)
        DO 107 I=1,NL
        WRITE(6,105)TIM,DEPTH(I),WC(I),COND(I),NFLUX(I),RET(I)
 105    FORMAT(F10.5,6X,F6.2,F8.4,F9.1,3F10.5)
  107   CONTINUE
        K=K+1
  950   CONTINUE
        TEL=TEL+1.
        SFLAST=SFLUX
  100   CONTINUE
        TELLER=TELLER+1.
        TOVOLW=0.
        WC1=WC(1)
        WC2=WC(2)
TERMINAL
        NOSORT
        WRITE(6,101)TELLER,TIM,STIME,DELT,CUMIN,CUDRAN,TOVOLW,          ...
        DIFVOL,LOSS
        DO 108 I=1,NL
        WRITE(6,105)TIM,DEPTH(I),WC(I),COND(I),NFLUX(I),RET(I)
  108   CONTINUE
        TOTIME=TOTIME+TIM
        TIM=0.
        K=1
        FINISH WC1=0.6,WC2=0.6,TIM=71
METHOD RECT
TIMER FINTIM=90000.,DELT=0.001
END
STOP
ENDJOB
```

the flux in (irrigation water), and flux out (potential evaporation) as functions of time. Other input information includes initial water content data as a function of depth, the thickness of the soil compartments, the number of soil layers, and the lower boundary condition. The integration time interval DELT is calculated using the following equation:

$$\text{DELT} \leq \frac{\text{TCOM}}{K'\theta} \qquad (61)$$

where TCOM is the thickness of the soil layer and

$$K'\theta = \frac{dK}{d\theta} \quad . \qquad (62)$$

4. METHODS AND MATERIALS

4.1 Location

The experiments were conducted during the springs and summers of 1975 and 1976 at the Plant Science Research Center of New Mexico State University, located 16 km south of Las Cruces, New Mexico, USA (106^o W, 32^o N, elevation 1214 m). The climate at this location is usually characterized as hot, semi-arid continental with average maximum and minimum temperatures of 39^o C and -13^o C, respectively. The annual mean precipitation is approximately 200 mm, much of which falls during the months of July, August, and part of September. The annual average windspeed is 172 km/day.

The soil at the experimental site was classified as Glendale clay loam (mixed calcareous; thermic family of Typic Torrifluvent). Physical and chemical properties of the soils are listed in Table (3). The experimental plot layout is shown in Figure (6).

4.2 Lysimeters

Ten non-weighing-type lysimeters were constructed. The dimensions of the lysimeters are given in Fig. (7). The lysimeters consisted of wooden boxes, 150 cm x 100 cm and 150 cm deep, lined with several sheets of plastic. Three porous candles 30 cm long and 5 cm in diameter (Selas Flotronics, Huntington Valley, Pennsylvania) were placed near the bottom of each lysimeter to collect drainage water under a constant suction of 600 cm H_2O. The lysimeters were back-filled with soil in the same layer sequence (from 0-60 cm below the surface: clay

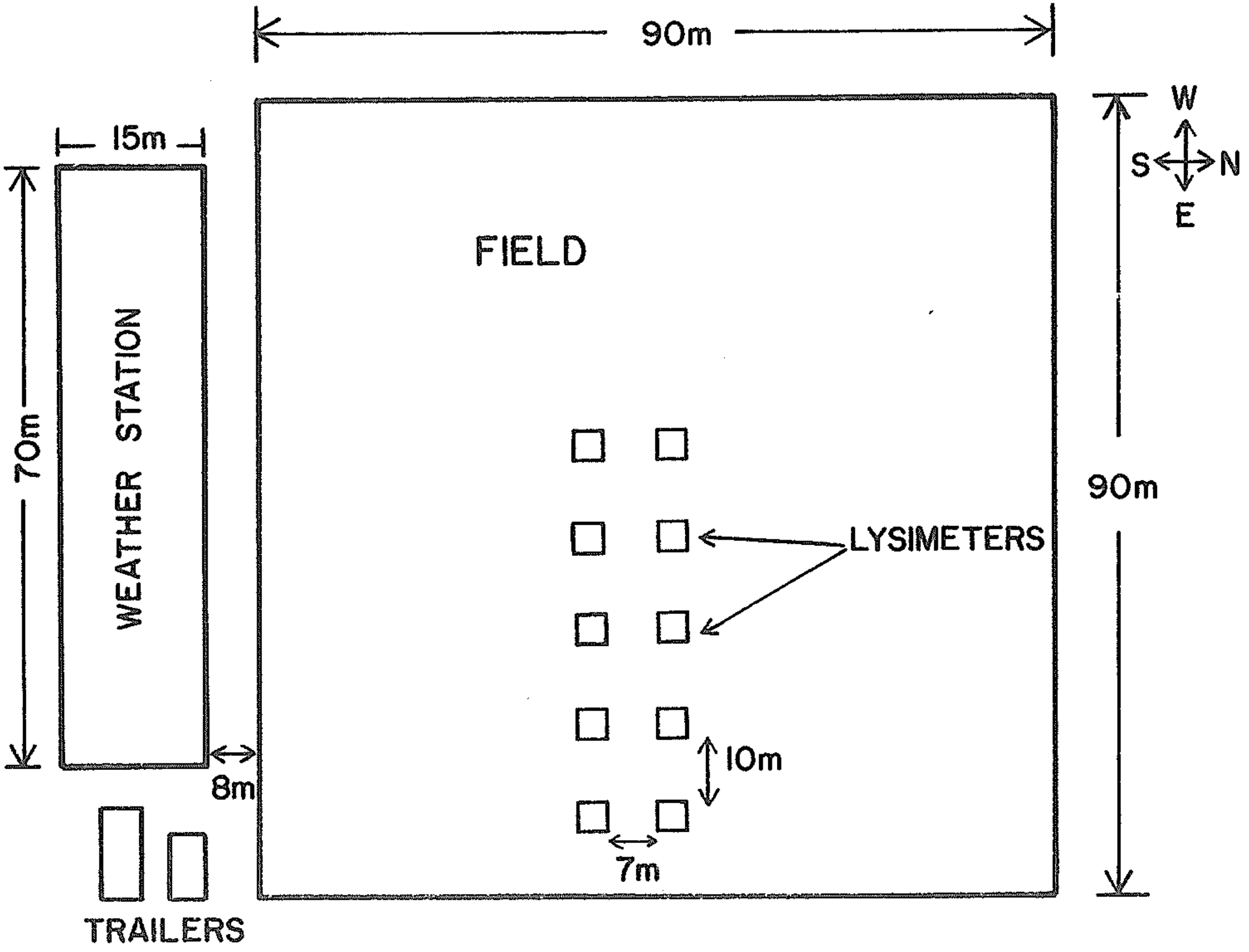

Figure 6. Experimental plot at New Mexico State University Plant Science Research Center.

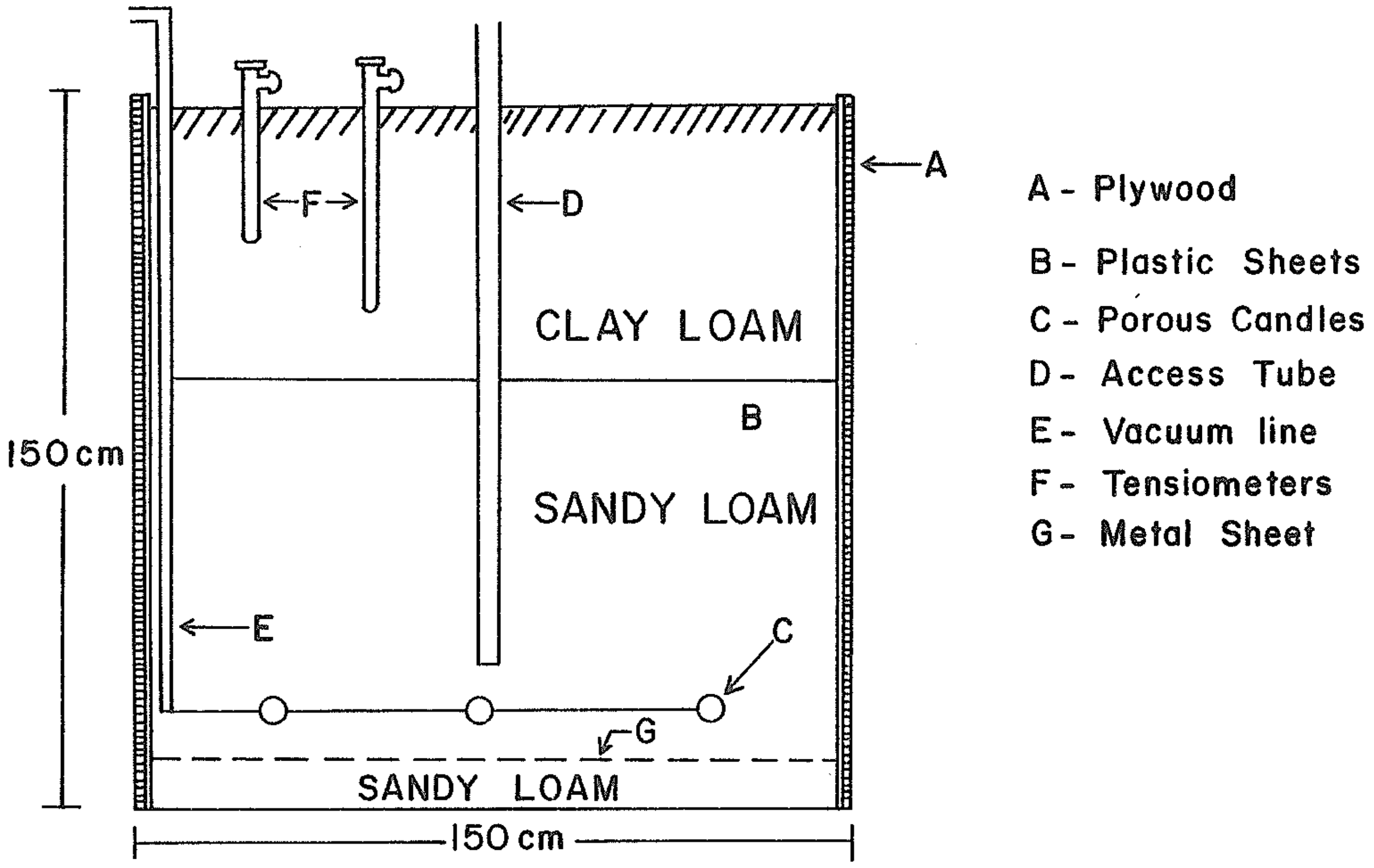

Figure 7. Schematic diagram of the lysimeter installation.

Table 3. Texture and some chemical properties of the soil profile of the Glendale clay loam from the lysimeters.

		Sample	
Measured	Units	Surface (0-60) cm	Subsurface (60-150) cm
Texture		Clay Loam	Sandy Loam
Sand	%	21.70	71.40
Silt	%	41.40	21.20
Clay	%	36.90	7.40
pH		7.57	7.60
EC_e	mmhos	2.26	1.32
NO_3^-	ppm	157.30	46.00
% H_2O of the saturation extract		48.00	20.00
Na^+	meq/L	10.90	7.73
Mg^{++}	meq/L	0.06	0.035
K^+	meq/L	0.54	0.23
Ca^{++}	meq/L	11.69	4.62
HCO_3^-	meq/L	5.52	2.93
Cl^-	meq/L	1.02	0.46
$SO_4^=$	meq/L	12.35	8.20

loam, and from 60-150 cm: sandy loam) and at approximately the same density as the field. The clay loam and sandy loam used to backfill the lysimeters were air-dried and mixed separately in a large cement mixer in order to obtain an identical soil profile in all lysimeters. A neutron access tube and two tensiometers were placed in each lysimeter. The lysimeters were located in two rows (five per row) and spaced at a distance of 7 m along each row.

Acala cotton (*Gossypium hirsutum*) strain B-344 was planted in rows 1 m apart at an approximate plant population of 7 plants per m^2. The cotton field was approximately one hectare. Plants in the experimental field area were uniformly fertilized with N, P, and K at a rate of 91 kg/ha, 45 kg/ha, and 45 kg/ha, respectively.

The field and the lysimeters were irrigated using a trickle irrigation system. Water was applied to the lysimeters once a week, and the amount applied was measured volumetrically. In 1976, two lysimeters, one in each treatment, were not planted and irrigated, but left bare throughout the season.

Soil, plant, and climatic measurements were taken during 1975 and 1976.

4.3 Soil Measurements

Soil water content. Soil water-content measurements were obtained by the neutron scattering method. The equipment and procedures used are described in detail by van Bavel and Stirk (1967), and will be only briefly outlined here.

Thin-walled aluminum access tubes, 6 cm outside diameter (O.D.) and 150 cm long, were installed vertically in the lysimeters. The equipment used to measure soil water content included a Troxler probe fitted with a 100 millicurie Americium Beryllium source, and a line-operated Troxler portable scaler provided with a recycling timer for detecting thermal neutron flux. The scaler counts the total number of pulses in a predetermined increment of time (usually 15 seconds).

The accuracy of the neutron probe readings depends upon the development of a good calibration curve that relates the neutron count rate to water content (van Bavel and Stirk, 1967). The neutron meter was calibrated for Glendale clay loam by preparing 5 containers (45 cm in diameter and 55 cm high) of soil at various water contents. Figure (8) shows the experimental and the factor calibration curves for the neutron probe. The best fit for the data by least squares differences is:

$$\theta = 0.3456CR - 0.0064 \qquad (63)$$

as compared to

$$\theta = 0.41CR - 0.0337 \qquad (64)$$

supplied by the manufacturer. θ is volumetric water content, and CR is the ratio of soil count rate to the shield standard count rate. Eq. (63) agrees reasonably well with the calibration curve determined by Dane (1972) for the same probe but different soils. Eq. (63) was used for water-content calculations throughout this study.

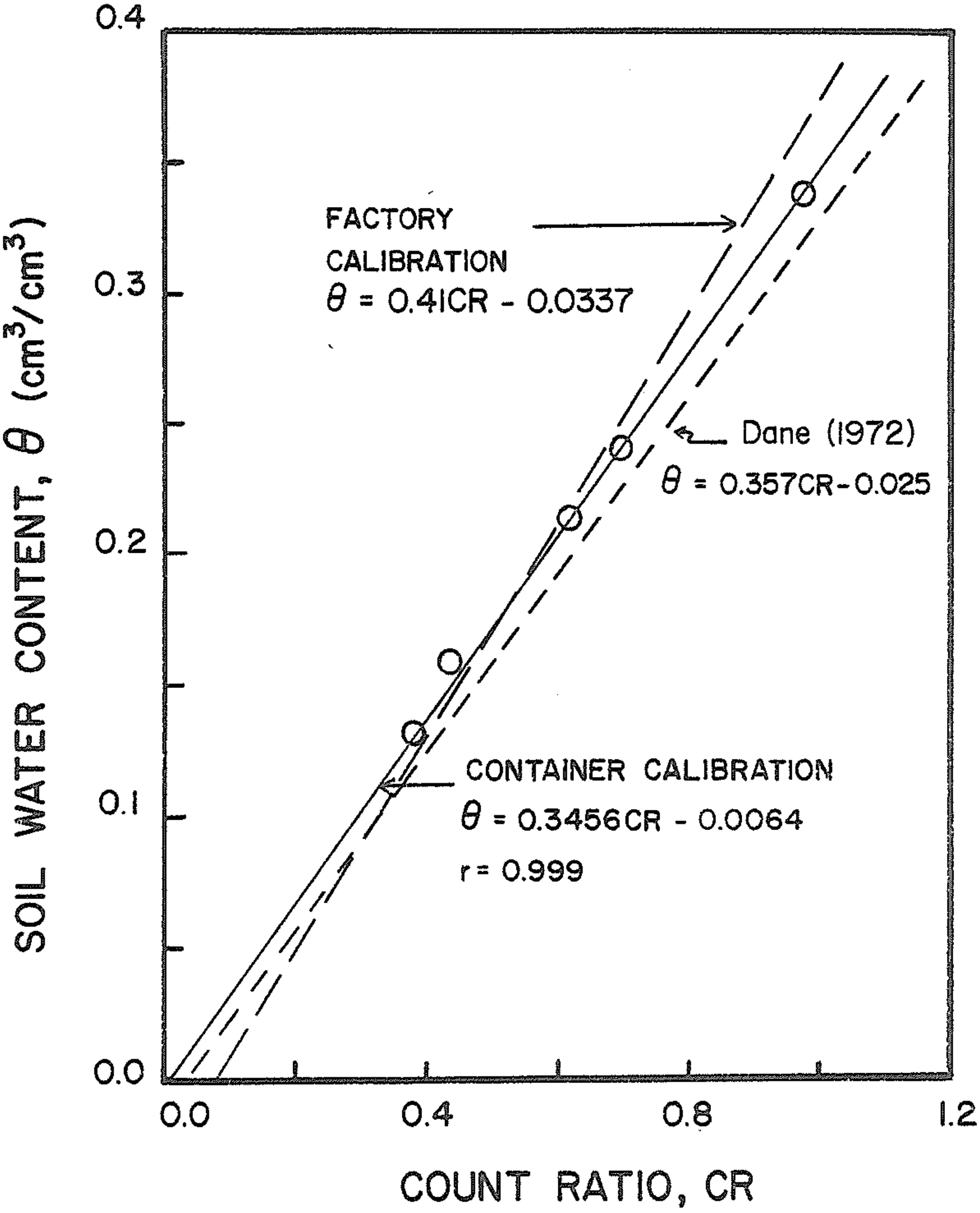

Figure 8. The calibration curve presented by solid line was used in the present investigation.

The neutron method is not accurate near the soil surface. Gravimetric samples were taken using a soil sampler described by Walker et al. (1976). Samples were taken at 0-1, 1-2, 2-3, 3-6, 6-10, and 10-15 cm. Surface evaporation was measured three times a week by weighing triplicate buckets filled with soil. The buckets, 30 cm in diameter and 30 cm deep, were embedded in the field soil between the rows such that the top was flush with the surface of the soil.

Pressure potential-water content relationship. The pressure potential-water content relationships were determined for the clay loam and sandy loam using the pressure plate apparatus (Richards 1941 and Woodruff 1941) and Buchner funnels filled with soil, saturated, and placed in a container in which the air pressure was increased to various levels above the ambient air pressure.

Pressure potential in the field was measured with tensiometers installed with their tips at 30 and 45 cm below the soil surface. Readings were taken three times a week during the growing season.

Hydraulic conductivity-water content relationship. Knowledge of the unsaturated hydraulic conductivity and diffusivity values at different water contents is essential before any of the mathematical theories of water flow can be put into practice. Hydraulic conductivity and diffusivity can be obtained from either steady-state or transient-state flow systems.

The relationship between hydraulic conductivity and soil water-content was determined by developing a steady-state method similar in approach to the crust method developed by Hillel and Gardner (1970).

The principle of the method is based on establishing a steady-state flow within the lysimeters by pumping water onto the surface at a constant rate using a low flow metering pump (models RRP1G50 and RRP1G400 from Fluid Metering, Inc.). The water was applied evenly at 30 points over the surface of the lysimeter through equal lengths of fine tubing connected to a small cylinder. Initially, low flow rates were used. After establishing steady-state conditions, as indicated by an approximately constant rate of drainage, the water content and pressure potential values were recorded. Flow rates were increased and this procedure was repeated until a maximum flux was reached. At fluxes less than 0.5 cm/day, hydraulic conductivity values were determined by the instantaneous profile method described by Nielsen and Biggar (1961).

4.4 Climatic Measurements

The following climatological measurements were taken:

Pan evaporation. Evaporation from a water surface was measured using a Class A pan. Daily readings were taken in the morning.

Incoming solar radiation. An Epply Model 50 pyroheliometer was used to measure incoming solar radiation.

Net radiation. Net radiation was measured in the test field with a net radiometer similar to those described by Fritschen (1965) for a period long enough to establish the regression coefficients needed to convert the solar radiation to the net radiation.

Barometric pressure. YSI/Sostman barometer (type 2014) was used to measure barometric pressure.

Relative humidity. The relative humidity was measured with a hygrothermograph. Temperature and humidity values at 4 A.M. and 4 P.M. were used to compute average daily relative humidities, using the procedure described in the Smithsonian Meteorological Tables (List, 1966).

Wind speed. A wind speed (MRI Model 1022S) was used to measure the wind speed.

Rain gauge. A Meteorology Research Incorporated tipping bucket rain gauge (MRI Model 302) was used to measure the rainfall.

Most of these instruments were connected to an automatic data acquisition system which recorded the output at 20 minute intervals. The location of the weather station is approximately 50 meters south of the test field. For more details on the weather station and the instrumentation, see Atmar et al. (1977).

4.5 Plant Measurements

Leaf area. The leaf areas of plants grown in the lysimeters were measured with a portable area meter (Model LI-300, LICOR). Leaf samples were also collected from the field surrounding the lysimeters on a weekly basis. They were used to obtain the relationship between leaf area and leaf weight (leaves dried at 70° C for 43 hours).

Plant pressure potential. A pressure bomb, similar to the apparatus described and used by Scholander et al. (1964) was used to measure plant water-potential. The method consists of cutting a leaf from a plant, sealing the leaf petiole with a rubber gasket, placing the leaf with gasket in the chamber, and increasing the pressure until water from the xylem tubes can be observed. The pressure in the bomb should be equivalent to the absolute value of the pressure in the stem before the cut. Daily triplicate samples from the lower, middle, and upper parts of the plants were taken every hour from 7:00 A.M. to 7:00 P.M. for the period of August 2 to 9, 1976.

Plant dry weight. Plant dry weights were determined every week by oven-drying duplicate samples at 70° C for 2 days. Dry weights of the leaves, stems, and bolls were determined separately for each sample.

Estimation of root mass. An inexpensive and efficient method for separating root mass from soil was developed (Al-Khafaf, Wierenga and Williams, 1977). The method is similar to the procedure used by Robinson and Kurst (1962) and Malone (1962) for separating weed seeds from soil. The method involves chemical dispersion of the soil followed by flotation, and the straining of roots and organic matter from the surface of the suspension. Roots are separated from organic debris, divided into fine and suberized roots, and the dry weights of fine and suberized roots are determined.

In the procedure for separating the root mass, the soil containing roots was excavated from the field soil profile, and placed in 70-liter plastic containers. Salt solution containing 40 g/liter of sodium hexametaphosphate was added to the soil in a ratio of one part soil to five parts salt solution. Sodium hexametaphosphate was added to disperse the soil, and to separate the roots from the soil. Root separation was further enhanced by stirring the soil suspension, and by manually breaking the larger clods and aggregates. Dry, 78% pure $CaCl_2$ was finally added to the soil suspension in a ratio of one gram $CaCl_2$ to 2 grams of soil suspension. The $CaCl_2$ was obtained from a local tire retail outlet. Its solution is used in tractor tires to increase their weight. Upon addition of the $CaCl_2$ to the soil suspension, the soil solution mixture was further agitated by mechanical means or by hand, and then allowed to stand. As a result of the increase in density caused by the addition of $CaCl_2$ to the suspension (final density of the solution 1.5 g/liter), roots and organic matter floated to the surface of the container. The roots and organic matter were skimmed from the surface with a fine wire strainer and transferred to a plastic dish pan. The agitation and skimming were repeated approximately four times, until no roots were observed in the suspension. The soil suspension was allowed to stand for four hours, and then filtered through cheesecloth. The root mass collected on the cheesecloth was generally less than 0.5% of the root mass skimmed from the surface of the suspension.

The roots and organic matter removed from the soil suspension were soaked in tap water for two hours. Differences in density caused most of the roots to sink to the bottom of the dish pan, and the organic trash to float to the surface of the water. After removing the remaining roots from the organic trash using forceps, the organic trash was skimmed from the surface of the water. The larger suberized roots were separated from the root mass, based on visual observation of diameter and color. Subsamples were taken from the suberized root mass and from the remaining root mass, and the diameters of the roots in each of these subsamples were determined under a microscope. The air-dry weights of the root samples were determined by air-drying for 48 hours at 70° C.

Ten plastic barrels (53 cm in diameter and 68 cm deep) were filled with thoroughly mixed soil to have the same bulk density as that of the lysimeters. The final makeup of the profile in the barrels was: 0-60 cm, clay loam, and 60-68 cm, sandy loam. Holes were made in the bottom of each barrel to provide drainage. The barrels were embedded in one row of a 1 ha field with the bottoms 68 cm below the soil surface and the sand in the barrels in direct contact with the sand of the supporting subsoil. The barrels were spaced at a distance of 120 cm from center to center.

Starting on June 21, 1976, one embedded barrel was removed each week from the field plot and sectioned into 10 cm layers.

The effects of different water applications (wet and dry treatments), irrigation methods (trickle and furrow irrigation), and crop densities (single and double row treatments) on root distribution patterns were investigated by determining the root mass distribution in a number of 100 cm x 100 cm and 100 cm deep blocks of soil randomly selected from each field treatment. Each 1 m^3 block of soil was sectioned in ten 10-cm-deep layers. Each layer was in turn sectioned in 20-cm-wide strips, with the middle of the center strip along the plant row. The roots in this 20 x 100 x 10-cm-deep strip of soil were determined as above.

4.6 Field Test

The field containing the embedded barrels was seeded with upland cotton (*Gossypium hirsutum*), Acala strain (B-344) on May 20, 1975, and May 5, 1976. The rows were spaced at 100 cm and the average cotton stand was seven plants/m^2. The cotton was irrigated at weekly intervals with trickle lines 10 cm below the ridge of each row. The amount of water applied was based on consumptive use data determined for cotton at the site during the previous year.

4.7 Treatments

The irrigation treatments consisted of a wet and a dry treatment. The amount of water applied to the wet treatment was approximately equal to potential evapotranspiration. The soil pressure potential was kept between -0.1 and -0.6 bars. The dry treatment was irrigated every three weeks. The soil pressure potential varied between -0.1 and -20 bars.

5. RESULTS AND DISCUSSION

This chapter will consist of four parts:

5.1 Cotton growth and development

5.2 Potential evaporation

5.3 Evapotranspiration

5.4 Simulation.

5.1 Cotton Growth and Development

Leaf area and leaf dry weight. The dry weights of the leaves and stems, and the LAI of the wet and dry treatments for 1975 and 1976 are presented in tables (4) and (5), respectively. The variation in dry weights and LAI for similar treatments between the two seasons resulted from different growth conditions. Results of the leaf area measurements taken in 1976 are shown in Figure (9). Each data point represents the average of two samples for each irrigation interval. In 1976, both the wet and dry treatments showed a small increase in LAI during the first 40 days following emergence, then a rapid increase until the crops reached maturity at approximately 100 days after emergence (Fig. 9). The decrease in LAI toward the end of the growing period was due to plant maturity. The relationship between the dry weight of the leaves per unit soil surface area (LDW) and LAI is shown in Figure (10). The best fit, using linear regression analysis, is:

$$\mathrm{LDW} = 0.0692\mathrm{LAI} \qquad (65)$$

where LDW is in kg m^{-2}. The correlation coefficient (r) is 0.992. Eq. (65) is for the entire growing season.

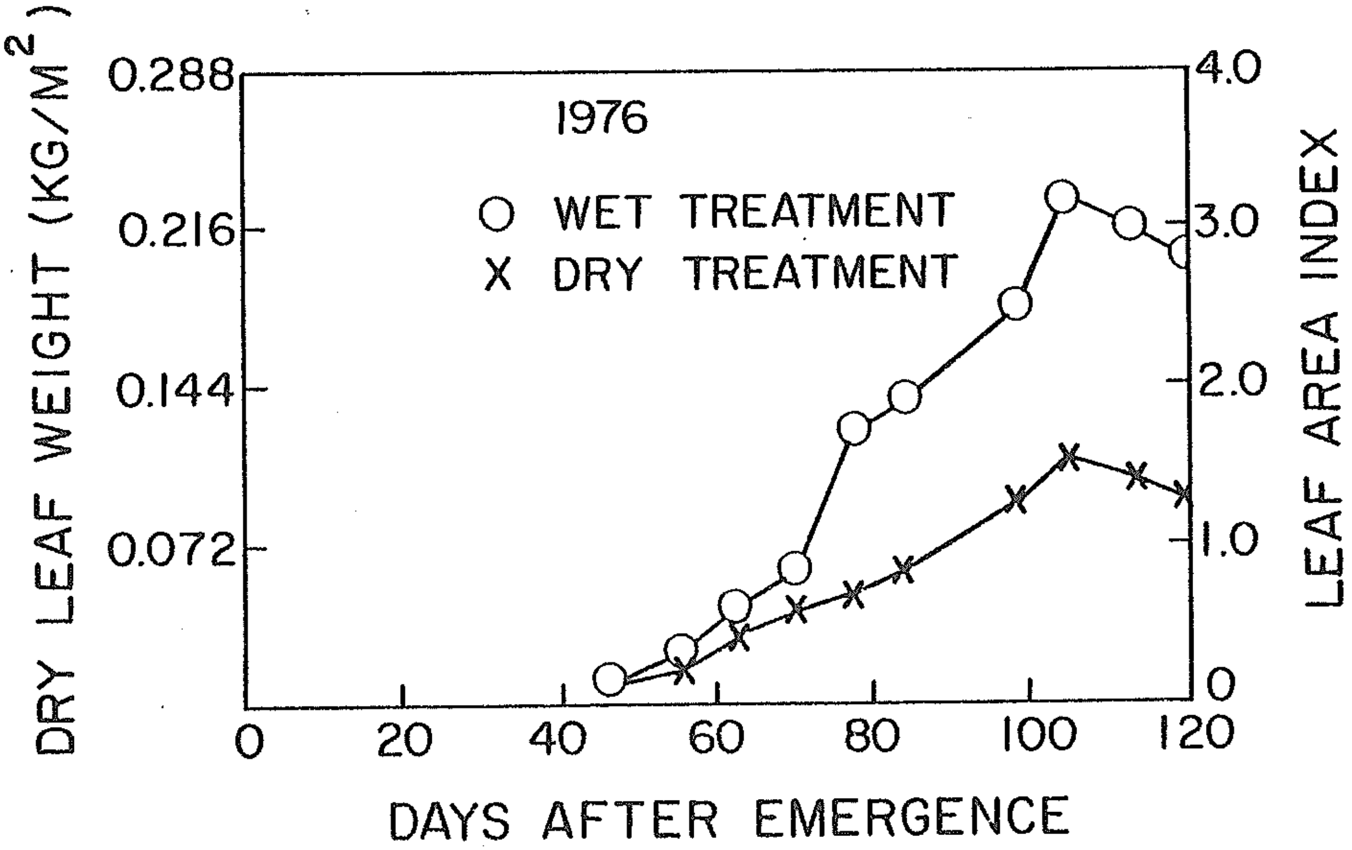

Figure 9. The relationship between leaf area index, leaf dry weight and time after emergence for cotton, 1976.

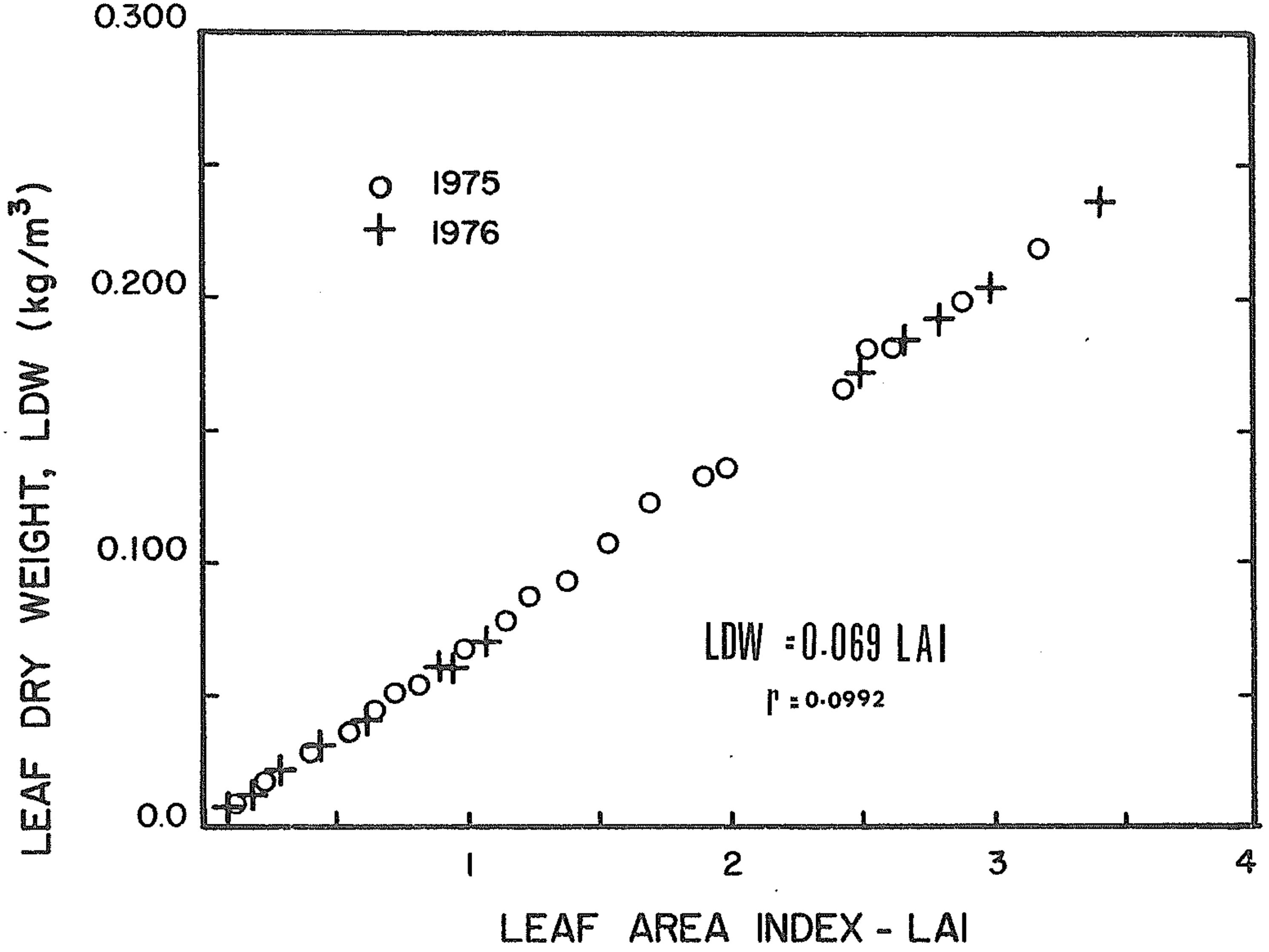

Figure 10. The relationship between leaf area index and leaf dry weight for cotton in 1975 and 1976.

Table 4. Leaf-, stem-, and total dry weights, and leaf area index for cotton (wet and dry treatments) 1975.

	1975							
	Wet Treatment				Dry Treatment			
	Dry weight (g m^{-2})				Dry weight (g m^{-2})			
Date	Leaves	Stems	Total	LAI	Leaves	Stems	Total	LAI
6-4			0.92				0.92	
6-11			1.97				1.97	
6-21			3.40				3.40	
7-1			10.88	0.09			6.81	0.05
7-9	12.25	7.05	19.30	0.17	7.93	4.32	12.25	0.10
7-16	32.40	19.63	52.03	0.44	21.00	12.80	33.80	0.30
7-23	58.98	49.95	108.93	0.95	39.15	26.46	65.61	0.63
7-30	69.49	57.06	126.55	1.08	59.50	42.85	102.35	0.89
8-13	205.50	283.00	488.50	3.02	172.60	183.40	356.00	2.51
8-23	236.00	285.50	521.50	3.42	191.50	227.00	418.50	2.81
9-6	205.00	280.00	485.00	3.00	185.30	225.00	410.30	2.67

Table 5. Leaf-, stem-, and total dry weights, and leaf area index for cotton (wet and dry treatments) 1976.

	1976							
	Wet Treatment				Dry Treatment			
	Dry weight (g m^{-2})				Dry weight (g m^{-2})			
Date	Leaves	Stems	Total	LAI	Leaves	Stems	Total	LAI
6-16	7.80	4.10	11.90	0.11	7.56	4.20	11.76	0.11
6-25	18.00	10.00	28.00	0.26	14.30	6.71	21.01	0.20
7-2	47.00	31.62	78.62	0.66	27.10	19.71	46.81	0.42
7-8	56.30	54.16	110.46	0.82	37.30	40.00	77.30	0.58
7-15	123.10	123.16	246.26	1.69	53.10	54.12	107.22	0.72
7-22	136.10	143.88	279.88	1.90	56.21	84.92	140.13	0.83
7-29	136.20	142.17	278.37	1.98	82.50	82.76	164.26	1.15
8-5	180.60	201.30	381.90	2.52	90.50	84.35	174.85	1.25
8-12	220.00	256.90	476.90	3.17	109.20	112.20	221.40	1.56
8-19	200.60	246.71	447.31	2.90	97.30	105.63	202.93	1.40
9-9	184.50	241.56	426.06	2.63	73.00	79.20	152.20	1.00
9-16	165.30	228.30	393.60	2.44	51.00	67.32	118.92	0.73

Root growth. Embedded containers: Root dry weights of the plants grown in the embedded containers are given in Table (6) and plotted versus depth in Figure (11) for June 21, July 5, July 19, and August 9, 1976. The solid line indicates the dry weight of the fine plus the suberized roots. The parameters to define fine and suberized roots are given in Table (7). Figure (11) shows that the densities of fine roots and suberized roots vary with depth and time. Suberized roots of established plants were concentrated near the soil surface and fine roots spread fairly evenly throughout the soil profile. On June 21 the density of the fine roots was 2.37 g/barrel and the density of suberized roots was 0.50 g/barrel. The growth rates of the fine roots were 1.02, 0.76, and 0.03 g/day for the periods June 21 to July 5, July 5 to July 19, and July 19 to August 9, respectively. The growth rates of the suberized roots were 0.36, 1.14, and 0.17 g/day for the same periods. The results show that the increase in the weight of the fine roots was 0.40 g and of the suberized roots 2.54 g during the period July 19 to August 9. Since blooming started on July 8, it appears that the root system was nearly fully developed when the bolls started to form.

Figure (12) shows the relationship between dry weight of the fine roots and LAI of the plants in the containers. The results indicate that the fine root system was nearly fully developed when the LAI reached a value of 2.5.

Field samples: Root and shoot dry weights were also determined for cotton grown in the undisturbed field soil outside the embedded

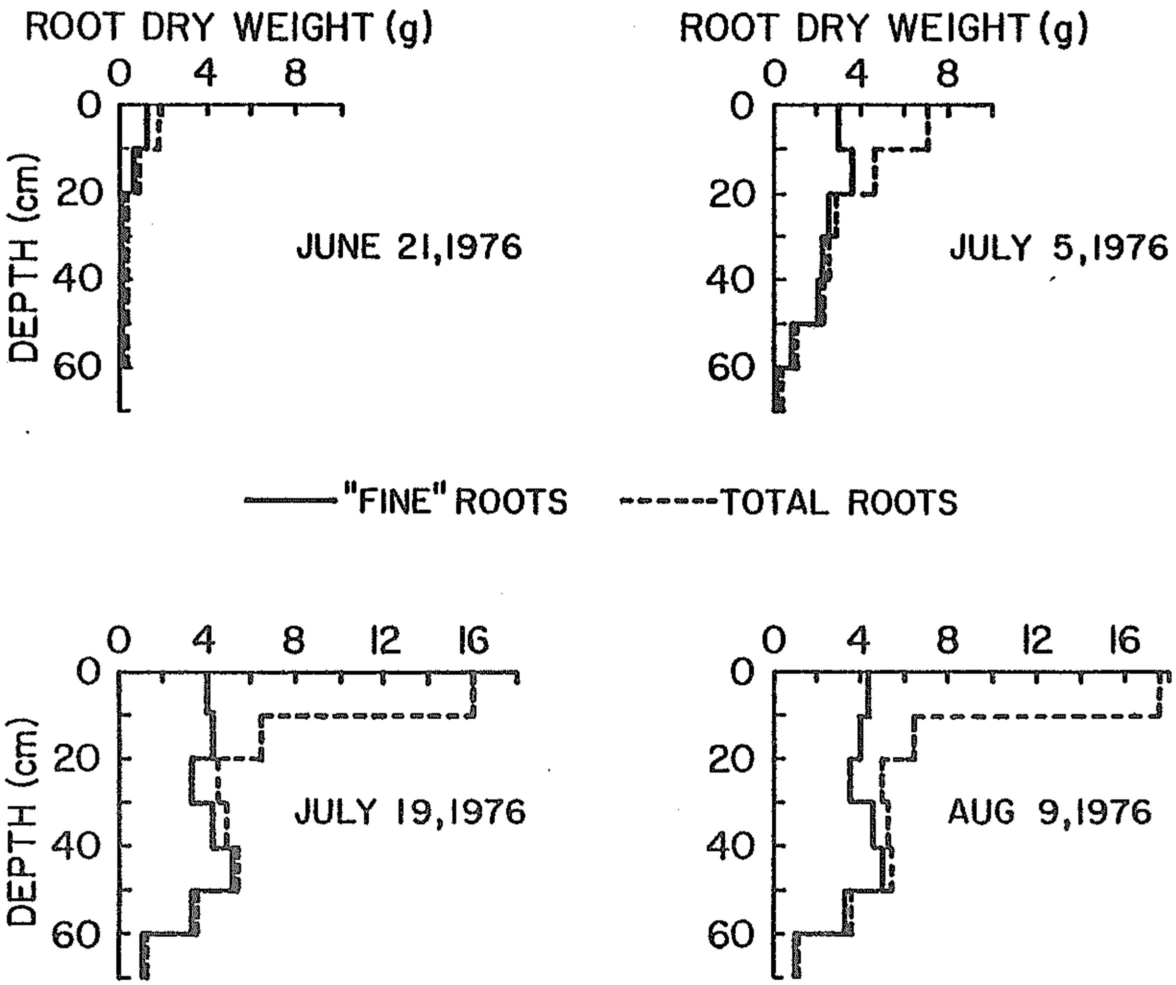

Figure 11. Root distribution as a function of time and depth for cotton grown in the embedded containers.

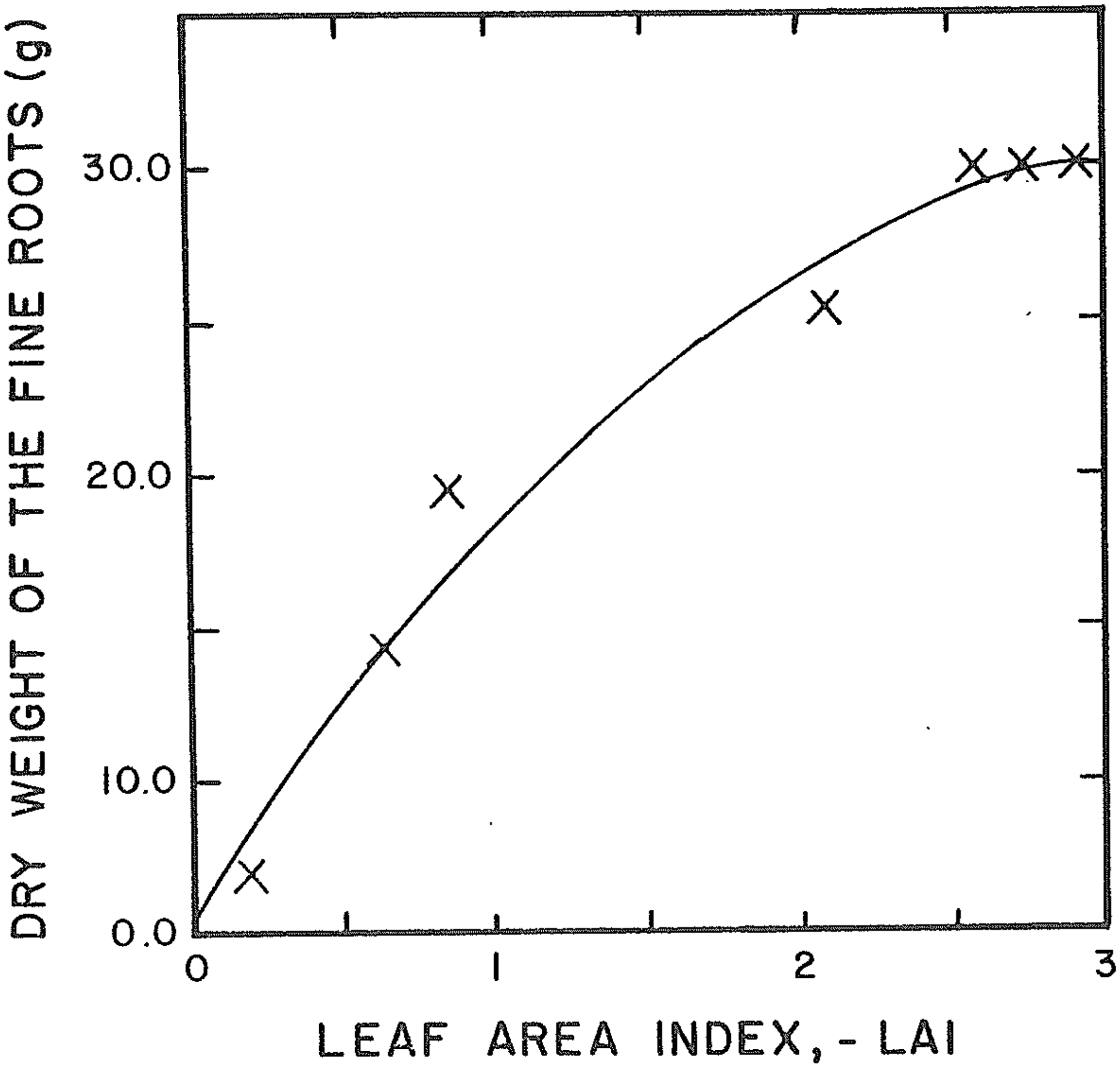

Figure 12. The relationship between dry weight of the fine root and leaf area index for cotton grown in the embedded containers in 1976.

Table 6. Dry weight distribution of fine and suberized roots as function of time and depth, and dry weight of leaf and stem and root/shoot ratio. Samples taken from the embedded containers, 1976.

Depth (cm)	Date 6/21	 7/5	 7/19	 8/9
		Dry Weights of Fine Roots (g)		
0-10	1.28	3.04	4.00	4.36
10-20	0.75	3.75	4.20	4.03
20-30	0.13	2.54	3.29	3.49
30-40	0.10	2.30	4.10	4.56
40-50	0.08	2.12	5.10	4.97
50-60	0.03	0.87	3.40	3.27
60-68	0.00	0.10	1.16	0.90
Total	2.37	14.72	25.25	25.58
		Dry Weights of Suberized Roots (g)		
0-10	0.49	4.11	12.19	13.39
10-20	0.08	1.03	2.33	2.44
20-30	0.06	0.30	0.92	1.46
30-40	0.05	0.10	0.76	0.73
40-50	0.02	0.07	0.28	0.35
50-60	0.00	0.06	0.08	0.31
60-68	0.00	0.05	0.05	0.30
Total	0.70	5.62	16.61	18.98
Leaves dry weight (g)	3.7	15.79	48.23	56.00
Stem dry weight (g)	2.12	16.63	72.20	74.50
Bolls dry weight (g)	-	-	-	94.4
R/S*	0.53	0.63	0.35	0.34

$$*R/S = \frac{\text{Fine + suberized}}{\text{Leaves + stem}}$$

Table 7. Mean and standard deviation of fine and suberized roots. Samples were taken August 23, 1976, from the last container.

	Fine Roots					Suberized Roots		
			Percent of roots that have a diameter less than					
Depth (cm)	Mean (mm)	S.D.	0.08	0.24 (mm)	0.40	Mean (mm)	S.D.	Range of Diameter (mm)
0-10	0.242	0.096	1	60	95	1.060	2.196	11.7 - 0.4
10-20	0.244	0.087	0	58	100	1.285	1.517	5.6 - 0.4
20-30	0.236	0.093	2	54	98	0.949	0.731	4.2 - 0.4
30-40	0.236	0.101	0	59	94	1.143	1.098	3.7 - 0.4
40-50	0.249	0.096	0	51	97	1.289	1.631	4.0 - 0.4
50-60	0.249	0.119	0	52	92	0.790	0.314	1.9 - 0.4
60-70	0.646	0.253	0	1	21	1.017	0.204	1.4 - 0.8

S.D. = Standard Deviation

\+ Number of Samples = 100

lysimeters. Root and shoot samples were taken in plots subject to the following treatments: wet and dry trickle irrigation, single and double row cropping with trickle irrigation and furrow irrigation. All root samples except the sample in the furrow-irrigated plot were taken within the one hectare experimental field. The furrow-irrigated area is at the south of the farm. The depth of the clay layer was 60-80 cm from the soil surface. All root samples except samples in the dry trickle-irrigated plot were taken in duplicate. One sample was taken in the dry trickle-irrigated plot.

The results are presented in Table (8). Two-dimensional representations of the root distribution in each of these treatments are given in Appendix (A) tables (1) - (7).

Dry weights of the fine roots are plotted versus depth in Figure (13) for the wet and dry trickle irrigation treatments. Amounts of irrigation water used on the wet and dry treatments were 52 and 35 cm, respectively. Figure (13) shows that the root mass varied with depth, for one location one dry and one wet, and reached a maximum at a depth of 20 cm in both treatments. The trickle line was 10 cm below the soil surface. The field was irrigated once a week with an average of approximately 4 cm water applied per irrigation. A typical water content distribution versus depth is plotted in Figure (14) for plots which were irrigated by trickle irrigation on July 23, 1976. The water content reached a maximum value at a depth of 20 to 30 cm below the soil surface which may explain why the root mass was greatest at 20 cm below the soil surface. The dry weight of the fine roots in

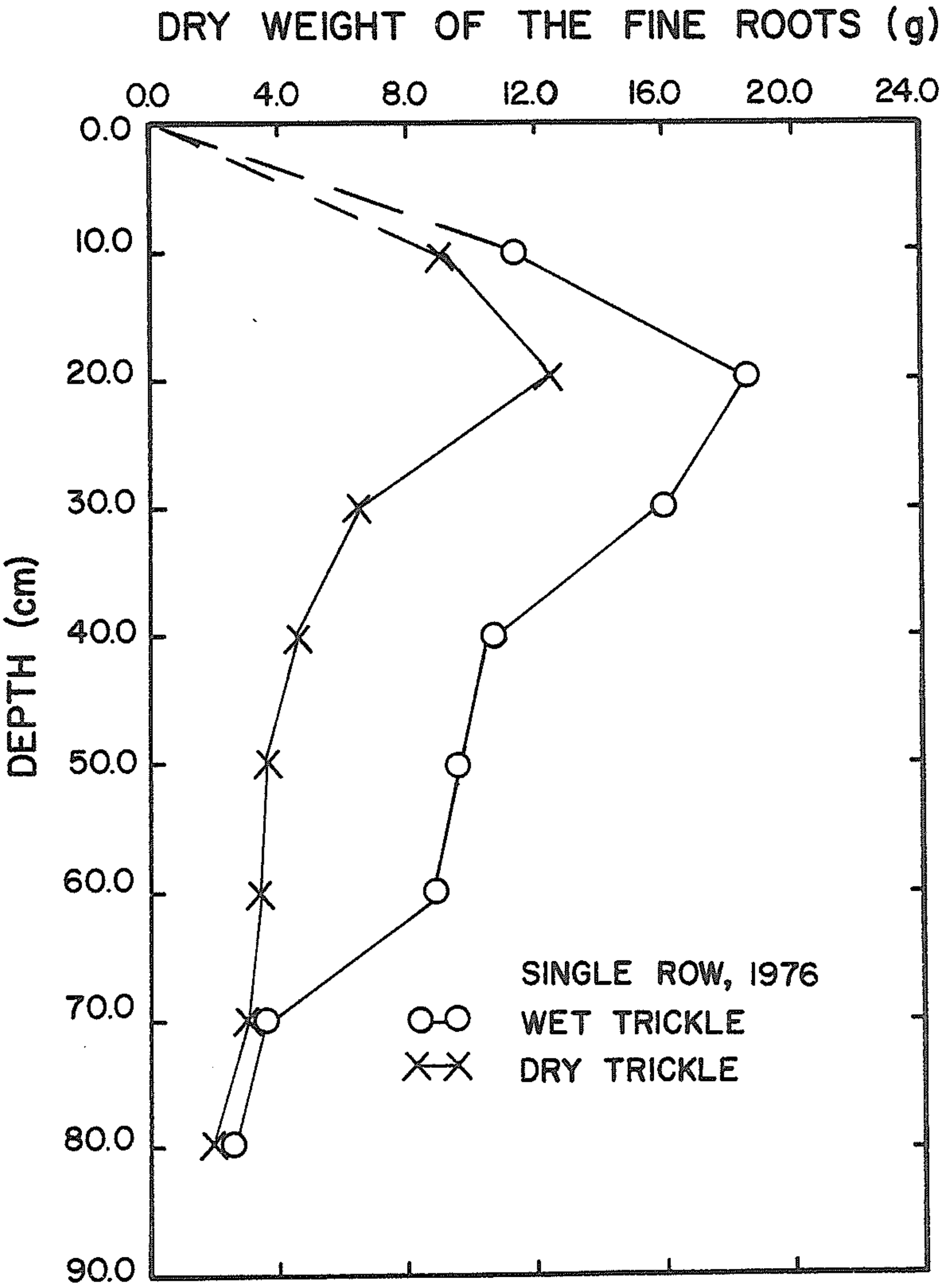

Figure 13. Root mass distribution of cotton grown in the field outside the containers and irrigated by trickle irrigation in 1976.

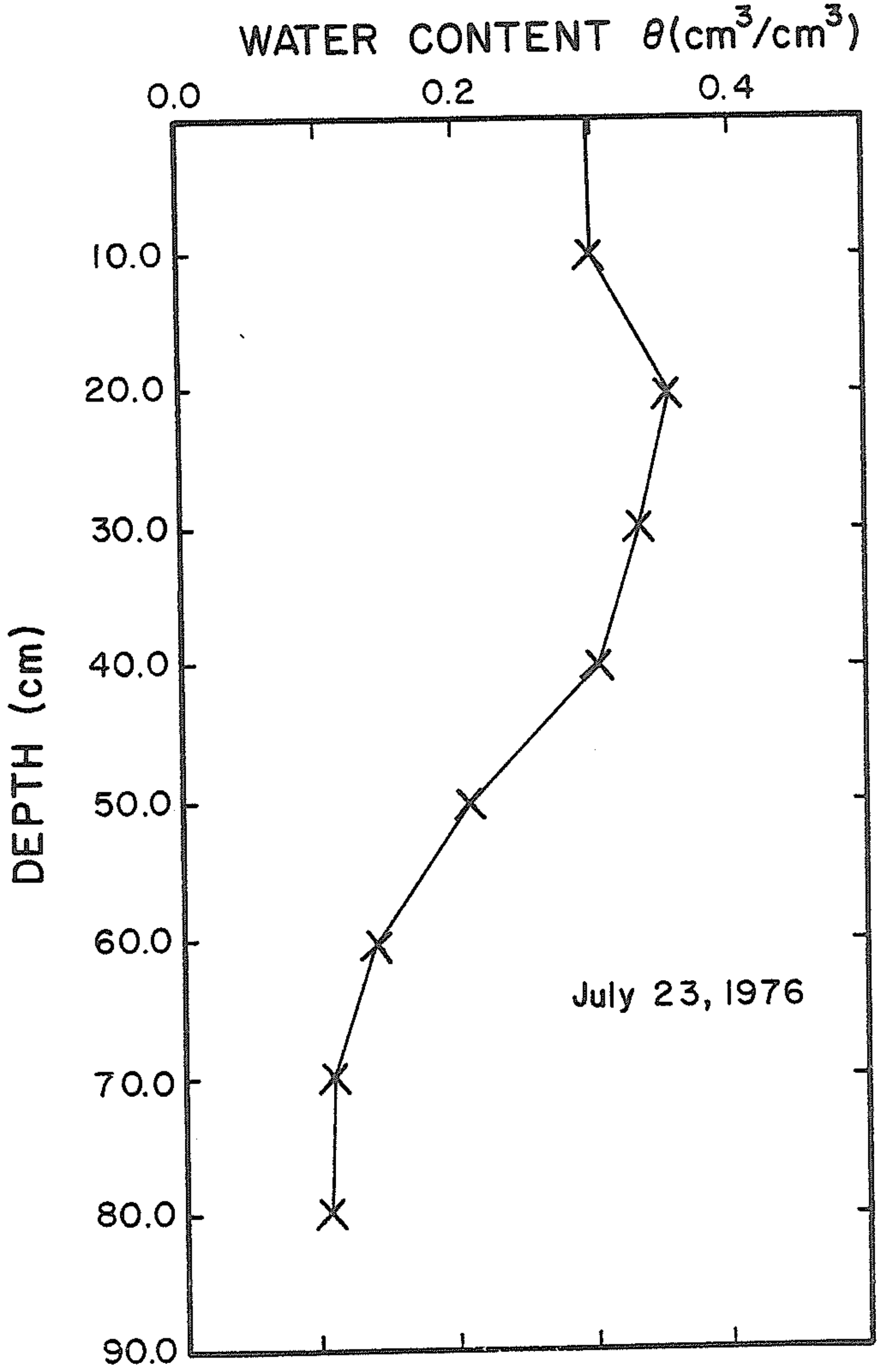

Figure 14. Water content distribution of the field irrigated using trickle irrigation system.

Table 8. Dry weights of different parts of the cotton plant. Field plot samples (1976).

Treatments	Date	Dry Weight (g)						
		Fine Roots	Suberized Root	Total	Leaves	Stems	Bolls	R/S
WTSR	8-10-76	81.75	42.29	124.04	80.00	110.00	112.00	0.65
	8-16-76	81.65	42.28	123.93	81.40	117.30	114.40	0.62
DTSR	8-3-76	45.72	21.44	77.16	32.40	41.20	54.10	1.05
WTDR	8-17-76	112.91	75.46	188.37	204.00	210.00	214.90	0.45
	8-20-76	115.16	70.92	186.08	193.60	223.10	348.40	0.45
WSSR	8-13-76	59.96	51.19	111.15	93.20	122.30	143.60	0.52
	8-18-76	59.56	53.52	113.08	100.30	135.70	175.40	0.48

WTSR = Wet Treatment - Trickle Irrigation - Single Row

DTSR = Dry Treatment - Trickle Irrigation - Single Row

WTDR = Wet Treatment - Trickle Irrigation - Double Row

WSSR = Wet Treatment - Furrow Irrigation - Single Row

$$R/S = \text{Roots/Shoots} = \frac{\text{Fine} + \text{Suberized}}{\text{Leaves} + \text{Stems}}$$

the wet treatment was 1.78 times that of the weight of the fine roots in the dry treatment (see Table 8). Root-to-shoot ratios are 1.05 and 0.63 for the dry and wet treatments, respectively. This indicates that when the plants were under water stress, the reduction in the shoot growth was more than for root growth.

Figure (15) shows root dry weight versus depth for single and double row cotton. The single rows were planted 100 cm apart and the double rows were also spaced at 100 cm. The distribution patterns were approximately the same in both treatments, but the total dry weight of the fine roots in the double rows was 1.4 times greater than in the single rows. The root-to-shoot ratios were 0.63 and 0.45 for the single and double rows wet treatments, respectively. Apparently competition tends to reduce root growth more than shoot growth (Kramer, 1969). The root mass from the trickle- and furrow-irrigated wet treatments are plotted in Figure (16). The data show that the root densities tend to be more uniform with depth under furrow irrigation, as compared with trickle irrigation. The field was furrow-irrigated every two weeks with approximately 8 cm of water applied per irrigation. Measurements of soil water content were not taken for the furrow-irrigated plots at the time.

The statistical analysis indicates that the dry weights of the fine roots for the treatments given in Table (8) are significant at 5% confidence level.

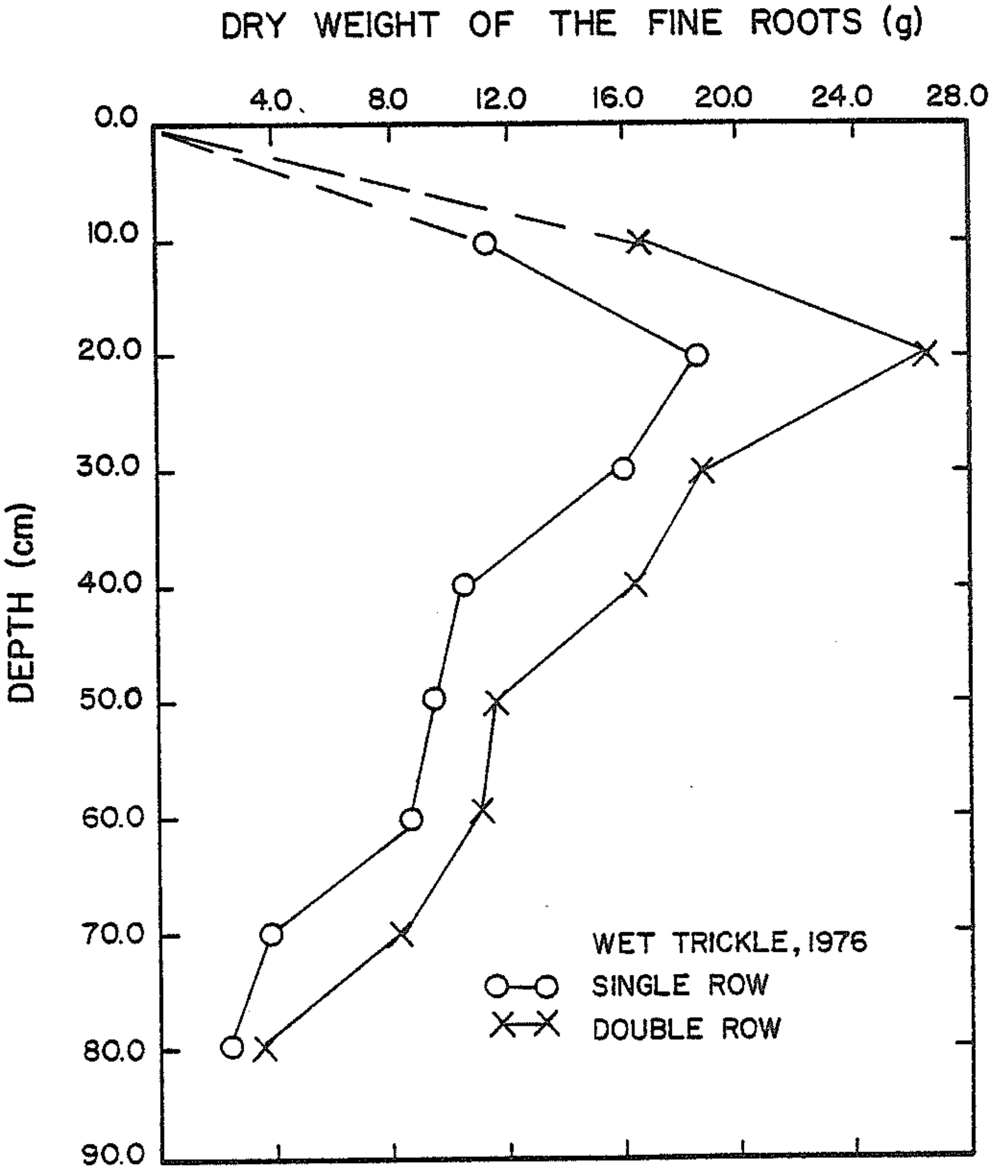

Figure 15. Root mass distribution of single and double row cotton, irrigated by trickle irrigation.

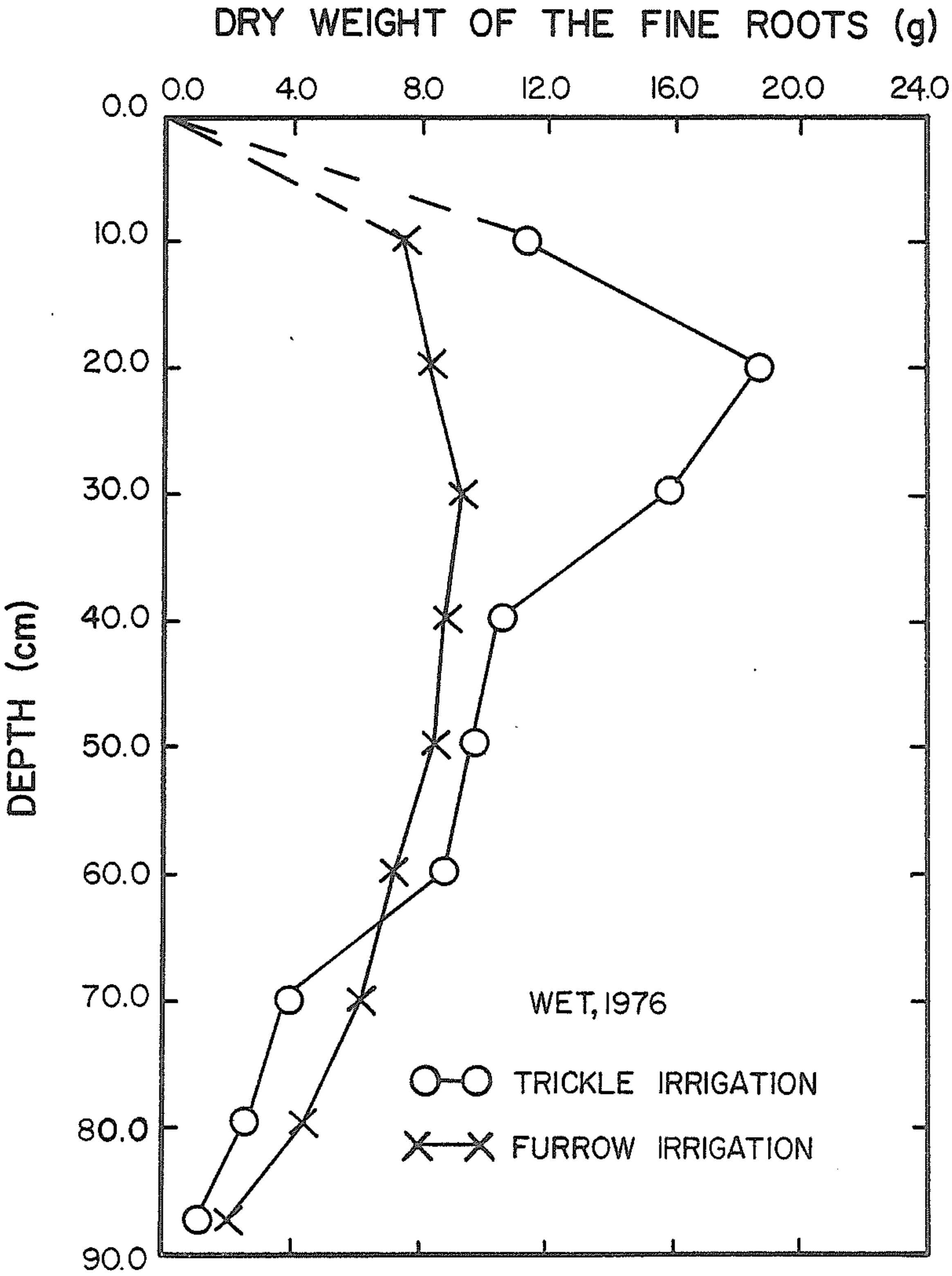

Figure 16. Root mass distribution of cotton irrigated by trickle and furrow irrigation.

5.2 Potential Evaporation

Methods for estimating potential evaporation were discussed in Chapter 2. A CSMP program is listed in Appendix (B), Tables (23 and (24) which calculates Eo using the following methods:

- A. Combination methods
  1. Penman equation
  2. Van Bavel equation
- B. Empirical methods
  1. Jensen-Haise equation
  2. Priestley-Taylor equation
  3. Christiansen-Hargreaves equation
  4. Net radiation
- C. Pan evaporation.

The climatological data was introduced into the CSMP program through nonlinear function generators (AFGEN). These data were maximum and minimum temperature, solar radiation, relative humidity, pan evaporation, and daily wind run. The program was designed to calculate Eo on a daily basis for the months of April through September for 1975 and 1976. In addition, an example is presented in Appendix B which shows how to calculate the constants, parameters, and data needed with a desk calculator, and how to compute Eo using any one of the methods mentioned above. Since the Penman equation is widely used, the Eo estimated by this method will be used as a measure of the evaporation and the results from the other methods will be compared with it.

The pan coefficient was obtained by correlating the data from a Class A pan with the results obtained with the Penman method. A pan coefficient of 0.78 ± 0.04 was found.

Cumulative Eo, calculated using the CSMP program, is listed in Tables (25) and (26), Appendix B. Figures (17) and (18) show the cumulative Eo plotted versus time for the months of April through September for 1975 and 1976, respectively. The potential evaporation rates for the growing seasons of 1975 and 1976 calculated using the CSMP program are listed in Table (1). The potential evaporation rates calculated with the desk calculator for the month of August 1975 are also presented. Potential evaporation rates calculated using the different methods are compared to rates calculated with the Penman equation. The differences in the potential evaporation rates obtained with the different methods and with Penman's equation are also listed in Table (9). The results show that Eo as estimated by the van Bavel, the Priestley-Taylor, the net radiation and the pan evaporation methods agreed reasonably well with cumulative Eo estimated with Penman's method. Differences were less than 5%. These methods therefore may be used to estimate potential evaporation from a free water surface in southern New Mexico. It should also be noted that the utility of the combination method is somewhat restricted by the availability of the data. Input data are not always available. On the other hand, pan evaporation data are widely available. The results in Figures (17) and (18) and Table (9) indicate that the evaporation pan provides a good method for long term prediction of Eo as

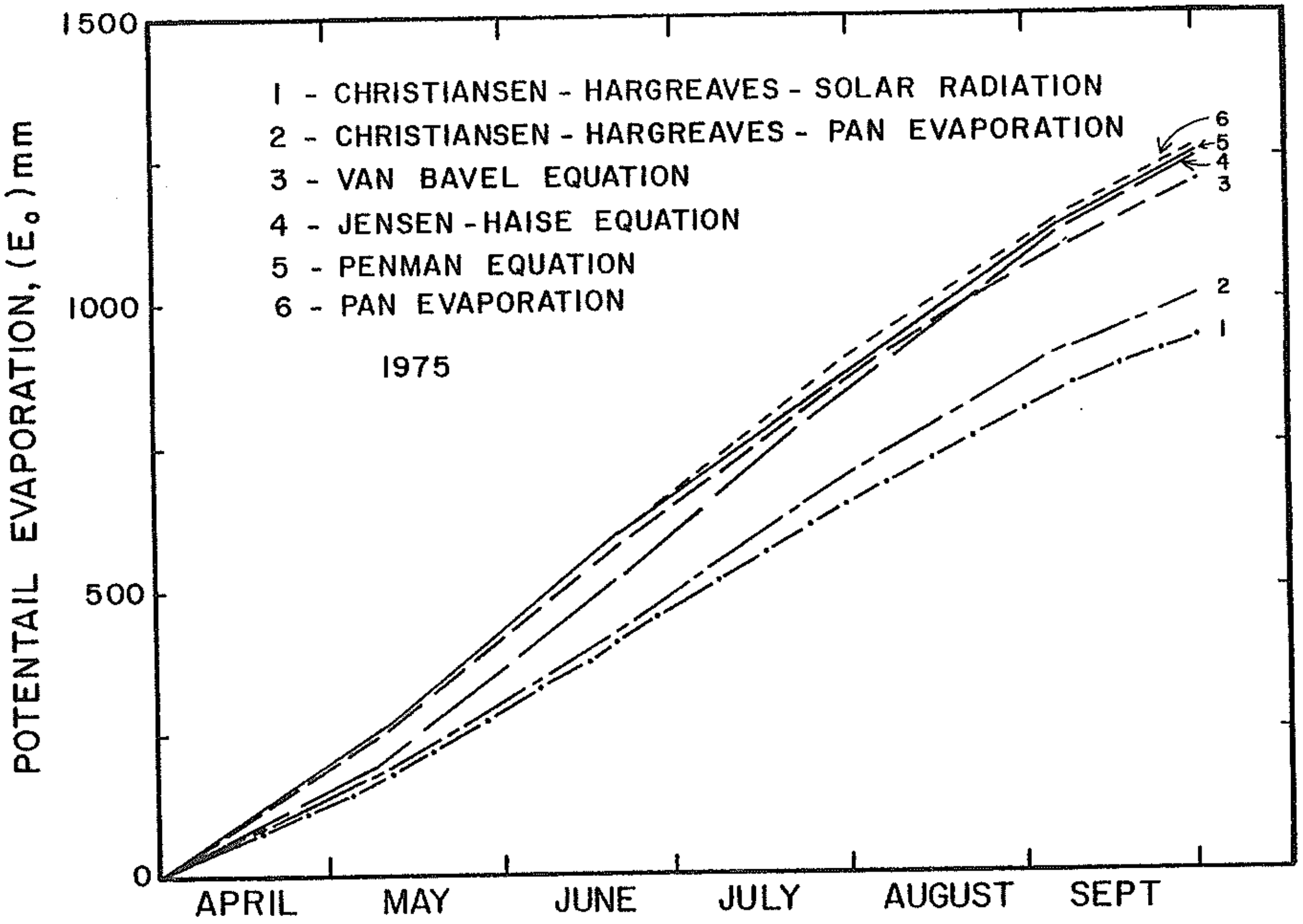

Figure 17. Cumulative potential evaporation calculated by different methods for the period of April through September, 1975.

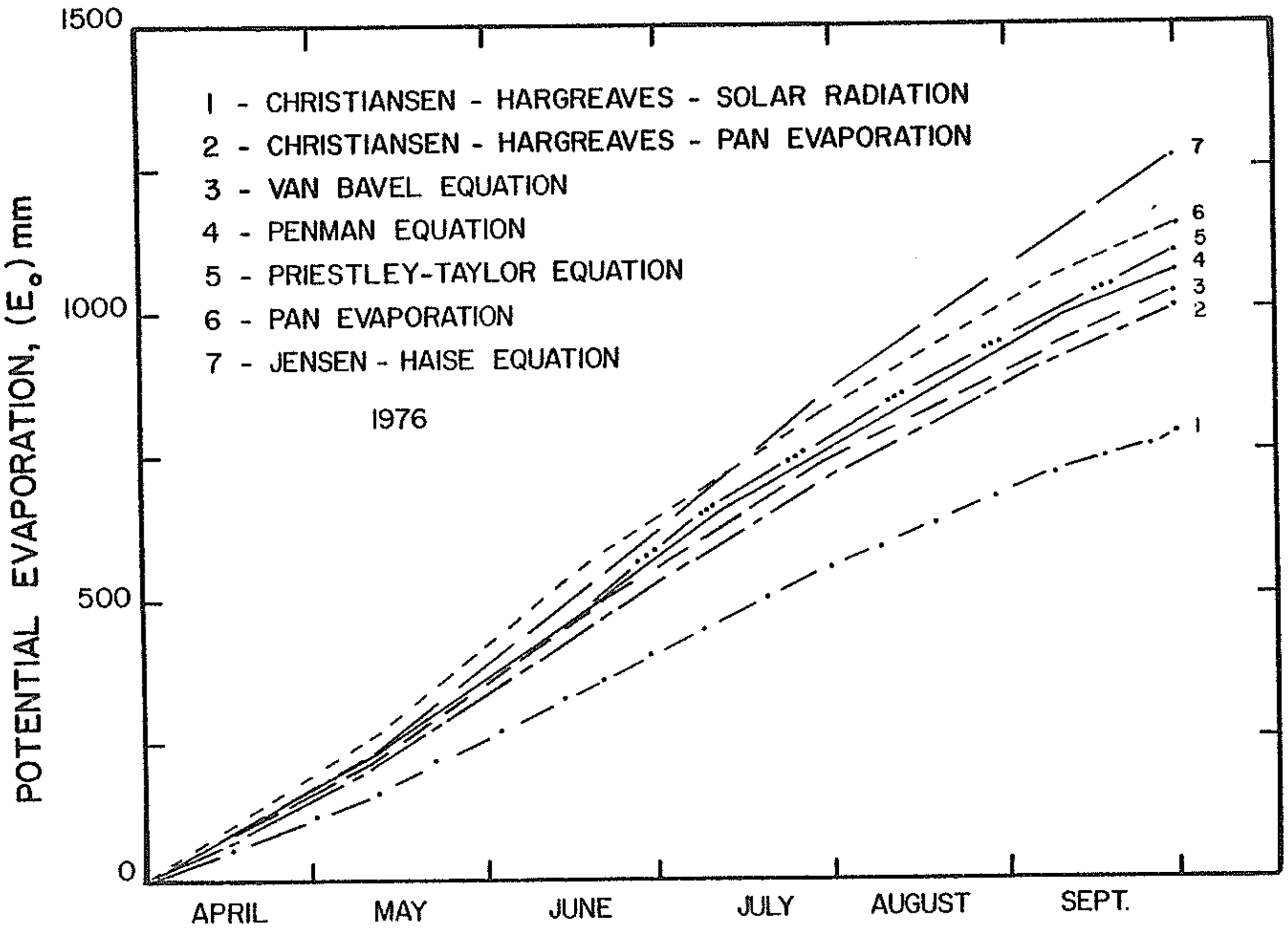

Figure 18. Cumulative potential evaporation calculated by different methods for the period of April through September, 1976.

Table 9. The rate of potential evaporation (Eo) calculated using different equations compared to the rate of Eo calculated by the Penman equation.

Method	The rate of Eo (mm day^{-1})			Percent deviation from Penman		
	Desk Calculator August 1975	Computer Program April-October		August 1975	April-October	
		1975	1976		1975	1976
Penman	6.3	6.87	5.82	---	--	--
Van Bavel	5.9	6.60	5.57	-6.3	-3.9	-4.3
Christiansen-Hargreaves						
a. Pan correlation	7.73	5.48	5.52	22.7	-20.3	-5.2
b. Solar radiation	4.84	5.08	4.14	-23.2	-26.1	-28.9
Jensen-Haise	7.00	6.83	6.79	11.1	-0.6	16.7
Priestley-Taylor	6.55	6.83	6.02	4.0	-0.6	3.4
Net Radiation	6.24	6.81	5.95	-0.9	-0.9	2.2
Pan Evaporation	6.23	6.82	6.14	-1.1	-0.7	5.5

compared to other methods. Measurement of Eo with a pan is inexpensive and is easily used by farmers or by a county agent.

The Jensen-Haise and Christiansen-Hargreaves equations were developed by using correlation techniques from a wide range of climatic conditions, but unfortunately the parameters in these equations differ depending upon location and local conditions.

5.3 Evapotranspiration

Evapotranspiration data from lysimeters. The evapotranspiration (ET) was obtained from the measurements of the amounts of irrigation water applied, the volumes of drainage water, and from the daily changes in soil water storage using the water balance equation:

$$ET = \Delta\theta \cdot L + q - D_r \qquad (66)$$

where θ is the water content (cm^3/cm^3), L is the thickness of the soil layer under consideration in cm, q is irrigation or rain in cm, and D_r is drainage in cm. Table (27) in Appendix C contains potential evaporation calculated by the Penman equation (Eo), irrigation or rain (q), evapotranspiration (ET), soil evaporation (Es), and leaf area index (LAI) for different treatments during 1975. Tables (28) - (35) in Appendix C contain the amount of soil water in 100 cm of soil (SW), irrigation or rain (q), drainage (D_r), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) for different treatments during 1976. Differences in total water content between the four replicate lysimeters in each treatment were less than 2 percent.

The cumulative ET values computed with Eq. (66) for 1975 and 1976 are presented in Fig. (19) for wet treatment, and in Fig. (20) for dry treatment. The data in these figures indicate that the cumulative ET values in 1975 and 1976 were nearly the same.

Because of the lack of an independent reliable method for determining ET at the experimental site, it is difficult to evaluate the accuracy of ET values. The largest uncertainty is introduced through the measurement of soil water-content with the neutron probe. However, differences in the water-content profiles of the duplicate bare lysimeters are measured with the neutron probe were less than 3 percent. Fig. (21) shows the total amounts of the water in the profile of the two bare lysimeters during the growing season, 1976. On June 6, a rainfall of 2.5 cm was measured at the weather station near the lysimeters. This rainfall caused a 1.8 cm increase in profile water content measured the next morning. Since soil evaporation on June 6 was 0.5 cm, 1.8 + 0.5 = 2.3 cm of the 2.5 cm rainfall was accounted for. Considering the errors in measuring in precipitation and in measuring water content with the neutron probe near the surface, such an agreement is encouraging.

Soil evaporation. Figure (22) shows cumulative soil evaporation, Es, as a function of time after irrigation, obtained from the measured water losses from the layers at 0-3 cm, 0-6 cm, 0-10 cm, and 0-15 cm when no canopy was present. The cumulative water losses determined from neutron probe data are also presented along with the measured

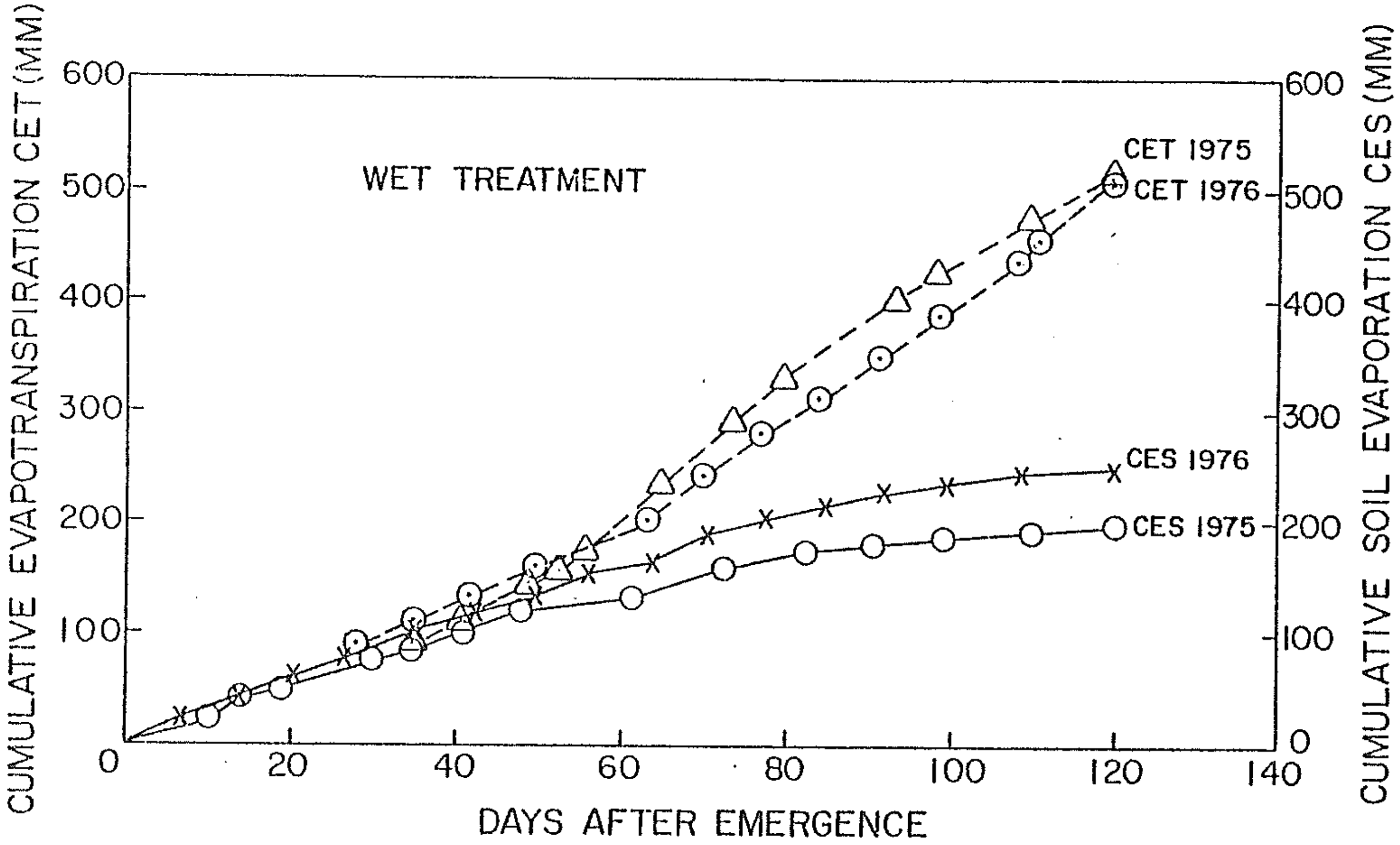

Figure 19. Average cumulative evapotranspiration and soil evaporation as measured with lysimeter in the wet treatment during 1975 and 1976.

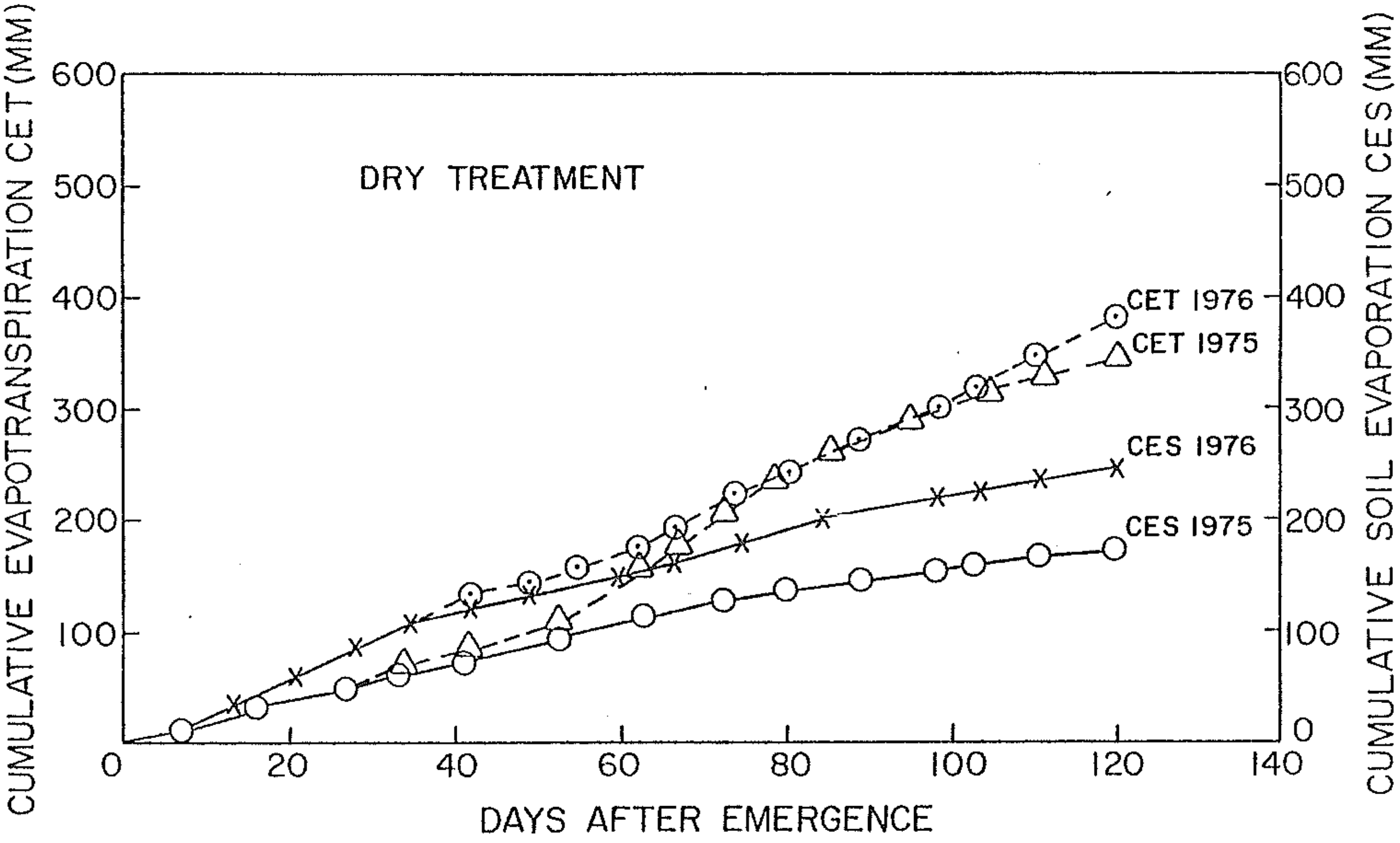

Figure 20. Average cumulative evapotranspiration and soil evaporation as measured with lysimeters in the dry treatment during 1975 and 1976.

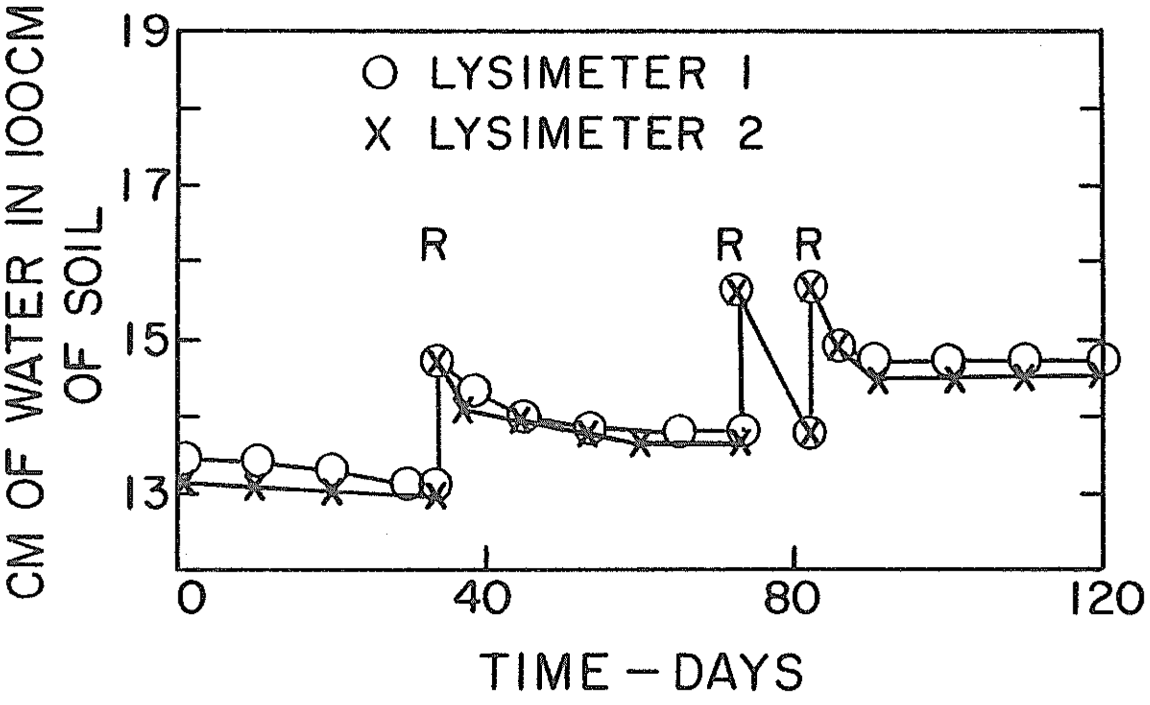

Figure 21. Changes in total amount of water held in two bare lysimeters, as measured with a neutron probe during the growing season of 1976.

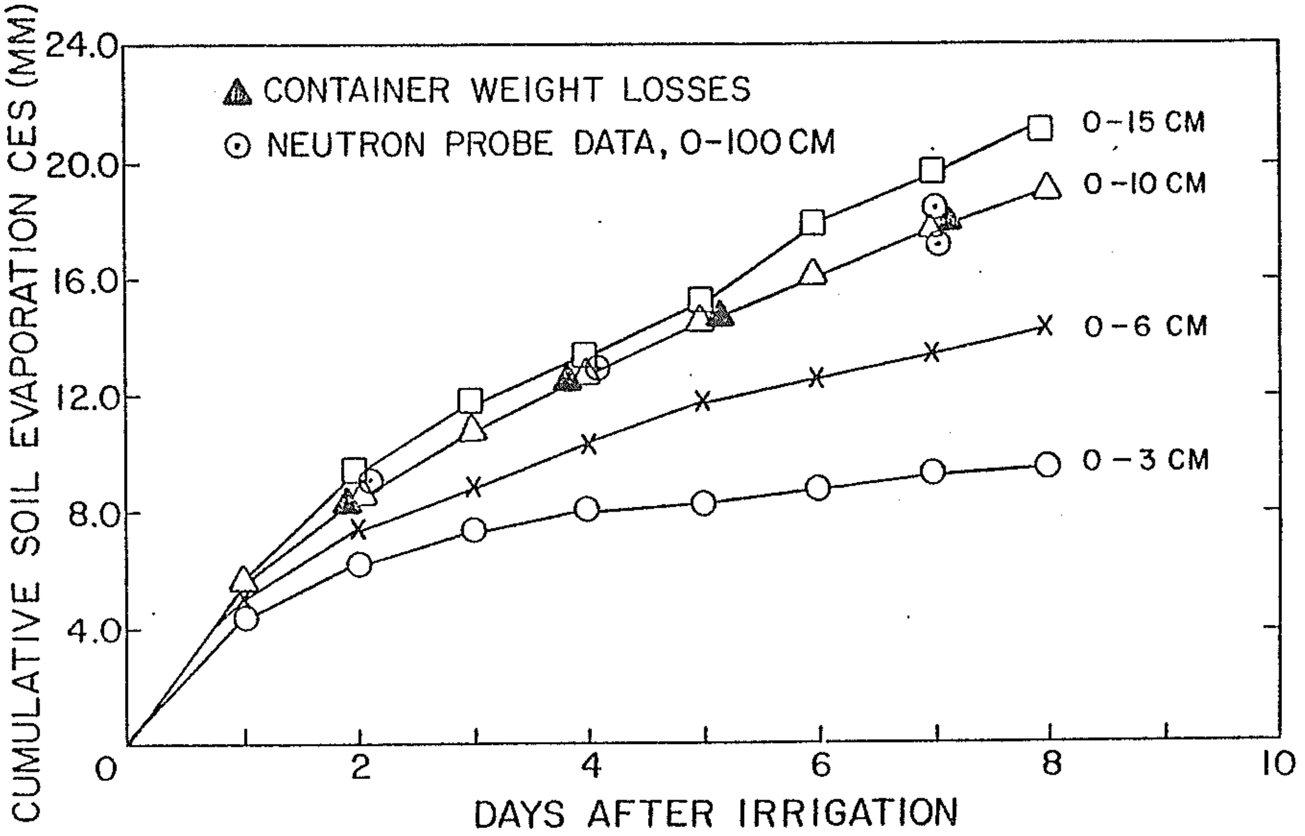

Figure 22. The relationship between soil evaporation (Es) and time after irrigation.

evaporation from the embedded buckets in the field. The data show that the soil surface evaporation decreases with increased drying of the soil. The data in this figure also show reasonable agreement between the evaporation, estimated from the differences in water contents from 0 to 10 cm, and evaporation estimated from the daily water depletion of the entire profile, as well as evaporation from the embedded buckets. Thus these methods (0-10 cm gravimetric samples, and embedded buckets) were assumed to be applicable under a crop canopy also.

The decrease in the rate of soil surface evaporation with time after irrigation or rainfall during the fall stage of evaporation may be expressed as follows (Black et al., 1969):

$$Es = a(t)^{b} - a(t - 1)^{b} \qquad (67)$$

where a and b are coefficients which vary with soil type, and t is time in days after irrigation. a is the soil evaporation one day after irrigation. For the Glendale clay loam soil, a is 5.8 mm/day A value for b = 0.6 was found by curve fitting the data from 0-10 cm depth. When a crop canopy is present, the use of Eq. (67) would result in values of Es which are too large due to shading by the canopy.

Under a crop canopy and assuming moist soil, soil evaporation is largely controlled by the evaporative demand, and by the degree of shading by the crop. In Fig. (23) we have plotted the ratio of soil evaporation which occurred during the first day after irrigation (Eso) to potential evaporation (Eo) versus the leaf area index (LAI). Soil evaporation was determined in 1975 by gravimetric sampling. In 1976, soil evaporation was determined by gravimetric sampling for the first month of the growing season and from the embedded buckets during the remainder of the growing season. In 1975, the lysimeters were irrigated through the trickle system. Soil samples were taken near the trickle line and in between trickle lines. The triangles in Fig. (23) are the data obtained near a trickle line and the crosses indicate the average of the water contents measured near and between the lines. In 1976, irrigation water was applied uniformly over the surface of the lysimeters.

Figure (23) indicates that if LAI>0.2, the value of Eso/Eo is a unique function of LAI, regardless of the relative position of measurements with respect to the trickle line. This finding is rather contradictory, since soil water-contents measured near a trickle line following irrigation were greater than those measured between the lines. The net energy that reached the soil surface through the crop canopy was probably so low that the evaporation from wet soil surfaces was the same as that from relatively dry soil surfaces, and the data presented in later sections indeed support this hypothesis. For subsequent days, surface evaporation near trickle lines was virtually the same as evaporation between the trickle lines. The relationship between Eso and LAI can be expressed in the following manner:

$$\mathrm{Eso} = \mathrm{Eo} \cdot e^{-0.623\mathrm{LAI}} \qquad (68)$$

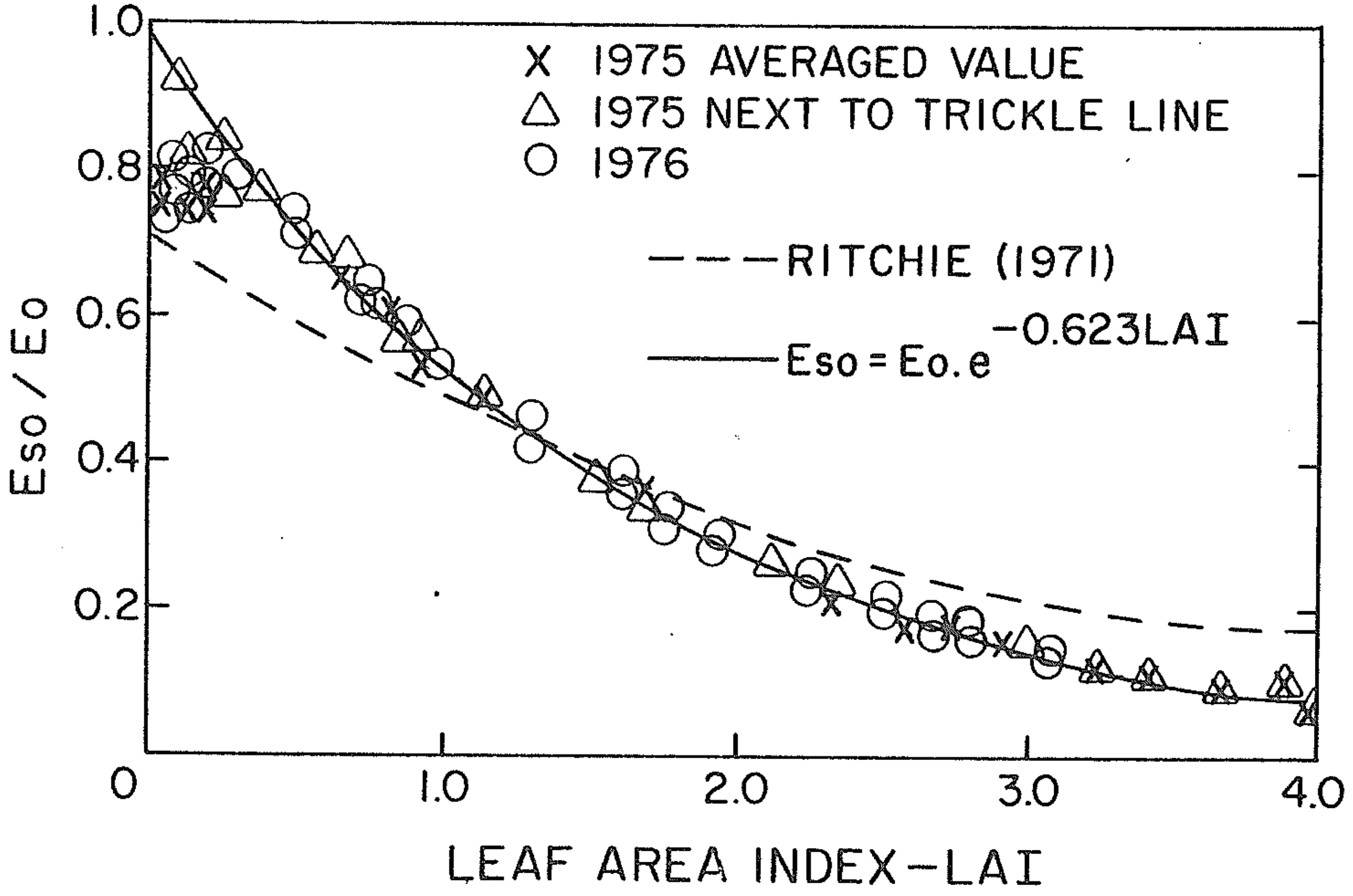

Figure 23. The relationship between the ratio of soil evaporation during one day after irrigation (Eso) to potential evaporation (Eo) and leaf area index (LAI).

For LAI less than 0.2, the data points showed considerable scattering (Fig. 23). However, values of Eso/Eo were nearly always close to 0.80 during the first day after irrigation regardless of the potential evaporation. Thus, if Eq. (68) is used to estimate Eso, a maximum value of 5.8 mm should be used for this soil. This limit would vary depending on the soil type (e.g., Ritchie (1972)), and also on the area of the wetted soil surface under trickle irrigation when the plants are small. Figure (23) also includes the relationship between Eso and LAI as estimated by Ritchie (1972). In Ritchie's method Eso was predicted using an empirical relationship between leaf area index and net radiation measured at the soil surface. This method evidently gives a lower Eso than our observed values when LAI<1.2. This deviation is probably caused by ignoring the wind and humidity effects on evaporation when the crops are relatively small. For LAI>1.2, Ritchie's method estimates a greater Eso than what we observed. This deviation is probably caused by ignoring temperature differences between the wet soil surface and the air above the canopy. The temperature of the wet soil surface is usually lower than the air above the canopy, and for each drop of 5° C the estimated Eso decreases by approximately 5% (see Penman equation 5).

<u>Transpiration</u>. Transpiration (Ep) was determined by subtracting Es from the measured evapotranspiration. When soils contain sufficient water, the Ep is controlled largely by the evaporative demand and crop cover. The ratio of the transpiration, which took place during the first day after irrigation (Epo), to the potential evaporation Eo,

calculated by Penman equation, is plotted agsinst the leaf area index (Fig. 24). The expression which fits the data points reasonably well is:

$$Epo = Eo\ (1 - e^{-0.623LAI}) \qquad (69)$$

Note that the sum of the Eso in Eq. (68) plus the Epo in Eq. (69) is equal to Eo indicating that potential plant and soil evaporation is equal to evaporative demands when soil water is not limiting for evaporation and transpiration.

Ritchie (1972) presented a similar empirical relationship between Epo/Eo and LAI for cotton grown under dryland conditions. The dashed line in Fig. (24) shows the best-fitting curve for his data, which differs slightly from the empirical equation proposed by Ritchie (1972). The observed ratio of Epo/Eo obtained by Ritchie (1972) is evidently greater than ours when LAI is small. This may be caused by the underestimation of Eso with his model. Also, recall that the empirical equation of Ritchie (1972) yielded values for Eso which were at least 5 percent greater than ours when LAI exceeded 2.0. Thus, it is possible that Epo/Eo may deviate by about 5 percent. It is uncertain if this 5 percent deviation represents the difference in transpiration characteristics of cotton or is caused by experimental errors. For all practical purposes, however, this agreement would be satisfactory.

Effect of soil water on transpiration. It is generally assumed that transpiration decreases with decreasing soil water-content in the root zone. In Fig. (25) the ratio of Ep to Epo is plotted versus

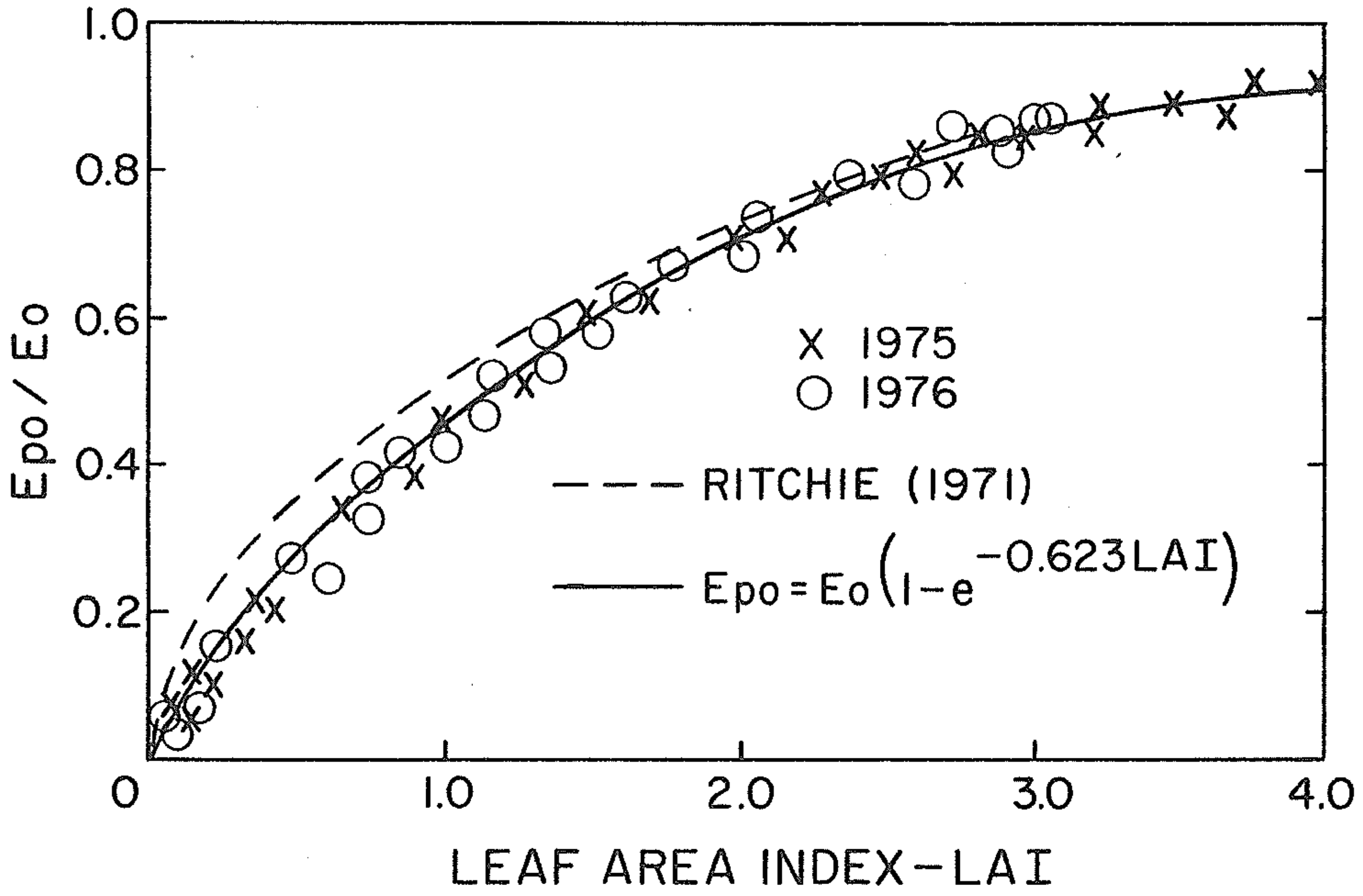

Figure 24. The relationship between the ratio of transpiration during one day after irrigation (Epo) to potential evaporation (Eo) and leaf area index (LAI).

the fraction of available water (FAW) remaining in the lysimeters for the 1975 and 1976 crop years. Available water is defined here as the difference in volumetric water content between -0.10 and -15 bars. The values for Ep used to construct Fig. (25) were measured data. Epo was estimated with Eq. (69) using the same LAI and Eo as observed when Ep was measured. The data in Fig. (25) indicate that Ep decreased after approximately 60 percent of the available water was depleted. (The water content of the soil in the wet lysimeter was never depleted beyond this value.) Ritchie et al. (1972) found that 75 percent depletion of available water was the onset point for Ep reduction in Houston black clay. With zero available water the ratio of Ep/Epo falls somewhere between 0.1 and 0.2. This indicates that transpiration continued after the soil water potential had decreased beyond the -15 bar limit.

The curve-linear relationship of Ep/Epo was approximated by

$$Ep/Epo = 1/(1 + 6.2\ e^{-15.2FAW}) \qquad (70)$$

Actual ET versus potential evaporation. Figure (26) shows the ratio of measured evapotranspiration versus calculated potential evaporation (Eo with Penman) as a function of days since emergence for the wet and the dry treatments during 1976. This ratio when averaged over the growing season is equivalent to the crop coefficient frequently used to convert values of Eo to actual evapotranspiration estimates. The ratio of actual ET to Eo for the wet and dry treatments was the same during the first 42 days. The wet and dry treatments

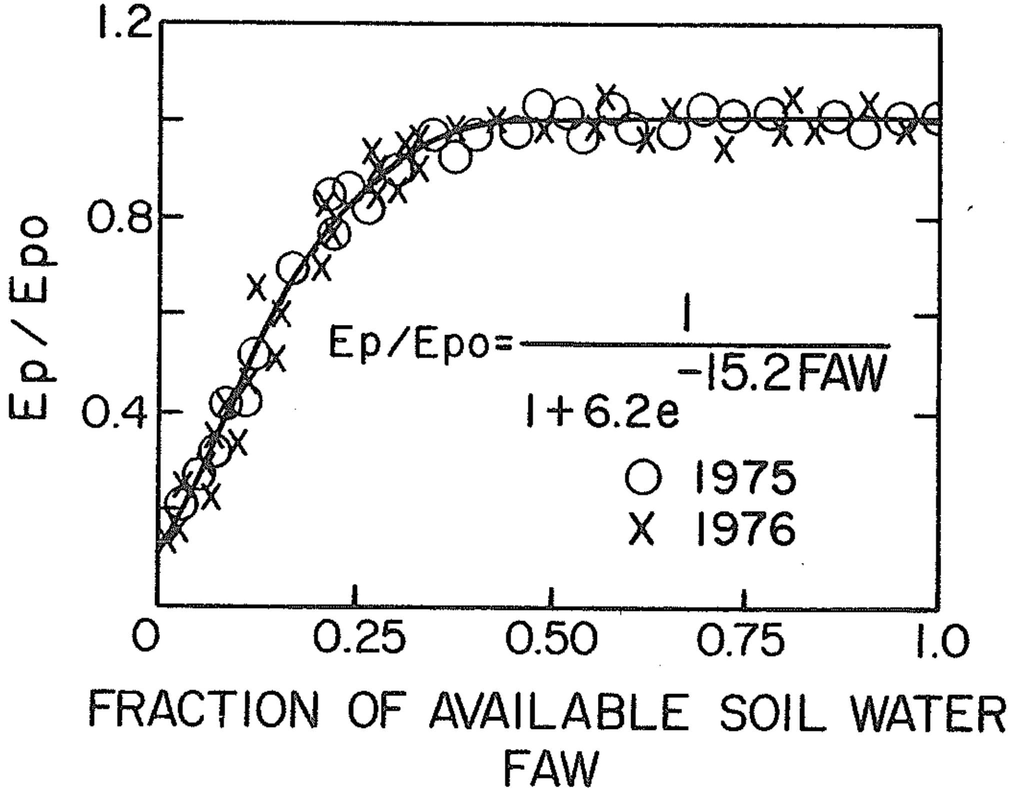

Figure 25. The relationship between the ratio of transpiration (Ep) to potential transpiration (Epo) and fraction of available water remaining in a lysimeter.

received the same amount of water until growth was established. Early in the growing season most of the ET occurs as soil evaporation. The fluctuations observed in ET/Eo during this period (Fig. 26) are mainly a result of the timing of irrigations.

Large differences in ET/Eo between the wet and dry treatments during the latter part of the growing season were apparently caused by differences in LAI, and also by differences in the available water in the root zone. Figure (26) also includes a reduced growth curve obtained by assuming the same vegetative growth as in the dry treatment, and that soil water was not limiting for transpiration. Equation (69) and the soil evaporation data for the dry treatment were used for constructing this curve.

The difference in ET/Eo between the dry treatment and the reduced growth case expresses the effect of soil water on the crop coefficient implying that soil water is an important factor in controlling evapotranspiration. The difference in ET/Eo between the wet and the reduced growth case also signifies the effect of leaf area index (or the vegetative growth) on the crop coefficient. The vegetative growth under existing farm conditions, however, varies greatly and can produce substantially different coefficients.

The above analyses clearly show that evaporative flux depends on leaf area index, amount of soil water and the potential evaporative demand, and cannot be quantified by a fixed crop coefficient. The empirical equations obtained here provide a means of correcting the effect of these factors on evapotranspiration, and agreed reasonably well with the results of Ritchie et al. (1971-1972).

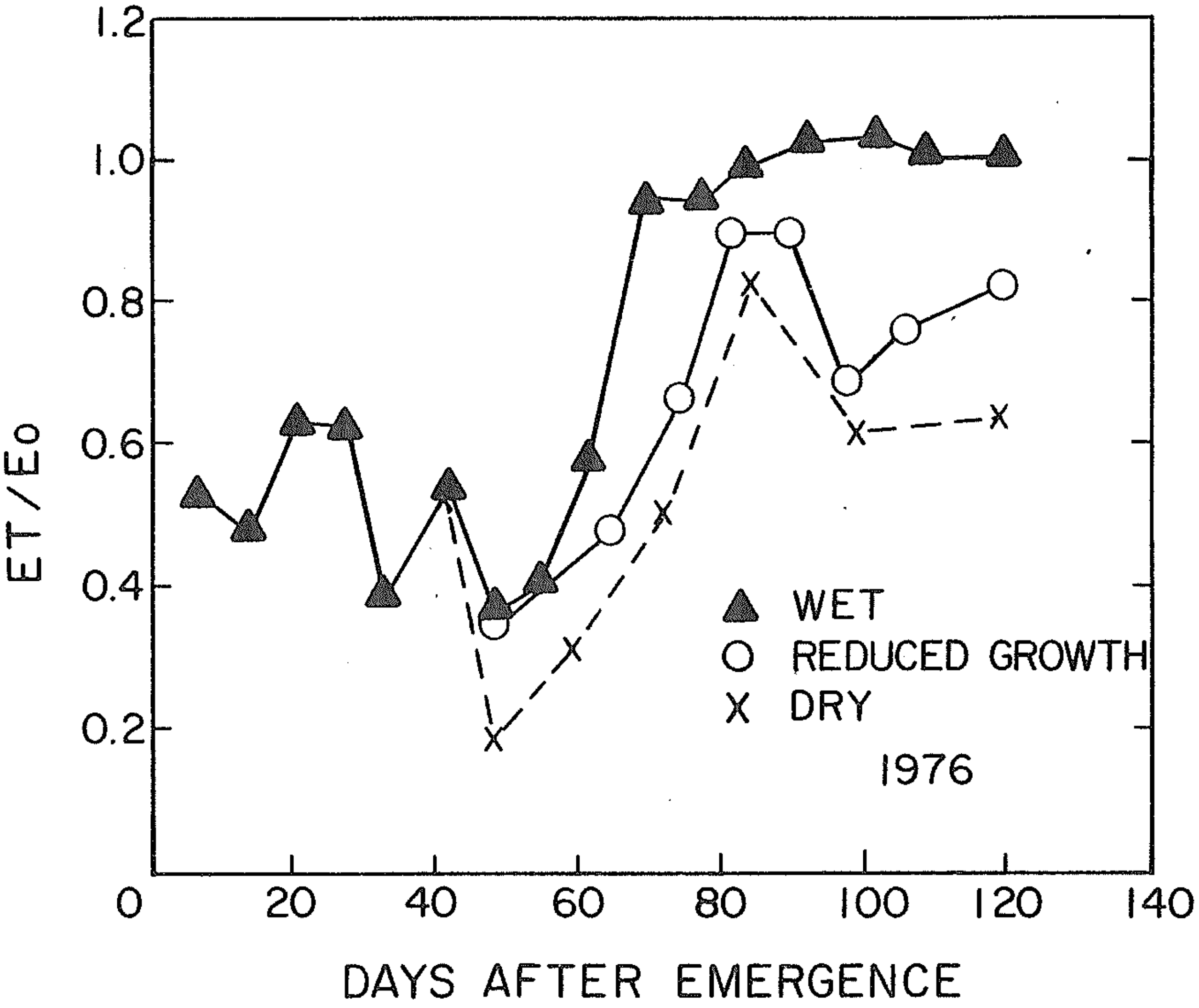

Figure 26. The ratio of actual transpiration (ET) over computed potential evaporation (Eo) as a function of time after emergence.

As a check on the empirical relationships presented by equations (67)-(70), we have used data from the 1976 cropping season to compute evapotranspiration (ET), and surface evaporation (Es). These computed values of ET and Es were then compared with measured values of ET and Es. The results are presented in Fig. (27) for the wet treatment and in Fig. (28) for the dry treatment. Values of 5.8 and 0.6 were used for the coefficients a and b, respectively. Eo was computed with the Penman equation. Soil surface evaporation on the first day after irrigation was computed from the measured leaf area index, with

$$Eso = Eo \cdot e^{-0.623LAI}$$

On successive days after irrigation surface evaporation was computed from:

$$Es = 5.8t^{0.6} - 5.8(t - 1)^{0.6}$$

Potential transpiration was computed from

$$Epo = Eo(1 - e^{-0.623LAI})$$

Knowing the amount of available water (FAW) in the soil profile, the actual transpiration was computed from the potential transpiration with:

$$Ep = Epo/(1 + 6.2\ e^{-15.2FAW})$$

Addition of Ep and Es or Eso gave the evapotranspiration ET presented in Figs. (27) and (28).

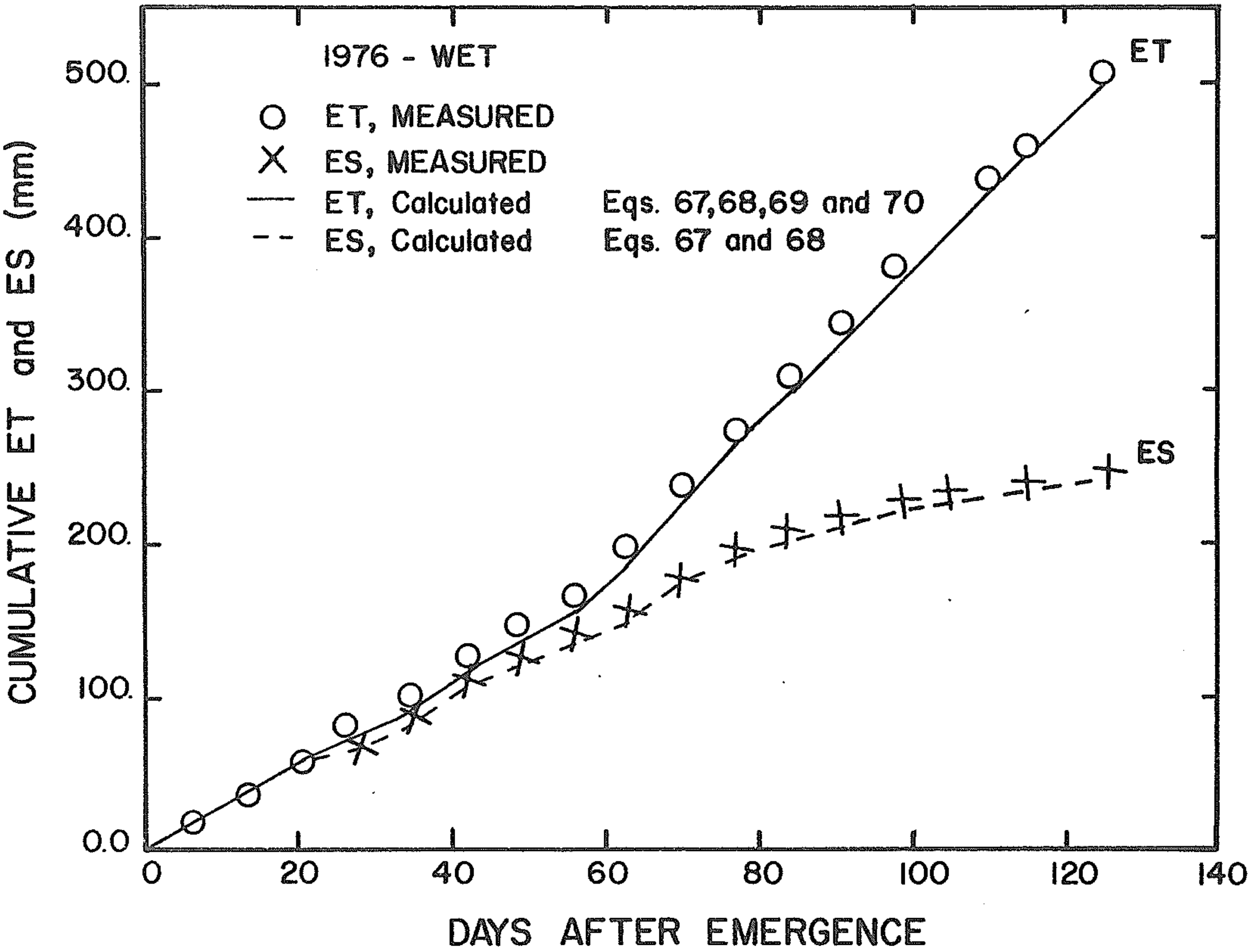

Figure 27. Comparison between measured and computed evapotranspiration and soil evaporation for wet treatment in 1976.

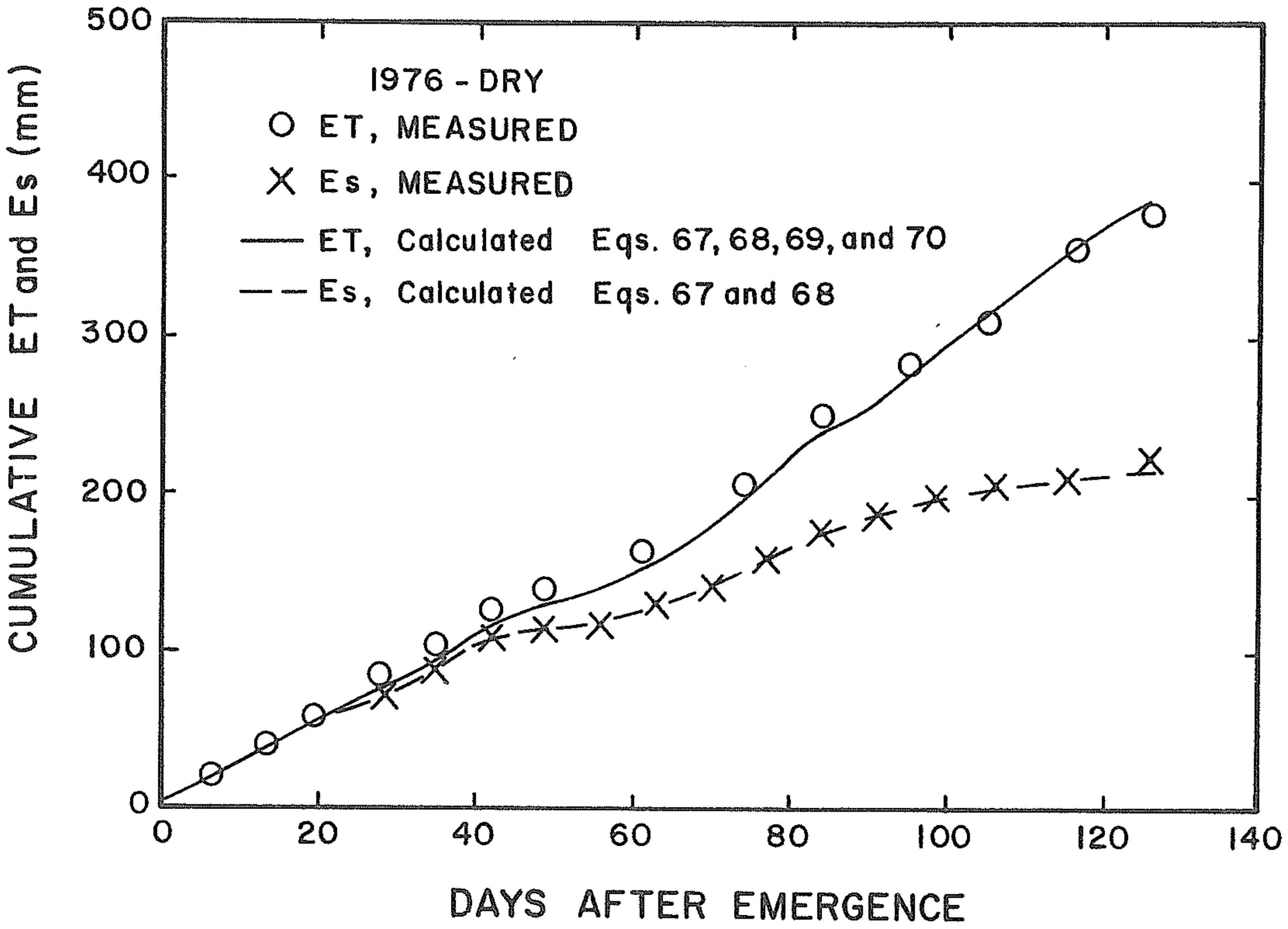

Figure 28. Comparison between measured and computed evapotranspiration and soil evaporation for dry treatment in 1976.

The observed and computed cumulative ET and Es agree. This should be expected since the coefficients in equations (67)-(70) were derived by curve-fitting experimental data from 1975 and 1976.

A further test of equations (67)-(70) is made by comparing computed cumulative ET and Es with data from Ritchie (1972) for sorghum grown on Houston black clay in central Texas. A value of 3.5 mm/day, as reported by Ritchie, was used for the coefficient a, while for b the value of 0.6 was taken. Data on Eo, LAI, irrigation and rainfall, measured ET and Es for sorghum were taken from Ritchie (1972). Observed and computed cumulative ET and Es are presented in Fig. (29). There is a good agreement between observed and computed cumulative ET and Es for Ritchie's sorghum data. It therefore appears that the empirical relationships presented by equations (67)-(70) may have some general applicability. However, further testing with other crops is necessary before recommendations can be made.

5.4 Simulation

The pressure potential-water content relationship for Glendale clay loam used in this study is presented in Fig. (30). The data can be represented by

$$\psi = -1.253 \times 10^{7} e^{-27.08(\theta)} \tag{71}$$

where ψ is the pressure potential in cm of water. The pressure potential-water content relationship for the sandy loam is presented in Figure (31). The data can be represented by the following function:

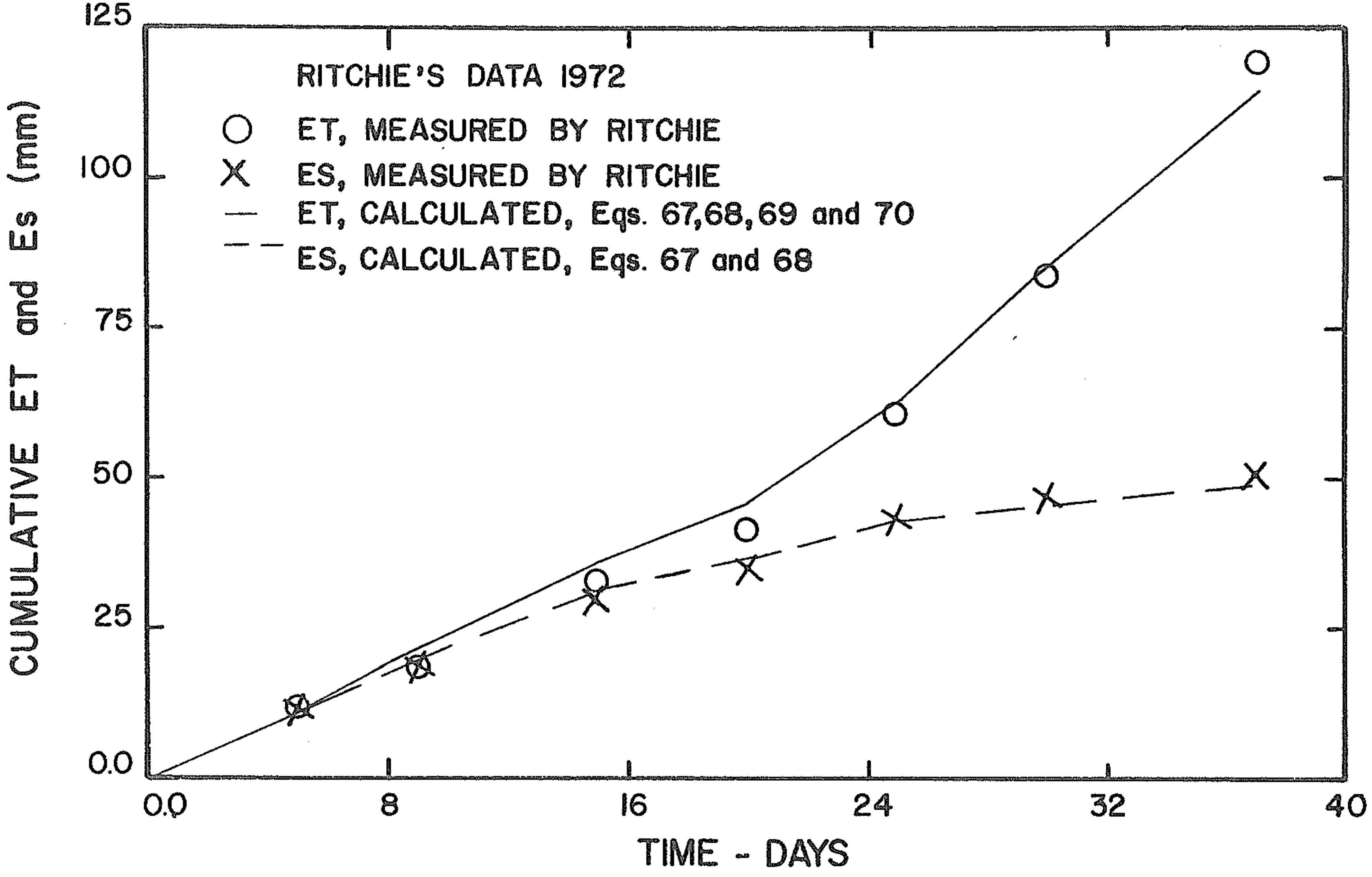

Figure 29. Comparison between measured evapotranspiration (ET) and soil evaporation (Es) reported by Ritchie (1972) and computed ET and Es for Ritchie's condition using the empirical relationships developed in this study.

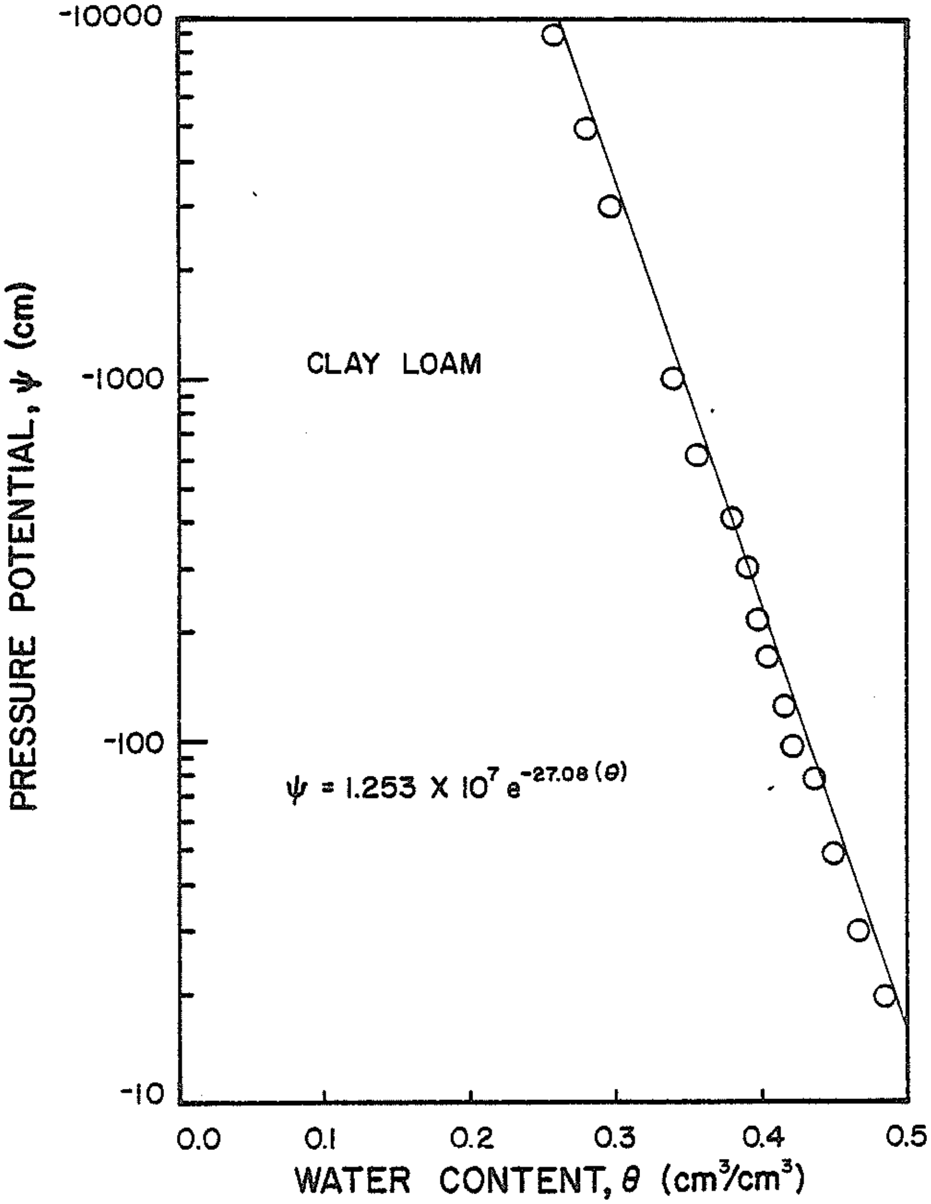

Figure 30. The relationship between the pressure potential and water content of Glendale clay loam.

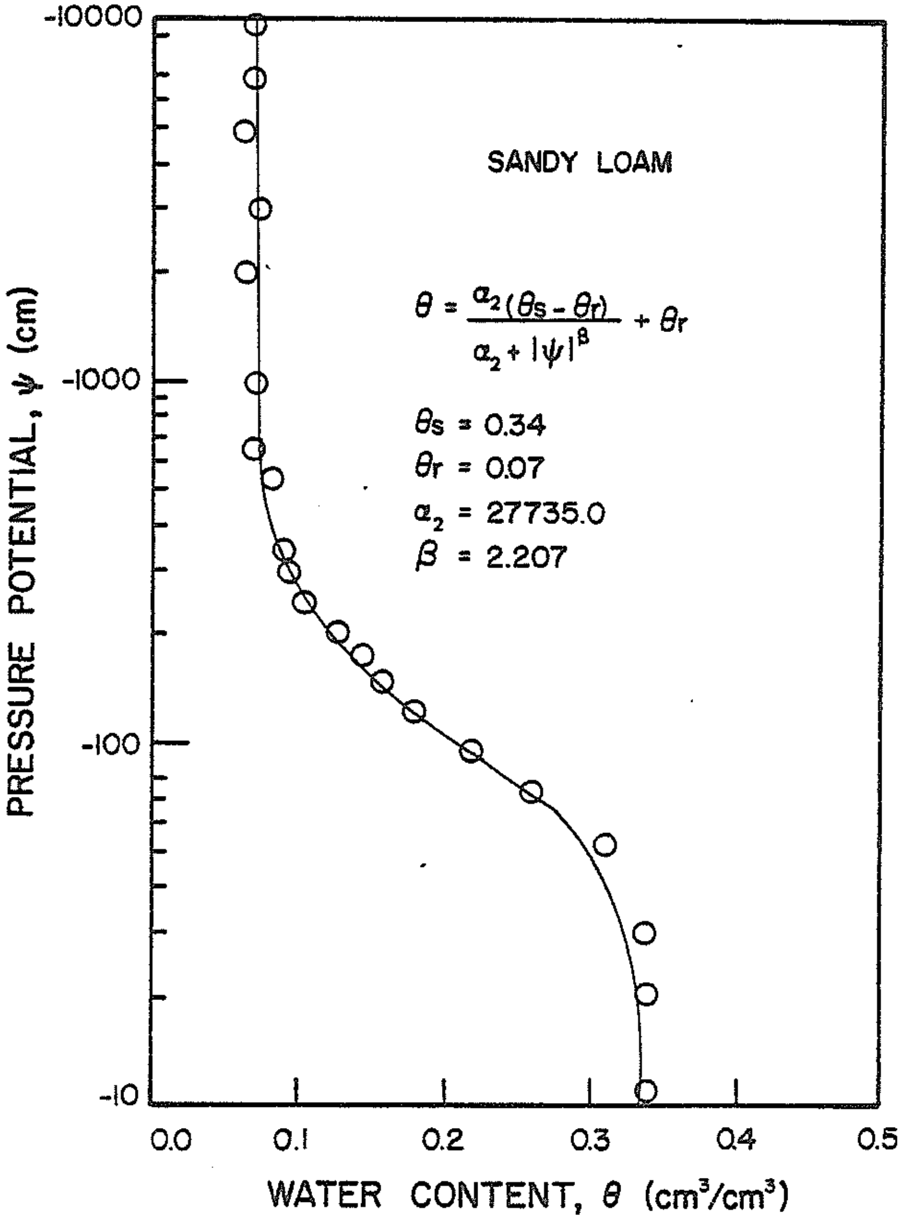

Figure 31. The relationship between the pressure potential and water content of sandy loam used with lysimeter (60-150 cm).

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{\alpha_2}{\alpha_2 - |\psi|^\beta} \tag{72}$$

where θ_s is the saturation water content (0.34), θ_r is the residual water content (0.07), α_2 and β are coefficients equal to 2.7735.0 and 2.207, respectively.

The hydraulic conductivity-water content relationship was obtained by steady-state and instantaneous profile methods as described in Materials and Methods. The following analytical expression is obtained by a least square fit through the data points (Figure 32):

$$K(\theta)_1 = 5.83 \times 10^{-7} \cdot e^{(37.2\theta)} \tag{73}$$

where $K(\theta)_1$ is hydraulic conductivity for the Glendale clay loam. The hydraulic conductivity-water content relationship for the sandy loam is also plotted in Figure (32) and the best fit is given by:

$$K(\theta)_2 = 0.0073 \cdot e^{(20.75\theta)} \tag{74}$$

where $K(\theta)_2$ is hydraulic conductivity for the sandy loam. Water content, pressure potential, hydraulic conductivity, and diffusivity values are listed in Tables (10) and (11) for the clay loam and sandy loam, respectively.

An empirical parameter in the simulation of water movement in soil with actively growing roots is the root extraction term. The root extraction term, or the amount of water extracted from each soil layer, RETA(I), was defined as:

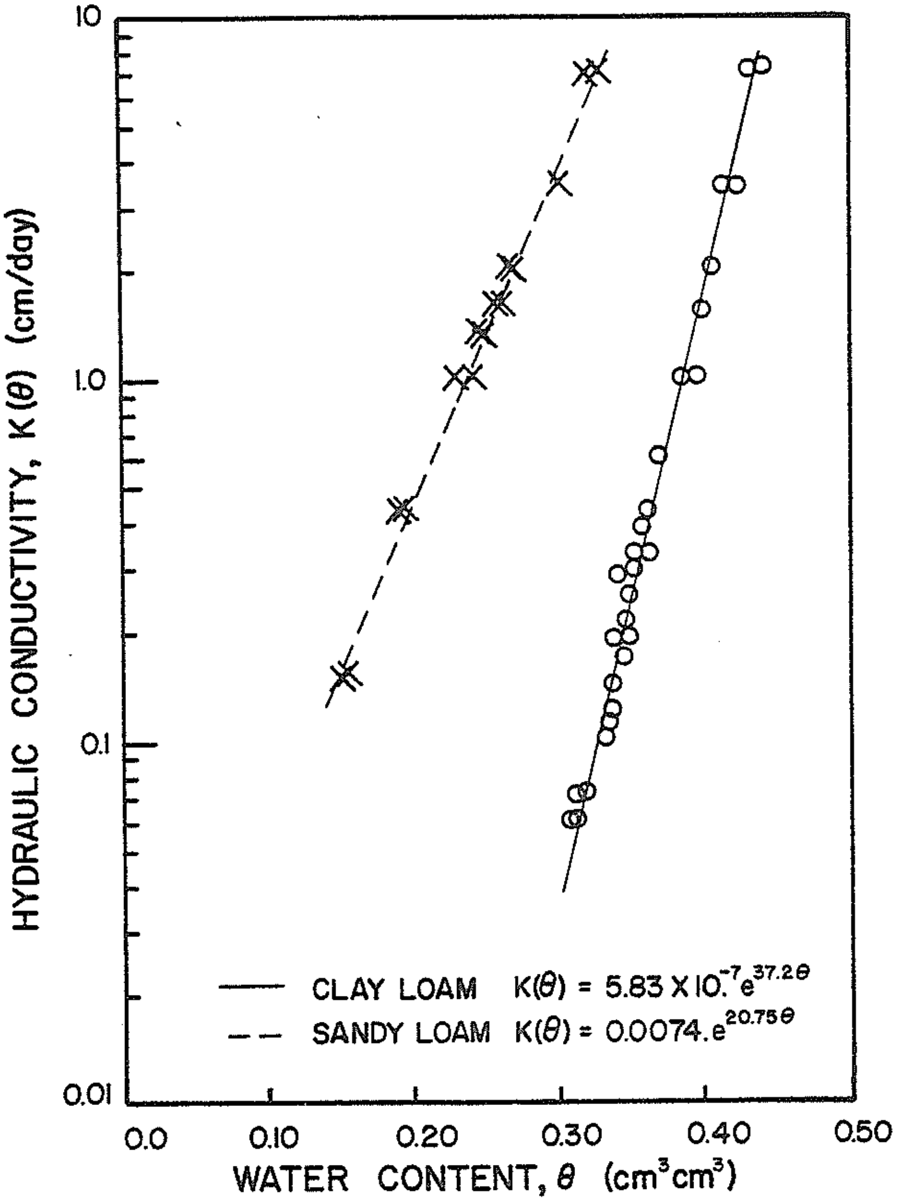

Figure 32. The relationships between hydraulic conductivity and water content for soils used in this study.

Table 10. Soil water-content, pressure potential, hydraulic conductivity and diffusivity of the Glendale clay loam in the lysimeters.

Water Content $cm^3\ cm^{-3}$	Pressure Potential cm of H_2O	Hydraulic Conductivity cm day^{-1}	Diffusivity $cm^2\ day^{-1}$
0.01	9557498.0	0.000001	210.6
0.02	7290165.0	0.000001	222.8
0.03	5560713.0	0.000002	235.7
0.04	4241543.0	0.000002	249.3
0.05	3235319.0	0.000003	263.7
0.06	2467800.0	0.000004	279.0
0.07	1882365.0	0.000006	295.1
0.08	1435808.0	0.000008	312.2
0.09	1095190.0	0.000011	330.2
0.10	835377.3	0.000015	349.3
0.11	637200.2	0.000021	369.5
0.12	486036.8	0.000030	390.9
0.13	370733.9	0.000041	413.5
0.14	282784.4	0.000057	437.4
0.15	215699.3	0.000079	462.7
0.16	164528.6	0.000110	489.5
0.17	125497.3	0.000152	517.8
0.18	95725.5	0.000211	547.7
0.19	73016.5	0.000293	579.3
0.20	55694.7	0.000406	612.8
0.21	42482.2	0.000564	648.3
0.22	32404.1	0.000782	685.8
0.23	24716.9	0.001084	725.4
0.24	18853.2	0.001503	767.3
0.25	14380.6	0.002084	811.7
0.26	10969.1	0.002891	858.6
0.27	8366.9	0.004009	908.3
0.28	6382.0	0.005560	960.8
0.29	4868.0	0.007710	1016.3
0.30	3713.1	0.010692	1075.1
0.31	2832.2	0.014828	1137.2
0.32	2160.3	0.020563	1203.0
0.33	1647.8	0.028517	1272.5
0.34	1256.9	0.039548	1346.1
0.35	958.7	0.054845	1423.9
0.36	731.3	0.076059	1506.2
0.37	557.8	0.105479	1593.3
0.38	425.4	0.146278	1685.4
0.39	324.5	0.202858	1782.8
0.40	274.5	0.281325	1885.9

Table 10 (cont'd.)

Water Content $cm^3\ cm^{-3}$	Pressure Potential cm of H_2O	Hydraulic Conductivity cm day^{-1}	Diffusivity $cm^2\ day^{-1}$
0.41	188.8	0.390141	1994.9
0.42	144.0	0.541048	2110.3
0.43	109.8	0.750326	2232.3
0.44	83.8	1.040553	2361.3
0.45	63.9	1.443041	2497.8
0.46	48.7	2.001210	2642.2
0.47	37.1	2.775280	2795.0
0.48	28.3	3.848768	2956.5
0.49	21.6	5.337399	3127.4
0.50	16.5	7.401997	3308.3

Table 11. Soil water-content, pressure potential, hydraulic conductivity, and diffusivity of the sandy loam 60-150 cm in the lysimeters.

Water Content cm^3 cm^{-3}	Pressure Potential cm of H_2O	Hydraulic Conductivity cm day^{-1}	Diffusivity cm^2 day^{-1}
0.07	3703.6	0.03	18666.5
0.08	449.7	0.04	704.5
0.09	323.4	0.05	338.8
0.10	264.4	0.06	236.7
0.11	227.8	0.07	194.0
0.12	201.8	0.09	173.9
0.13	182.0	0.10	164.9
0.14	166.0	0.14	162.8
0.15	152.7	0.16	165.4
0.16	141.3	0.20	171.9
0.17	131.3	0.25	181.8
0.18	122.4	0.31	195.1
0.19	114.3	0.38	211.8
0.20	106.8	0.47	232.2
0.21	99.9	0.58	256.8
0.22	93.4	0.71	286.0
0.23	87.2	0.87	320.7
0.24	81.3	1.08	361.6
0.25	75.6	1.32	409.7
0.26	69.9	1.63	466.3
0.27	64.4	2.01	532.8
0.28	58.8	2.47	611.0
0.29	53.0	3.04	703.0
0.30	47.1	3.74	811.2
0.31	40.7	4.60	938.6
0.32	33.4	5.66	1088.8
0.33	24.4	6.97	1266.0
0.34	7.8	8.57	1475.1

$$\text{RETA(I)} = \text{EP*RDC(I)} \tag{75}$$

where EP is the rate of transpiration, and RDC(I) is the root distribution coefficient.

Most of the previously developed models assumed that water uptake is proportional to the root distribution in any given layer. However, it should be noted that root activity varies with the depth from soil surface (Kramer, 1969).

The root distribution coefficient RDC(I) was determined as follows: It was assumed that the redistribution of soil water 3 to 4 days after irrigation is negligible; then the changes in soil water content as observed with the neutron meter in each lysimeter are a result of water uptake by roots only. The rate of water uptake can therefore be determined from neutron meter data that were taken at given time intervals in each lysimeter. It was assumed that RDC(I) is a function of the fraction of the root mass (RDF(I)) and the rooting depth, or:

$$\text{RDC(I)} = \text{RDF(I)*F}(z/z_1) \tag{76}$$

where $F(z/z_1)$ is a function of rooting depth. From Eq. (75) it follows that:

$$\text{RDC(I)} = \frac{\text{RETA(I)}}{\text{EP}} \tag{77}$$

Substituting equation (77) into (76) and rearranging yields:

$$\frac{\text{RETA(I)/EP}}{\text{RDF(I)}} = F(z/z_1) \tag{78}$$

where RETA(I) is assumed to be the changes in the water content observed by neutron probe in any given layer, Ep is plant transpiration, RDF(I) is the relative amount of root density in any given layer, z is distance from soil surface to point in question, and z_1 is the depth of root zone at any given time.

Figure (33) shows $\frac{\text{RETA(I)/EP}}{\text{RDF(I)}}$ plotted versus z/z_1 on semilog paper. Using curve-fitting the following mathematical expression was obtained:

$$\frac{\text{RETA(I)/EP}}{\text{RDF(I)}} = 2.0 \cdot e^{-1.58(z/z_1)} \qquad (79)$$

Substituting Equation (77) into (79) and rearranging yields:

$$\text{RDC(I)} = \text{RDF(I)} \times 2.0 \times e^{-1.58(z/z_1)} \qquad (80)$$

Simulated and measured water-content profiles of the wet treatment for lysimeters 1 and 2 are plotted in Figures (34a,b) for the period June 21 through August 20, 1976. Figures (35a,b) show the simulated and measured water-content profiles of the dry treatment for lysimeters 6 and 9 for the period June 21 through August 20, 1976. The experimental data points were obtained with the neutron probe. Water content was measured at 10 cm intervals to a depth of 100 cm. Figures (34a,b) and (35a,b) indicate a reasonably good agreement between the computed and the measured water-content values at the depths 20, 30, and 40 cm. Agreement, however, was less satisfactory at the depths of 50, 60, and 70 cm are not accurate, because the soil profile in the lysimeters consisted of two layers (from 0-60 cm, clay loam

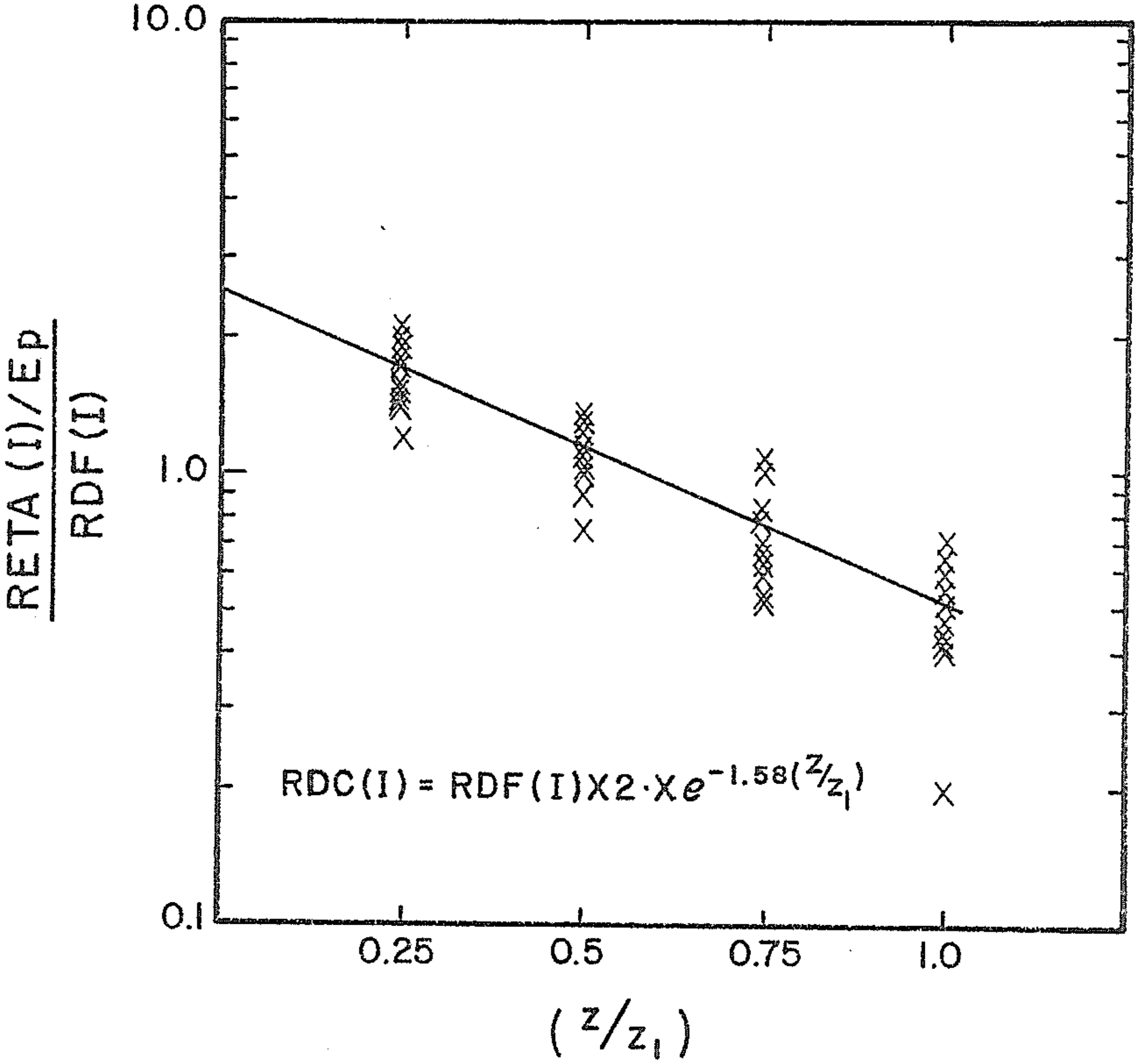

Figure 33. The relationship between root distribution coefficient (RDC = $\frac{\text{RETA/Ep}}{\text{RDF}}$) versus root depth. RETA is Wierenga root water uptake, Ep is transpiration, and RDF is fraction of the root mass.

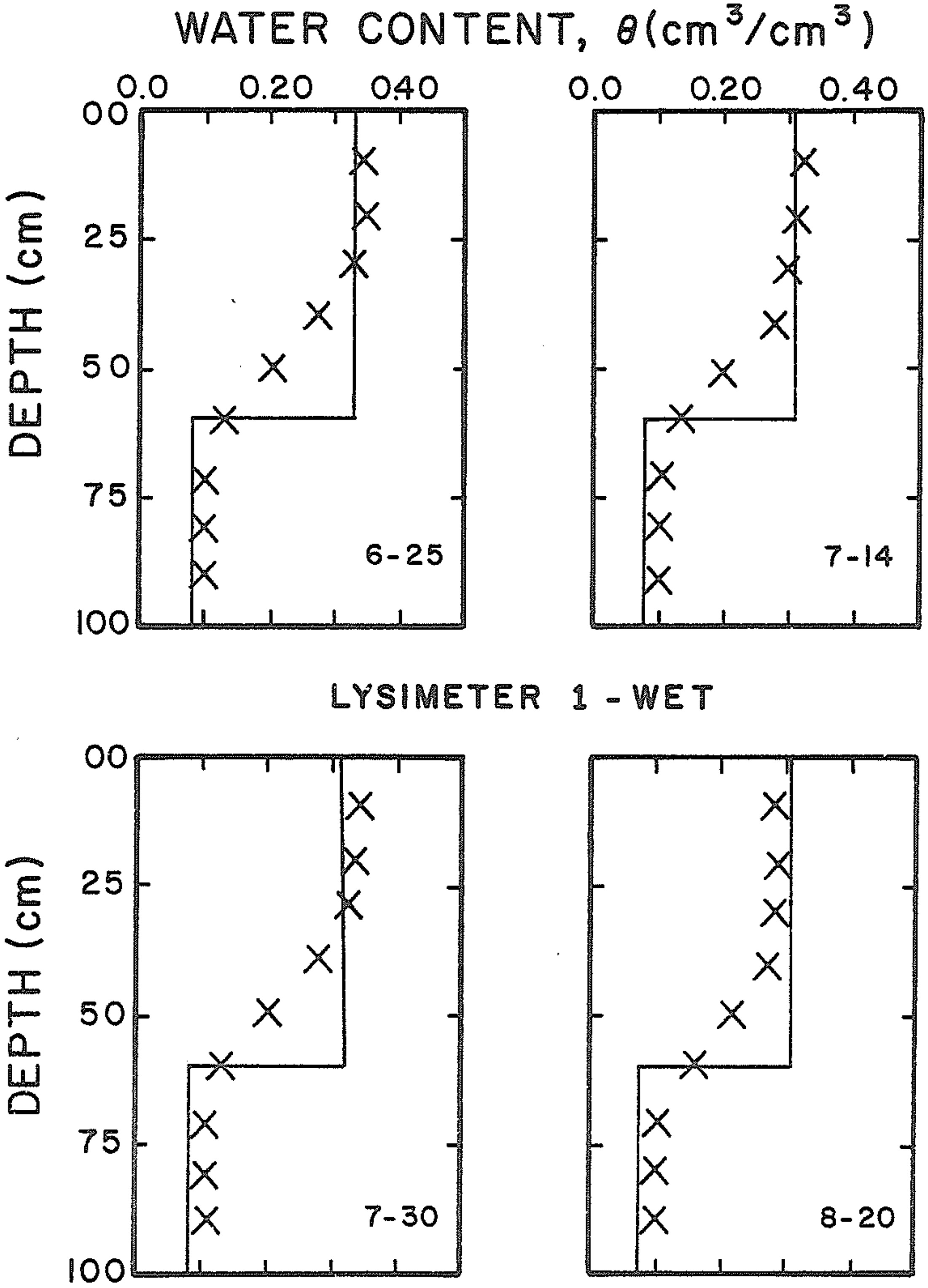

Figure 34a. Comparison between measured and simulated water-content profiles for the wet treatment lysimeter 1 in 1976.

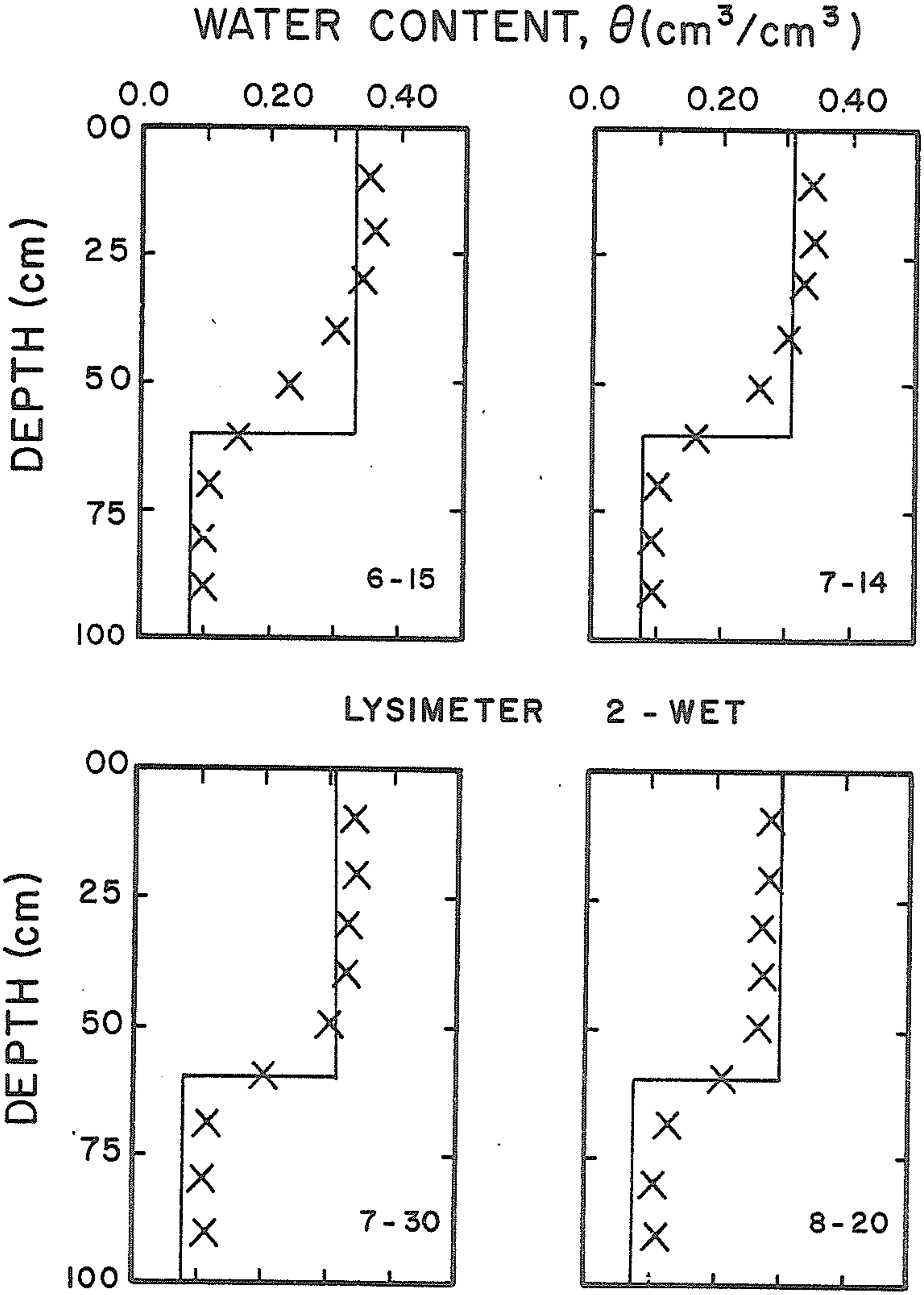

Figure 34b. Comparison between measured and simulated water-content profiles for the wet treatment lysimeter 2 in 1976.

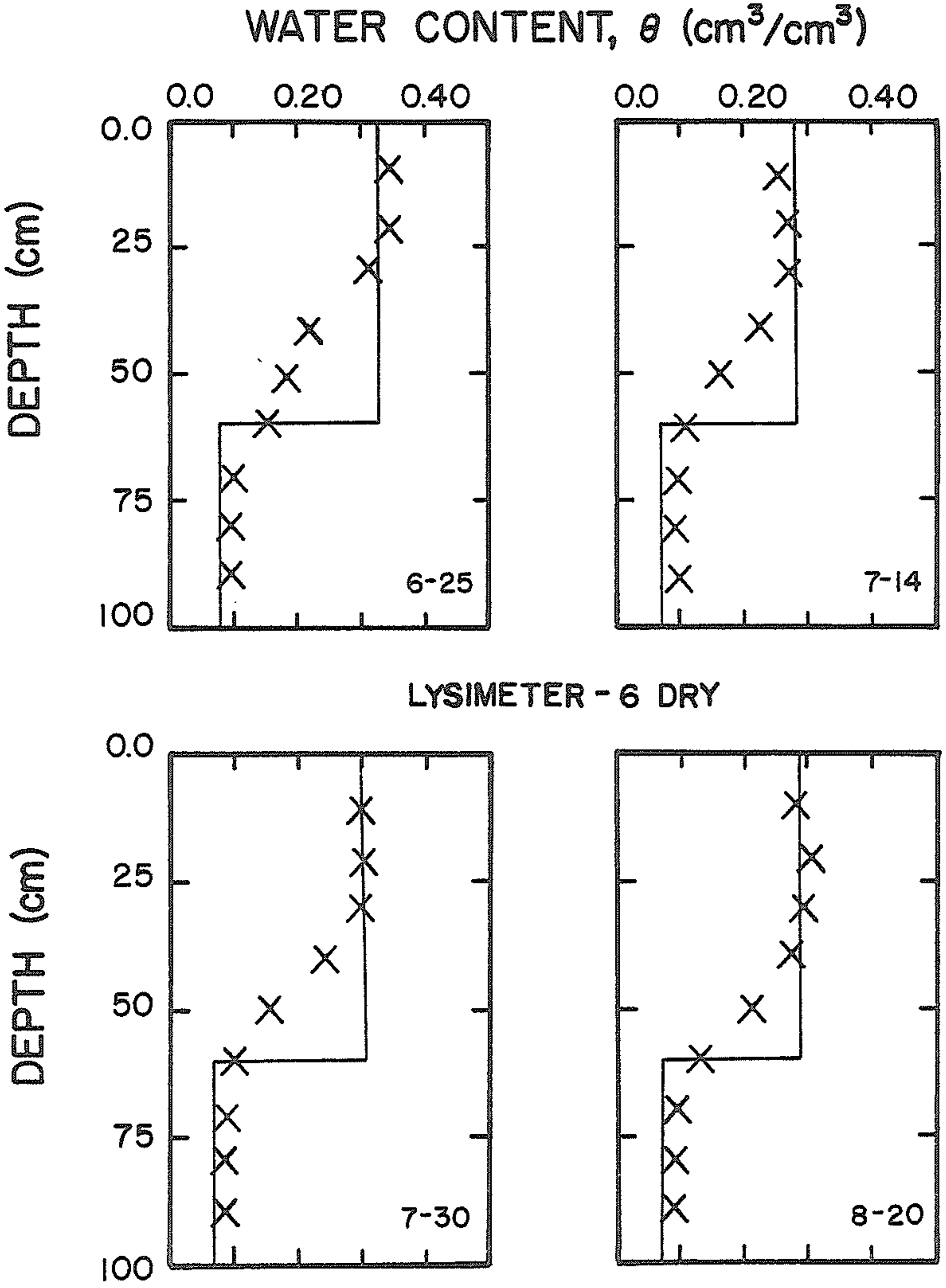

Figure 35a. Comparison between measured and simulated water-content profiles for the dry treatment lysimeter 6 in 1976.

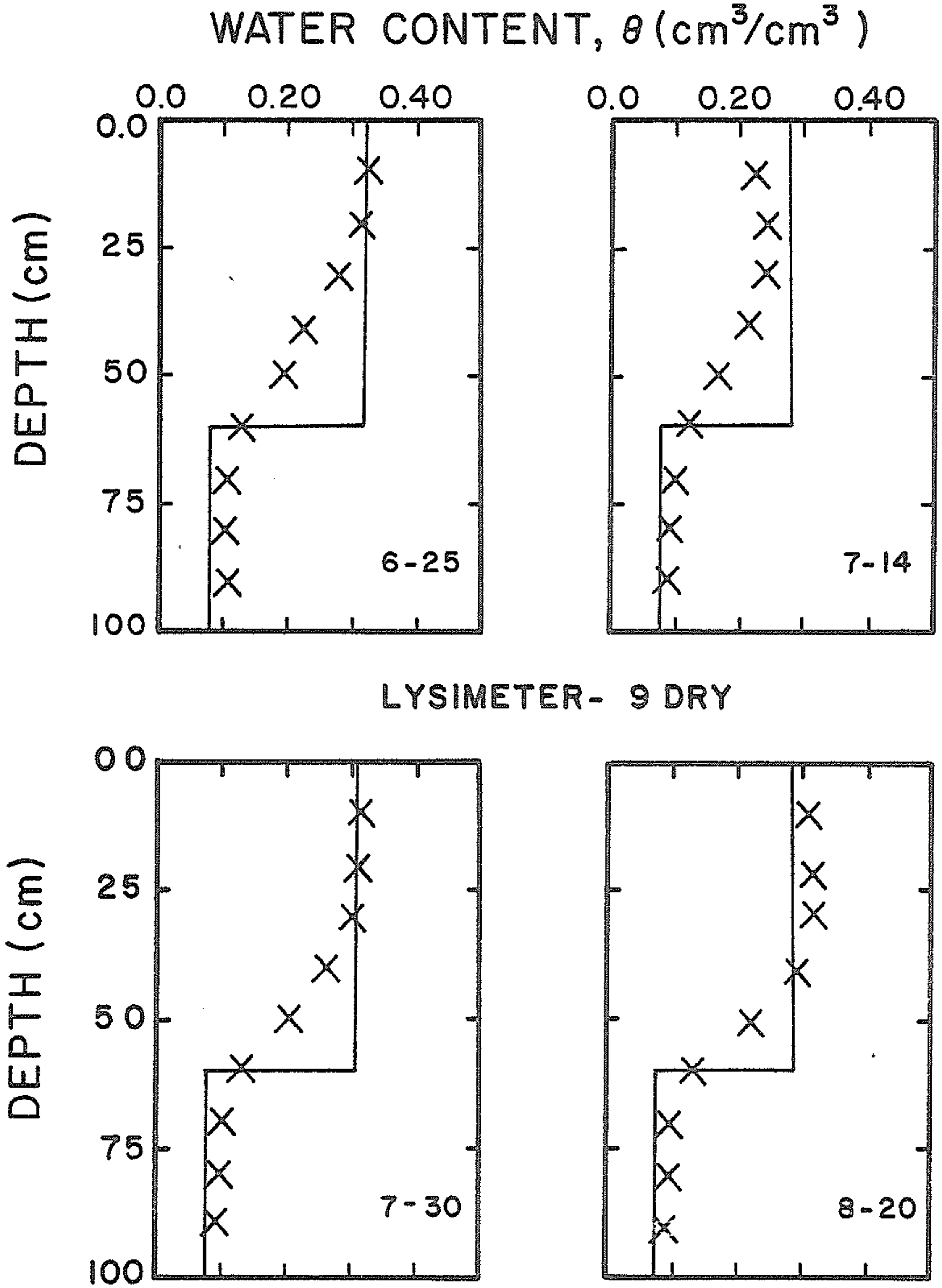

Figure 35b. Comparison between measured and simulated water-content profile for the dry treatment lysimeter 9 in 1976.

and from 60-140 cm, sandy loam) and the effective diameter of the neutron probe was more than 30 cm. Differences between the computed and measured water-content values for the sandy loam soils were 2% of the actual water-content values. The same calibration curve (Eq. 63) was employed to calculate water-content values for both the clay loam and sandy loam soils. Separate calibration curves should have been developed and used for the calculation of water contents of sandy loam and clay loam soils. Gravimetric samples from the entire soil profile should have been taken at various times during the growing season to check the calibration curve of the neutron probe and to get accurate water-content data at the interface of the clay loam and sandy loam soils.

The measured water-content profiles of the four lysimeters were plotted with the computed water-content profiles in Figures (36) and (37) for wet and dry treatment, respectively, during the month of August, 1976. The average variations for the four lysimeters of each treatment at depths of 20, 30, and 40 cm were 0.03 cm^3/cm^3. The average variations at depths of 70 to 100 cm were less than 0.02 cm^3/cm^3. Figures (36) and (37) indicate a good agreement between the measured and the simulated water-content profiles. Notice that the simulated water-content profiles of the different periods are all in the range of the measured water-content profiles at depths of 20, 30 and 40 cm for the wet and dry treatments, respectively.

Figures (38) and (39) show the simulated and the measured water content data at 30 and 90 cm during the months of July and August,

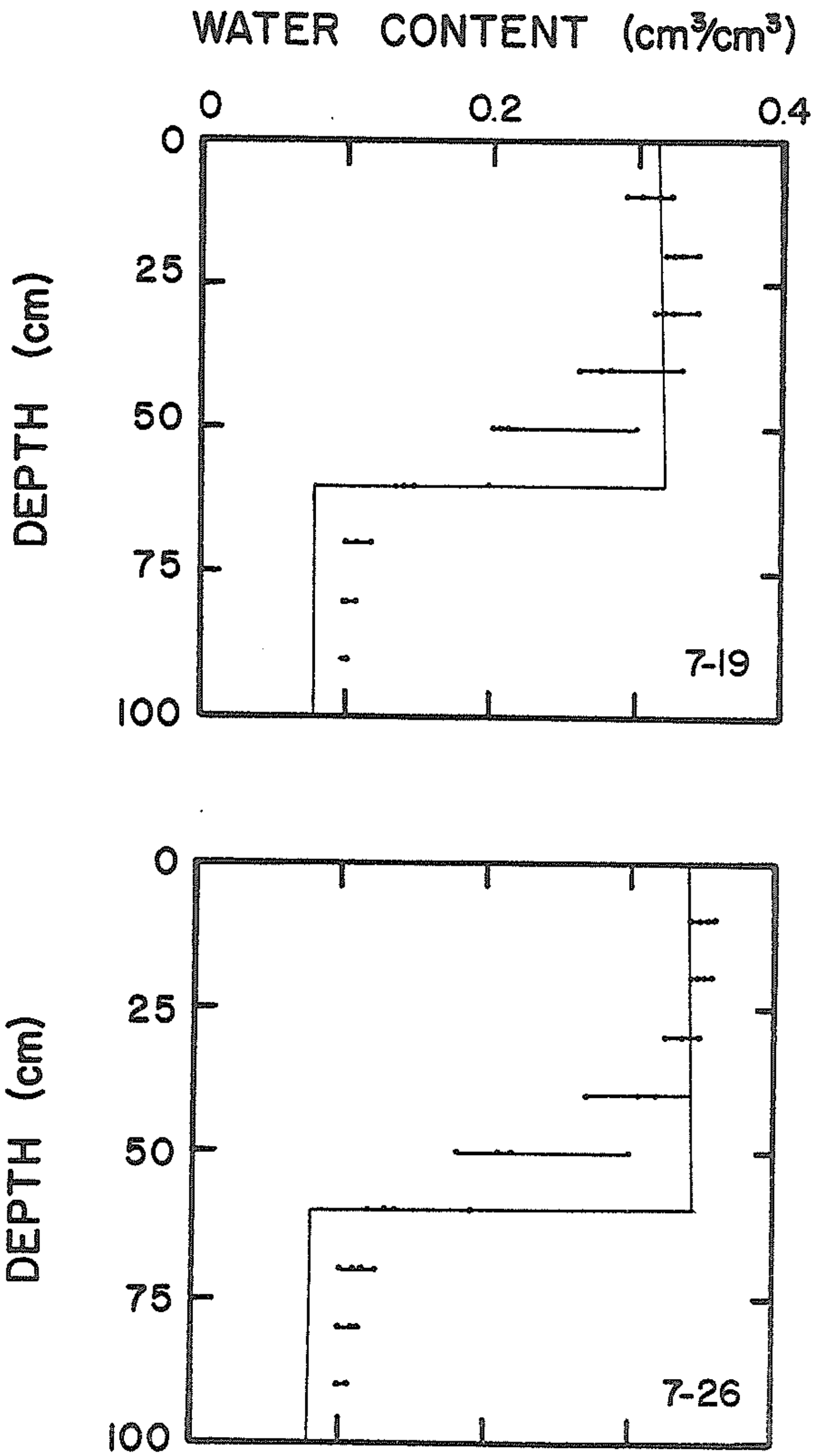

Figure 36. Variation in measured water-content profile of four lysimeters for the wet treatment in 1976.

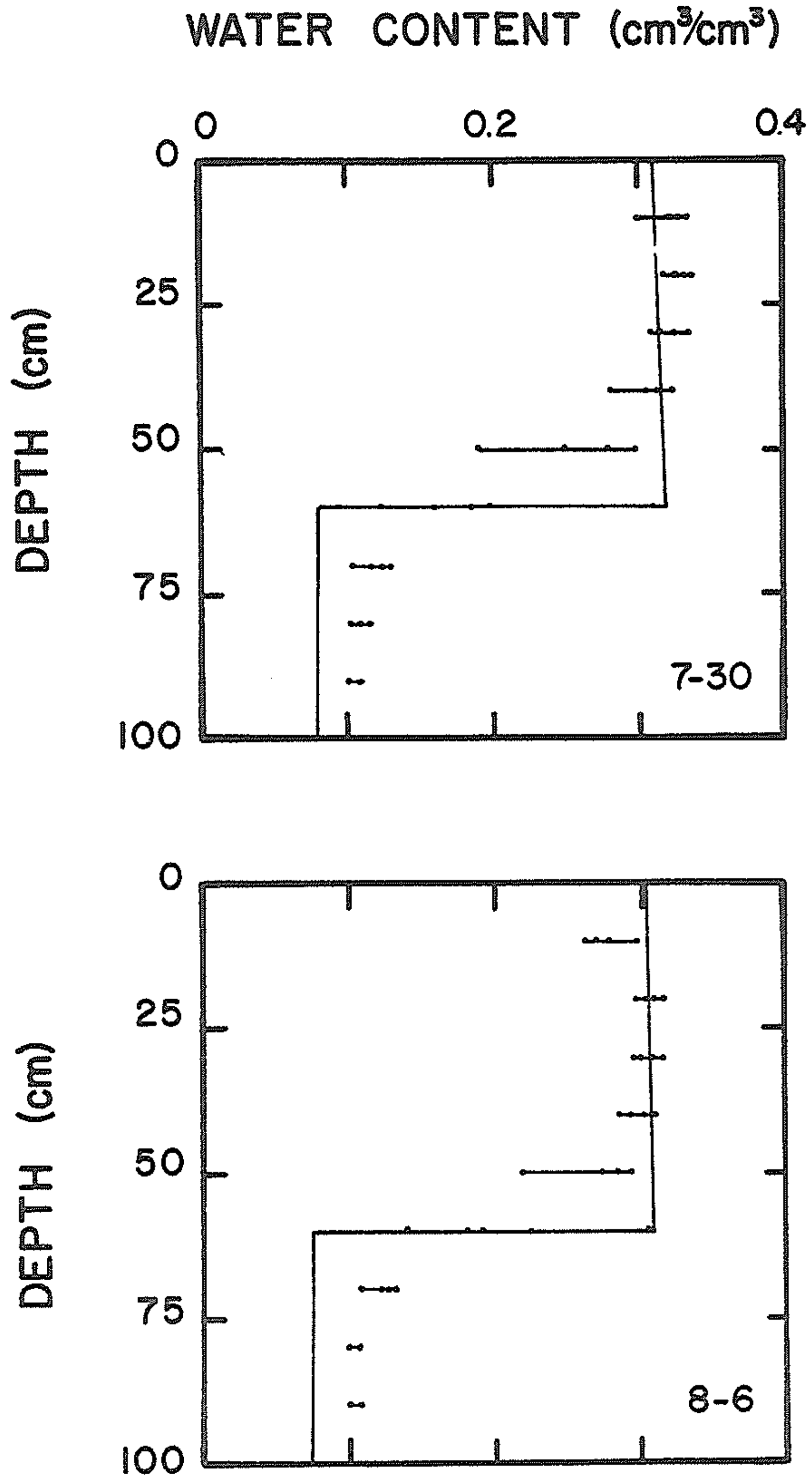

Figure 36 (cont'd.)

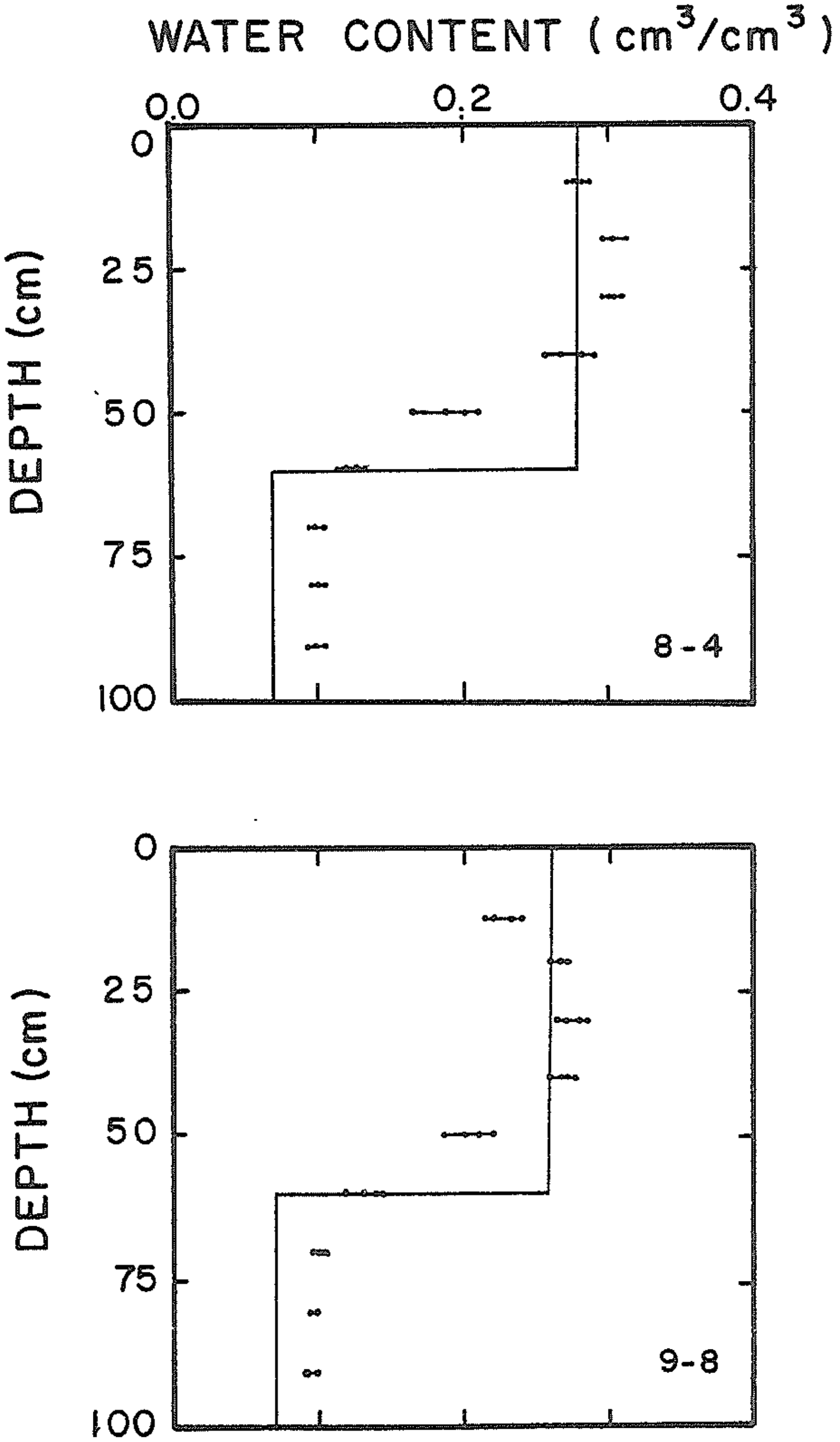

Figure 37. Variation in measured water-content profile of four lysimeters for dry treatment in 1976.

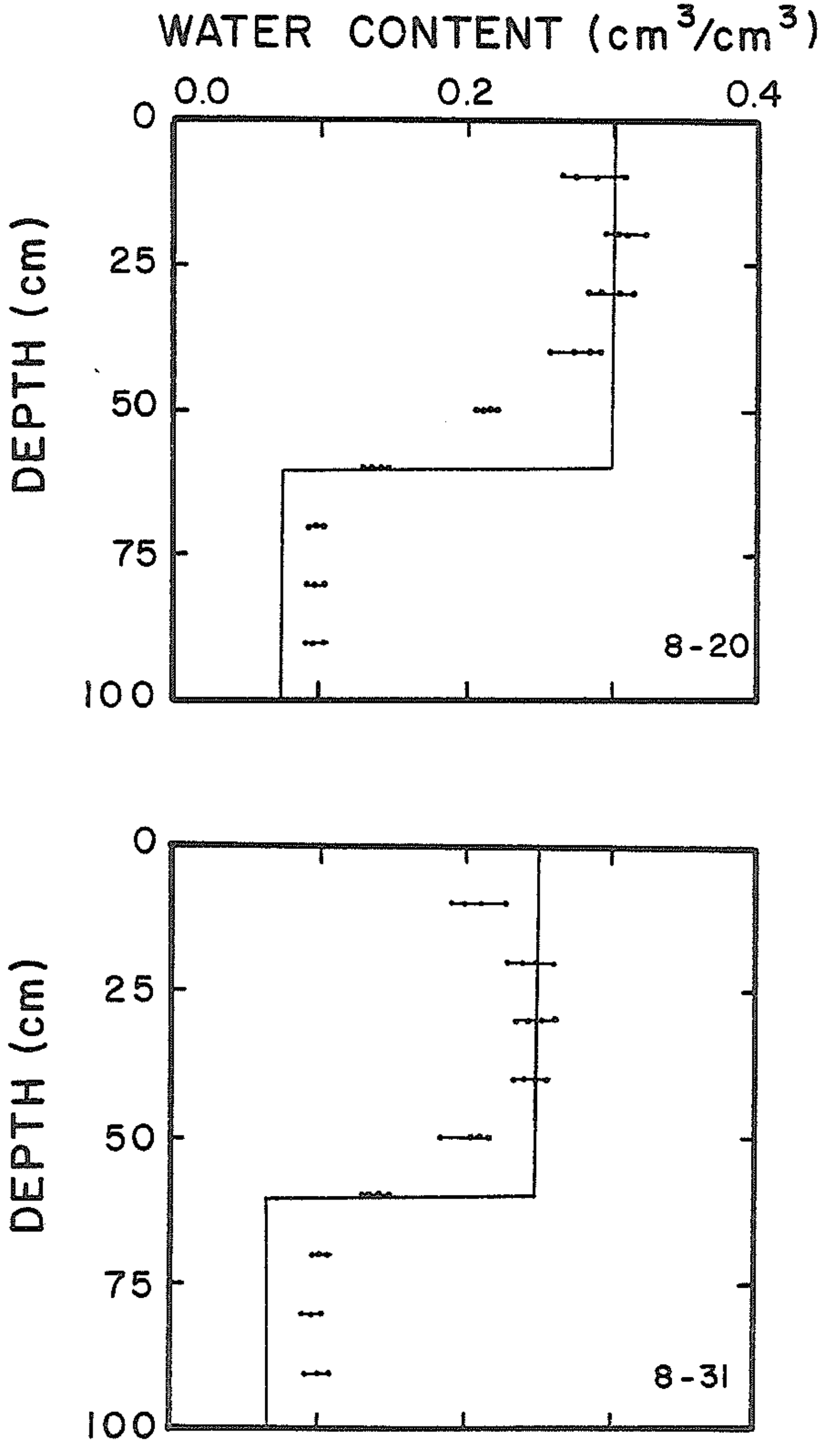

Figure 37 (cont'd.)

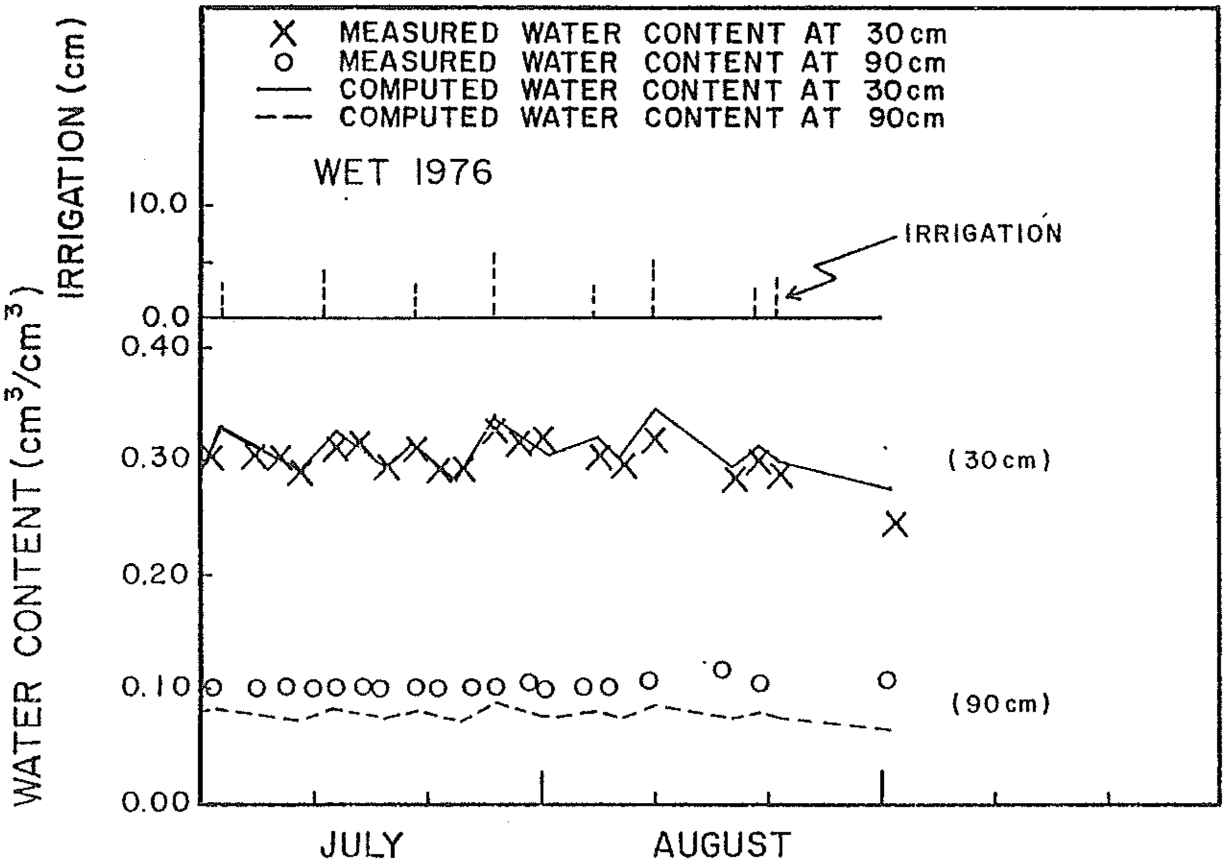

Figure 38 Comparison between measured and simulated water-content values at 30 and 90 cm during the months of July and August for wet treatment 1976.

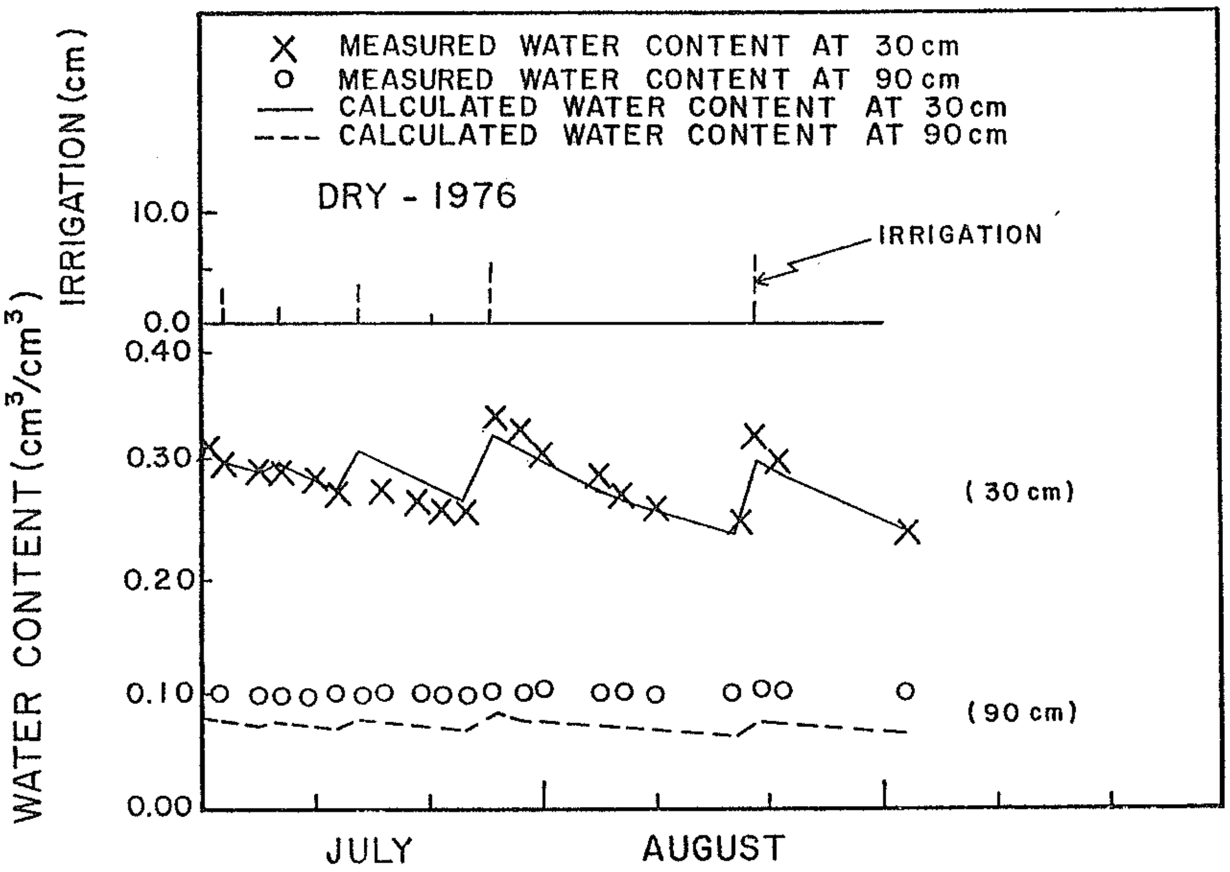

Figure 39 Comparison between measured and simulated water-content values at 30 and 90 cm during the months of July and August for dry treatment 1976.

1976, for wet and dry treatments, respectively. Figures (38) and (39) indicate a good agreement between the simulated and measured water-content values at 30 cm. At 90 cm the measured water-content values were 0.02 cm^3/cm^3 greater than the computed values. Figure (40) compares the simulated and measured amounts of water in 100 cm of the soil during the period July 1 through August 31, 1976, for the wet treatment. The measured data represent the average of four lysimeters. Figure (40) shows reasonable agreement between the simulated and measured amounts of water in 100 cm of the soil profile throughout the 71-day simulation period.

Volume of drainage water was measured and simulated for the period July 1 through August 31, 1976. For the wet treatment, the amount of drainage water simulated was 2.5 cm as compared to an average measured value of 3.2 cm for the four lysimeters. For the dry treatment, the simulated value of the drainage water was 2.0 cm and the average measured value was zero.

The results of the simplified model are compared with the results of the simulation model for the period July 30 through August 31, 1976, in Figure (41). There is a reasonable agreement between the soil water-content values predicted with two models. Considering the simplicity of this model, the close agreement between its predicted water contents and water contents measured with the neutron probe is encouraging. Table (12) shows the values of ET, drainage, and total water in the profile at the end of a 32-day simulation period. There is a very close agreement between the amounts of ET and drainage

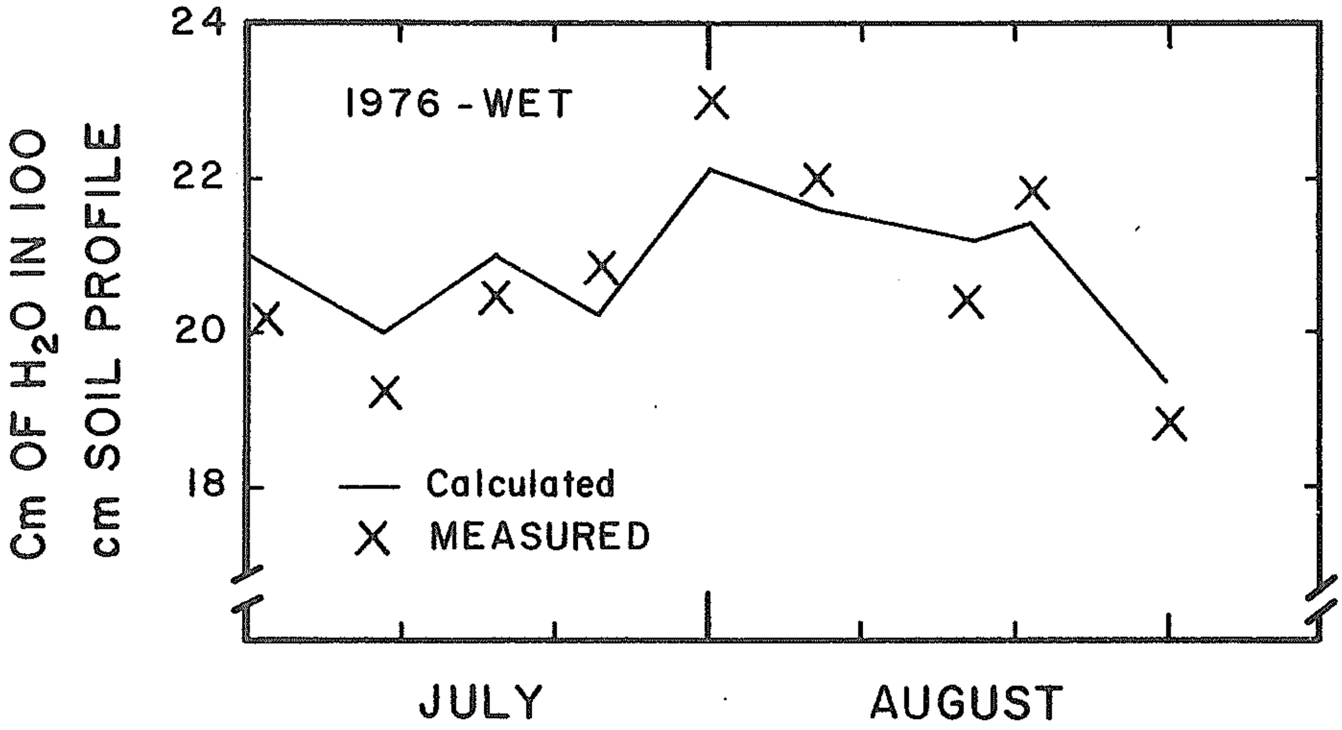

Figure 40. Comparison between measured and calculated total amount of water in 100 cm of soils for wet treatment in 1976.

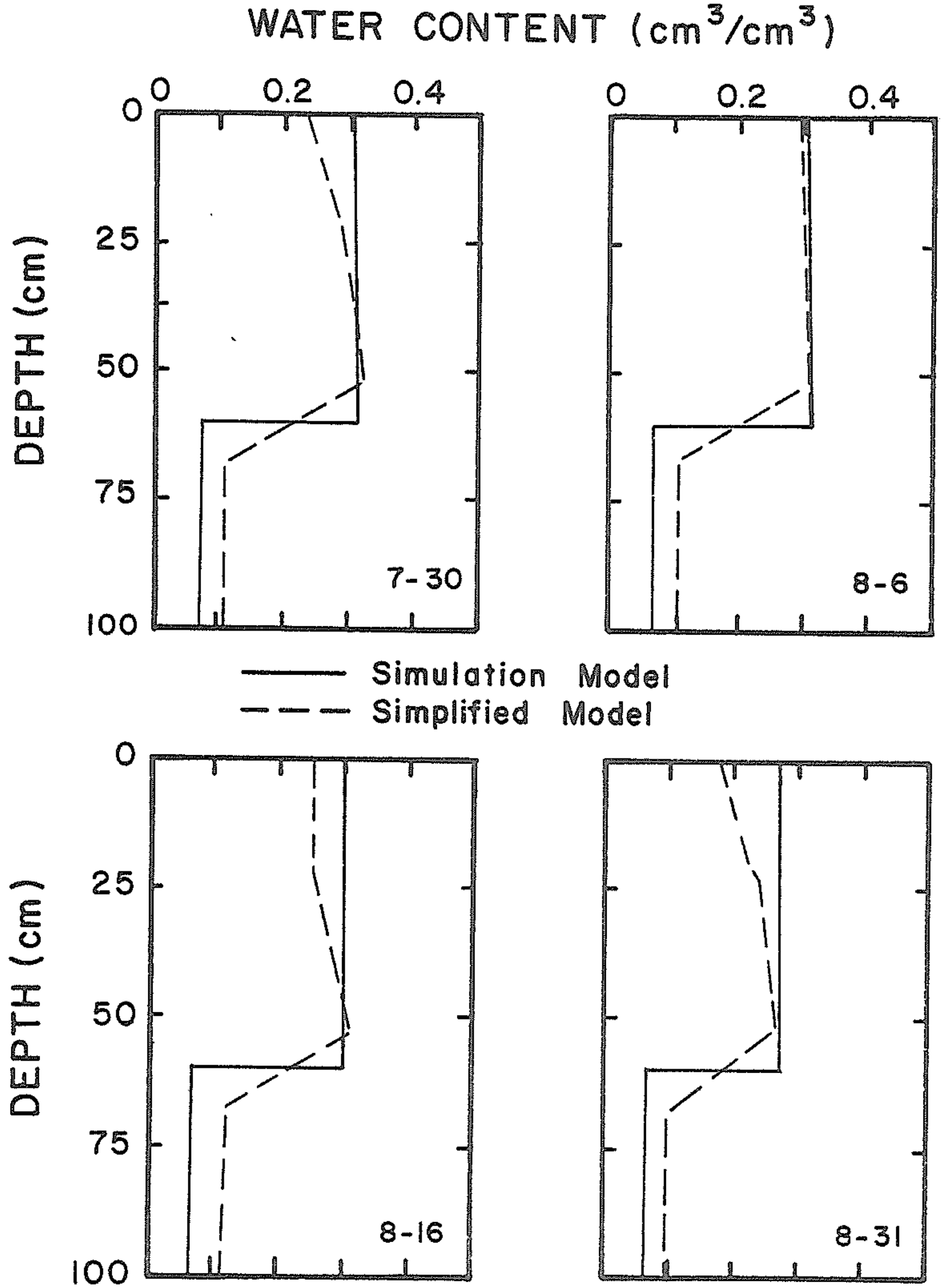

Figure 41. Comparison between the calculated water-content profiles using the simulation model and the simplified model.

Table 12. Evapotranspiration (ET), total water in profile and drainage predicted using the simulation and simplified models for 32 days.

	Simplified model	Simulation model
	(cm)	
ET	17.28	16.56
Total water in profile	20.47	20.35
Drainage	2.24	2.00

Table 13. Effect of change in hydraulic conductivity on evapotranspiration, total water in profile and drainage (71 days). Simulation Model.

	Conditions		
	K(θ) cm	K(θ)/5 cm	K(θ) x 5 cm
Irrigation water	33.14	33.14	33.14
Evapotranspiration	33.07	33.50	30.04
Total water in profile	21.77	22.34	20.38
Drainage	2.48	1.52	6.80

water simulated with the two models. Further testing of this model with additional data is needed in order to predict soil water content-profiles, ET, and drainage. The simple model seems to be promising. The computer time was reduced 100 times as compared to the simulation model.

5.5 Sensitivity of the Model

In order to test the sensitivity of the model, various parameters were changed in the program and the results compared with the original ones.

Hydraulic conductivity. To test the effect of the hydraulic conductivity, water-content distributions were computed with three sets of hydraulic conductivity data. The first set of hydraulic conductivity data were those of the soil used in the lysimeters. These data are given in Tables (10) and (11). Two additional sets of hydraulic conductivity data were obtained by multiplying and dividing the data from the first set by 5, respectively. These additional two sets of data were then used to compute the infiltration and redistribution of water in a lysimeter, for the same boundary conditions. The results are plotted in Figure (42) for the period August 9 through August 31, 1976. The comparisons indicate that there is reasonably good agreement among simulated soil water-content profiles for the different hydraulic conductivity data. The variations in water content as a result of using $K(\theta)$ or $K(\theta)/5$ were less than 0.01 cm^3/cm^3. The variations in water content were less than 0.03 cm^3/cm^3 as a result of using $K(\theta)$ or $K(\theta) \times 5$. The simulated amount of

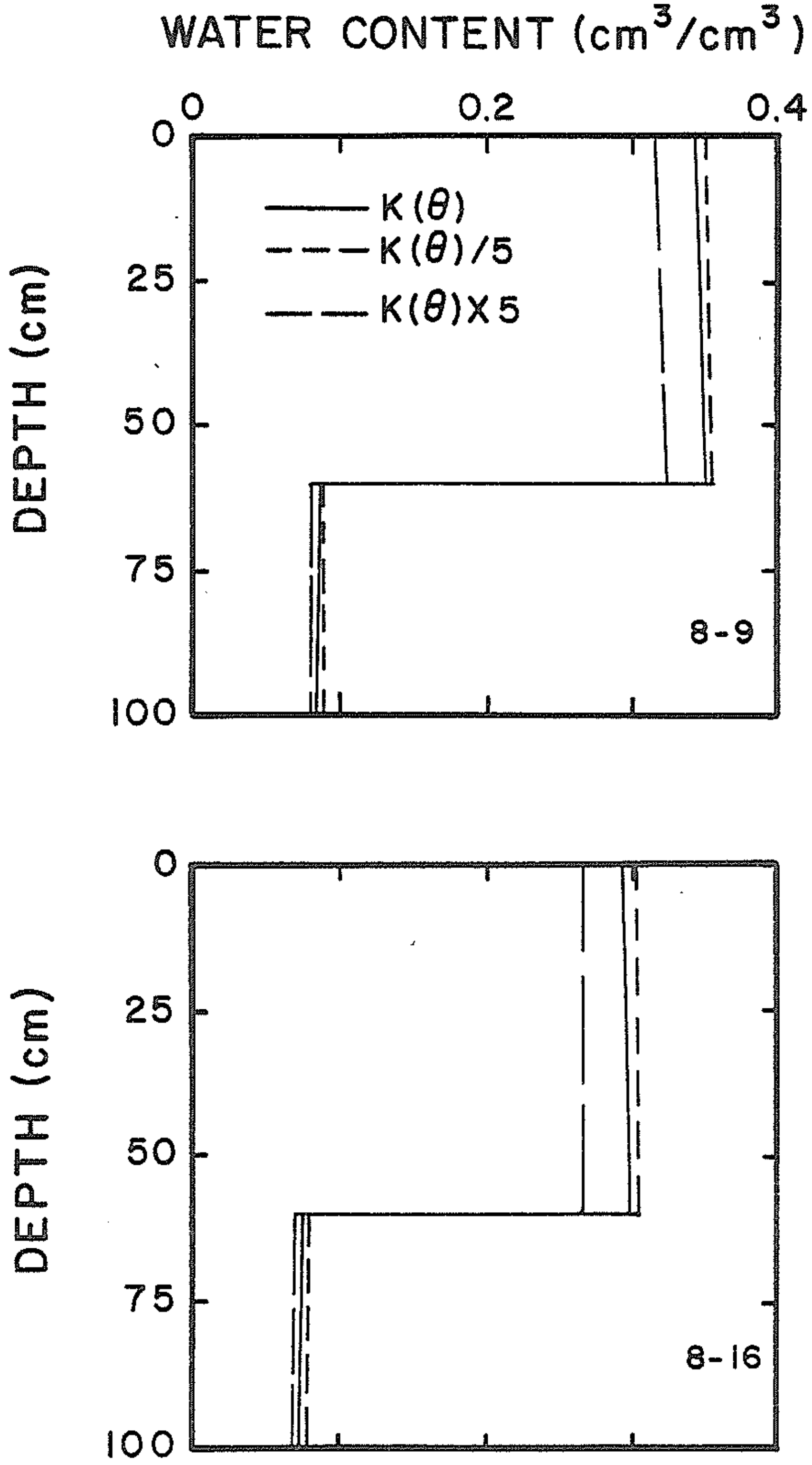

Figure 42. Water-content distribution computed with three different hydraulic conductivity versus water-content relationships.

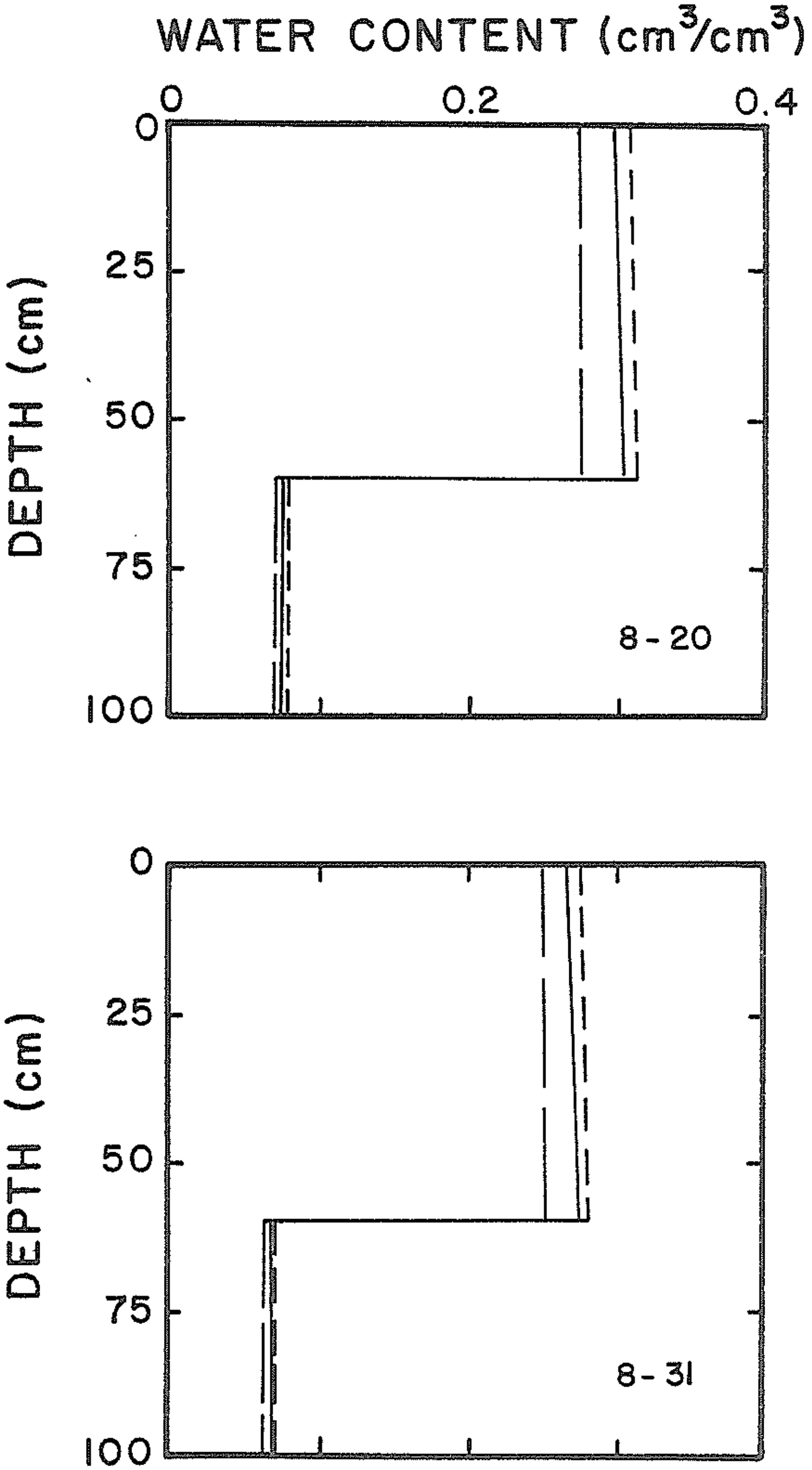

Figure 42 (cont'd.)

evapotranspiration, drainage, and total water in the profile at the end of the 71-day simulation period are given in Table (13) for the different hydraulic conductivity data. The percent of error in ET as a result of using K(θ) or 5 x K(θ) or K(θ)/5 are 9.0 and 1.3%, respectively. The amount of the drainage as a result of using K(θ), 5 x K(θ), and K(θ)/5 are 2.48, 6.80, and 1.52 cm, respectively. It appears that an error in determining hydraulic conductivity values will have a small effect on the simulated value of soil water-content profiles and ET, but it will have a larger effect on the amount of drainage water. This depends on the initial conditions, i.e., wet or dry profile.

Root mass distribution. The model is tested, also, by using different sets of root mass distribution as illustrated in Fig. (43). These are: a) a linear decrease in the root mass distribution from 0.33 at the soil surface to 0.0 at the bottom of the root zone, b) a linear increase in the root mass distribution from 0.0 at the soil surface to 0.33 at the middle of the root zone, then a linear decrease to 0.0 at the bottom of the root zone.

Although the results are not shown here, the soil water-content profiles agree very well with the results of the original condition during the 71-day period. Table (14) contains soil evaporation, transpiration, total water in the profile, and drainage values at the end of 71 days. The results show that root distribution has very little or no effect on the model.

Potential evaporation. Another test of the sensitivity of the model was made by using different values of potential evaporation:

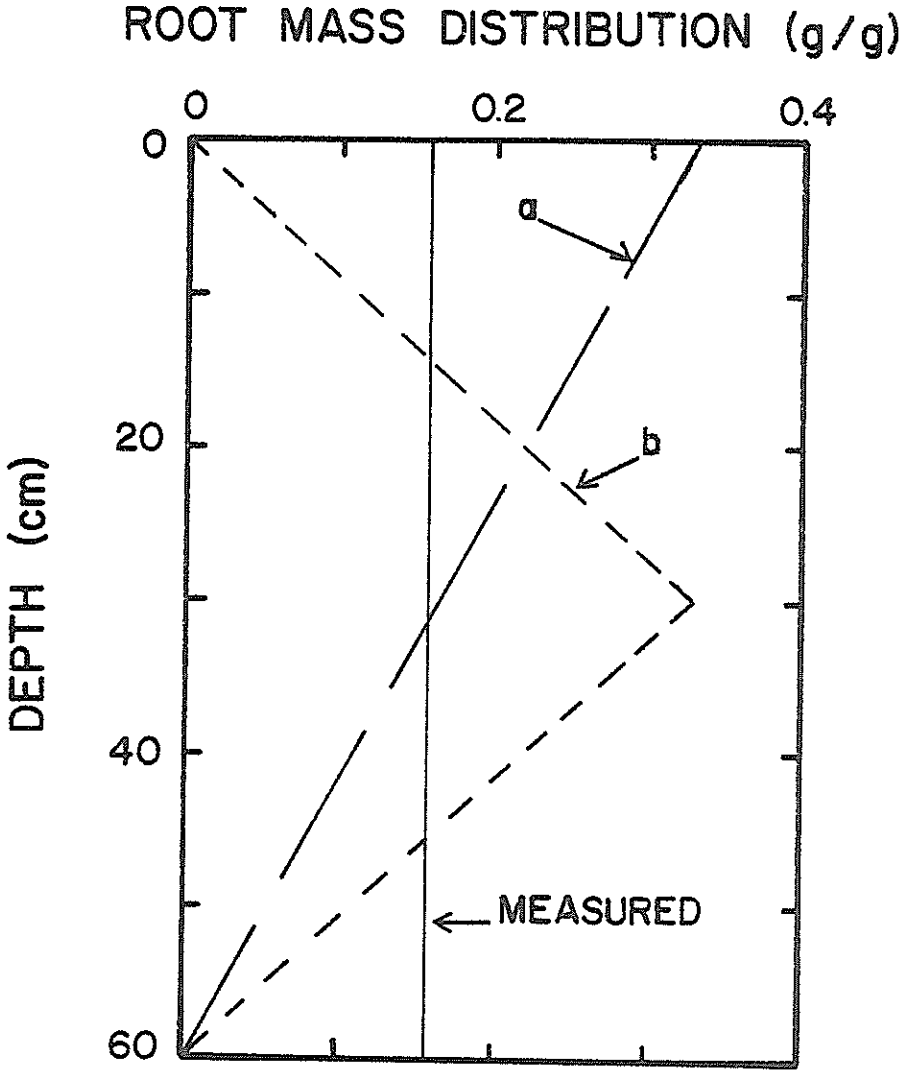

Figure 43. Schematic root distributions used in the simulation model.

Table 14. Effect of different types of root mass distribution on soil evaporation, transpiration, total water in profile, and drainage (71 days). Simulation model.

	Root Mass Distribution		
	Measured cm	a* cm	b** cm
Irrigation water	33.14	33.14	33.14
Soil evaporation	11.29	11.29	11.29
Transpiration	21.78	21.97	22.01
Total water in profile	21.77	21.64	21.61
Drainage	2.48	2.46	2.46

* a See Fig. 43.
**b. See Fig. 43.

Table 15. Effect of change in potential evaporation on soil evaporation, transpiration, total water in profile and drainage (71 days). Simulation model.

	Potential Evaporation cm day^{-1}		
	Eo cm	Eo x 0.64 cm	Eo x 1.27 cm
Irrigation water	33.14	33.14	33.14
Soil evaporation	11.29	8.50	13.07
Transpiration	21.84	15.00	22.04
Total water in profile	21.77	30.09	19.84
Drainage	2.47	4.09	2.27

Eo x 0.64 and Eo x 1.27 cm/day. The soil water-content profiles are plotted in Figure (44). Soil water-content values are 25% too high when potential evaporation is assumed to be 0.35 and 15% too low when potential evaporation is assumed to be 0.70. Soil evaporation, transpiration, total water in the profile, and drainage values at the end of 71 days are tabulated in Table (15). Soil evaporation values are 16% too high and 25% too low when potential evaporation values of 0.70 and 0.35 cm/day, respectively, are used. Values for transpiration are 31% too low and values for drainage are 66% too high when Eo is 0.35.

In the past, most of the modeling techniques have shown hydraulic conductivity to be of fundamental importance in determining the magnitude and distribution of the water uptake. The above analysis clearly indicates that water uptake by the roots is controlled by external evaporation conditions rather than by the hydraulic properties of the soil.

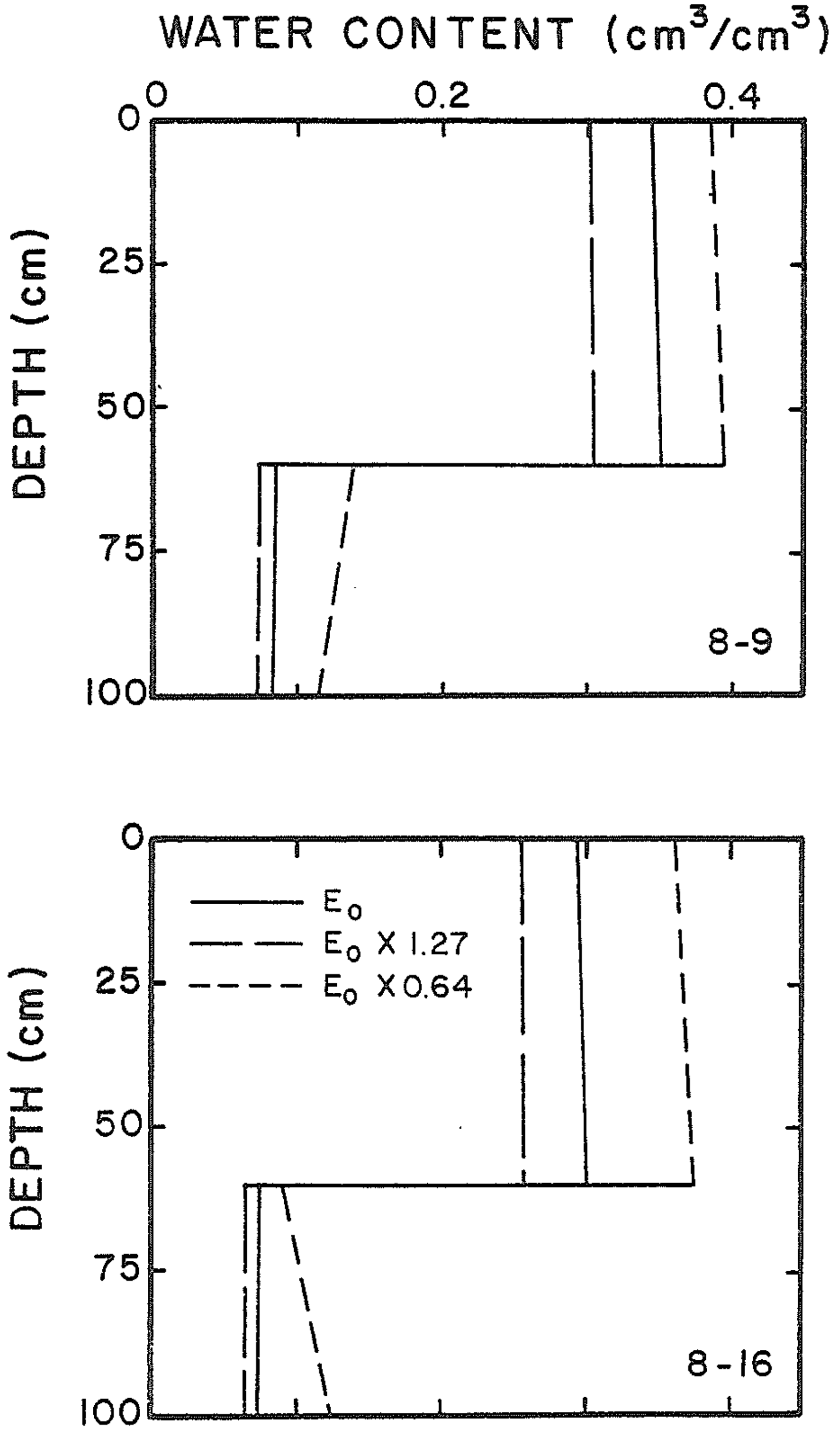

Figure 44. Water-content distribution computed with three different values of potential evaporation.

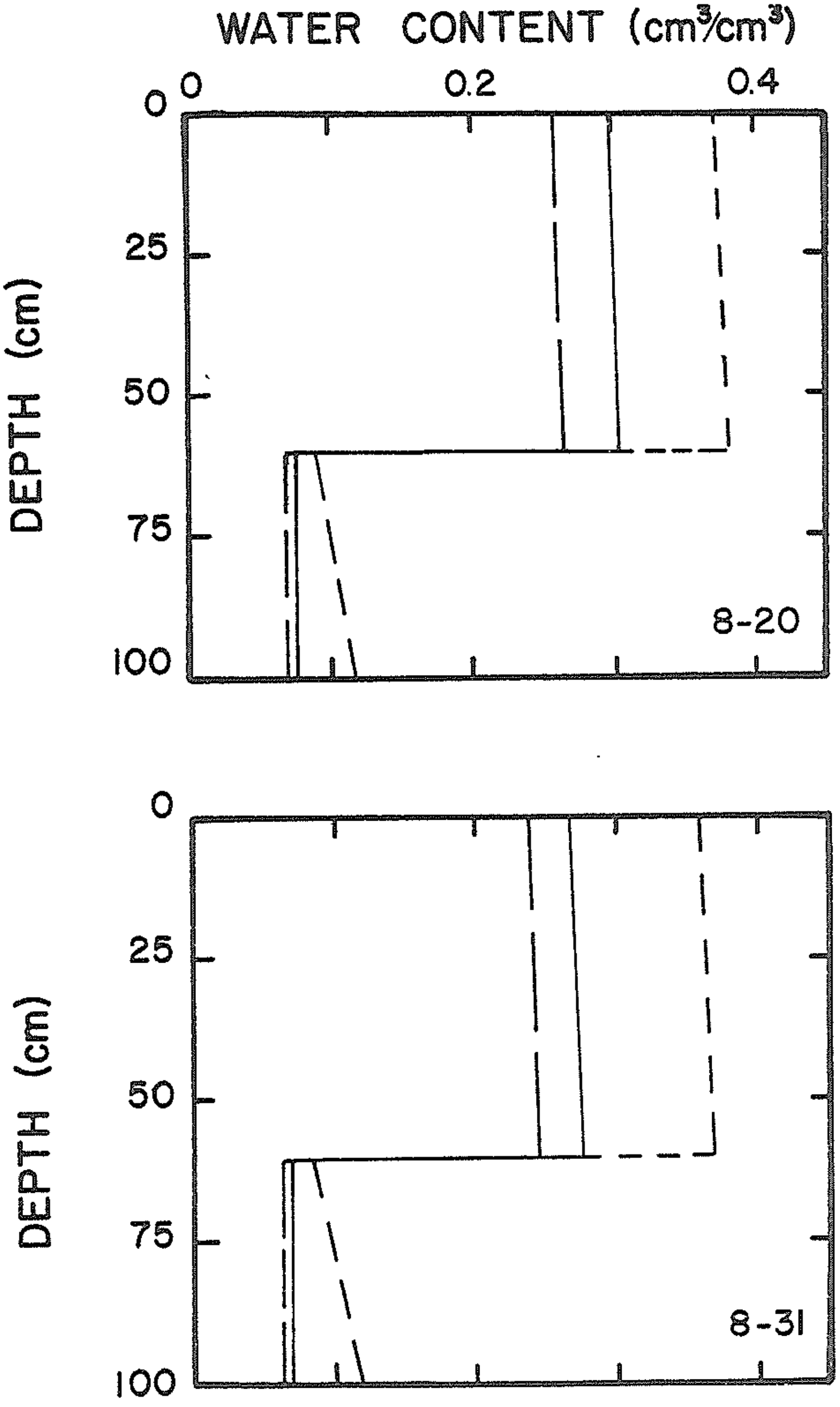

Figure 44 (cont'd.)

6. SUMMARY AND CONCLUSIONS

A CSMP simulation model was developed to predict soil water-content profiles. The model is for layered soils and one-dimensional flow, and can be applied for both limiting and nonlimiting soil water conditions.

Simulation is an approximate method. With careful approximations made in a particular simulation model, the accuracy in the results will be sufficiently accurate for most purposes.

The model consists of the general flow equation with the root extraction term:

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta z}\left[K(\theta)\frac{\delta H}{\delta z}\right] + \mathrm{RETA}(z,t)$$

where RETA(z,t) is the root water-uptake from a particular layer controlled by transpiration, and a root distribution coefficient. The root distribution coefficient is a function of the fraction of root mass and the relative position of the roots in the root zone at a given time. The basic input data needed for the simulation model are:

1. Plant properties: Root mass distribution as a function of depth and time and leaf area index as a function of time.

2. Soil properties: The pressure potential-water content, hydraulic conductivity-water content, and diffusivity-water content relationships. Initial water content at time zero, water-content values at field capacity and wiltling point.

3. The boundary conditions: Potential evaporation and the lower boundary condition.

Most of the parameters were determined in the field. The studies involved two years of field experiments with cotton. Climatic data were collected at a weather station near the field plots. Ten non-weighing lysimeters were installed to measure actual evapotranspiration. Soil water-content was measured with a neutron probe and by the gravimetric sampling method. The hydraulic conductivities of the clay loam and the sandy loam were measured by using a steady-state technique.

The leaf areas of plants were measured every week using a leaf area meter. Root distribution was determined by employing the flotation method (Al-Khafaf et al., 1977).

Empirical equations were developed to calculate soil evaporation at two stages: 1) When the soil surface is sufficiently wet and soil evaporation is controlled by available energy and plant shade, and 2) upon drying of the soil surface, when evaporation is controlled by hydraulic properties of the soils.

Transpiration was calculated as a function of leaf area index, potential evaporation and soil water-content.

The empirical relationships were tested for local conditions and for central Texas. The calculated results agreed very well with measured data.

The simulated soil water-content profiles agreed reasonably well with the measured soil water-content profiles for two dry and the wet treatments. The effects of changes in hydraulic conductivity, root mass distribution and potential evaporation were tested with the model.

The advantage of the model developed in this study over the existing models are: 1) It is simple, easy to program, and unlike most other models, does not require extensive mathematical skill; 2) knowledge about root water potential and plant resistances are not required. The model is accurate for most purposes. The disadvantages of simulation models is the requirement for a large amount of computer time. Also, the model developed herein does not take account of hysteresis.

This model and others like it require a large amount of input information. A simplified model to describe soil water-content distributions and root water-uptake was also evaluated. There is a reasonable agreement between the water-content distributions predicted with the two models.

Conclusions:

1) The flotation method developed in this study for determining root mass in soils is inexpensive and efficient. It appears to be less time-consuming than most other methods used for removing roots from soil.
2) The empirical relationships developed in this study for calculating soil evaporation and transpiration agreed with those developed by Ritchie (1972) for dryland farming conditions in central Texas.
3) It was found that 60% of the available water was depleted before transpiration rate decreased below the potential level.

4) The water uptake by the cotton roots at any particular point in the soil profile was found to be a function of the root mass at that point and the depth below the soil surface.

5) This study showed agreement between water-content distributions observed in a layered soil during a 70-day growing period and those computed with explicit finite difference simulation model.

6) The results of this study indicate that water content distributions are to a large extent controlled by the external evaporation demand, rather than by the hydraulic properties of the soil.

BIBLIOGRAPHY

Al-Khafaf, S., P. J. Wierenga, and B. C. Williams. 1977. A flotation method for determining root mass in soil. Agron. J. 69(6):1025-1026.

Atmar, J. W., M. D. Bradley, J. J. Ellington, M. A. Ellstrom, G. M. Flachs, J. L. Fowler, H. G. Kinzer and F. C. Webb. 1977. The construction of an automic microenvironmental telemetry network as an entomological observatory. (Submitted to the Environmental Entomology).

Bahrani, B., and S. A. Taylor. 1961. Influence of soil moisture potential and evaporative demand on the actual evapotranspiration from an alfalfa field. Agron. J. 53(4):233-237.

Bhuiyan, S. I., E. A. Hiler, C. H. M. van Bavel, and A. R. Aston. 1971. Dynamic simulation of vertical infiltration into unsaturated soils. Water Resour. Res. 7:1597-1606.

Black, T. A., W. R. Gardner, and G. W. Thurtell. 1969. The prediction of evaporation, drainage and soil water storage for a bare soil. Soil Sci. Soc. Amer. Proc. 33:655-660.

Bosen, J. F. 1960. A formula for approximation of saturation vapor pressure over water. Monthly Weather Rev. 88(8):275-276.

Brunt, D. 1952. Physical and dynamical meteorology, 2nd ed. University Press, Cambridge. 428 pp.

Butler, P. F. and J. A. Prescott. 1955. Evapotranspiration from wheat and pasture in relation to available moisture. Austral. J. Agr. Res. 6:52-61.

Campbell, R. B., J. H. Chang, and D. C. Cox. 1959. Evapotranspiration of sugar cane in Hawaii as measured by in-field lysimeters in relation to climate. Proc. 10th Congr. Int'l. Soc. Sugar Cane Techn., pp. 637-654.

Christiansen, J. E., and G. H. Hargreaves. 1969. Irrigation requirement from evaporation. Trans. Intern. Comm. on Irrig. and Drain., Vol. III 23.569-650.

Crank, J., and M. E. Henry. 1949. Diffusion in media with variable properties. Part 1. The effect of a variable diffusion coefficient on the rates of absorption and desorption. Trans. Faraday Soc. 45:636-650.

Dane, J. H. 1972. Effect of hysteresis on the prediction of infiltration, redistribution and drainage of water in large soil columns. M.S. Thesis, New Mexico State University, Las Cruces.

Danielson, R. E. 1967. Root system in relation to irrigation. In Irrigation of agricultural lands, Vol. II., ed. by R. M. Hogan, H. R. Haise and T. W. Edminster. Amer. Soc. of Agron. Madison, Wisconsin.

Denmead, O. T. and R. H. Shaw. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. J. 54(5):385-398.

de Wit, C. T., and H. Van Keulen. 1972. Simulation of transport processes in soils. Pudoc, Wageningen.

Eagleman, J. R., and W. L. Decker. 1956. The role of soil moisture in evapotranspiration. Agron. J. 57:626-629.

Feddes, R. A., E. Bresler, and S. P. Neuman. 1974. Field test of a modified numerical model for water uptake by root systems. Water Resour. Res. 10:1199-1206.

Feddes, R. A., and P. E. Rijtema. 1972. Water withdrawal by plant roots. J. Hydrol. 17:33-59.

Frissel, M. J., P. Poelstra, and P. Reiniger. 1970. Chromatographic transport through soils. III. A simulation model for the evaluation of the apparent diffusion coefficient in undisturbed soils with tritiated water. Plant and Soil 33:161-176.

Fritschen, L. J. 1965. Miniature net radiometer improvements. J. Appl. Meteorol. 4:528-532.

Fuchs, M., and E. Stanhill. 1963. The use of class A evaporation pan data to estimate the irrigation water requirements of the cotton crop. Israel J. Agr. Res. 13(2):63-78.

Gardner, W. R. 1960. Dynamic aspects of water availability to plants. Soil Sci. 89:63-73.

Gardner, W. R. 1964. Relation of root distribution to water uptake and availability. Agron. J. 56:35-41.

Glover, J., and J. Forsgate. 1964. Transpiration from short grass. Quart. J. Roy. Met. Soc. 90:320-324.

Halstead, M. H. 1954. The heat flux of momentum, heat, and water vapor in microclimatology. Laboratory of Climatology Publication 7(2):326-361.

Hanks, R. J., and S. E. Bowers. 1962. Numerical solution of moisture flow equation for infiltration into layered soils. Soil Sci. Soc. Amer. Proc. 26:530-534.

Hanks, R. J., A. Klute, and E. Bresler. 1969. A numeric method for estimating infiltration, redistribution, drainage and evaporation of water from soil. Soil Resour. Res. 5:1064-1069.

Havens, A. V. 1956. Using climatic data to estimate water in soil. New Jersey Agr. 38:6-10.

Haverkamp, R., M. Vanclin, J. Touma, P. J. Wierenga, and G. Vanchoud. 1977. A comparison of numerical simulation models for one-dimensional infiltration.

Hillel, D., and W. P. Gardner. 1970. Measurement of unsaturated conductivity and diffusivity by infiltration through impeding layer. Soil Sci. 109:

Holmes, R. M. 1961. Estimation of soil moisture content using evaporation data. Proc. Hydrol. Symp. 2, Toronto. pp. 184-199.

Holmes, R. M., and B. M. Robertson. 1959. A modulated soil moisture budget. Monthly Weather Review 67:101-106.

Holmes, R. M., and G. W. Robertson. 1963. Application of the relationship between actual and potential evapotranspiration in dry land agriculture. Amer. Soc. Agr. Engin. Trans., A.S.A.E. 6(1): 65-67.

IBM Corporation. 1972. System/360 Continuous System Modeling Program, User's Manual. Program number 360-CX-16X, IBM Publ. No. GH20-0367-4, White Plains, N.Y.

Jensen, M. E. 1973. Consumptive use of water and irrigation water requirements. American Soc. of Civil Engineers.

Jensen, M. E., and H. R. Haise. 1963. Estimating evapotranspiration from solar radiation. Amer. Soc. of Civ. Eng. Proc., J. of the Irrigation and Drainage Division 89(IR4):15-41.

Jury, W. A., W. R. Gardner, P. G. Saffigna, and C. B. Tanner. 1976. Model for predicting simultaneous movement of nitrate and water through a loamy sand. Soil Sci. 122:36-43.

Kanemasu, E. T., L. R. Stone, and W. L. Power. 1976. Evapotranspiration model tested for soybean and sorghum. Agronomy J. 68: 569-572.

Klute, A. 1952. Some theoretical aspects of the flow of water in unsaturated soils. Soil Sci. Soc. Amer. Proc. 16:144-148.

Knoerr, K. R. 1961. Exponential depletion of soil moisture at forest sites in the Sierra Nevada. J. Grophys. Res. 66:1556.

Kramer, P. J. 1950. Effects of wilting on the subsequent intake of water by plants. Amer. J. Bot. 37:280-284.

Kramer, P. J. 1969. Plant and soil water relationships: A modern synthesis. McGraw-Hill, New York.

Lambert, J. R., and V. W. T. Penning de Vries. 1973. Dynamics of water in the soil-plant-atmosphere system: a model named Troika. In J. Jacobs, O. L. Lange, J. S. Olson and W. Wieser (Eds.), Ecological studies. Analysis and synthesis. Vol. 4. Springer-Verlag, Berlin, Heidelberg, New York. pp. 257-273.

List, J. L. 1966. Smithsonian meteorological tables. Smithsonian Institution, Washington, D. C. 527 pp.

Malone, C. R. 1962. A rapid method for enumeration of viable seeds in soil. Weeds 15:381-382.

Molz, F. J. 1971. Interaction of water uptake and root distribution. Agron. J. 63:608-610.

Molz, F. J. 1975. Potential distribution in the soil-root system. Agron. J. 67:726-729.

Molz, F. J., and I. Remson. 1970. Extraction-term models of soil moisture use of transpiring plants. Water Resour. Res. 6:1346-1356.

Molz, F. J., and I. Remson. 1971. Application of an extraction-term model to the study of the moisture flow to plant roots. Agron. J. 63:72-77.

Molz, F. J., I. Remson, A. A. Fungaroli, and R. L. Drake. 1968. Soil moisture availability for transpiration. Water Resour. Res. 4: 1161-1169.

Newman, E. I. 1969. Resistance to water flow in soil and plant. I. Soil resistance in relation to amounts of root: theoretical estimates. J. Appl. Ecol. 16:1-12.

Nielsen, D. R. and J. W. Biggar. 1961. Measuring capillary conductivity. Soil Sci. 92:192-193.

Nimah, M. N., and R. J. Hanks. 1973a. Model for estimating soil water, plant and atmospheric interrelation: I. Description and sensitivity. Soil Sci. Soc. Am. Proc. 37:522-527.

Nimah, M. N., and R. J. Hanks. 1973b. Model for estimating soil water, plant and atmospheric interrelation: II. Field test of model. Soil Sci. Soc. Am. Proc. 37:528-532.

Ogata, G., L. A. Richards, and W. R. Gardner. 1960. Transpiration of alfalfa determined from soil water content changes. Soil Sci. 89:179-182.

Ordin, L., and S. Gairon. 1961. Diffusion of tritiated water into roots as influenced by water status of tissue. Plant Physiol. 36(3):331-335.

Penman, H. L. 1948. Natural evaporation from open water surface, bare soil, and grass. Proc. Roy. Soc. Ser. A. 193:120-146.

Penman, H. L. 1949. The dependence of transpiration on weather and soil conditions. J. Soil Sci. 1:74-89.

Penman, H. L. 1963. Vegetation and hydrology, Tech. Comm. No. 53. Commonwealth Bureau of Soils, Horpenden, Eng. 125 pp.

Philip, J. R. 1955. Numerical solution of equations of the diffusion type with diffusivity concentration-dependent. Trans. Faraday Soc. 51:885-892.

Philip, J. R. 1957. Evaporation and moisture and heat fields in the soil. J. Meteorol. 14:354-366.

Pierce, L. T. 1958. Estimating seasonal and short-term fluctuations in evapotranspiration from meadow crops. Amer. Met. Soc. B. 39(2):73-78.

Priestley, C. H. B., and R. J. Taylor. 1972. On the assessment of the surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100:81-92.

Pruitt, W. O., and M. L. Jensen. 1955. Determining when to irrigate. Agr. Engr. 36:389-396.

Remson, I., R. L. Drake, S. S. McNeary, and E. M. Walls. 1965. Vertical drainage of an unsaturated soil. Amer. Soc. Civil Eng. Proc. J. Hydraulics Div. 91:55-74.

Remson, I., A. A. Fungaroli, and G. M. Hornberger. 1967. Numerical analysis of soil moisture systems. Amer. Soc. Civil Ent. Proc. J. Irrig. Drain. Div. 3:153-166.

Remson, I., G. M. Hornberger, and F. J. Molz. 1971. Numerical methods in subsurface hydrology. Wiley-Interscience. A division of John Wiley & Sons, Inc. 389 pp.

Richards, L. A. 1941. A pressure membrane apparatus for soil suction. Soil Sci. 51:377-386.

Ritchie, J. T. 1971. Dryland evaporative flux in a subhumid climate: I. Micrometeorological influences. Agron. J. 63:51-55.

Ritchie, J. T. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8:1204-1213.

Ritchie, J. T. 1973. Influence of soil water status and meteorological conditions on evaporation from a corn canopy. Agronomy J. 65:893-897.

Ritchie, J. T., and Earl Burnett. 1971. Dryland evaporative flux in a subhumid climate: plant influences. Agron. J. 63:56-62.

Ritchie, J. T., E. Burnett, and R. C. Henderson. 1972. Dryland evaporative flux in a subhumid climate. II. Soil water influences. Agron. J. 64:168-173.

Robinson, E. L., and C. A. Kurst. 1962. Distribution of witchweed seeds in the soil. Weeds 10:335-336.

Rose, C. W., and W. R. Sterns. 1967. Determination of withdrawal of water from soil by crop roots as a function of depth and time. Aust. J. Soil. Res. 5:11-19.

Rosenberg, N. J., H. E. Hart and K. W. Brown. 1968. Evapotranspiration review of research. Nebraska Agr. Exp. Sta. Bull. MP 20.

Rubin, J. 1966. Theory of rainfall uptake by soils initially drier than their field capacity and its applications. Water Resour. Res. 2:739-749.

Rubin, J., and R. Steinhardt. 1963. Soil water relations during rain infiltration. I. Theory. Soil Sci. Soc. Amer. Proc. 27: 246-251.

Rubin, J., and R. Steinhardt. 1964. Soil water relations during rain infiltration. III. Water uptake at incipient ponding. Soil Sci. Soc. Amer. Proc. 28:614-619.

Scholander, P. F., H. T. Hammel, E. A. Hemmingsen, and E. D. Bradstreet. 1964. Hydrostatic pressure and osmotic potential in leaves of mangroves and some other plants. Proc. Nat. Acad. Sci. 52:119-125.

Shaw, R. H. 1963. Estimation of soil moisture under corn. Iowa Agr. and Home Econ. Expt. Sta. Res. B. 520:968-980.

Stanhill, G. 1961. A comparison of methods of calculating potential evapotranspiration from climatic data. Israel J. Agr. Res. 11: 159-171.

Stanhill, G. 1962. The control of field irrigation practice from measurements of evaporation. Israel J. Agr. Res. 12:51-62.

Tanner, C. B. 1967. Measurement of evapotranspiration, pp. 534-574. In R. M. Hagen (ed.)., Irrigation of agricultural lands. Agronomy No. 11. Amer. Soc. of Agron., Madison, Wisconsin.

Tanner, C. B., and W. A. Jury. 1976. Estimating evaporation and transpiration from a row crop during incomplete cover. Agr. J. 68:239-243.

Thornwaite, C. W., and J. R. Mathers. 1955. The water budget and its use in irrigation, pp. 346-358. In Alfred Stefferud (ed.). Water, the yearbook of agriculture, 1955. U.S. Department of Agriculture, Washington, D. C.

van Bavel, C. H. M. 1966. Potential evaporation: The combination concept and its experimental verification. Water Resour. Res. 2:455-467.

van Bavel, C. H. M. 1976. Evapotranspiration of alfalfa under field conditions. Agr. Meteorol. 4(1):165-176.

van Bavel, C. H. M., and J. Ahmed. 1976. Dynamic simulation of water depletion in the root zone. Water Resour. Res. 2:189-212.

van Bavel, C. H. M., and G. B. Stirk. 1967. Soil water measurement with an 241 Am-Be source and an application to evaporimetry. J. Hydrol. 5:40-46.

van Genuchten, M. Th., and p. J. Wierenga. 1974. Simulation of one-dimensional solute transfer in porous media. N. Mex. Agr. Exp. Sta. Bull. 628. 40 pp.

van Keulen, H., and C. G. E. M. van Beek. 1971. Water movement in layered soils - A simulation model. Neth. J. Agric. Sci. 19: 138-158.

Veihmeyer, F. J., and A. H. Hendrickson. 1927. Soil moisture conditions in relation to plant growth. Plant Physiol., Lancaster 2:71-82.

Veihmeyer, F. J., and A. H. Hendrickson. 1931. The moisture equivalent as a measure of the field capacity of the soil. Soil Sci. 32:181-194.

Veihmeyer, F. J., and A. H. Hendrickson. 1955. Does transpiration decrease as soil moisture decreases? Amer. Geophys. Union Trans. 36:425-448.

Walker, M. E., J. R. Stansell, Jr., and J. E. Shannon. 1976. Precision soil samples. Agron. J. 68:431-543.

Watson, D. J. 1974. Comparative physiological studies on the growth of field crop. II. The effect of varying nutrient supply on net assimilation rate and leaf area. Ann. Bot. 11:375-407.

West, E. S., and O. Perkman. 1953. Effect of soil moisture on transpiration. Aust. J. Agr. Res. 4:326-333.

Whisler, F. D., and A. Klute. 1965. The numerical analysis of infiltration considering hysteresis into a vertical soil column at equilibrium under gravity. Soil Sci. Soc. Amer. Proc. 29:489-494.

Whisler, F. D., A. Klute, and R. J. Millington. 1968. Analysis of steady state evapotranspiration from a soil comumn. Soil Sci. Soc. Amer. Proc. 32:167-174.

Whisler, F. D., A. Klute, and R. J. Millington. 1970. Analysis of radial, steady state solution, and solute flow. Soil Sci. Soc. Amer. Proc. 34:382-387.

Wiebe, H. H. 1966. Matric potential of several plant tissues and biocolloids. Plant Physiol. 49(9):1439-1442.

Wierenga, P. J., and C. T. de Wit. 1970. Simulation of heat transfer in soils. Soil Sci. Soc. Amer. Proc. 34:845-848.

Woodruff, C. M. 1941. Soil moisture and plant growth in relation to pH. Soil Sci. Soc. Amer. Proc. 5:36-41.

Wu, A. Y. K. 1967. The relationship between soil moisture content and the rate of evapotranspiration. J. Austral. Inst. Agr. Sci. 33:41-42.

Zahner, R. 1967. Refinement in empirical functions for realistic soil moisture regimes under forest cover, p. 261. In W. E. Sopper and H. W. Lull (eds.). Forest hydrology. Pergamon Press, Oxford.

APPENDIX A

Root-mass distributions as a function of time and depth for different treatments.

Table 16. Dry weights of fine and suberized roots in two-dimensional distribution. Field plot sample, wet, trickle-irrigated, single row. August 16, 1976.

Depth cm	Distance from the center of the row (cm) 50 40 30 20 10 0 10 20 30 40 50									
					Fine Roots (g)					
0-10	0.40	0.83	0.95	1.16	2.20	2.20	1.16	0.95	0.83	0.40
10-20	1.08	1.58	2.41	2.53	1.78	1.78	2.53	2.41	1.58	1.08
20-30	1.10	1.43	1.91	2.07	1.60	1.60	2.07	1.91	1.43	1.10
30-40	0.83	0.99	1.18	1.31	1.08	1.08	1.31	1.18	0.99	0.83
40-50	0.81	0.96	1.13	1.07	0.91	0.91	1.07	1.13	0.96	0.81
50-60	0.78	0.81	0.90	0.98	0.93	0.93	0.99	0.90	0.81	0.78
60-70	0.21	0.30	0.38	0.54	0.45	0.45	0.54	0.38	0.30	0.21
78-80	0.10	0.20	0.26	0.33	0.40	0.40	0.32	0.26	0.20	0.10
80-90	-	0.05	0.08	0.13	0.21	0.21	0.14	0.08	0.04	-
90-100	-	-	-	0.05	0.10	0.10	0.05	-	-	-
					Suberized Roots (g)					
0-10	0.12	0.21	0.44	0.72	9.90	9.90	0.72	0.44	0.21	0.12
10-20	0.05	0.14	0.31	0.49	2.52	2.52	0.49	0.31	0.14	0.05
20-30	0.15	0.23	0.30	0.28	1.05	1.05	0.28	0.30	0.23	0.15
30-40	0.07	0.15	0.30	0.23	0.68	0.68	0.23	0.30	0.15	0.07
40-50	0.07	0.21	0.08	0.35	0.41	0.41	0.35	0.08	0.21	0.07
50-60	0.04	0.10	0.21	0.26	0.45	0.45	0.26	0.21	0.10	0.04
60-70	0.04	0.05	0.05	0.08	0.11	0.11	0.08	0.05	0.05	0.04
70-80	0.05	0.04	0.04	0.07	0.08	0.08	0.07	0.04	0.04	0.05
80-90	-	-	-	0.04	0.07	0.07	0.04	-	-	-
90-100	-	-	-	0.01	0.05	0.05	0.01	-	-	-

Table 17. Dry weights of fine and suberized roots in two-dimensional distribution. Field plot sample, wet, trickle-irrigated, single row. August 10, 1976.

Depth	Distance from the center of the row (cm)										
cm	50	40	30	20	10	0	10	20	30	40	50
					Fine Roots (g)						
0-10	0.43	0.76	1.05	1.25	2.31	2.31	1.26	1.05	0.76	0.43	
10-20	1.18	1.53	2.34	2.48	1.95	1.95	2.48	2.34	1.53	1.18	
20-30	1.10	1.50	1.80	1.94	1.53	1.53	1.94	1.80	1.50	1.10	
30-40	0.92	1.05	1.06	1.29	1.00	1.00	1.29	1.06	1.05	0.94	
40-50	0.81	0.93	0.98	1.03	0.96	0.96	1.03	0.98	0.93	0.81	
50-60	0.82	0.90	0.93	0.98	0.81	0.81	0.98	0.93	0.90	0.32	
60-70	0.25	0.31	0.35	0.54	0.55	0.55	0.54	0.35	0.31	0.25	
70-80	0.17	0.08	0.21	0.35	0.31	0.31	0.35	0.21	0.08	0.17	
80-90	0.08	-	0.10	0.16	0.13	0.13	0.16	0.10	-	0.08	
90-100	-	-	-	0.09	0.08	0.08	0.09	-	-	-	
					Suberized Roots (g)						
0-10	0.09	0.20	0.40	0.70	9.40	9.40	0.70	0.40	0.20	0.09	
10-20	0.07	0.15	0.33	0.38	2.93	2.93	0.38	0.33	0.15	0.06	
20-30	0.05	0.12	0.21	0.30	1.27	1.27	0.30	0.22	0.11	0.05	
30-40	0.09	0.31	0.37	0.40	1.19	1.19	0.40	0.36	0.30	0.09	
40-50	0.10	0.14	0.21	0.31	0.49	0.49	0.30	0.21	0.14	0.10	
50-60	0.09	0.08	0.15	0.21	0.30	0.30	0.20	0.15	0.08	0.09	
60-70	0.03	0.05	0.07	0.10	0.11	0.11	0.10	0.07	0.05	0.03	
70-80	0.01	0.05	0.04	0.05	0.09	0.09	0.05	0.04	0.05	0.01	
80-90	-	-	0.02	0.02	0.05	0.05	0.02	0.02	-	-	
90-100	-	-	-	-	0.04	0.04	-	-	-	-	

Table 18. Dry weights of fine and suberized roots in two-dimensional distribution. Field plot sample, wet, trickle-irrigated, double row. August 17, 1976.

Depth	Distance from the center of the row (cm)										
cm	50	40	30	20	10	0	10	20	30	40	50
					Fine Roots (g)						
0-10	0.47	1.02	1.97	2.25	2.78	2.78	2.25	1.97	1.02	0.47	
10-20	1.24	2.00	2.56	3.66	3.15	3.15	3.66	2.56	2.00	1.24	
20-30	1.71	1.80	2.15	2.25	1.50	1.50	2.25	2.15	1.80	1.71	
30-40	0.78	1.00	1.34	1.39	1.18	1.18	1.39	1.34	1.00	0.78	
40-50	1.50	1.55	1.66	1.81	2.15	2.15	1.81	1.66	1.55	1.50	
50-60	0.65	0.85	0.90	0.92	1.03	1.03	0.92	0.90	0.85	0.65	
60-70	0.49	1.12	1.22	1.35	1.26	1.26	1.35	1.22	1.15	0.49	
70-80	0.25	0.34	0.37	0.52	0.45	0.45	0.52	0.37	0.34	0.25	
80-90	-	-	0.08	0.31	0.21	0.21	0.31	0.08	-	-	
90-100	-	-	0.12	0.20	0.10	0.10	0.20	0.12	-	-	
					Suberized Roots (g)						
0-10	0.05	0.09	0.13	0.68	23.38	23.38	0.68	0.13	0.09	0.05	
10-20	0.05	0.15	0.35	0.54	6.23	6.23	0.54	0.35	0.15	0.05	
20-30	0.05	0.13	0.22	0.31	1.88	1.88	0.31	0.22	0.13	0.05	
30-40	0.12	0.12	0.17	0.21	0.93	0.93	0.21	0.17	0.12	0.12	
40-50	0.05	0.06	0.08	0.20	0.41	0.41	0.20	0.08	0.06	0.05	
50-60	0.04	0.04	0.05	0.12	0.21	0.21	0.12	0.05	0.04	0.04	
60-70	0.03	0.05	0.08	0.09	0.15	0.15	0.09	0.08	0.05	0.03	
70-80	0.02	0.04	0.05	0.09	0.10	0.10	0.09	0.05	0.04	0.02	
80-90	-	-	-	0.04	0.08	0.08	0.04	-	-	-	
90-100	-	-	-	0.05	0.05	0.05	0.05	-	-	-	

Table 19. Dry weights of fine and suberized roots in two-dimensional distribution. Field plot sample, wet, trickle-irrigated, double row. August 20, 1976.

Depth	Distance from the center of the row (cm)										
cm	50	40	30	20	10	0	10	20	30	40	50
					Fine Roots (g)						
0-10	0.53	1.00	1.85	2.35	2.51	2.51	2.35	1.85	1.00	0.53	
10-20	1.10	1.64	4.00	4.15	3.28	3.28	4.15	4.00	1.64	1.10	
20-30	1.58	1.95	2.15	2.35	1.50	1.50	2.35	2.15	1.95	1.58	
30-4	0.84	1.24	1.40	1.50	1.25	1.25	1.50	1.40	1.24	0.84	
40-50	1.31	1.30	1.50	1.77	1.92	1.92	1.77	1.50	1.30	1.31	
50-60	0.53	0.85	0.92	0.88	1.07	1.07	0.88	0.92	0.85	0.53	
60-70	0.43	1.06	1.32	1.42	1.32	1.32	1.42	1.32	1.06	0.21	
70-80	0.21	0.30	0.35	0.40	0.45	0.45	0.40	0.35	0.30	0.21	
80-90	-	0.05	0.10	0.18	0.21	0.21	0.18	0.10	0.05	-	
90-100	-	-	0.03	0.09	0.10	0.10	0.09	0.03	-	-	
					Suberized Roots (g)						
0-10	0.09	0.12	0.20	0.50	20.63	20.63	0.50	0.20	0.12	0.09	
10-20	0.07	0.18	0.48	1.27	5.00	5.00	1.27	0.48	0.18	0.07	
20-30	0.05	0.19	0.32	0.63	1.37	1.37	0.63	0.32	0.19	0.05	
30-40	0.04	0.09	0.63	0.50	0.75	0.75	0.50	0.36	0.09	0.04	
40-50	0.10	0.15	0.14	0.20	0.62	0.62	0.20	0.14	0.15	0.10	
50-60	0.05	0.07	0.12	0.10	0.22	0.22	0.10	0.12	0.07	0.05	
60-70	0.03	0.05	0.20	0.10	0.23	0.23	0.10	0.20	0.05	0.03	
70-80	0.01	0.04	0.05	0.06	0.10	0.10	0.06	0.05	0.04	0.01	
80-90	-	0.02	0.01	0.08	0.10	0.10	0.08	0.01	0.02	-	
90-100	-	-	-	0.01	0.05	0.05	0.01	-	-	-	

Table 20. Dry weight of fine and suberized roots in two-dimensional distribution. Field plot sample, wet, furrow-irrigated, single row. August 18, 1976.

Depth cm	Distance from the center of the row (cm) 50	40	30	20	10	0	10	20	30	40	50
Fine Roots (g)											
0-10	-	0.06	0.86	1.07	1.38	1.38	1.07	0.86	0.06	-	
10-20	0.12	0.45	0.88	2.20	1.50	1.50	2.20	0.88	0.45	0.12	
20-30	0.35	0.95	0.86	1.00	1.56	1.56	1.00	0.85	0.95	0.35	
30-40	0.81	0.75	0.85	0.90	1.00	1.00	0.90	0.85	0.75	0.81	
40-50	0.62	0.58	0.69	0.70	0.72	0.72	0.70	0.69	0.58	0.62	
50-60	0.68	0.72	0.75	0.85	1.11	1.11	0.85	0.75	0.72	0.68	
60-70	0.54	0.62	0.75	0.72	0.91	0.91	0.72	0.75	0.62	0.54	
70-80	0.40	0.41	0.42	0.45	0.48	0.48	0.45	0.42	0.41	0.40	
80-90	0.13	0.21	0.31	0.25	0.21	0.21	0.25	0.31	0.21	0.13	
90-100	-	-	0.05	0.13	0.08	0.08	0.13	0.05	-	-	
Suberized Roots (g)											
0-10	-	0.05	0.05	0.41	10.18	10.18	0.41	0.05	0.05	-	
10-20	0.09	0.17	0.50	1.00	8.00	8.00	1.00	0.50	0.17	0.09	
20-30	0.03	0.06	0.12	0.20	2.50	2.50	0.20	0.17	0.06	0.03	
30-40	0.04	0.08	0.15	0.18	0.70	0.70	0.18	0.15	0.08	0.04	
40-50	0.03	0.05	0.09	0.13	0.25	0.25	0.13	0.09	0.09	0.03	
50-60	0.05	0.09	0.10	0.17	0.30	0.30	0.14	0.10	0.09	0.05	
60-70	0.04	0.05	0.10	0.20	0.23	0.23	0.20	0.10	0.05	0.04	
70-80	0.05	0.04	0.05	0.09	0.21	0.21	0.09	0.06	0.04	0.05	
80-90	-	-	0.02	0.05	0.16	0.16	0.05	0.02	-	-	
90-100	-	-	-	-	0.09	0.09	-	-	-	-	

Table 21. Dry weights of the fine and suberized roots in two-dimensional distribution. Field plot sample, wet, furrow-irrigated, single row. August 13, 1976.

Depth	Distance from the center of the row (cm)									
cm	50 40	40 30	30 20	20 10	10 0	0 10	10 20	20 30	30 40	40 50
0-10	-	0.21	0.92	1.00	1.46	1.46	1.00	0.92	0.21	-
10-20	0.19	0.39	0.79	1.15	1.47	1.47	1.15	0.79	0.39	0.19
20-30	0.38	0.73	0.72	1.15	1.46	1.46	1.15	0.72	0.73	0.38
30-40	0.80	0.80	0.98	1.00	1.04	1.04	1.00	0.98	0.80	0.80
40-50	0.50	0.63	0.67	0.69	0.75	0.75	0.69	0.67	0.63	0.50
50-60	0.65	0.71	0.77	0.88	1.03	1.03	0.88	0.77	0.71	0.65
60-70	0.70	0.65	0.76	0.81	0.87	0.87	0.81	0.76	0.65	0.70
70-80	0.35	0.50	0.48	0.45	0.41	0.41	0.45	0.48	0.50	0.35
80-90	-	0.10	0.12	0.21	0.21	0.21	0.21	0.21	0.10	-
90-100	-	-	0.09	0.01	0.10	0.10	0.01	0.09	-	-
					Suberized Roots (g)					
0-10	-	0.04	0.06	0.43	9.62	9.62	0.43	0.06	0.04	-
10-20	0.05	0.10	0.41	1.06	7.16	7.16	1.06	0.41	0.10	0.05
20-30	0.06	0.19	0.24	0.33	2.25	2.25	0.33	0.24	0.19	0.06
30-40	0.05	0.05	0.12	0.23	0.75	0.75	0.23	0.12	0.05	0.05
40-50	0.05	0.09	0.15	0.30	0.39	0.39	0.30	0.15	0.09	0.05
50-60	0.04	0.10	0.08	0.18	0.25	0.25	0.18	0.08	0.10	0.04
60-70	0.03	0.07	0.09	0.10	0.15	0.15	0.10	0.09	0.07	0.03
70-80	0.03	0.04	0.08	0.08	0.10	0.10	0.08	0.08	0.04	0.03
90-100	-	-	0.01	0.05	0.02	0.02	0.05	0.01	-	-

Table 22. Dry weights of fine and suberized roots in two-dimensional distribution. Field plot sample, dry, trickle-irrigated, single row. August 3, 1976.

Depth cm	← Distance from the center of the row (cm) →										
	50	40	30	20	10	0	10	20	30	40	50
					Fine Roots (g)						
0-10	0.46	0.53	0.80	1.06	1.75	1.75	1.06	0.80	0.53	0.46	
10-20	1.06	1.10	1.14	1.19	1.78	1.78	1.19	1.14	1.10	1.06	
20-30	0.50	0.60	0.72	0.74	0.60	0.60	0.74	0.72	0.60	0.50	
30-40	0.16	0.20	0.22	0.44	0.33	0.33	0.44	0.22	0.20	0.16	
40-50	0.34	0.39	0.48	0.67	0.49	0.49	0.67	0.48	0.39	0.34	
50-60	0.35	0.36	0.42	0.48	0.50	0.50	0.48	0.42	0.36	0.35	
60-70	0.25	0.35	0.30	0.35	0.28	0.28	0.35	0.30	0.35	0.25	
70-80	0.15	0.28	0.30	0.31	0.22	0.22	0.31	0.30	0.28	0.15	
80-90	-	-	0.08	0.08	0.19	0.19	0.08	0.08	-	-	
90-100	-	-	-	0.07	0.09	0.09	0.07	-	-	-	
					Suberized Roots (g)						
0-10	0.04	0.09	0.27	0.92	3.72	3.72	0.92	0.07	0.09	0.04	
10-20	0.02	0.03	0.18	0.42	1.75	1.75	0.42	0.18	0.03	0.02	
20-30	0.05	0.08	0.07	0.19	0.73	0.73	0.19	0.07	0.08	0.05	
30-40	0.03	0.06	0.06	0.14	0.24	0.24	0.14	0.06	0.06	0.03	
40-50	0.04	0.05	0.09	0.16	0.29	0.29	0.16	0.09	0.05	0.04	
50-60	0.03	0.05	0.08	0.09	0.12	0.12	0.09	0.08	0.05	0.03	
60-70	0.03	0.06	0.07	0.08	0.11	0.11	0.08	0.07	0.06	0.03	
70-80	0.02	0.04	0.05	0.05	0.07	0.07	0.05	0.05	0.04	0.02	
80-90	-	-	-	-	0.03	0.03	-	-	-	-	
90-100	-	-	-	-	0.02	0.02	-	-	-	-	

APPENDIX B

Potential Evaporation

Example:

As an example of how to use the various equations and which constants and parameters were used, we have computed the average potential evaporation for the month of August 1976 using a desk calculator.

Source data:

Location - Las Cruces, New Mexico, USA

Latitude - 30°N

Elevation - 3980 ft = 1213.9 m

Mean maximum air temperature = 88.60°F = 31.45°C

Mean minimum air temperature = 60.87°F = 16.04°C

Mean dew point temperature = 57.23°F = 14.01°C

Mean dry bulb temperature = 70.85°F = 21.58°C

Mean wet bulb temperature = 63.44°F = 17.47°C

Mean average temperature = 74.735°F = 23.745°C

Mean wind speed at 2 m height = 83.35 mi day^{-1} = 134.15 km day^{-1}

Mean solar radiation = 519.8 ly day^{-1}

Mean pan evaporation = 7.77 mm day^{-1}.

Most of the parameters required for computing E_o by the selected methods in this paper can be found in the Smithsonian Meteorological Tables (List, 1966), or can be computed using the following equations (For more information, see Jensen (1973), p. 122):

Constants:

κ is Von Karman's constant (dimensionless). It is a universal gas constant with an average value of 0.41.

Cp is specific heat of air (cal g^{-1} $^{o}C^{-1}$). It changes slightly with atmospheric pressure. A constant value of 0.242 was used in the computations.

L is latent heat of vaporization (cal g^{-1}). L changes with temperature but is not affected by atmospheric pressure. L was calculated using the equation developed by Brunt (1952).

$$L = 595 - 0.51\ (T) \tag{1B}$$

where T is average temperature in (^{o}C).

Atmospheric Pressure (P) and Density (ρ): Atmospheric pressure and density are approximated by a linear relationship based on NACA (National Advisory Committee for Aeronautics) standard atmosphere tables (Jensen, 1973). P and ρ are computed as follows:

$$P = 1013 - 0.1055 \times \text{elev. (Mb; elev. in m)} \tag{2B}$$

$$P = 1013 - 0.03217 \times \text{elev. (Mb; elev. in ft)} \tag{3B}$$

$$\rho = 0.00123 - 0.000034 \times \text{elev}/305\ (\text{g cm}^{-3};\ \text{elev. in m}) \tag{4B}$$

$$\rho = 0.00123 - 0.000034 \times \text{elev}/1000\ (\text{g cm}^{-3};\ \text{elev. in ft}) \tag{5B}$$

Vapor pressure: Vapor pressure over water was computed using the non-linear relationship presented by Bosen (1960).

$$e \simeq 33.8639\ [(0.0041T + 0.676)^8 - 0.000019\ |T + 16| + 0.001316] \tag{6B}$$

for $60^\circ F < T < 130^\circ F$, (e in inches of Hg), and

$$e \simeq 33.8639\ [(0.00738T + 0.8072)^8 - 0.000019\ |1.8T + 48| + 0.001316] \tag{7B}$$

for $-51^\circ C < T < 54^\circ C$, (e in mb).

Slope of the saturation vapor pressure curve, Δ: Jensen (1973) used Bosen's formulas for saturation vapor pressure to evaluate Δ which varies with temperature.

$$\Delta = \frac{de_s}{dT} \simeq 33.8639\ [0.0328\ (0.0041T + 0.676)^7 - 0.000019] \tag{8B}$$

for $T \leq -23^\circ C$ (Δ in mb ${}^\circ C^{-1}$).

Psychrometer constant, γ: The psychrometer constant is the balance between sensible heat gains from air flowing past a wet bulb thermometer and sensible heat transformed into latent heat.

$$\gamma = \frac{CpP}{0.622L} \tag{9B}$$

where γ is in mb ${}^\circ C^{-1}$ or in inches Hg ${}^\circ F^{-1}$.

Calculation of the constants:

$T = 23.745^{o}C$

Dew point = $14.01^{o}C$

$e = 16.00$ mb (Eq. 7B)

$e = 16.00$ mb (From NACA tables)

$e_s = 29.37$ mb (Eq. 7B)

$e_s = 29.40$ mb (From NACA tables)

$L = 682.89$ cal g^{-1} (Eq. 1B)

$\gamma = 0.591$ mb ${}^{o}C^{-1}$ (Eq. 9B)

$RH = e/e_s = 54.5\%$

$\Delta = 1.765$ mb ${}^{o}C^{-1}$ (Eq. 8B)

$\rho = 1.095 \times 10^{-3}$ gm cm^{-3} (Eq. 4B)

ALB = 0.10

Rn = 364.29 Ly day^{-1}

P = 884.93 mb (Eq. 2B)

Penman (1963):

$$E_o = \frac{\Delta Rn + \gamma\ Ea}{\Delta + \gamma} \qquad \text{(Eq. 5)}$$

$$Ea = 15.36\ (1.0 + 0.0062 \times 134.15)(29.37 - 16.005) \qquad \text{(Eq. 6)}$$

$$Ea = 376.03$$

$$E_o = 367.24 \text{ ly day}^{-1}$$

$$E_o = 6.3 \text{ mm day}^{-1}$$

van Bavel (1966a):

$$E_o = \frac{(\Delta/\gamma)Rn + LB_V\ (e_s - e)}{\Delta/\gamma + 1} \qquad \text{(Eq. 8)}$$

$$B_V = \frac{\rho\varepsilon\kappa^2}{P} \cdot \frac{U_2}{[\ln(Z/Zo)]^2} \qquad \text{(Eq. 9)}$$

$$\frac{L\rho\varepsilon\kappa^2}{P} = \frac{582.89(1.095 \times 10^{-3})(0.622)(0.41)^2}{884.93} = 7.54 \times 10^{-5}$$

$$\text{cal cm}^{-3}\ \text{mb}^{-1}$$

$$7.54 \times 10^{-5}\ \text{cal cm}^{03}\ \text{mb}^{-1} \times 10^{5}\ \text{cm Km}^{-1} = 7.54\ \text{cal cm}^{-2}$$

$$\text{mb}^{-1}\ \text{Km}^{-1}$$

Assume Zo = 2.0 mm:

$$LBv = \frac{7.54 \times 134.15}{\left\{\ln\left(\frac{2000}{2}\right)\right\}^2} = 21.2\ \text{cal cm}^{-2}\ \text{mb}^{-1}\ \text{day}^{-1}$$

$$Eo = \frac{(1.765/0.591)364.29 + 21.2(29.37 - 16.0)}{(1.765/0.591) + 1.0}$$

$$Eo = 344\ \text{cal cm}^{-2}\ \text{day}^{-1}$$

$$Eo = 5.9\ \text{mm day}^{-1}$$

Jensen-Haise method:

$$T_2 = 33.3^{\circ}C,\ e_2 = 51.1\ \text{mb} \qquad \text{(Eq. 7B)}$$

$$T_1 = 17.8^{\circ}C,\ e_1 = 20.4\ \text{mb} \qquad \text{(Eq. 7B)}$$

$$C_H = \frac{50}{51.1 - 20.4} = 1.63 \qquad \text{(Eq. 12)}$$

$C_1 = 38 - (2 \times 1213.9/305) = 30.04$ (Eq. 14)

$C_T = \frac{1}{30.04 + 7.6(1.63)} = 0.024$ (Eq. 11)

$T_x = -2.5 - 0.14(51.1 - 20.4) - (1213.9/550)$

$= -9.0$ (Eq. 16)

$Eo = 0.024(23.745 - (-9.0))519.8$

$= 408.5$ ly day^{-1} (Eq. 10)

$Eo = 7.00$ mm day^{-1}

Christiansen and Hargreaves(1969):

a. Solar radiation

$E_o = 0.492\ R_s C_{tt} C_{ww} C_{hh}$ (Eq. 22)

$C_{tt} = 0.463 + 0.425(23.745/20) + 0.112(23.745/20)^2$ (Eq. 24)

$C_{tt} = 1.1250$

$C_{ww} = 0.672 + 0.406(83.35/100) - 0.0780(83.35/100)^2$ (Eq. 25)

$C_{ww} = 0.9562$

$C_{hh} = 1.035 + 0.240(54.5/60)^2 - 0.275(54.5/60)^3$ (Eq. 26)

$C_{hh} = 1.0269$

$Eo = 0.492 \times 519.8 \times 1.125 \times 0.9562 \times 1.0261$

$Eo = 282.0$ ly day^{-1}

$Eo = 4.84$ mm day^{-1}

b. Pan correlation

$$Eo = 0.755\ E_{pan} C_t C_w C_h \qquad \text{(Eq. 17)}$$

$$C_t = 1.017 \qquad \text{(Eq. 19)}$$

$$C_w = 1.344 \qquad \text{(Eq. 20)}$$

$$C_h = -.964 \qquad \text{(Eq. 21)}$$

$$Eo = 7.73 \text{ mm day}^{-1}$$

Priestley-Taylor:

$$Eo = \alpha \frac{\Delta}{\Delta + \gamma} Rn \qquad \text{(Eq. 27)}$$

$$Eo = 1.4 \times \frac{1.765}{1.765 \times 0.591} \times 364.29 = 382.07 \text{ ly day}^{-1}$$

$$Eo = 6.55 \text{ mm day}^{-1}$$

Class A pan evaporation:

$$Eo = E_{pan} \cdot K_p \qquad \text{(Eq. 28)}$$

K_p was obtained by correlation between potential evaporation calculated using Penman's equation and evaporation from the class A pan. It was found to be equal to 0.78 ± 0.04 for south-central New Mexico.

$$Eo = 0.80 \times 7.77 = 6.23 \text{ mm day}^{-1}$$

Net radiation:

$$Eo = Rn$$

$$Eo = 364.29 \text{ ly day}^{-1}$$

$$Eo = 6.25 \text{ mm day}^{-1}$$

Table 23. CSMP program to calculate potential evaporation using different equations for 1975.

```
$$$CONTINUOUS SYSTEM MODELING PROGRAM  III   V1M3   TRANSLATOR OUTPUT$$$

TITLE  SAMIR  AL-KHAFAF PH.D. 1977  PLANT AND SOIL EVAPORATION
*      1975  DATA
*****************************************************************************
*****************************************************************************
*        *    ALBEDO REFLECTION COEFFICIENT = 0.07+0.053*LAI                *
*        *    ATC    AVERAGE AIR TEMPERATURE, DEGREES C                      *
*        *    ATF    AVERAGE AIR TEMPERATURE, DEGREES F                      *
*        *    BV     TURBULENT TRANSFER COEFFICIENT, MM/DAY/MB               *
*        *    C2     CONSTANT FOR JENSEN-HAISE EQUATION = 7.6               *
*        *    CEOPR  PREISTLY-TAYLOR POTENTIAL EVAPORATION, MM               *
*        *    CEOP   CUMULATIVE PENMAN POTENTIAL EVAPORATION,MM              *
*        *    CEOVB  CUMULATIVE VAN BAVEL POTENTIAL EVAPORATION, MM          *
*        *    CEOJH  CUMMULATIVE JENSEN-HAISE POTENTIAL EVAPORATION MM/DAY   *
*        *    CEOPEC CUMMULATIVE CHRISTIANSEN-HARGREAVES POTENTIAL EVAPORATION *
*        *    CEORSC CUMMULATIVE CHRISTIANSEN-HARGREAVES POTENTIAL EVAPORATION *
*        *    CP  =  SPECIFEC HEAT CONSTANT                                  *
*        *    CT     TEMP. COEFFICIENT JENSEN - HAISE                        *
*        *    D      DELTA/GAMMA                                             *
*        *    DA     SATURATED VAPOR PRESSURE DEFICIT, MB                    *
*        *    DA1    SATURATED VAPOR PRESSURE DEFICIT IN MM OF HG            *
*        *    DELTA  SLOPE OF THE SATURATED VAPOR PRESSURE CURVE, MB/DEGREE C  *
*        *    DEN  = AIR DENSITY IN G/M**3                                   *
*        *    DPTC = DEW POINT TEMPARATURE IN DEGREE C                       *
*        *    E1,E2= VAP PRES COEFFICIENTS OF WARMEST MONTH FOR J-H EQUATION  *
*        *    EOP    PENMAN POTENTIAL EVAPORATION, MM/DAY                    *
*        *    EOPR   PREISTLY-TAYLOR POTENTIAL EVAPORATION, MM/DAY           *
*        *    EOVB   VAN BAVEL POTENTIAL EVAPORATION, MM/DAY                 *
*        *    EP     CLASS A PAN EVAPORATION, IN./DAY                        *
*        *    EOJH   JENSEN-HAISE POTENTIAL EVAPORATION MM/DAY               *
*        *    EOPEC  CHRISTIANSEN-HARGREAVES 1968 USING PAN EVAPORATION MM/DAY *
*        *    EORSC  CHRISTIANSEN-HARGREAVES 1968 USING SOLAR RADIARION MM/DAY *
*        *    EA     A MEASURE OF THE DRYING POWER OF THE AIR, MM/DAY       V *
*        *    EHG    SATURATED VAPOR PRESSURE OF THE WET BULB TEMPERATURE,IN.HG*
*        *    ELEV   ELEVATION OF LASCRUCES NEW MEXICO                       *
*        *    GAMMA  PSYCHROMETRIC CONSTANT, MB/DEGREE C                     *
*        *    HL     LATENT HEAT OF VAPURIZATION, CAL/G                      *
*        *    HO     NET RADIATION, MM/DAY                                   *
*        *    LAI    LEAF AREA INDEX                                         *
*        *    PR  =  PRESSURE IN MILIBARS                                    *
*        *    RL     LONG WAVE RADEATION CAL/CM-CM/DAY = -24.                *
*        *    RN     NET RADIATION, CAL/CM-CM/DAY                            *
*        *    RS     SOLAR RADIATION CAL/CM-CM/DAY                           *
*        *    TMIN   MINUMUM DAILY TEMPERATURE, DEGREES F                    *
*        *    TMAX   MAXIMUM DAILY TEMPERATURE, DEGREES F                    *
*        *    TX     TEMP. COEFFICIENT JENSEN - HAISE                        *
*        *    U2     WIND SPEED AT 2 METERS ABOVE THE GROUND, MILES/DAY      *
*        *    VPA1   ACTUAL VAPOR PRESSURE OF THE AIR, MB                    *
*        *    VPS1   SATURATED VAPOR PRESSURE AT MEAN TEMPERATURE, MB        *
*        *    VK  =  VON KARMAN'S CONSTANT = .41                             *
*        *    W      WIND SPEED, KM/DAY                                      *
*        *    WS     WIND SPEED. M/SEC                                       *
*        *    ZA     ANEMOMETER HEIGHT, M                                    *
*        *    ZO     ROUGHNESS LENGTH, MM                                    *
*****************************************************************************
*****************************************************************************
/     REAL TMAX(900),TMIN(900),DPTF(900),U2(900),RS(900),PAN(900)
      PARAMETER KP=0.78,TO=20.0,U0=100.,VK=0.41,CP=0.242,ZA=2.,C2=7.6
      PARAMETER ELEV=1213.9,RHO=60.,RL=-24.,E1=20.4,E2=51.1
```

Table 23 (cont'd.)

```
      PARAMETER  ZO=2.
********************************************************************************
INITIAL
      NOSORT
      CEOJH=0.0
      CEOP=0.0
      CEOCHS=0.0
      CEOCHP=0.0
      CEOPAN=0.0
      CEOPR=0.0
      CEOBV=0.0
      PR=1013.-0.1055*ELEV
      DEN=0.00123-0.000034*ELEV/305.
      FUNCTION TMAXT=0.0,0.0,...
   1,     71.000,   2,     63.000,   3,     72.000,...
   4,     79.000,   5,     76.000,   6,     70.000,...
   7,     55.000,   8,     58.000,   9,     67.000,...
  10,     64.000,  11,     67.000,  12,     73.000,...
  13,     66.000,  14,     73.000,  15,     82.000,...
  16,     85.000,  17,     80.000,  18,     62.000,...
  19,     72.000,  20,     82.000,  21,     86.000,...
  22,     84.000,  23,     81.000,  24,     83.000,...
  25,     84.000,  26,     83.000,  27,     68.000,...
  28,     75.000,  29,     76.000,  30,     76.000,...
  31,     80.000,  32,     80.000,  33,     82.000,...
  34,     81.000,  35,     77.000,  36,     73.000,...
  37,     75.000,  38,     81.000,  39,     85.000,...
  40,     85.000,  41,     85.000,  42,     90.000,...
  43,     88.000,  44,     89.000,  45,     89.000,...
  46,     87.000,  47,     85.000,  48,     87.000,...
  49,     77.000,  50,     80.000,  51,     86.000,...
  52,     73.000,  53,     76.000,  54,     82.000,...
  55,     89.000,  56,     91.000,  57,     90.000,...
  58,     84.000,  59,     80.000,  60,     76.000,...
  61,     89.000,  62,     92.000,  63,     96.000,...
  64,     98.000,  65,     95.000,  66,     96.000,...
  67,     98.000,  68,     90.000,  69,     91.000,...
  70,     90.000,  71,     91.000,  72,     88.000,...
  73,     95.000,  74,     96.000,  75,    100.000,...
  76,    100.000,  77,     96.000,  78,     93.000,...
  79,     92.000,  80,     90.000,  81,     90.000,...
  82,     90.000,  83,     93.000,  84,     95.000,...
  85,     97.000,  86,     97.000,  87,     99.000,...
  88,    100.000,  89,    100.000,  90,     99.000,...
  91,     94.000,  92,     91.000,  93,     91.000,...
  94,     89.000,  95,     90.000,  96,     92.000,...
  97,     92.000,  98,     96.000,  99,     91.000,...
 100,     95.000, 101,     98.000, 102,     96.000,...
 103,     84.000, 104,     89.000, 105,     92.000,...
 106,     93.000, 107,     90.000, 108,     96.000,...
 109,     93.000, 110,     96.000, 111,     94.000,...
 112,     89.000, 113,     95.000, 114,     95.000,...
 115,     90.000, 116,     88.000, 117,     88.000,...
 118,     90.000, 119,     96.000, 120,     84.000,...
 121,     92.000, 122,     98.000, 123,     97.000,...
 124,     94.000, 125,     93.000, 126,     89.000,...
 127,     92.000, 128,     91.000, 129,     90.000,...
 130,     94.000, 131,     92.000, 132,     89.000,...
 133,     88.000, 134,     89.000, 135,     90.000,...
```

Table 23 (cont'd.)

```
 136,     89.000, 137,     92.000, 138,     94.000,...
 139,     92.000, 140,     97.000, 141,     90.000,...
 142,     82.000, 143,     90.000, 144,     89.000,...
 145,     90.000, 146,     94.000, 147,     94.000,...
 148,     94.000, 149,     86.000, 150,     90.000,...
 151,     95.000, 152,     97.000, 153,     94.000,...
 154,     92.000, 155,     91.000, 156,     82.000,...
 157,     86.000, 158,     82.000, 159,     77.000,...
 160,     86.000, 161,     85.000, 162,     88.000,...
 163,     90.000, 164,     90.000, 165,     69.000,...
 166,     65.000, 167,     77.000, 168,     85.000,...
 169,     87.000, 170,     90.000, 171,     90.000,...
 172,     90.000, 173,     85.000, 174,     77.000,...
 175,     73.000, 176,     78.000, 177,     79.000,...
 178,     82.000, 179,     83.000, 180,     86.000,...
 181,     86.000, 182,     87.000, 183,     84.00
      FUNCTION THINT=0.0,0.0,...
   1,     38.000,   2,     34.000,   3,     26.000,...
   4,     32.000,   5,     31.000,   6,     37.000,...
   7,     36.000,   8,     30.000,   9,     26.000,...
  10,     41.000,  11,     37.000,  12,     44.000,...
  13,     32.000,  14,     30.000,  15,     34.000,...
  16,     43.000,  17,     48.000,  18,     39.000,...
  19,     35.000,  20,     34.000,  21,     37.000,...
  22,     49.000,  23,     37.000,  24,     34.000,...
  25,     43.000,  26,     46.000,  27,     46.000,...
  28,     28.000,  29,     34.000,  30,     37.000,...
  31,     35.000,  32,     41.000,  33,     43.000,...
  34,     43.000,  35,     44.000,  36,     40.000,...
  37,     33.000,  38,     33.000,  39,     36.000,...
  40,     49.000,  41,     44.000,  42,     43.000,...
  43,     46.000,  44,     45.000,  45,     63.000,...
  46,     64.000,  47,     52.000,  48,     51.000,...
  49,     46.000,  50,     49.000,  51,     49.000,...
  52,     47.000,  53,     44.000,  54,     38.000,...
  55,     42.000,  56,     45.000,  57,     39.000,...
  58,     48.000,  59,     46.000,  60,     47.000,...
  61,     43.000,  62,     48.000,  63,     50.000,...
  64,     59.000,  65,     53.000,  66,     46.000,...
  67,     52.000,  68,     58.000,  69,     55.000,...
  70,     53.000,  71,     52.000,  72,     53.000,...
  73,     57.000,  74,     58.000,  75,     57.000,...
  76,     58.000,  77,     59.000,  78,     52.000,...
  79,     62.000,  80,     55.000,  81,     57.000,...
  82,     55.000,  83,     51.000,  84,     59.000,...
  85,     71.000,  86,     67.000,  87,     56.000,...
  88,     55.000,  89,     63.000,  90,     64.000,...
  91,     72.000,  92,     66.000,  93,     68.000,...
  94,     69.000,  95,     68.000,  96,     63.000,...
  97,     66.000,  98,     64.000,  99,     67.000,...
 100,     62.000, 101,     64.000, 102,     69.000,...
 103,     65.000, 104,     59.000, 105,     55.000,...
 106,     68.000, 107,     69.000, 108,     64.000,...
 109,     60.000, 110,     63.000, 111,     63.000,...
 112,     64.000, 113,     65.000, 114,     66.000,...
 115,     65.000, 116,     59.000, 117,     64.000,...
 118,     62.000, 119,     62.000, 120,     63.000,...
 121,     61.000, 122,     59.000, 123,     59.000,...
 124,     63.000, 125,     66.000, 126,     60.000,...
```

Table 23 (cont'd.)

```
127,     57.000, 128,     61.000, 129,     54.000,...
130,     59.000, 131,     61.000, 132,     63.000,...
133,     58.000, 134,     56.000, 135,     60.000,...
136,     64.000, 137,     60.000, 138,     58.000,...
139,     60.000, 140,     64.000, 141,     60.000,...
142,     64.000, 143,     62.000, 144,     62.000,...
145,     62.000, 146,     63.000, 147,     62.000,...
148,     64.000, 149,     63.000, 150,     65.000,...
151,     61.000, 152,     56.000, 153,     59.000,...
154,     58.000, 155,     63.000, 156,     61.000,...
157,     61.000, 158,     62.000, 159,     62.000,...
160,     60.000, 161,     60.000, 162,     63.000,...
163,     63.000, 164,     62.000, 165,     58.000,...
166,     52.000, 167,     57.000, 168,     53.000,...
169,     54.000, 170,     51.000, 171,     55.000,...
172,     57.000, 173,     60.000, 174,     53.000,...
175,     45.000, 176,     40.000, 177,     42.000,...
178,     40.000, 179,     40.000, 180,     40.000,...
181,     41.000, 182,     43.000, 183,     46.000
      FUNCTION DPTFT=0.0,0.0,...
  1,     24.000,   2,     24.000,   3,     23.000,...
  4,     26.000,   5,     24.000,   6,     29.000,...
  7,     30.000,   8,     27.000,   9,     26.000,...
 10,     32.000,  11,     40.000,  12,     35.000,...
 13,     34.000,  14,     29.000,  15,     24.000,...
 16,     40.000,  17,     34.000,  18,     35.000,...
 19,     32.000,  20,     25.000,  21,     31.000,...
 22,     34.000,  23,     32.000,  24,     32.000,...
 25,     34.000,  26,     38.000,  27,     31.000,...
 28,     30.000,  29,     30.000,  30,     35.000,...
 31,     31.000,  32,     35.000,  33,     34.000,...
 34,     35.000,  35,     32.000,  36,     34.000,...
 37,     33.000,  38,     31.000,  39,     32.000,...
 40,     54.000,  41,     42.000,  42,     32.000,...
 43,     27.000,  44,     32.000,  45,     30.000,...
 46,     29.000,  47,     45.000,  48,     36.000,...
 49,     40.000,  50,     24.000,  51,     36.000,...
 52,     41.000,  53,     35.000,  54,     36.000,...
 55,     36.000,  56,     37.000,  57,     44.000,...
 58,     46.000,  59,     44.000,  60,     45.000,...
 61,     48.000,  62,     40.000,  63,     38.000,...
 64,     40.000,  65,     42.000,  66,     38.000,...
 67,     36.000,  68,     56.000,  69,     51.000,...
 70,     49.000,  71,     49.000,  72,     49.000,...
 73,     57.000,  74,     54.000,  75,     41.000,...
 76,     35.000,  77,     46.000,  78,     46.000,...
 79,     47.000,  80,     57.000,  81,     61.000,...
 82,     57.000,  83,     48.000,  84,     62.000,...
 85,     64.000,  86,     59.000,  87,     42.000,...
 88,     52.000,  89,     66.000,  90,     61.000,...
 91,     69.000,  92,     68.000,  93,     63.000,...
 94,     68.000,  95,     70.000,  96,     62.000,...
 97,     69.000,  98,     65.000,  99,     64.000,...
100,     57.000, 101,     60.000, 102,     65.000,...
103,     61.000, 104,     55.000, 105,     59.000,...
106,     54.000, 107,     61.000, 108,     66.000,...
109,     60.000, 110,     62.000, 111,     62.000,...
112,     67.000, 113,     66.000, 114,     64.000,...
115,     64.000, 116,     61.000, 117,     62.000,...
```

Table 23 (cont'd.)

```
118,     61.000, 119,      63.000, 120,      66.000,...
121,     56.000, 122,      52.000, 123,      47.000,...
124,     58.000, 125,      63.000, 126,      63.000,...
127,     56.000, 128,      48.000, 129,      53.000,...
130,     51.000, 131,      56.000, 132,      48.000,...
133,     51.000, 134,      64.000, 135,      58.000,...
136,     60.000, 137,      56.000, 138,      57.000,...
139,     55.000, 140,      59.000, 141,      59.000,...
142,     65.000, 143,      64.000, 144,      64.000,...
145,     59.000, 146,      60.000, 147,      54.000,...
148,     55.000, 149,      64.000, 150,      62.000,...
151,     58.000, 152,      51.000, 153,      56.000,...
154,     56.000, 155,      58.000, 156,      62.000,...
157,     58.000, 158,      56.000, 159,      63.000,...
160,     56.000, 161,      58.000, 162,      57.000,...
163,     60.000, 164,      59.000, 165,      52.000,...
166,     51.000, 167,      57.000, 168,      44.000,...
169,     47.000, 170,      53.000, 171,      56.000,...
172,     54.000, 173,      60.000, 174,      53.000,...
175,     38.000, 176,      37.000, 177,      37.000,...
178,     33.000, 179,      27.000, 180,      30.000,...
181,     29.000, 182,      29.000, 183,      39.000
        FUNCTION U2T=0.0,0.0,...
  1,    288.000,   2,     115.000,   3,      66.000,...
  4,    110.000,   5,      82.000,   6,     145.000,...
  7,    239.000,   8,     175.000,   9,      79.000,...
 10,    227.000,  11,     444.000,  12,     204.000,...
 13,    153.000,  14,      78.000,  15,      82.000,...
 16,    176.000,  17,     387.000,  18,     171.000,...
 19,    171.000,  20,      82.000,  21,      92.000,...
 22,    106.000,  23,     122.000,  24,      71.000,...
 25,    112.000,  26,     170.000,  27,     210.000,...
 28,     89.000,  29,     157.000,  30,      58.000,...
 31,    106.000,  32,     127.000,  33,      56.000,...
 34,    170.000,  35,     248.000,  36,     130.000,...
 37,     72.000,  38,      88.000,  39,      62.000,...
 40,    130.000,  41,      94.000,  42,     135.000,...
 43,    126.000,  44,     127.000,  45,     194.000,...
 46,    254.000,  47,     150.000,  48,     117.000,...
 49,    122.000,  50,     182.000,  51,     156.000,...
 52,    151.000,  53,      68.000,  54,      63.000,...
 55,     63.000,  56,     100.000,  57,     148.000,...
 58,    198.000,  59,     140.000,  60,      70.000,...
 61,     77.000,  62,      60.000,  63,      92.000,...
 64,     91.000,  65,     102.000,  66,      89.000,...
 67,    134.000,  68,      90.000,  69,      99.000,...
 70,     94.000,  71,     137.000,  72,      66.000,...
 73,     77.000,  74,      71.000,  75,     168.000,...
 76,     95.000,  77,     133.000,  78,     142.000,...
 79,    186.000,  80,      93.000,  81,     104.000,...
 82,     90.000,  83,      65.000,  84,     195.000,...
 85,    109.000,  86,      87.000,  87,      53.000,...
 88,     99.000,  89,     110.000,  90,     135.000,...
 91,    160.000,  92,     142.000,  93,     168.000,...
 94,    162.000,  95,     100.000,  96,      71.000,...
 97,     78.000,  98,     105.000,  99,      80.000,...
100,     75.000, 101,     113.000, 102,     120.000,...
103,     96.000, 104,      59.000, 105,      88.000,...
106,    163.000, 107,     157.000, 108,      93.000,...
```

Table 23 (cont'd.)

```
109,     81.000, 110,     58.000, 111,    123.000,...
112,     83.000, 113,     91.000, 114,     99.000,...
115,     98.000, 116,    124.000, 117,     98.000,...
118,    126.000, 119,     76.000, 120,     52.000,...
121,     63.000, 122,     39.000, 123,     61.000,...
124,    128.000, 125,    100.000, 126,    114.000,...
127,     81.000, 128,     90.000, 129,     56.000,...
130,     64.000, 131,    108.000, 132,    122.000,...
133.     76.000, 134,     72.000, 135,     73.000,...
136,     65.000, 137,    109.000, 138,     87.000,...
139,     84.000, 140,     53.000, 141,    112.000,...
142,     76.000, 143,    101.000, 144,     54.000,...
145,     52.000, 146,     53.000, 147,     86.000,...
148,    129.000, 149,    110.000, 150,     49.000,...
151,     51.000, 152,     68.000, 153,     97.000,...
154,     96.000, 155,    183.000, 156,    126.000,...
157,    116.000, 158,    100.000, 159,    100.000,...
160,    149.000, 161,     80.000, 162,    111.000,...
163,     76.000, 164,    153.000, 165,    236.000,...
166,    183.000, 167,     25.000, 168,     44.000,...
169,     41.000, 170,     49.000, 171,     81.000,...
172,     79.000, 173,     73.000, 174,    168.000,...
175,     77.000, 176,     55.000, 177,     68.000,...
178,     40.000, 179,     41.000, 180,     30.000,...
181,     34.000, 182,     43.000, 183,    120.00
        FUNCTION RST=0.0,0.0,...
  1,    578.700,   2,    611.100,   3,    576.500,...
  4,    542.300,   5,    544.200,   6,    296.700,...
  7,    511.300,   8,    505.500,   9,    433.800,...
 10,    424.600,  11,    542.600,  12,    584.700,...
 13,    602.500,  14,    624.300,  15,    634.500,...
 16,    588.400,  17,    587.000,  18,    640.200,...
 19,    636.700,  20,    640.400,  21,    510.300,...
 22,    403.600,  23,    544.200,  24,    630.300,...
 25,    607.700,  26,    157.900,  27,    666.200,...
 28,    659.200,  29,    653.400,  30,    584.200,...
 31,    653.000,  32,    650.500,  33,    650.000,...
 34,    650.000,  35,    651.200,  36,    672.500,...
 37,    673.200,  38,    670.200,  39,    659.700,...
 40,    294.800,  41,    657.900,  42,    664.700,...
 43,    678.000,  44,    673.400,  45,    671.800,...
 46,    375.100,  47,    583.900,  48,    643.500,...
 49,    555.500,  50,    687.200,  51,    695.000,...
 52,    628.500,  53,    650.900,  54,    693.800,...
 55,    688.900,  56,    660.000,  57,    616.500,...
 58,    567.100,  59,    542.400,  60,    535.000,...
 61,    693.100,  62,    651.800,  63,    676.500,...
 64,    664.300,  65,    642.600,  66,    675.800,...
 67,    665.000,  68,    408.700,  69,    641.200,...
 70,    594.200,  71,    630.000,  72,    686.400,...
 73,    657.500,  74,    641.500,  75,    630.400,...
 76,    690.000,  77,    693.700,  78,    685.700,...
 79,    650.400,  80,    671.100,  81,    671.900,...
 82,    670.000,  83,    540.000,  84,    670.000,...
 85,    600.000,  86,    670.000,  87,    600.000,...
 88,    670.000,  89,    670.000,  90,    670.000,...
 91,    668.300,  92,    683.500,  93,    677.100,...
 94,    483.800,  95,    543.500,  96,    612.000,...
 97,    544.700,  98,    633.600,  99,    591.300,...
```

Table 23 (cont'd.)

```
100,    649.500, 101,    601.300, 102,    488.300,...
103,    354.900, 104,    663.100, 105,    630.500,...
106,    666.500, 107,    672.500, 108,    461.400,...
109,    480.000, 110,    510.000, 111,    554.600,...
112,    543.200, 113,    622.100, 114,    390.600,...
115,    598.400, 116,    560.000, 117,    554.900,...
118,    648.800, 119,    500.000, 120,    365.800,...
121,    616.300, 122,    649.900, 123,    570.500,...
124,    578.900, 125,    517.000, 126,    510.000,...
127,    643.300, 128,    640.000, 129,    641.000,...
130,    559.200, 131,    521.400, 132,    524.100,...
133,    613.500, 134,    437.800, 135,    470.000,...
136,    531.600, 137,    605.700, 138,    588.900,...
139,    581.000, 140,    607.600, 141,    503.300,...
142,    403.000, 143,    497.000, 144,    447.500,...
145,    573.100, 146,    545.500, 147,    594.400,...
148,    575.600, 149,    607.700, 150,    562.600,...
151,    572.400, 152,    571.300, 153,    571.500,...
154,    517.300, 155,    554.500, 156,    411.900,...
157,    498.600, 158,    239.200, 159,    186.400,...
160,    443.700, 161,    355.300, 162,    474.300,...
163,    529.600, 164,    332.100, 165,    339.300,...
166,    290.000, 167,    403.500, 168,    526.000,...
169,    531.900, 170,    469.900, 171,    504.300,...
172.    504.700, 173,    497.200, 174,    390.200,...
175,    523.900, 176,    517.200, 177,    509.900,...
178,    500.600, 179,    503.100, 180,    469.700,...
181,    486.800, 182,    460.100, 183,    419.800
      FUNCTION PANT=0.0,0.0,....
  1,      0.400,   2,      0.230,   3,      0.240,...
  4,      0.310,   5,      0.290,   6,      0.180,...
  7,      0.280,   8,      0.260,   9,      0.200,...
 10,      0.310,  11,      0.360,  12,      0.330,...
 13,      0.300,  14,      0.250,  15,      0.310,...
 16,      0.430,  17,      0.600,  18,      0.310,...
 19,      0.310,  20,      0.300,  21,      0.280,...
 22,      0.220,  23,      0.360,  24,      0.300,...
 25,      0.340,  26,      0.250,  27,      0.410,...
 28,      0.300,  29,      0.390,  30,      0.240,...
 31,      0.380,  32,      0.400,  33,      0.260,...
 34,      0.460,  35,      0.430,  36,      0.280,...
 37,      0.280,  38,      0.310,  39,      0.310,...
 40,      0.180,  41,      0.280,  42,      0.430,...
 43,      0.370,  44,      0.410,  45,      0.520,...
 46,      0.330,  47,      0.370,  48,      0.390,...
 49,      0.330,  50,      0.470,  51,      0.460,...
 52,      0.410,  53,      0.280,  54,      0.300,...
 55,      0.300,  56,      0.350,  57,      0.480,...
 58,      0.440,  59,      0.290,  60,      0.240,...
 61,      0.330,  62,      0.330,  63,      0.380,...
 64,      0.460,  65,      0.470,  66,      0.400,...
 67,      0.500,  68,      0.240,  69,      0.370,...
 70,      0.390,  71,      0.480,  72,      0.310,...
 73,      0.350,  74,      0.370,  75,      0.760,...
 76,      0.530,  77,      0.540,  78,      0.530,...
 79,      0.630,  80,      0.410,  81,      0.440,...
 82,      0.440,  83,      0.310,  84,      0.470,...
 85,      0.370,  86,      0.450,  87,      0.340,...
 88,      0.430,  89,      0.450,  90,      0.440,...
```

Table 23 (cont'd.)

```
  91,        0.460,  92,        0.450,   93,         0.500,...
  94,        0.350,  95,        0.310,   96,         0.200,...
  97,        0.370,  98,        0.400,   99,         0.340,...
 100,        0.360, 101,        0.400,  102,         0.220,...
 103,        0.360, 104,        0.310,  105,         0.430,...
 106,        0.440, 107,        0.430,  108,         0.270,...
 109,        0.280, 110,        0.260,  111,         0.410,...
 112,        0.280, 113,        0.330,  114,         0.280,...
 115,        0.330, 116,        0.340,  117,         0.270,...
 118,        0.390, 119,        0.740,  120,         0.190,...
 121,        0.320, 122,        0.420,  123,         0.180,...
 124,        0.440, 125,        0.810,  126,         0.340,...
 127,        0.350, 128,        0.370,  129,         0.310,...
 130,        0.320, 131,        0.430,  132,         0.380,...
 133,        0.310, 134,        0.220,  135,         0.270,...
 136,        0.260, 137,        0.390,  138,         0.340,...
 139,        0.410, 140,        0.260,  141,         0.300,...
 142,        0.190, 143,        0.280,  144,         0.180,...
 145,        0.260, 146,        0.290,  147,         0.330,...
 148,        0.290, 149,        0.350,  150,         0.270,...
 151,        0.300, 152,        0.310,  153,         0.350,...
 154,        0.330, 155,        0.370,  156,         0.240,...
 157,        0.300, 158,        0.170,  159,         0.090,...
 150,        0.340, 161,        0.160,  162,         0.280,...
 163,        0.230, 164,        0.270,  165,         0.440,...
 156,        0.180, 167,        0.100,  168,         0.210,...
 159,        0.230, 170,        0.220,  171,         0.280,...
 172,        0.240, 173,        0.260,  174,         0.270,...
 175,        0.200, 176,        0.230,  177,         0.190,...
 178,        0.130, 179,        0.270,  180,         0.110,...
 181,        0.200, 182,        0.180,  163,         0.29
*******************************************************************************
DYNAMIC
NOSORT
      TMAX=AFGEN(TMAXT,TIME)
      TMIN=AFGEN(TMINT,TIME)
      DPTF=AFGEN(DPTFT,TIME)
      RS=AFGEN(RST,TIME)
      U2=AFGEN(U2T,TIME)
      PAN=AFGEN(PANT,TIME)
      E=PAN*25.4
*CONVERT WIND SPEED FROM MILE/DAY TO KM/DAY
      W = U2*1.609344
*     TO CONVERT TEMPERATURE FRON DEGREE F TO DEGREE C
      ATF = (TMAX+TMIN)/2.
      ATC = 5.*(ATF-32.)/9.
      DPTC=5*(DPTF-32.)/9.0
*     RITCHIE'S EQUATION TO CALCULATE ALBEDO
      ALBEDO=0.10
      HL=(595.-0.51*ATC)
*     TO CALCULATE NET RADIATION
      RN=0.83*(1.-ALBEDO)*RS+RL
      VPS1=33.8639*((0.00738*ATC+.8072)**8-(0.000019*ABS(1.8*ATC+48)...
+0.001316))
      VPA1=33.8639*((.00738*DPTC+.8072)**8-(.000019*ABS(1.8*DPTC+48)...
+0.001316))
*     TO CALCULATE RELATIVE HUMIDITY, PERCENTAGE
      RH=(VPA1/VPS1)*100
      DELTA=33.8639*(0.05904*(0.00739*ATC+0.8072)**7-0.0000342)
```

Table 23 (cont'd.)

```
      GAMMA=CP*PR/(0.622*HL)
*     PENMAN EQUATION CALCULATE POTENTIAL EVAPORATION FROM FREE WATER SURFACE
      EA=15.36*(1.0+0.0062*W)*(VPS1-VPA1)
      EOP=((DELTA*RN+GAMMA*EA)/(DELTA+GAMMA))/HL*10
      IF(EOP.LT.0.0)EOP=0.0
      CEOP=CEOP+EOP
*     VANBAV EQUATION TO CALCULATE POTENTIAL EVAPORATION FROM FREE WATER SURFACE
      BV1=(HL*DEN*0.622*VK**2)/PR
*     TO CONVERT BV1 UNITS FROM CAL/CM**3-MB TO CAL/CM**2-MB-KM
      BV2=BV1*10.**5
      LBV=(BV2*W)/((ALOG(ZA*1000/Z0))**2)
      EOBV=(((DELTA/GAMMA)*RN+(LBV*(VPS1-VPA1)))/((DELTA/GAMMA)+1.0))...
      /HL*10
      IF(EOBV.LT.0.0) EOBV=0.0
      CEOBV=CEOBV+EOBV
*      J-H EQUATION TO CALCULATE POTENTIAL EVAPORATION FROM FREE WATER SURFACE
      CH=50./(E2-E1)
      C1=38.-(2.*ELEV/305.)
      CT=1./(C1+C2*CH)
      TX=-2.5-0.14* (E2-E1)-(ELEV/550.)
      EOJH=CT*(ATC-TX)*RS/HL*10
      CEOJH=CEOJH+EOJH
*     CHRIS-HAR EQUARIONS TO CALCULATE POTENTIAL EVAP FROM FREE WATTER SURFACE
*     PAN CORRELATION
      CCT2=0.862+0.179*(ATC/T0)-0.041*((ATC/T0)**2)
      CCW2=1.189-0.240*(U2/U0)+0.051*(U2/U0)**2
      CCH2=0.449+0.620*(RH/RH0)-0.119*(RH/RH0)**2
      EOCHP=(0.755*E*CCT2*CCW2*CCH2)
      CEOCHP=CEOCHP+EOCHP
*     SOLAR RADIATION
      CHH2=1.035+0.240*(RH/RH0)**2-0.275*(RH/RH0)**3
      CWW2=0.672+0.406*(U2/U0)-0.078*(U2/U0)**2
      CTT2=0.463+0.425*(ATC/20.)+0.112*(ATC/20.)**2
      EOCHS=(0.492*RS*CTT2*CWW2*CHH2)/HL*10
      CEOCHS=CEOCHS+EOCHS
*     PR-TAY EQATION TO CALCULATE POTENTIAL EVAP FROM FREE WATER SURFACE
      EOPR=(RN*DELTA*1.4)/((DELTA+GAMMA)*HL)*10
      CEOPR=CEOPR+EOPR
*     FODIFIED PAN EQUATION TO CALCULATE POTENTIAL EVAP FROM FREE WATER SURFACE
      EOPAN=F*0.80
      CEOPAN=CEOPAN+EOPAN
*     NET RADIATION
      EORN=RN/HL*10
      CEORN=CEORN+EORN
**********************************************************************************
      PRINT CEOP,CEOBV,CEOPR,CEORN,CEOPAN,CEOJH,CEOCHP,CEOCHS
      TIMER FINTIM=183.,DELT=1.,PRDEL=1.
END
STOP
```

Table 24. CSMP program to calculate potential evaporation using different equations for 1976.

```
$$$CONTINUOUS SYSTEM MODELING PROGRAM  III   V1M3   TRANSLATOR OUTPUT$$$

TITLE  SAMIR  AL-KHAFAF PH.D. 1977  PLANT AND SOIL EVAPORATION
*     1976  DATA
*************************************************************************
*************************************************************************
*          *     ALBEDO REFLECTION COEFFICIENT = 0.07+0.053*LAI           *
*          *     ATC    AVERAGE AIR TEMPERATURE, DEGREES C                *
*          *     ATF    AVERAGE AIR TEMPERATURE, DEGREES F                *
*          *     BV     TURBULENT TRANSFER COEFFICIENT, MM/DAY/MB         *
*          *     C2     CONSTANT FOR JENSEN-HAISE EQUATION = 7.6         *
*          *     CEOPR  PREISTLY-TAYLOR POTENTIAL EVAPORATION, MM         *
*          *     CEOP   CUMULATIVE PENMAN POTENTIAL EVAPORATION,MM        *
*          *     CEOVB  CUMULATIVE VAN BAVEL POTENTIAL EVAPORATION, MM    *
*          *     CEOJH  CUMMULATIVE JENSEN-HAISE POTENTIAL EVAPORATION MM/DAY *
*          *     CEOPEC CUMMULATIVE CHRISTIANSEN-HARGREAVES POTENTIAL EVAPORATION *
*          *     CEORSC CUMMULATIVE CHRISTIANSEN-HARGREAVES POTENTIAL EVAPORATION *
*          *     CP  =  SPECIFEC HEAT CONSTANT                            *
*          *     CT     TEMP. COEFFICIENT JENSEN - HAISE                  *
*          *     D      DELTA/GAMMA                                       *
*          *     DA     SATURATED VAPOR PRESSURE DEFICIT, MB              *
*          *     DA1    SATURATED VAPOR PRESSURE DEFICIT IN MM OF HG      *
*          *     DELTA  SLOPE OF THE SATURATED VAPOR PRESSURE CURVE, MB/DEGREE C  *
*          *     DEN  = AIR DENSITY IN G/M**3                             *
*          *     DPTC = DEW POINT TEMPARATURE IN DEGREE C                 *
*          *     E1,E2= VAP PRES COEFFICIENTS OF WARMEST MONTH FOR J-H EQUATION  *
*          *     EOP    PENMAN POTENTIAL EVAPORATION, MM/DAY              *
*          *     EOPR   PREISTLY-TAYLOR POTENTIAL EVAPORATION, MM/DAY     *
*          *     EOVB   VAN BAVEL POTENTIAL EVAPORATION, MM/DAY           *
*          *     EP     CLASS A PAN EVAPORATION, IN./DAY                  *
*          *     EOJH   JENSEN-HAISE POTENTIAL EVAPORATION MM/DAY         *
*          *     EOPEC  CHRISTIANSEN-HARGREAVES 1968 USING PAN EVAPORATION MM/DAY *
*          *     EORSC  CHRISTIANSEN-HARGREAVES 1968 USING SOLAR RADIARION MM/DAY *
*          *     EA     A MEASURE OF THE DRYING POWER OF THE AIR, MM/DAY      V *
*          *     EHG    SATURATED VAPOR PRESSURE OF THE WET BULB TEMPERATURE,IN.HG*
*          *     ELEV   ELEVATION OF LASCRUCES NEW MEXICO                 *
*          *     GAMMA  PSYCHROMETRIC CONSTANT, MB/DEGREE C               *
*          *     HL     LATENT HEAT OF VAPORIZATION, CAL/G                *
*          *     HO     NET RADIATION, MM/DAY                             *
*          *     LAI    LEAF AREA INDEX                                   *
*          *     PR  =  PRESSURE IN MILIBARS                              *
*          *     RL     LONG WAVE RADEATION CAL/CM-CM/DAY = -24.          *
*          *     RN     NET RADIATION, CAL/CM-CM/DAY                      *
*          *     RS     SOLAR RADIATION CAL/CM-CM/DAY                     *
*          *     TMIN   MINUMUM DAILY TEMPERATURE, DEGREES F              *
*          *     TMAX   MAXIMUM DAILY TEMPERATURE, DEGREES F              *
*          *     TX     TEMP. COEFFICIENT JENSEN - HAISE                  *
*          *     U2     WIND SPEED AT 2 METERS ABOVE THE GROUND, MILES/DAY *
*          *     VPA1   ACTUAL VAPOR PRESSURE OF THE AIR, MB              *
*          *     VPS1   SATURATED VAPOR PRESSURE AT MEAN TEMPERATURE, MB  *
*          *     VK  =  VON KARMAN'S CONSTANT = .41                       *
*          *     W      WIND SPEED, KM/DAY                                *
*          *     WS     WIND SPEED, M/SEC                                 *
*          *     ZA     ANEMOMETER HEIGHT, M                              *
*          *     Z0     ROUGHNESS LENGTH, MM                              *
*************************************************************************
*************************************************************************
/      REAL TMAX(900),TMIN(900),DPTF(900),U2(900),RS(900),PAN(900)
       PARAMETER KP=0.78,T0=20.0,U0=100.,VK=0.41,CP=0.242,ZA=2.,C2=7.6
       PARAMETER ELEV=1213.9,RHO=60.,RL=-24.,E1=18.74,E2=58.3
```

Table 24 (cont'd.)

```
       PARAMETER  ZO=2.
****************************************************************************************************
INITIAL
       NOSORT
       CEOJH=0.0
       CEOP=0.0
       CEOCHS=0.0
       CEOCHP=0.0
       CEOPAN=0.0
       CEOPP=0.0
       CEOBV=0.0
       PR=1013.-0.1055*ELEV
       DEN=0.00123-0.000034*ELEV/305.
       FUNCTION TMAXT=0.0,0.0,...
   1,     77.000,   2,     75.000,    3,      80.000,...
   4,     76.000,   5,     79.000,    6,      73.000,...
   7,     77.000,   8,     81.000,    9,      78.000,...
  10,     82.000,  11,     83.000,   12,      82.000,...
  13,     79.000,  14,     75.000,   15,      54.000,...
  16,     58.000,  17,     54.000,   18,      70.000,...
  19,     72.000,  20,     74.000,   21,      82.000,...
  22,     82.000,  23,     82.000,   24,      83.000,...
  25,     86.000,  26,     83.000,   27,      80.000,...
  28,     89.000,  29,     80.000,   30,      82.000,...
  31,     72.000,  32,     82.000,   33,      82.000,...
  34,     81.000,  35,     72.000,   36,      75.000,...
  37,     68.000,  38,     70.000,   39,      79.000,...
  40,     86.000,  41,     90.000,   42,      89.000,...
  43,     83.000,  44,     90.000,   45,      93.000,...
  46,     82.000,  47,     82.000,   48,      80.000,...
  49,     77.000,  50,     78.000,   51,      86.000,...
  52,     87.000,  53,     88.000,   54,      88.000,...
  55,     92.000,  56,     90.000,   57,      89.000,...
  58,     91.000,  59,     90.000,   60,      84.000,...
  61,     89.000,  62,     91.000,   63,      93.000,...
  64,     93.000,  65,     90.000,   66,      90.000,...
  67,     89.000,  68,     86.000,   69,      89.000,...
  70,     92.000,  71,     93.000,   72,      90.000,...
  73,     90.000,  74,     90.000,   75,      91.000,...
  76,     90.000,  77,     94.000,   78,      92.000,...
  79,     93.000,  80,     93.000,   81,      99.000,...
  82,    100.000,  83,     99.000,   84,      91.000,...
  85,     91.000,  86,     91.000,   87,      93.000,...
  88,     94.000,  89,     91.000,   90,      95.000,...
  91,     91.000,  92,     91.000,   93,      91.000,...
  94,     89.000,  95,     90.000,   96,      92.000,...
  97,     92.000,  98,     96.000,   99,      91.000,...
 100,     94.000, 101,     97.000,  102,      90.000,...
 103,     90.000, 104,     90.000,  105,      92.000,...
 106,     84.000, 107,     99.000,  108,      90.000,...
 109,     91.000, 110,     90.000,  111,      88.000,...
 112,     84.000, 113,     90.000,  114,      88.000,...
 115,     84.000, 116,     89.000,  117,      89.000,...
 118,     90.000, 119,     88.000,  120,      91.000,...
 121,     90.000, 122,     91.000,  123,      86.000,...
 124,     90.000, 125,     92.000,  126,      94.000,...
 127,    100.000, 128,     99.000,  129,      94.000,...
 130,     94.000, 131,     94.000,  132,      93.000,...
 133,     91.000, 134,     96.000,  135,      94.000,...
```

Table 24 (cont'd.)

```
136,     93.000, 137,     94.000, 138,      98.000,...
139,     89.000, 140,     87.000, 141,      88.000,...
142,     89.000, 143,     90.000, 144,      92.000,...
145,    105.000, 146,    106.000, 147,      93.000,...
148,     93.000, 149,     91.000, 150,      89.000,...
151,     85.000, 152,     87.000, 153,      88.000,...
154,     84.000, 155,     81.000, 156,      87.000,...
157,     93.000, 158,     73.000, 159,      79.000,...
160,     86.000, 161,     88.000, 162,      74.000,...
163,     77.000, 164,     86.000, 165,      86.000,...
166,     90.000, 167,     83.000, 168,      83.000,...
169,     86.000, 170,     85.000, 171,      86.000,...
172,     87.000, 173,     84.000, 174,      80.000,...
175,     80.000, 176,     86.000, 177,      80.000,...
178,     79.000, 179,     79.000, 180,      77.000,...
181,     75.000, 182,     80.000, 183,      83.000
      FUNCTION TMINT=0.0,0.0,...
  1,     28.000,   2,     37.000,   3,      36.000,...
  4,     40.000,   5,     50.000,   6,      45.000,...
  7,     36.000,   8,     39.000,   9,      54.000,...
 10,     46.000,  11,     43.000,  12,      43.000,...
 13,     46.000,  14,     40.000,  15,      42.000,...
 16,     36.000,  17,     32.000,  18,      29.000,...
 19,     37.000,  20,     37.000,  21,      37.000,...
 22,     48.000,  23,     46.000,  24,      40.000,...
 25,     41.000,  26,     46.000,  27,      47.000,...
 28,     43.000,  29,     63.000,  30,      58.000,...
 31,     43.000,  32,     36.000,  33,      46.000,...
 34,     52.000,  35,     49.000,  36,      44.000,...
 37,     46.000,  38,     40.000,  39,      43.000,...
 40,     43.000,  41,     50.000,  42,      46.000,...
 43,     44.000,  44,     39.000,  45,      46.000,...
 46,     46.000,  47,     48.000,  48,      48.000,...
 49,     49.000,  50,     49.000,  51,      54.000,...
 52,     47.000,  53,     44.000,  54,      46.000,...
 55,     46.000,  56,     44.000,  57,      59.000,...
 58,     48.000,  59,     50.000,  60,      49.000,...
 61,     43.000,  62,     43.000,  63,      56.000,...
 64,     67.000,  65,     64.000,  66,      65.000,...
 67,     62.000,  68,     63.000,  69,      64.000,...
 70,     64.000,  71,     58.000,  72,      57.000,...
 73,     47.000,  74,     48.000,  75,      51.000,...
 76,     54.000,  77,     54.000,  78,      57.000,...
 79,     54.000,  80,     52.000,  81,      71.000,...
 82,     60.000,  83,     69.000,  84,      63.000,...
 85,     52.000,  86,     51.000,  87,      54.000,...
 88,     57.000,  89,     58.000,  90,      59.000,...
 91,     64.000,  92,     66.000,  93,      68.000,...
 94,     69.000,  95,     68.000,  96,      63.000,...
 97,     66.000,  98,     64.000,  99,      64.000,...
100,     68.000, 101,     72.000, 102,      69.000,...
103,     63.000, 104,     62.000, 105,      64.000,...
106,     64.000, 107,     66.000, 108,      67.000,...
109,     64.000, 110,     66.000, 111,      62.000,...
112,     63.000, 113,     64.000, 114,      62.000,...
115,     60.000, 116,     62.000, 117,      59.000,...
118,     63.000, 119,     61.000, 120,      64.000,...
121,     65.000, 122,     64.000, 123,      59.000,...
124,     61.000, 125,     60.000, 126,      64.000,...
```

Table 24 (cont'd.)

```
 127,      57.000, 128,       56.000, 129,       60.000,...
 130,      61.000, 131,       60.000, 132,       60.000,...
 133,      63.000, 134,       60.000, 135,       63.000,...
 136,      56.000, 137,       59.000, 138,       60.000,...
 139,      61.000, 140,       61.000, 141,       66.000,...
 142,      60.000, 143,       62.000, 144,       61.000,...
 145,      68.000, 146,       57.000, 147,       59.000,...
 148,      60.000, 149,       59.000, 150,       60.000,...
 151,      59.000, 152,       57.000, 153,       57.000,...
 154,      53.000, 155,      060.000, 156,       55.000,...
 157,      57.000, 158,      053.000, 159,       59.000,...
 160,      56.000, 161,      052.000, 162,       61.000,...
 163,      56.000, 164,       55.000, 165,       55.000,...
 166,      56.000, 167,      064.000, 168,       59.000,...
 169,      58.000, 170,      059.000, 171,       53.000,...
 172,      52.000, 173,      054.000, 174,       53.000,...
 175,      53.000, 176,       52.000, 177,       59.000,...
 178,      57.000, 179,      050.000, 180,       51.000,...
 181,      46.000, 182,      043.000, 183,       47.000
      FUNCTION OPTFT=0.0,0.0,...
   1,      28.000,   2,       34.000,   3,       38.000,...
   4,      50.000,   5,       44.000,   6,       34.000,...
   7,      33.000,   8,       39.000,   9,       47.000,...
  10,      46.000,  11,       41.000,  12,       52.000,...
  13,      41.000,  14,       46.000,  15,       46.000,...
  16,      40.000,  17,       32.000,  18,       30.000,...
  19,      36.000,  20,       36.000,  21,       38.000,...
  22,      40.000,  23,       44.000,  24,       40.000,...
  25,      40.000,  26,       40.000,  27,       46.000,...
  28,      50.000,  29,       60.000,  30,       42.000,...
  31,      46.000,  32,       37.000,  33,       50.000,...
  34,      58.000,  35,       58.000,  36,       48.000,...
  37,      52.000,  38,       51.000,  39,       40.000,...
  40,      41.000,  41,       51.000,  42,       50.000,...
  43,      38.000,  44,       42.000,  45,       48.000,...
  46,      63.000,  47,       65.000,  48,       56.000,...
  49,      56.000,  50,       56.000,  51,       52.000,...
  52,      44.000,  53,       46.000,  54,       44.000,...
  55,      36.000,  56,       46.000,  57,       60.000,...
  58,      44.000,  59,       30.000,  60,       38.000,...
  61,      38.000,  62,       48.000,  63,       51.000,...
  64,      63.000,  65,       64.000,  66,       65.000,...
  67,      64.000,  68,       60.000,  69,       60.000,...
  70,      54.000,  71,       58.000,  72,       48.000,...
  73,      42.000,  74,       50.000,  75,       36.000,...
  76,      36.000,  77,       50.000,  78,       51.000,...
  79,      50.000,  80,       55.000,  81,       69.000,...
  82,      62.000,  83,       62.000,  84,       60.000,...
  85,      56.000,  86,       52.000,  87,       54.000,...
  88,      59.000,  89,       62.000,  90,       62.000,...
  91,      60.000,  92,       68.000,  93,       63.000,...
  94,      68.000,  95,       70.000,  96,       62.000,...
  97,      69.000,  98,       65.000,  99,       56.000,...
 100,      64.000, 101,       69.000, 102,       70.000,...
 103,      66.000, 104,       63.000, 105,       67.000,...
 106,      68.000, 107,       65.000, 108,       66.000,...
 109,      64.000, 110,       70.000, 111,       66.000,...
 112,      66.000, 113,       65.000, 114,       61.000,...
 115,      63.000, 116,       62.000, 117,       62.000,...
```

Table 24 (cont'd.)

```
118,     63.000, 119,     66.000, 120,     68.000,...
121,     64.000, 122,     64.000, 123,     62.000,...
124,     64.000, 125,     62.000, 126,     67.000,...
127,     55.000, 128,     48.000, 129,     59.000,...
130,     58.000, 131,     62.000, 132,     62.000,...
133,     34.000, 134,     57.000, 135,     63.000,...
136,     58.000, 137,     63.000, 138,     60.000,...
139,     66.000, 140,     65.000, 141,     66.000,...
142,     61.000, 143,     60.000, 144,     62.000,...
145,     57.000, 146,     60.000, 147,     61.000,...
148,     62.000, 149,     62.000, 150,     63.000,...
151,     60.000, 152,     58.000, 153,     56.000,...
154,     54.000, 155,     58.000, 156,     52.000,...
157,     52.000, 158,     60.000, 159,     59.000,...
150,     55.000, 161,     63.000, 162,     60.000,...
163,     57.000, 164,     58.000, 165,     50.000,...
156,     54.000, 167,     68.000, 168,     61.000,...
169,     64.000, 170,     64.000, 171,     59.000,...
172,     53.000, 173,     59.000, 174,     59.000,...
175,     52.000, 176,     58.000, 177,     67.000,...
178,     62.000, 179,     63.000, 180,     56.000,...
181,     56.000, 182,     46.000, 183,     48.000
       FUNCTION U2T=0.0,0.0,...
  1,     90.000,   2,     59.000,   3,    106.000,...
  4,    218.000,   5,    167.000,   6,    110.000,...
  7,    100.000,   8,    194.000,   9,    194.000,...
 10,     59.000,  11,    154.000,  12,    137.000,...
 13,    110.000,  14,    180.000,  15,    217.000,...
 16,    250.000,  17,    182.000,  18,     94.000,...
 19,    154.000,  20,     58.000,  21,     64.000,...
 22,    103.000,  23,    122.000,  24,     80.000,...
 25,     95.000,  26,    154.000,  27,    112.000,...
 28,    132.000,  29,    169.000,  30,    126.000,...
 31,     59.000,  32,     71.000,  33,    171.000,...
 34,    157.000,  35,    191.000,  36,    197.000,...
 37,    416.000,  38,    200.000,  39,     58.000,...
 40,     68.000,  41,    100.000,  42,    165.000,...
 43,     88.000,  44,     62.000,  45,    140.000,...
 46,    283.000,  47,    135.000,  48,    138.000,...
 49,     80.000,  50,     77.000,  51,    110.000,...
 52,    105.000,  53,     66.000,  54,    118.000,...
 55,    185.000,  56,    158.000,  57,    103.000,...
 58,    112.000,  59,    148.000,  60,    136.000,...
 61,     48.000,  62,     82.000,  63,    194.000,...
 64,    188.000,  65,    152.000,  66,    131.000,...
 67,    180.000,  68,    126.000,  69,     70.000,...
 70,     75.000,  71,     91.000,  72,    122.000,...
 73,     60.000,  74,     89.000,  75,    141.000,...
 76,    102.000,  77,     86.000,  78,    178.000,...
 79,     89.000,  80,    180.000,  81,     76.000,...
 82,     64.000,  83,    145.000,  84,    166.000,...
 85,     78.000,  86,     80.000,  87,     79.000,...
 88,    139.000,  89,     71.000,  90,     90.000,...
 91, 100.000   ,  92,    142.000,  93,    168.000,...
 94,    162.000,  95,    100.000,  96,     71.000,...
 97,     78.000,  98,    105.000,  99,    122.000,...
100,    122.000, 101,    137.000, 102,    108.000,...
103,     75.000, 104,     81.000, 105,     93.000,...
106,     85.000, 107,    165.000, 108,    101.000,...
```

Table 24 (cont'd.)

```
109,     96.000, 110,     69.000, 111,    111.000,...
112,     84.000, 113,     79.000, 114,     69.000,...
115,    126.000, 116,     65.000, 117,     54.000,...
118,     58.000, 119,     77.000, 120,     83.000,...
121,     61.000, 122,     62.000, 123,     59.000,...
124,     80.000, 125,    105.000, 126,     42.000,...
127,     54.000, 128,     61.000, 129,     84.000,...
130,     84.000, 131,     82.000, 132,     77.000,...
133,     38.000, 134,     90.000, 135,     56.000,...
136,     59.000, 137,     71.000, 138,    100.000,...
139,    103.000, 140,    103.000, 141,    127.000,...
142,     87.000, 143,     57.000, 144,    124.000,...
145,     79.000, 146,     64.000, 147,     62.000,...
148,     54.000, 149,    101.000, 150,    126.000,...
151,    101.000, 152,     69.000, 153,     92.000,...
154,     84.000, 155,     80.000, 156,     33.000,...
157,     71.000, 158,     59.000, 159,     44.000,...
160,     37.000, 161,    114.000, 162,    220.000,...
163,    101.000, 164,     49.000, 165,     50.000,...
166,     90.000, 167,    146.000, 168,     75.000,...
169,     92.000, 170,    110.000, 171,     40.000,...
172,     77.000, 173,     91.000, 174,     69.000,...
175,     46.000, 176,     70.000, 177,     64.000,...
178,    100.000, 179,     63.000, 180,     99.000,...
181,     88.000, 182,    106.000, 183,    100.00
       FUNCTION RST=0.0,0.0,...
  1,    512.000,   2,    520.000,   3,    500.000,...
  4,    540.000,   5,    550.000,   6,    517.900,...
  7,    593.300,   8,    486.300,   9,    470.700,...
 10,    542.800,  11,    579.800,  12,    520.300,...
 13,    495.900,  14,    228.200,  15,    355.100,...
 16,    435.000,  17,    534.000,  18,    519.600,...
 19,    527.200,  20,    563.700,  21,    539.600,...
 22,    480.600,  23,    514.500,  24,    527.000,...
 25,    522.500,  26,    570.100,  27,    525.200,...
 28,    518.500,  29,    456.000,  30,    533.300,...
 31,    575.600,  32,    556.100,  33,    309.000,...
 34,    364.000,  35,    375.700,  36,    451.400,...
 37,    553.900,  38,    554.900,  39,    559.700,...
 40,    568.800,  41,    505.200,  42,    522.900,...
 43,    591.700,  44,    580.700,  45,    546.400,...
 46,    548.500,  47,    524.700,  48,    535.700,...
 49,    354.600,  50,    427.400,  51,    554.200,...
 52,    584.100,  53,    581.400,  54,    539.700,...
 55,    591.300,  56,    591.100,  57,    574.800,...
 58,    579.700,  59,    594.600,  60,    608.600,...
 61,    589.900,  62,    596.700,  63,    534.200,...
 64,    547.800,  65,    543.800,  66,    550.400,...
 67,    546.600,  68,    590.300,  69,    570.700,...
 70,    582.500,  71,    600.500,  72,    603.500,...
 73,    625.300,  74,    541.300,  75,    603.000,...
 76,    618.000,  77,    603.500,  78,    601.800,...
 79,    606.100,  80,    588.200,  81,    552.200,...
 82,    514.800,  83,    481.700,  84,    629.600,...
 85,    623.200,  86,    601.000,  87,    615.900,...
 88,    608.200,  89,    569.500,  90,    579.300,...
 91,    600.000,  92,    683.500,  93,    677.100,...
 94,    483.800,  95,    543.500,  96,    612.000,...
 97,    544.700,  98,    633.600,  99,    564.500,...
```

Table 24 (cont'd.)

```
 100,     563.000, 101,    536.600, 102,     461.400,...
 103,     443.500, 104,    473.600, 105,     524.000,...
 106,     368.600, 107,    461.900, 108,     503.400,...
 109,     547.800, 110,    371.900, 111,     297.700,...
 112,     419.900, 113,    528.900, 114,     421.700,...
 115,     473.700, 116;    479.800, 117,     483.800,...
 118,     494.600, 119,    470.500, 120,     481.000,...
 121,     378.300, 122,    520.200, 123,     283.800,...
 124,     535.600, 125,    535.400, 126,     520.700,...
 127,     541.200, 128,    537.400, 129,     466.700,...
 130,     505.500, 131,    480.400, 132,     476.300,...
 133,     507.300, 134,    475.400, 135,     505.800,...
 136,     468.600, 137,    472.600, 138,     399.100,...
 139,     436.000, 140,    439.700, 141,     474.500,...
 142,     457.800, 143,    514.200, 144,     484.200,...
 145,     462.200, 146,    500.300, 147,     484.900,...
 148,     478.200, 149,    277.000, 150,     369.000,...
 151,     504.400, 152,    476.300, 153,     404.500,...
 154,     398.700, 155,    367.600, 156,     465.100,...
 157,     414.100, 158,    137.300, 159,     371.000,...
 160,     460.300, 161,    375.300, 162,     123.200,...
 163,     423.300, 164,    438.600, 165,     477.800,...
 166,     430.400, 167,    377.400, 168,     431.200,...
 169,     381.700, 170,    406.100, 171,     490.400,...
 172,     431.800, 173,    446.600, 174,     441.600,...
 175,     426.700, 176,    365.400, 177,     416.300,...
 178,     275.200, 179,    397.300, 180,     408.900,...
 181,     490.200, 182,    520.400, 183,     512.900
        FUNCTION PANT=0.0,0.0,....
   1,       0.260,   2,      0.180,   3,       0.310,...
   4,       0.350,   5,      0.410,   6,       0.290,...
   7,       0.300,   8,      0.300,   9,       0.310,...
  10,       0.310,  11,      0.300,  12,       0.410,...
  13,       0.330,  14,      0.270,  15,       0.170,...
  16,       0.200,  17,      0.250,  18,       0.230,...
  19,       0.340,  20,      0.220,  21,       0.280,...
  22,       0.370,  23,      0.370,  24,       0.340,...
  25,       0.350,  26,      0.450,  27,       0.320,...
  28,       0.380,  29,      0.360,  30,       0.350,...
  31,       0.270,  32,      0.310,  33,       0.330,...
  34,       0.280,  35,      0.240,  36,       0.310,...
  37,       0.480,  38,      0.300,  39,       0.250,...
  40,       0.310,  41,      0.330,  42,       0.540,...
  43,       0.370,  44,      0.340,  45,       0.460,...
  46,       0.350,  47,      0.380,  48,       0.340,...
  49,       0.130,  50,      0.270,  51,       0.410,...
  52,       0.460,  53,      0.390,  54,       0.470,...
  55,       0.000,  56,      0.470,  57,       0.360,...
  58,       0.380,  59,      0.500,  60,       0.530,...
  61,       0.290,  62,      0.390,  63,       0.490,...
  64,       0.400,  65,      0.440,  66,       0.420,...
  67,       0.400,  68,      0.350,  69,       0.300,...
  70,       0.400,  71,      0.440,  72,       0.470,...
  73,       0.000,  74,      0.350,  75,       0.570,...
  76,       0.370,  77,      0.500,  78,       0.580,...
  79,       0.380,  80,      0.520,  81,       0.400,...
  82,       0.400,  83,      0.480,  84,       0.000,...
  85,       0.360,  86,      0.410,  87,       0.390,...
  88,       0.470,  89,      0.350,  90,       0.420,...
```

Table 24 (cont'd.)

```
  91,      0.430,  92,      0.450,  93,       0.500,...
  94,      0.350,  95,      0.310,  96,       0.200,...
  97,      0.370,  98,      0.400,  99,       0.490,...
 100,      0.410, 101,      0.400, 102,       0.270,...
 103,      0.160, 104,      0.050, 105,       0.280,...
 106,      0.240, 107,      0.440, 108,       0.380,...
 109,      0.390, 110,      0.150, 111,       0.030,...
 112,      0.190, 113,      0.320, 114,       0.030,...
 115,      0.300, 116,      0.220, 117,       0.240,...
 118,      0.340, 119,      0.330, 120,       0.220,...
 121,      0.260, 122,      0.320, 123,       0.180,...
 124,      0.320, 125,      0.330, 126,       0.250,...
 127,      0.360, 128,      0.360, 129,       0.320,...
 130,      0.380, 131,      0.000, 132,       0.290,...
 133,      0.280, 134,      0.380, 135,       0.310,...
 136,      0.320, 137,      0.310, 138,       0.360,...
 139,      0.310, 140,      0.310, 141,       0.330,...
 142,      0.370, 143,      0.270, 144,       0.300,...
 145,      0.340, 146,      0.330, 147,       0.310,...
 148,      0.280, 149,      0.160, 150,       0.240,...
 151,      0.290, 152,      0.290, 153,       0.220,...
 154,      0.310, 155,      0.190, 156,       0.270,...
 157,      0.310, 158,      0.030, 159,       0.160,...
 160,      0.240, 161,      0.220, 162,       0.130,...
 163,      0.210, 164,      0.220, 165,       0.270,...
 166,      0.250, 167,      0.310, 168,       0.370,...
 169,      0.310, 170,      0.010, 171,       0.140,...
 172,      0.310, 173,      0.240, 174,       0.300,...
 175,      0.160, 176,      0.200, 177,       0.060,...
 178,      0.230, 179,      0.110, 180,       0.270,...
 181,      0.190, 182,      0.260, 183,       0.000
***********************************************************************
DYNAMIC
NOSORT
      TMAX=AFGEN(TMAXT,TIME)
      TMIN=AFGEN(TMINT,TIME)
      DPTF=AFGEN(DPTFT,TIME)
      RS=AFGEN(RST,TIME)
      U2=AFGEN(U2T,TIME)
      PAN=AFGEN(PANT,TIME)
      E=PAN*25.4
*CONVERT WIND SPEED FROM MILE/DAY TO KM/DAY
      W=U2*1.609314
      ATF = (TMAX+TMIN)/2.
      ATC = 5.*(ATF-32.)/9.
      DPTC=5*(DPTF-32.)/9.0
*     RITCHIE'S EQUATION TO CALCULATE ALBEDO
      ALBEDO=0.10
      HL=(595.-0.51*ATC)
*     TO CALCULATE NET RADIATION
      RN=0.83*(1.-ALBEDO)*RS+RL
      VPS1=33.8639*((0.00738*ATC+.8072)**8-(0.000019*ABS(1.8*ATC+48)...
+0.001316))
      VPA1=33.8639*((.00738*DPTC+.8072)**8-(.000019*ABS(1.8*DPTC+48)...
+0.001316))
*     TO CALCULATE RELATIVE HUMIDITY, PERCENTAGE
      RH=(VPA1/VPS1)*100
      DELTA=33.8639*(0.05904*(0.00738*ATC+0.8072)**7-0.0000342)
      GAMMA=CP*PR/(0.622*HL)
```

Table 24 (cont'd.)

```
*      PENMAN EQUATION CALCULATE POTENTIAL EVAPORATION FROM FREE WATER SURFACE
       EA=15.36*(1.0+0.0062*W)*(VPS1-VPA1)
       EOP=((DELTA*RN+GAMMA*EA)/(DELTA+GAMMA))/HL*10
       IF(EOP.LT.0.0)EOP=0.0
       CEOP=CEOP+EOP
*      VANBAV EQUATION TO CALCULATE POTENTIAL EVAPORATION FROM FREE WATER SURFACE
       BV1=(HL*DEN*0.622*VK**2)/PK
*      TO CONVERT BV1 UNITS FROM CAL/CM**3-MB TO CAL/CM**2-MB-KM
       BV2=BV1*10.**5
       LBV=(BV2*W)/((ALOG(ZA*1000/Z0))**2)
       EOBV=(((DELTA/GAMMA)*PN+(LBV*(VPS1-VPA1)))/((DELTA/GAMMA)+1.0))...
       /HL*10
       IF(EOBV.LT.0.0) EOBV=0.0
       CEOBV=CEOBV+EOBV
*       J-H EQUATION TO CALCULATE POTENTIAL EVAPORATION FROM FREE WATER SURFACE
       CH=50./(E2-E1)
       C1=38.-(2.*ELEV/305.)
       CT=1./(C1+C2*CH)
       TX=-2.5-0.14* (E2-E1)-(ELEV/550.)
       EOJH=CT*(ATC-TX)*RS/HL*10
       CEOJH=CEOJH+EOJH
*      CHRIS-HAR EQUARIONS TO CALCULATE POTENTIAL EVAP FROM FREE WATTER SURFACE
*      PAN CORRELATION
       CCT2=0.862+0.179*(ATC/TO)-0.041*((ATC/TO)**2)
       CCW2=1.189-0.240*(U2/U0)+0.051*(U2/U0)**2
       CCH2=0.449+0.620*(RH/RHO)-0.119*(RH/RHO)**2
       EOCHP=(0.755*E*CCT2*CCW2*CCH2)
       CEOCHP=CEOCHP+EOCHP
*      SOLAR RADIATION
       CHH2=1.035+0.240*(RH/RHO)**2-0.275*(RH/RHO)**3
       CWW2=0.672+0.406*(U2/U0)-0.078*(U2/U0)**2
       CTT2=0.463+0.425*(ATC/20.)+0.112*(ATC/20.)**2
       EOCHS=(0.492*RS*CTT2*CWW2*CHH2)/HL*10
       CEOCHS=CEOCHS+EOCHS
*      PR-TAY EQATION TO CALCULATE POTENTIAL EVAP FROM FREE WATER SURFACE
       EOPR=(RN*DELTA*1.4)/((DELTA+GAMMA)*HL)*10
       CEOPR=CEOPR+EOPR
*      FODIFIED PAN EQUATION TO CALCULATE POTENTIAL EVAP FROM FREE WATER SURFACE
       EOPAN=E*0.80
       CEOPAN=CEOPAN+EOPAN
*      NET RADIATION
       EORN=RN/HL*10
       CEORN=CEORN+EORN
********************************************************************************
       PRINT CEOP,CEOBV,CEOPR,CEORN,CEOPAN,CEOJH,CEOCHP,CEOCHS
METHOD RECT
       TIMER FINTIM=183.,DELT=1.,PRDEL=1.
END
STOP
```

Table 25. Cumulative potential evaporation calculated using different equations for south central New Mexico in 1975.

```
SAMIR  AL-KHAFAF PH.D. 1977  PLANT AND SOIL EVAPORATION

TIME        CEJP        CEDRV       CEDPR       CEDRN       CEDPAN        CEJH        CEDCHP        CEJCHS
0.0         0.0         0.0         -3.20347    -0.79451    4.84466E-06   0.0         4.19822E-06   0.0
 1.00000     5.2991      4.9640      4.9444      5.2894      4.5132        4.7423      3.2648        3.2772
 2.00000     10.537      9.6964      10.413      11.485      8.1708        9.9998      6.2105        6.5145
 3.00000     16.032      14.959      15.782      17.433      14.470        15.299      11.135        10.210
 4.00000     21.425      20.530      21.611      23.089      21.582        21.022      17.257        14.112
 5.00000     28.347      27.552      27.900      30.493      29.913        27.724      23.504        19.264
 6.00000     34.366      33.322      33.618      36.671      35.805        33.339      27.766        23.247
 7.00000     40.648      39.315      39.946      43.799      41.902        39.410      32.281        27.477
 8.00000     46.988      45.910      45.300      49.604      47.998        44.823      36.652        31.806
 9.00000     53.414      52.505      50.773      55.203      54.297        50.732      41.436        35.441
10.0000      59.158      57.839      57.022      61.711      60.596        57.280      47.041        40.326
11.0000      66.226      64.933      63.657      68.693      66.692        64.133      51.527        45.535
12.0000      71.650      70.313      69.541      74.909      75.023        70.218      58.932        49.545
13.0000      77.528      75.952      75.131      80.017      81.729        76.018      64.137        53.603
14.0000      80.591      79.124      77.368      83.309      87.215        78.409      68.679        55.342
15.0000      83.210      81.788      80.625      87.395      93.670        81.311      71.703        56.747
16.0000      87.100      85.803      84.628      92.489      94.734        84.762      75.164        59.205
17.0000      91.591      90.473      89.316      98.023      99.814        88.484      79.106        62.201
18.0000      96.536      95.164      94.337      104.99      104.49        92.923      82.687        65.324
19.0000      102.27      100.93      99.785      111.28      111.43        98.058      87.839        69.279
20.0000      107.71      105.90      105.71      118.03      115.87        103.69      91.981        72.714
21.0000      113.36      111.06      111.63      124.48      121.56        109.61      96.242        76.375
22.0000      119.40      116.77      117.17      130.23      129.07        115.52      101.89        80.458
23.0000      125.54      122.75      123.08      136.35      136.59        121.73      107.82        84.881
24.0000      131.35      128.15      128.98      142.65      143.50        127.76      113.39        88.793
25.0000      137.50      133.94      134.95      148.90      150.61        134.00      118.88        93.013
26.0000      144.77      141.24      141.57      155.76      159.75        140.95      125.40        98.308
27.0000      150.72      146.99      147.57      162.05      166.26        147.22      130.77        102.63
28.0000      156.80      152.98      153.64      168.26      173.98        153.73      137.22        107.22
29.0000      162.41      158.66      159.19      173.68      181.30        160.07      143.64        111.64
30.0000      169.67      165.72      165.68      180.09      188.41        167.29      148.72        116.87
31.0000      174.93      170.67      171.88      186.99      193.90        173.32      153.97        120.25
32.0000      180.78      176.06      177.98      193.68      200.19        179.37      159.02        124.09
33.0000      185.00      180.38      181.37      197.21      206.90        183.10      164.54        126.83
34.0000      189.13      184.52      185.53      201.45      212.59        187.71      169.72        129.77
35.0000      192.42      187.85      189.59      205.02      217.47        191.92      174.33        131.74
36.0000      197.51      193.11      194.48      211.16      223.77        196.87      179.55        135.38
37.0000      203.03      199.08      200.40      217.78      233.52        202.61      189.86        138.28
38.0000      207.75      203.87      206.19      224.42      239.62        200.08      195.38        141.31
39.0000      213.60      209.18      212.45      231.14      244.70        214.43      197.64        145.13
40.0000      219.95      215.00      219.05      237.90      250.99        221.36      204.73        149.45
41.0000      226.11      220.86      225.17      244.03      257.70        228.20      210.39        154.04
42.0000      232.72      227.54      231.30      250.30      268.67        234.95      219.12        159.12
43.0000      239.50      233.90      238.19      257.43      276.19        242.02      224.01        163.82
44.0000      245.85      239.70      244.94      264.42      283.13        249.10      230.53        168.14
45.0000      252.91      246.69      251.57      271.30      292.45        256.43      237.75        173.55
46.0000      257.65      251.48      257.88      277.58      299.55        263.04      244.69        176.16
47.0000      261.85      255.69      263.97      283.86      307.29        269.50      252.75        177.67
48.0000      267.24      261.05      270.13      290.28      314.19        275.96      259.14        181.62
49.0000      270.69      264.32      274.06      294.39      316.83        280.15      261.81        183.78
50.0000      274.87      269.26      278.85      299.43      322.32        285.26      267.34        186.43
51.0000      281.45      274.65      285.61      306.11      330.65        292.76      274.37        191.55
52.0000      288.44      281.35      292.56      313.15      339.99        300.24      281.66        196.71
53.0000      294.81      287.22      299.42      320.16      347.92        307.53      288.47        201.18
54.0000      301.54      293.73      305.81      326.64      357.47        314.44      295.79        206.09
55.0000      309.52      301.96      312.65      333.77      357.47        321.57      295.79        211.76
56.0000      316.94      309.44      319.69      340.91      367.02        329.14      303.03        217.49
```

```
SAMIR  AL-KHAFAF PH.D. 1977  PLANT AND SOIL EVAPORATION

TIME        CEDP       CEDRV      CEDPP      CEURN      CEUPAN     CEDJH      CEDCHP     CEDCHS
57.0000     323.62     315.87     326.95     347.85     374.33     337.47     309.73     222.87
58.0000     330.97     322.94     334.00     354.86     382.05     345.27     315.53     228.34
59.0000     339.66     331.61     341.28     362.05     392.22     353.32     321.57     234.37
60.0000     347.49     339.33     348.51     369.41     402.99     361.03     329.01     240.08
61.0000     354.11     345.18     355.47     376.53     400.88     368.44     333.65     244.39
62.0000     360.76     351.44     362.58     383.73     416.09     376.07     340.43     249.28
63.0000     368.77     359.75     369.32     390.17     426.76     383.90     347.74     255.50
64.0000     376.51     367.69     376.52     396.79     434.89     392.67     354.43     262.24
65.0000     383.30     374.48     383.52     403.36     443.83     400.97     362.36     268.04
66.0000     389.97     381.06     390.63     410.01     452.36     409.45     370.15     273.70
67.0000     396.72     387.92     397.59     416.60     460.49     417.59     377.33     279.43
68.0000     403.79     394.86     405.09     423.76     467.69     426.24     383.62     285.33
69.0000     410.48     401.09     412.43     430.66     473.70     434.80     389.32     290.55
70.0000     417.89     407.92     420.01     437.73     481.83     443.92     396.13     296.32
71.0000     425.07     414.75     427.70     445.01     490.77     452.86     404.98     302.12
72.0000     433.03     422.48     435.31     452.33     500.32     461.55     411.29     308.37
73.0000     440.21     428.99     442.88     459.91     510.32     469.79     411.29     313.37
74.0000     446.54     434.96     449.41     466.42     507.43     476.98     417.36     319.06
75.0000     455.08     443.41     456.86     473.72     519.01     485.29     424.78     324.24
76.0000     463.35     451.23     464.57     481.22     526.53     493.96     429.79     330.19
77.0000     470.85     458.25     472.21     488.54     536.69     502.73     438.03     335.95
78.0000     479.33     466.92     479.85     495.84     548.49     511.55     446.76     342.85
79.0000     486.82     473.96     487.50     503.19     556.20     520.27     453.03     348.63
80.0000     494.44     481.79     494.85     510.31     556.76     528.60     461.51     354.99
81.0000     501.41     488.26     502.35     517.01     574.89     538.13     469.27     360.86
82.0000     507.77     494.08     509.09     523.21     583.02     546.38     476.86     365.81
83.0000     515.13     501.37     515.53     528.99     592.77     554.57     484.69     371.97
84.0000     523.30     509.62     523.71     536.66     592.77     564.18     484.69     379.16
85.0000     530.27     516.21     531.52     544.29     600.09     572.92     491.43     384.52
86.0000     537.20     522.71     538.94     551.56     608.42     581.20     498.69     389.78
87.0000     544.44     529.50     546.71     559.04     616.34     590.07     505.61     395.40
88.0000     552.03     537.02     554.51     566.42     625.89     599.13     513.73     401.88
89.0000     558.33     542.96     561.72     573.31     633.00     607.48     520.72     406.67
90.0000     565.19     549.50     569.20     580.33     641.54     616.32     528.64     412.25
91.0000     572.57     556.56     577.00     587.62     650.29     625.56     536.36     418.39
92.0000     580.46     564.40     586.00     595.98     659.42     636.25     544.87     425.37
93.0000     589.22     573.25     594.98     604.26     669.50     647.01     553.39     433.41
94.0000     595.34     579.41     601.75     610.07     676.69     654.63     559.86     438.60
95.0000     601.47     585.36     608.34     616.63     692.99     663.23     566.15     443.52
96.0000     608.56     592.01     616.30     624.07     697.06     672.62     570.01     449.17
97.0000     614.67     597.84     623.42     630.66     694.57     681.21     577.67     453.94
98.0000     622.35     605.26     631.82     638.38     702.70     691.35     585.12     460.61
99.0000     629.90     612.59     639.13     645.21     712.66     700.04     593.20     466.81
100.000     637.25     619.76     646.59     652.04     720.99     709.20     600.48     473.19
101.000     644.48     626.90     653.84     658.53     729.12     718.39     607.69     479.70
102.000     649.91     632.17     659.82     664.35     734.60     725.73     613.08     484.05
103.000     654.95     636.90     665.43     669.32     737.05     732.44     616.37     487.80
104.000     660.51     642.13     671.42     674.99     738.87     739.56     617.35     492.06
105.000     666.55     647.93     678.20     681.30     744.56     747.69     622.92     496.89
106.000     670.42     651.64     682.70     685.61     749.44     753.04     628.04     499.51
107.000     677.16     658.45     688.80     691.14     758.38     760.73     635.62     505.24
108.000     683.21     664.27     695.31     697.19     766.10     768.60     642.96     510.17
109.000     689.71     670.49     702.39     703.81     774.02     777.03     650.41     515.46
110.000     693.86     674.38     707.07     708.17     777.07     782.00     653.64     518.39
111.000     697.49     677.87     710.65     711.57     777.63     787.22     654.23     520.90
112.000     701.97     682.16     715.82     716.54     781.54     793.25     658.21     524.14
113.000     708.02     687.89     722.61     722.91     788.04     801.32     664.61     528.86
```

```
SAMIR  AL-KHAFAF PH.D. 1977  PLANT AND SOIL EVAPORATION

TIME        CEUP       CEJRV      CEUPK      CEOFN      CEDPAN     CEJJH      CEJCHP     CEOCHS
114.000     713.02     692.48     727.06     721.90     788.65     837.55     665.20     532.50
115.000     718.30     697.67     733.67     733.55     794.75     814.20     670.98     536.55
116.000     723.01     702.79     739.73     739.29     799.22     821.34     675.37     540.65
117.000     729.13     707.67     745.77     745.08     804.10     828.37     680.32     544.42
118.000     734.78     712.88     752.07     751.01     811.00     835.06     687.20     548.61
119.000     739.84     717.70     757.95     756.63     817.71     842.75     694.10     552.27
120.000     745.25     722.45     764.11     762.39     822.18     850.16     698.63     556.39
121.000     749.83     726.99     768.87     766.83     827.46     855.98     703.88     559.68
122.000     755.80     732.53     775.57     773.09     833.97     863.59     713.33     564.22
123.000     759.07     735.46     778.89     776.32     837.62     864.01     714.00     566.35
124.000     765.09     741.17     785.70     782.77     844.13     875.98     720.49     570.97
125.000     771.51     747.35     792.53     789.22     850.83     884.03     726.65     576.18
126.000     777.31     752.66     799.31     795.50     855.91     892.23     732.00     580.39
127.000     784.07     758.69     806.35     802.03     863.23     900.70     738.39     585.41
128.000     791.11     764.95     813.29     808.52     870.54     908.97     744.18     590.48
129.000     797.04     770.47     819.23     814.09     877.04     916.10     750.01     595.03
130.000     803.49     776.48     825.73     820.17     884.75     923.88     756.80     600.05
131.000     809.31     781.94     831.86     825.92     884.75     931.21     756.80     604.57
132.000     815.01     787.25     837.91     831.62     890.66     938.43     762.41     608.93
133.000     821.82     792.88     844.41     837.71     896.35     946.17     766.34     613.23
134.000     828.15     798.78     850.52     843.40     904.07     953.55     772.94     618.10
135.000     834.12     804.23     857.07     849.48     910.37     961.46     779.09     622.61
136.000     839.64     809.23     862.93     855.08     916.87     968.32     785.24     626.60
137.000     845.18     814.38     868.93     860.72     923.17     975.48     791.38     630.79
138.000     850.76     819.62     874.02     865.44     930.48     981.77     797.74     635.01
139.000     855.68     824.38     879.46     870.61     936.78     988.21     803.95     638.74
140.000     860.61     829.14     884.91     875.83     943.08     994.60     810.14     642.44
141.000     866.33     834.77     890.96     881.51     949.79     1001.8     816.41     647.09
142.000     871.75     839.88     896.60     886.96     957.31     1008.6     823.51     651.21
143.000     877.74     845.34     903.22     893.15     962.79     1016.3     828.78     655.65
144.000     883.87     851.33     909.38     898.94     968.89     1023.6     834.22     660.63
145.000     890.83     857.61     915.64     904.49     975.80     1031.8     839.70     665.99
146.000     897.33     863.49     922.24     910.51     982.50     1040.0     845.69     671.02
147.000     903.00     868.68     928.39     916.31     988.80     1047.2     851.78     675.24
148.000     908.54     873.71     934.47     927.03     994.49     1054.5     857.40     679.28
149.000     912.30     877.24     937.77     925.17     997.74     1058.6     860.44     681.87
150.000     916.95     881.78     942.29     929.49     1002.6     1064.0     864.94     685.37
151.000     922.67     887.29     948.51     935.53     1008.5     1071.1     870.47     689.77
152.000     928.06     892.29     954.35     941.22     1014.4     1077.7     876.11     693.68
153.000     933.16     897.06     959.27     945.99     1018.9     1083.5     880.10     697.37
154.000     937.82     901.40     963.95     950.67     1025.2     1088.7     885.88     700.62
155.000     942.10     905.38     968.31     954.96     1029.0     1093.7     889.57     703.59
156.000     947.34     909.91     973.96     960.50     1034.5     1100.1     894.75     707.02
157.000     952.85     914.85     979.11     965.39     1040.8     1106.3     900.08     710.86
158.000     954.02     915.92     980.38     966.73     1041.4     1107.9     900.75     711.46
159.000     957.89     919.42     984.73     971.36     1044.7     1112.8     904.16     713.91
160.000     962.97     923.89     990.31     976.54     1049.6     1119.2     908.93     717.28
161.000     966.98     927.91     994.75     980.93     1054.0     1124.2     913.33     720.10
162.000     969.15     930.16     995.97     982.16     1056.7     1125.9     915.70     721.18
163.000     973.65     934.50     1000.9     987.15     1060.9     1131.3     919.77     724.34
164.000     978.39     938.80     1006.2     992.35     1065.4     1137.3     924.27     727.54
165.000     983.95     943.72     1011.9     998.05     1070.9     1143.8     929.18     731.31
166.000     989.47     948.07     1017.2     1003.1     1076.9     1149.9     933.97     735.32
167.000     993.55     952.94     1021.8     1007.6     1082.3     1155.4     939.73     738.28
168.000     998.22     957.33     1027.0     1012.7     1089.8     1161.3     947.25     741.56
169.000     1002.4     961.30     1031.6     1017.1     1096.1     1166.7     953.58     744.48
170.000     1006.8     965.64     1036.6     1021.9     1096.3     1172.4     953.78     747.72
```

```
SAMIR  AL-KHAFAF PH.D. 1977  PLANT AND SOIL EVAPORATION

TIME        CEDP       CEDRV      CEDPR      CEDRY      CEDPAN     CEDJH      CEDCIP     CEDCHS
171.000     1011.8     970.23     1042.5     1027.8     1099.1     1178.9     956.77     750.97
172.000     1016.9     974.93     1047.6     1032.9     1105.4     1184.7     962.46     754.56
173.000     1021.7     979.53     1052.9     1039.2     1110.3     1190.7     967.19     758.00
174.000     1026.1     983.65     1058.1     1043.4     1116.4     1196.3     973.48     760.82
175.000     1030.6     987.72     1063.0     1048.5     1119.7     1201.7     976.63     763.77
176.000     1034.7     991.45     1067.3     1052.7     1123.7     1206.5     980.64     766.48
177.000     1038.4     995.14     1072.2     1057.6     1124.9     1212.1     982.01     768.46
178.000     1041.3     997.90     1075.3     1060.7     1129.6     1215.7     986.73     770.30
179.000     1044.7     1001.2     1079.8     1065.4     1131.8     1220.5     989.23     771.84
180.000     1048.9     1005.2     1084.4     1070.2     1137.3     1225.5     994.55     774.61
181.000     1053.1     1009.4     1089.8     1076.0     1141.2     1231.0     998.50     777.16
182.000     1058.7     1014.8     1095.6     1082.2     1146.5     1236.9     1003.0     781.15
183.000     1064.5     1020.3     1101.6     1088.4     1146.5     1243.2     1003.0     785.35
```

Table 26. Cumulative potential evaporation calculated using different equations for south central New Mexico in 1976.

```
SAMIR  AL-KHAFAF PH.D. 1977  PLANT AND SOIL EVAPORATION

 TIME        CEOP        CEOBV       CEOPP       CEOPN        CEOPAN        CEOJH       CEOTCHP       CEOCHS
0.0          0.0         0.0        -0.20347    -0.79461      4.84466E-06  0.0          4.19822E-06  0.0
 1.00000      8.1845      7.1289      5.8115      6.1417       6.4917       4.9863       3.9350      4.7322
 2.00000     14.107      14.875      11.692      13.468       11.165        9.4191       7.1273      8.5479
 3.00000     19.476      19.781      17.260      20.358       16.042       13.668       10.630      11.733
 4.00000     25.633      25.678      22.944      26.036       22.341       18.462       14.837      15.618
 5.00000     31.372      30.984      28.509      33.331       28.234       23.025       18.826      19.095
 6.00000     35.548      35.141      31.386      36.697       31.092       25.514       21.314      21.279
 7.00000     40.753      40.695      36.039      42.742       37.581       28.879       25.505      24.623
 8.00000     45.553      45.607      40.532      48.719       42.864       32.036       29.153      27.713
 9.00000     49.617      49.352      44.493      53.797       46.928       34.907       32.230      30.061
 10.0000     55.105      55.245      48.704      58.773       53.228       38.453       36.572      33.363
 11.0000     61.723      62.870      54.144      65.243       60.543       42.820       43.746      36.413
 12.0000     69.030      70.510      60.522      72.247       67.248       48.387       48.320      41.515
 13.0000     74.646      76.148      66.356      79.400       73.344       52.827       52.998      45.441
 14.0000     80.549      81.667      72.625      86.992       78.424       57.780       56.839      49.213
 15.0000     87.514      88.137      79.538      94.650       84.724       63.749       60.770      53.647
 16.0000     95.092      95.884      86.345      101.74       93.461       70.090       67.131      59.215
 17.0000     105.44      108.02      93.136      108.82       105.65       76.416       75.946      64.443
 18.0000     111.61      114.28      99.487      116.52       111.95       81.350       80.610      68.876
 19.0000     118.45      121.25      106.06      124.19       118.25       86.690       85.005      73.717
 20.0000     125.44      127.74      113.04      131.92       124.35       92.715       89.063      78.146
 21.0000     131.64      133.51      118.74      138.01       130.04       97.922       92.997      82.140
 22.0000     137.48      138.99      123.40      142.75       134.51       102.50       96.022      85.693
 23.0000     143.93      145.26      129.34      149.26       141.82       107.75       101.08      89.997
 24.0000     150.53      151.35      136.25      156.07       147.92       113.75       105.63      94.311
 25.0000     157.90      158.43      143.25      164.20       154.83       120.23       110.40      99.442
 26.0000     161.85      162.52      144.80      165.81       159.91       121.95       113.87      100.94
 27.0000     169.92      170.98      151.99      173.86       168.24       128.06       119.29      106.62
 28.0000     176.12      176.88      158.63      181.81       174.33       133.29       123.89      110.72
 29.0000     183.34      184.15      165.51      189.70       182.26       138.99       129.23      115.78
 30.0000     189.06      189.37      171.74      196.71       187.14       144.29       133.26      119.42
 31.0000     196.10      196.14      178.82      204.60       194.86       150.36       138.71      124.25
 32.0000     203.54      203.43      186.12      212.47       202.99       156.85       144.47      129.60
 33.0000     210.54      209.75      193.57      220.34       208.27       163.63       148.47      134.18
 34.0000     218.62      217.98      200.97      228.21       217.62       170.34       154.74      140.07
 35.0000     227.47      227.54      208.28      236.09       226.35       176.84       160.30      145.11
 36.0000     234.61      234.56      215.50      244.22       232.04       182.93       164.42      151.73
 37.0000     240.98      240.51      222.51      252.36       237.73       188.65       168.93      155.42
 38.0000     247.93      247.08      229.75      260.47       244.03       194.81       173.51      160.10
 39.0000     254.97      253.45      237.15      268.45       250.33       201.39       178.18      164.67
 40.0000     258.76      257.21      240.46      271.81       253.99       204.77       181.40      167.22
 41.0000     266.10      264.19      248.16      279.79       259.68       211.93       185.88      172.61
 42.0000     274.72      272.68      256.09      287.96       268.42       219.48       191.44      178.82
 43.0000     283.61      281.35      264.23      296.11       275.93       227.25       195.94      185.07
 44.0000     292.28      289.82      272.30      304.29       284.27       234.97       201.76      191.32
 45.0000     303.20      301.17      280.99      312.50       294.83       244.06       207.09      199.30
 46.0000     312.19      311.23      285.63      316.89       301.55       249.10       210.73      203.85
 47.0000     319.77      318.81      292.67      323.94       309.05       255.99       216.29      209.64
 48.0000     328.11      326.87      300.51      331.76       316.98       263.66       221.60      215.72
 49.0000     334.54      333.14      306.76      338.42       323.69       267.33       226.70      220.30
 50.0000     344.04      342.92      314.81      346.77       333.24       276.02       232.05      226.87
 51.0000     353.13      352.05      323.20      355.24       342.54       284.86       238.15      233.13
 52.0000     360.13      359.06      330.20      362.03       350.91       291.06       244.59      238.97
 53.0000     366.94      365.34      337.46      370.70       356.69       297.48       248.90      243.52
 54.0000     373.93      371.85      345.19      379.08       362.70       304.29       253.72      248.26
 55.0000     381.67      378.87      353.35      387.46       368.03       311.95       258.29      253.53
 56.0000     389.78      3 6.58      361.33      395.48       375.91       319.67       263.28      259.47
```

SAMIR AL-KHAFAF PH.D. 1977 PLANT AND SOIL EVAPORATION

TIME	CEOP	CE-HV	CEOPK	CEOPH	CEOPAN	CE3JH	CEUCHP	CEUCHS
57.0000	397.12	393.90	360.52	402.93	385.66	326.38	270.71	265.04
58.0000	404.54	401.60	375.19	409.76	394.60	332.76	277.39	270.67
59.0000	410.94	407.94	381.37	416.26	400.49	338.48	281.99	275.38
60.0000	416.47	413.08	387.37	422.66	405.37	343.94	286.30	279.14
61.0000	423.81	420.03	395.62	431.10	412.08	351.72	292.14	284.60
62.0000	431.43	426.96	403.64	439.02	418.78	359.64	297.26	289.96
63.0000	440.20	435.15	412.19	447.27	426.59	369.33	302.57	295.42
64.0000	449.34	443.67	420.93	455.39	435.85	377.71	308.86	303.37
65.0000	457.81	451.72	429.09	463.21	444.40	386.11	315.62	309.80
66.0000	466.26	459.63	437.49	471.44	453.53	394.40	321.33	315.99
67.0000	475.19	468.99	446.02	479.55	463.69	403.33	327.68	323.20
68.0000	481.09	473.91	451.05	484.38	469.58	408.67	332.86	327.05
69.0000	488.89	481.36	459.13	492.18	477.10	416.91	339.00	333.25
70.0000	496.14	488.23	466.50	499.30	485.02	424.34	345.44	338.79
71.0000	504.16	496.15	474.34	507.03	494.78	432.21	352.94	345.23
72.0000	511.87	503.30	482.84	515.39	501.08	440.63	358.34	350.99
73.0000	519.61	510.57	491.33	523.41	508.19	449.53	364.67	357.21
74.0000	527.43	517.81	499.67	531.23	515.71	458.37	371.08	363.36
75.0000	537.64	528.36	507.94	539.91	531.15	467.26	380.62	371.20
76.0000	547.32	537.43	517.06	547.36	541.92	477.08	387.38	378.52
77.0000	556.94	546.47	526.14	555.85	552.89	486.72	395.02	386.41
78.0000	565.89	555.76	534.78	564.22	563.66	495.44	402.83	393.66
79.0000	575.65	565.80	543.24	572.15	576.46	504.40	411.52	401.55
80.0000	583.20	573.04	551.68	580.33	584.79	512.94	419.06	407.63
81.0000	590.64	580.28	560.20	588.52	593.73	521.65	427.40	413.74
82.0000	598.16	587.47	568.63	596.69	602.68	530.17	435.52	419.76
83.0000	604.79	593.40	575.31	603.19	608.97	536.99	440.76	424.42
84.0000	613.29	602.21	584.03	611.37	618.52	546.21	448.75	432.16
85.0000	621.30	609.91	592.17	618.68	626.04	555.45	455.21	439.24
86.0000	629.80	618.00	601.20	626.89	635.19	565.45	462.94	446.57
87.0000	637.65	624.83	609.00	634.17	642.10	573.78	468.05	452.05
88.0000	646.25	633.02	617.75	642.36	650.83	583.08	474.95	459.10
89.0000	654.46	640.99	626.75	650.56	659.98	593.01	483.25	466.45
90.0000	663.35	649.76	635.75	658.76	668.92	602.93	490.59	474.48
91.0000	671.89	658.32	644.82	666.95	678.26	613.07	498.84	482.53
92.0000	679.77	666.17	653.82	675.31	687.41	622.71	507.35	489.51
93.0000	688.54	675.02	662.80	683.59	697.57	632.43	515.87	497.55
94.0000	694.66	681.18	669.07	689.39	704.68	639.31	522.33	502.75
95.0000	700.79	687.12	676.16	695.96	710.98	647.05	528.63	507.67
96.0000	707.88	693.77	684.12	703.40	715.04	655.55	532.49	513.32
97.0000	713.99	699.60	691.23	709.98	722.56	663.30	540.15	518.09
98.0000	721.67	707.02	699.64	717.71	730.69	672.46	547.60	524.75
99.0000	728.67	713.63	707.39	724.09	737.63	680.88	554.14	530.47
100.000	736.62	721.04	715.93	732.82	744.91	690.05	560.50	536.91
101.000	744.60	728.74	723.93	740.14	753.04	698.88	567.29	543.77
102.000	751.29	735.23	730.41	746.00	757.51	706.23	571.20	549.44
103.000	755.79	739.47	734.74	750.14	764.83	710.91	578.02	557.70
104.000	763.30	746.41	743.18	758.22	771.13	719.58	583.76	558.41
105.000	770.41	753.20	751.15	765.89	779.86	727.75	591.86	564.08
106.000	780.07	762.89	760.04	774.04	788.80	737.47	598.42	572.42
107.000	788.85	771.74	768.96	782.26	797.54	747.12	605.60	580.42
108.000	793.97	776.66	774.74	787.77	803.03	753.26	611.08	584.26
109.000	799.87	782.17	780.84	793.51	808.72	759.61	616.31	588.81
110.000	806.08	787.80	787.50	799.65	814.00	767.13	621.33	593.55
111.000	813.17	794.73	794.72	806.36	822.33	774.96	628.60	599.57
112.000	819.14	800.45	801.68	812.91	828.02	782.37	634.36	604.15
113.000	826.51	807.50	809.92	820.49	834.71	791.37	640.71	610.38

```
SAMIR  AL-KHAFAF PH.D. 1977  PLANT AND SOIL EVAPORATION

TIME       CEDP       CEDAV      CEDPR      CEDRN      CEDPAN     CEDJU      CETCHP     CEDCHS
114.000    831.86     812.54     814.95     825.10     840.42     797.07     645.87     614.52
115.000    838.87     819.28     822.72     832.36     847.12     805.38     652.16     620.34
116.000    845.39     825.68     829.75     839.13     854.03     812.63     658.44     625.66
117.000    851.93     831.96     836.85     845.83     859.52     820.14     663.53     630.96
118.000    859.70     839.59     843.22     853.74     867.44     828.93     670.53     637.65
119.000    865.84     845.30     851.71     859.74     882.48     836.04     684.66     642.48
120.000    869.67     848.85     856.16     864.02     886.34     840.78     688.85     644.95
121.000    876.99     855.58     864.12     871.51     892.84     849.20     694.65     650.61
122.000    884.79     862.47     872.66     879.44     901.37     858.37     702.00     656.33
123.000    892.24     869.12     900.00     886.35     905.03     866.36     704.84     661.75
124.000    899.97     876.68     887.64     893.37     913.97     874.53     712.17     668.28
125.000    906.55     882.95     894.39     899.60     930.43     881.95     727.02     673.69
126.000    912.48     888.72     900.80     905.72     937.34     888.67     733.49     678.42
127.000    919.99     895.81     909.00     913.56     944.45     897.16     739.80     684.40
128.000    928.23     903.55     917.26     921.35     951.97     905.82     745.57     690.83
129.000    935.33     910.12     925.27     927.14     958.27     913.91     751.30     696.10
130.000    942.42     916.48     932.45     935.90     964.77     921.54     756.69     701.32
131.000    949.28     923.04     939.12     942.18     973.51     928.66     763.99     706.76
132.000    956.79     930.31     945.80     948.49     981.23     935.76     769.67     712.44
133.000    964.19     937.11     953.51     955.93     987.53     943.63     774.99     718.01
134.000    960.74     941.50     958.87     961.12     992.09     949.21     779.60     721.25
135.000    974.45     946.76     964.77     966.74     997.47     955.46     784.65     725.50
136.000    980.73     952.54     971.58     973.14     1002.8     962.72     789.63     730.28
137.000    988.34     959.88     979.37     980.50     1010.7     970.92     796.27     736.55
138.000    995.51     966.65     986.92     987.64     1017.6     978.89     802.33     742.20
139.000    1002.7     973.39     994.38     994.67     1025.9     986.75     809.46     747.95
140.000    1010.1     980.09     1002.4     1002.1     1031.2     995.61     814.26     753.72
141.000    1016.4     986.15     1008.8     1008.1     1037.3     1002.3     819.63     758.73
142.000    1020.7     990.24     1013.7     1012.9     1041.2     1007.5     823.62     761.72
143.000    1026.5     995.85     1020.0     1018.8     1046.9     1014.2     829.03     766.35
144.000    1031.5     1000.4     1025.6     1024.1     1050.5     1020.2     832.79     769.90
145.000    1038.1     1006.4     1033.0     1031.1     1055.8     1028.0     837.84     774.80
146.000    1044.6     1012.3     1040.1     1037.7     1061.7     1035.7     843.38     779.74
147.000    1052.3     1019.5     1047.8     1044.9     1068.4     1044.0     848.90     785.82
148.000    1060.3     1027.3     1055.4     1051.9     1074.3     1052.2     853.50     792.45
149.000    1067.0     1033.9     1063.1     1059.2     1081.4     1060.2     860.29     797.91
150.000    1073.5     1039.8     1070.4     1056.1     1086.9     1068.0     865.70     802.72
151.000    1080.3     1045.9     1077.8     1073.0     1093.0     1076.0     871.32     807.86
152.000    1087.5     1052.5     1085.2     1079.9     1099.3     1083.8     876.51     813.27
153.000    1094.7     1059.3     1092.5     1086.8     1106.4     1091.6     882.54     819.08
154.000    1101.2     1065.5     1099.1     1093.0     1113.1     1098.5     888.33     824.15
155.000    1109.0     1073.5     1106.2     1099.7     1120.6     1106.2     894.31     830.70
156.000    1113.8     1078.2     1111.2     1104.6     1125.5     1111.3     898.90     834.25
157.000    1119.9     1094.1     1117.4     1110.6     1131.6     1117.8     904.26     839.10
158.000    1123.5     1087.4     1120.1     1113.2     1135.0     1120.8     907.32     841.30
159.000    1125.6     1089.4     1122.1     1115.7     1136.9     1121.0     909.17     842.61
160.000    1131.6     1095.4     1127.6     1120.5     1143.8     1128.7     914.89     847.23
161.000    1136.0     1099.4     1131.8     1124.6     1147.0     1133.2     917.93     850.30
162.000    1142.2     1105.4     1137.8     1130.3     1152.7     1139.6     922.79     855.15
163.000    1148.6     1111.3     1144.6     1136.7     1157.4     1146.8     927.12     860.09
164.000    1153.7     1116.5     1148.7     1140.5     1162.9     1151.3     931.69     863.75
165.000    1159.3     1121.3     1152.4     1144.4     1171.8     1154.9     939.15     866.75
166.000    1161.4     1124.6     1155.4     1147.7     1175.5     1157.7     942.37     868.77
167.000    1165.4     1128.1     1160.1     1152.4     1177.3     1162.3     944.56     871.14
168.000    1171.5     1133.5     1166.4     1158.7     1181.8     1168.6     948.14     875.13
169.000    1177.6     1138.8     1172.9     1165.1     1186.5     1175.1     952.20     879.22
170.000    1182.9     1143.6     1178.6     1170.7     1190.9     1180.9     956.39     882.85
```

```
SAMIR  AL-KHAFAF PH.D. 1977  PLANT AND SOIL EVAPORATION

TIME         CEOP        CEQBV       CEOPR       CEQRN       CEQPAN      CEJJH       CEJCHP      CEQCHS
171.000      1189.9      1149.1      1184.8      1176.8      1196.6      1187.3      961.55      887.31
172.000      1195.0      1154.8      1191.1      1182.8      1201.5      1193.9      965.81      891.92
173.000      1200.6      1160.0      1197.3      1188.8      1206.8      1200.2      970.95      896.00
174.000      1205.3      1164.9      1201.7      1193.4      1212.3      1204.5      975.64      899.40
175.000      1210.9      1170.0      1207.4      1199.6      1216.3      1209.5      978.91      903.06
176.000      1216.3      1174.8      1213.0      1205.8      1221.0      1214.5      982.76      906.43
177.000      1221.9      1179.9      1218.7      1211.9      1224.9      1219.6      985.82      910.02
178.000      1227.3      1184.6      1224.2      1217.8      1227.5      1224.6      987.88      913.24
179.000      1233.0      1189.4      1229.8      1223.0      1233.0      1229.8      991.78      916.51
180.000      1238.3      1193.8      1235.1      1229.4      1235.2      1234.7      993.45      919.51
181.000      1243.9      1198.4      1240.7      1235.2      1239.3      1239.9      996.41      927.69
182.000      1249.5      1203.1      1246.0      1240.6      1242.9      1245.0      998.99      925.91
183.000      1255.2      1208.6      1250.7      1245.6      1248.8      1249.6      1003.3      929.62
```

APPENDIX C

Evapotranspiration data of different treatments for 1975 and 1976.

Table 27. Potential evaporation (Eo), irrigation or rain (q), evapotranspiration (ET), soil evaporation (Es), and leaf area index (LAI) of each irrigation interval for different treatments.

Irrigation	wet					medium				dry			
Interval	Eo	q	ET	Es	LAI	q	ET	Es	LAI	q	ET	Es	LAI
	- - - - - - -cm- - - - - - -				cm^2/cm^2	- - - - cm - - -			cm^2/cm^2	- - - - cm- - - -			cm^2/cm^2
6/2-4	2.43	1.39	0.74	0.74	0.00	1.04	0.72	0.71	0.00	0.96	0.69	0.68	0.00
6/4-10	4.98	2.57	1.22	1.20	0.00	1.10	1.19	1.18	0.00	0.66	0.80	0.80	0.00
6/10-16	5.40	5.42	1.84	1.82	0.02	4.00	1.80	1.76	0.02	2.25	1.61	1.57	0.02
6/16-23	5.70	1.06	1.22	1.00	0.05	0.75	1.08	0.93	0.05	0.45	0.83	0.70	0.03
6/23-27	2.92	1.80	1.20	1.10	0.07	1.00	1.09	0.96	0.08	0.74	0.59	0.50	0.04
6/27-7/1	3.24	1.45	1.33	1.20	0.08	1.00	1.29	1.09	0.09	0.65	0.72	0.63	0.05
7/1-5	3.20	1.80	1.20	0.95	0.13	1.10	1.22	0.90	0.12	0.62	0.64	0.51	0.07
7/5-8	2.31	0.94	1.04	0.77	0.16	0.94	0.90	0.67	0.15	0.77	0.68	0.52	0.09
7/8-11	2.43	0.33	0.62	0.36	0.22	0.15	0.70	0.30	0.21	0.33	0.49	0.30	0.15
7/11-18	5.18	3.32	3.30	2.25	0.35	2.29	3.58	2.20	0.47	1.54	1.87	1.55	0.29
7/18-22	2.24	4.38	1.80	1.00	0.68	2.14	1.90	1.00	0.75	1.42	1.55	0.74	0.55
7/22-28	3.54	2.18	3.33	1.59	1.00	0.52	3.40	1.84	0.95	0.10	1.48	0.80	0.78
7/28-8/1	2.72	6.86	2.50	1.00	1.25	4.20	2.25	0.97	1.08	3.78	2.28	0.83	0.90
8/1-5	1.88	8.40	1.68	0.42	1.83	8.40	1.67	0.42	1.65	2.77	1.72	0.58	1.40
8/5-11	4.14	2.54	4.13	0.84	2.73	1.58	4.05	0.93	2.54	0.51	3.60	0.66	2.10
8/11-14	1.92	2.74	1.94	0.27	3.42	2.27	1.77	0.36	2.90	0.74	1.66	0.30	2.40
8/14-19	3.40	3.06	3.40	0.27	3.63	0.74	3.37	0.47	3.15	0.74	2.55	0.63	2.60
8/19-9/6	10.64	4.10	10.52	0.78	3.95	4.10	10.42	1.29	3.44	3.00	5.69	1.83	2.85
9/6-11	2.30	3.00	2.28	0.19	4.00	3.00	1.74	0.30	3.34	0.17	0.60	0.40	2.90
9/11-24	6.24	4.60	5.30	0.76	3.33	4.60	5.50	1.00	2.80	4.60	3.00	1.30	2.00
Total	76.81	61.94	50.59	18.51		44.92	49.64	19.28		26.80	33.05	15.83	

Table 28. Soil water in 100 cm of soil (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for wet treatment lysimeter 1, 1976.

Date	SW	q	Dr	ET	Es	Ep
	- - - - - - - - - - - - - - mm - - - - - - - - - - - - - - - - -					
4-30	129.0					
		21.0				
5-07	131.2			18.8		
		60.0				
5-14	173.9			17.3		
		24.0				
5-21	176.1			20.9		
		25.8				
5-28	174.8			27.1		
		21.0				
6-04	175.7			20.1	16.3	3.8
		38.0				
6-11	187.8			25.1	21.2	3.9
		27.0				
6-18	195.7			19.1	14.0	5.1
		27.0				
6-25	201.1			21.6	14.3	7.3
		20.0				
7-02	192.8			28.3	13.0	15.3
		32.0				
7-09	18.4			43.4	23.0	20.4
		43.0				
7016	189.7			34.7	16.7	18.0
		31.0				
7-23	184.7			36.0	11.0	25.0
		56.0				
7-30	201.0		4.53	35.2	10.0	25.2
		30.0				
8-06	194.7			36.3	8.2	28.1
		47.8				
8-16	188.0		2.4	52.1	6.3	45.8
		24.0				
8-20	190.9		1.30	19.8	3.2	16.6
		32.0				
8-31	168.6			54.3	8.0	46.3

Table 29. Soil water in 100 cm of soils (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for wet treatment lysimeter 2, 1976.

Date	SW	q	Dr	ET	Es	Ep
	- - - - - - - - -	- - - - - -	- - - - - mm	- - - - - -	- - - - - -	- - - - - -
4-30	134.0					
		21.0				
5-07	136.1			19.0		
		60.0				
5-14	179.8			16.3		
		24.0				
5-21	183.5			20.3		
		25.8				
5-28	182.7			26.6		
		21.0				
6-04	184.7			19.0	16.0	3.0
		38.0				
6-11	20.14			21.3	21.2	0.1
		27.0				
6-18	208.7			19.7	14.0	5.7
		27.0				
6-25	215.3			20.4	14.0	6.4
		20.0				
7-02	210.3			25.0	10.0	15.0
		32.0				
7-09	205.0			37.3	15.2	22.1
		43.0				
7-16	218.7			29.3	10.1	18.2
		31.0				
7-23	223.5			26.2	2.3	24.9
		56.0				
7-30	237.0		12.8	29.8	4.1	25.7
		30.0				
8-06	222.2		16.1	28.9	2.0	26.9
		47.8				
8-16	199.5		16.8	53.5	4.3	49.2
		24.0				
8-20	206.4			17.1	1.0	16.1
		32.0				
8-31	187.5			50.9	3.0	47.9

Table 30. Soil water in 100 cm of soil (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for wet treatment lysimeter 3, 1976.

Date	SW	q	Dr	ET	Es	Ep
	- - - - - -	- - - - - -	- - - - mm	- - - - - -	- - - - - -	- - - - - -
4-30	132.5					
		21.0				
5-07	134.9			18.6		
		60.0				
5-14	171.8			23.1		
		24.0				
5-21	171.6			24.2		
		25.8				
5-28	173.0			24.4		
		21.0				
6-04	174.1			20.0	16.3	3.7
		38.0				
6-11	185.3			26.8	21.2	5.6
		27.0				
6-18	193;0			19.3	14.0	5.3
		27.0				
6-25	201.1			18.9	14.3	4.6
		20.0				
7-02	195.4			25.7	13.0	12.7
		32.0				
7-09	189.0			38.4	23.0	15.4
		53.0				
7-16	205.6			36.4	16.7	19.7
		41.0				
7-23	212.0			34.6	11.0	24.6
		86.0				
7-30	243.5		22.31	36.2	10.0	26.2
		30.0				
8-06	228.8		7.8	36.9	8.2	26.7
		47.8				
8-16	202.4		21.3	52.9	6.3	46.6
		24.0				
8-20	211.9			14.5	3.2	11.3
		32.0				
8-31	190.9			53.0	8.0	45.0

Table 31. Soil water in 100 cm of soil (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for wet treatment lysimeter 4, 1976.

Date	SW	q	Dr	ET	Es	Ep
	- - - - - -	- - - - - -	- - - - - mm	- - - - - -	- - - - - -	- - - - - -
4-30	130.9					
		21.0				
5-07	134.0			17.9		
		60.0				
5-14	172.0			22.0		
		24.0				
5-21	172.5			23.5		
		25.8				
5-28	171.3			27.0		
		21.0				
6-04	173.6			18.7	16.0	1.3
		38.0				
6-11	189.0			22.6	21.2	1.4
		27.0				
6-18	195.4			20.6	14.0	6.6
		27.0				
6-25	200.2			22.2	14.0	8.2
		20.0				
7-02	194.7			25.5	10.0	15.5
		32.0				
7-09	191.1			35.6	15.2	20.4
		43.0				
7-16	205.6			28.5	10.1	18.4
		31.0				
7-23	213.4			23.2	2.3	20.9
		56.0				
7-30	244.3			25.1	4.1	21.0
		30.0				
8-06	235.2		9.0	30.1	2.0	28.1
		47.8				
8-16	223.9		11.4	47.7	4.3	43.4
		24.0				
8-20	224.0		3.5	20.1	1.0	19.1
		32.0				
8-31	205.0			51.0	3.0	47.0

Table 32. Soil water in 100 cm of soil (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for dry treatment lysimeter 6, 1976.

Date	SW	q	Dr	ET	Es	Ep
	mm					
4-30	129.2					
		21.0				
5-07	130.8			19.4	1.96	---
		60.0				
5-14	168.3			22.5	18.0	4.5
		24.0				
5-21	171.7			20.6	20.8	0.0
		25.8				
5-28	173.0			25.5	10.9	14.6
		19.2				
6-04	170.6			21.6	17.6	4.0
		38.0				
6-11	181.1			27.5	21.8	5.7

6-18	174.8			6.6	5.9	0.7
		35.0				
6-30	184.7			25.1	14.5	10.6
		20.3				
7-12	167.6			38.4	20.0	18.4
		45.5				
7-23	166.4			46.6	30.0	16.6
		57.5				
8-06	182.6			41.3	15.8	25.5
		58.0				
8-31	164.8			77.9	24.0	53.9

Table 33. Soil water in 100 cm of soil (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for dry treatment lysimeter 7, 1976.

Date	SW	q	Dr	ET	Es	Ep
	- - - - - -	- - - - - -	- - - - - - mm	- - - - - -	- - - - - -	- - - - - -
4-30	130.9					
		21.0				
5-07	134.4			17.5	19.6	---
		60.0				
5-14	175.8			18.6	18.0	0.6
		24.0				
5-21	175.4			24.4	20.8	3.2
		25.8				
5-28	175.5			25.9	10.9	15.0
		19.2				
6-04	176.9			17.7	17.6	0.1
		38.0				
6-11	185.2			29.7	21.8	7.9

6-18	176.0			9.8	5.9	3.9
		35.0				
6-30	179.3			31.7	19.0	12.7
		20.3				
7-12	145.9			42.7	24.2	18.5
		45.5				
7-23	159.5			42.9	26.9	16.0
		72.0				
8-06	187.0			44.5	18.8	25.7
		58.0				
8-31	167.0			78.1	26.5	51.6

Table 34. Soil water in 100 cm of soil (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for dry treatment lysimeter 8, 1976.

Date	SW	q	Dr	ET	Es	Ep
			mm			
4-30	129.8					
		21.0				
5-07	133.6			17.2	19.6	--
		60.0				
5-14	169.5			24.1	18.0	6.1
		24.0				
5-21	169.0			24.5	20.8	3.8
		25.8				
5-28	169.0			25.8	10.9	14.9
		19.2				
6-04	167.9			20.3	17.6	2.7
		38.0				
6-11	178.7			27.2	21.8	5.4

6-18	167.6			11.1	5.9	5.2
		35.0				
6-30	178.3			24.3	19.0	5.3
		20.3				
7-12	154.1			44.5	24.2	20.3
		45.5				
7-23	155.8			43.8	26.9	16.9
		42.0				
8-06	180.5			47.3	18.8	26.5
		58.0				
8-31	159.9			78.5	26.5	52.0

Table 35. Soil water in 100 cm of soils (SW), irrigation or rain (q), drainage (Dr), evapotranspiration (ET), soil evaporation (Es), and transpiration (Ep) of each irrigation interval for dry treatment lysimeter 9, 1976.

Date	SW	q	Dr	ET	Es	Ep
	- - - - - - -	- - - - - - -	- - mm -	- - - - - - -	- - - - - - -	- - - - - - -
4-30	127.6					
		21.0				
5-07	130.4			18.2	19.6	--
		60.0				
5-14	172.4			18.0	18.0	--
		24.0				
5-21	174.5			22.1	20.8	0.3
		25.8				
5-28	173.6			26.7	10.9	15.8
		19.2				
6-04	171.5			22.3	17.6	5.7
		38.0				
6-11	182.5			27.0	21.8	5.2
		--				
6-18	174.1			8.4	5.9	2.5
		35.0				
6-30	182.3			26.8	14.5	12.3
		20.3				
7-12	157.2			45.4	20.0	25.4
		45.5				
7-23	156.7			46.0	30.0	16.0
		57.5				
8-06	172.6			41.5	15.8	25.8
		58.0				
8-31	154.6			77.0	24.0	53.0