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3. W. W. Hildreth

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16. Abstract

WATBAL1 is a soil water computer model that uses the IBM Continuous System Modeling Program III (CSMPIII) to solve the dynamic equations representing the soil, plant, and atmospheric physical or physiological processes considered. Using values describing the soil-plant-atmosphere characteristics, the model predicts evaporation, transpiration, drainage, and soil water profile changes from an initial soil water profile and daily meteorological data.

This report describes the model characteristics and simulations that were performed to determine the nature of the response to controlled variations in the input. The report also presents the results of the simulations and discusses a change that makes the response of the model more closely represent the observed characteristics of evapotranspiration and profile changes for dry soil conditions.

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DESCRIPTIVE AND SENSITIVITY ANALYSES OF WATBAL1: A DYNAMIC SOIL WATER MODEL

Job Order 71-322

This report describes the activities of the Soil Moisture project of the AgRISTARS program.

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LOCKHEED ENGINEERING AND MANAGEMENT SERVICES COMPANY, INC.

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PREFACE

The Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing is a 6-year program of research, development, evaluation, and application of aerospace remote sensing for agricultural resources, which began in fiscal year 1980. This program is a cooperative effort of the National Aeronautics and Space Administration, the U.S. Agency for International Development, and the U.S. Departments of Agriculture, Commerce, and the Interior.

The work which is the subject of this document was performed within the Earth Resources Research Division, Space and Life Sciences Directorate, at the Lyndon B. Johnson Space Center, National Aeronautics and Space Administration. Under Contract NAS 9-15800, personnel of Lockheed Engineering and Management Services Company, Inc., performed the tasks which contributed to the completion of this research.

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1. INTRODUCTION

WATBAL1 is a soil water point profile model developed by Dr. C. H. M. Van Bavel at Texas A&M University under contract to the NASA Johnson Space Center (ref. 1). This model is patterned after the soil-plant-atmospheric model presented earlier by Van Bavel and Ahmed (ref. 2). The computer program for the model is coded in IBM's latest Continuous System Modeling Program III (CSMPIII, refs. 2 and 3). The use of CSMPIII in soil water modeling has been reported by Dr. Van Bavel and his colleagues in a number of papers (ref. 4).

The CSMPIII has been developed primarily to solve the nonlinear partial differential equations of dynamic systems. The program has many calculation and printing capabilities in addition to standard FORTRAN routines. The general use of CSMPIII in soil water dynamics has been presented in a book by Hillel (ref. 5) in which the basic soil water model and the description of the capabilities and the use of CSMPIII are well described.

WATBAL1 has been designed to be general enough to represent realistically a wide range of soil-crop-atmospheric processes and conditions. In addition to the use of CSMPIII, WATBAL1 has several unique features that are not found in other soil water models. (See ref. 6 for the comparative characteristics of a number of soil water models.) For example, evaporation and transpiration are each determined separately and directly from the input data. Also, the water flow through the crop is determined by a difference in water potential divided by the appropriate crop resistance. Another feature is the determination of a canopy temperature from an energy balance approach.

The purpose of this report is to describe the model and its output characteristics as the inputs are varied over realistic ranges. These characteristics are determined from a simulation study which can also indicate the boundaries for realistic simulation and the sensitivity of the output to given changes in the input. A detailed summary of the model is provided in the next section.

2. MODEL SUMMARY

2.1 GENERAL

Any model of natural phenomena generally represents an approximation of the actual physical, chemical, or biological processes involved. A discussion of the general processes involved in soil water changes are discussed in detail in reference 6. These processes can be represented by the following equation:

$$\Delta SW = P - I + RO + L - E - T + F + D \tag{1}$$

where

ΔSW = the change in soil water for the layer for a given time interval

P = precipitation or irrigation

I = interception of P by the crop cover

RO = surface net lateral flow, convergence (+) (run-on), divergence (-) (runoff)

L = net subsurface lateral movement, generally considered negligible

E = evaporation (+) or condensation (-)

T = transpiration

F = net vertical flux in layer, gain (+), loss (-)

D = net flux at lower boundry, drainage (-), capillary rise (+)

Most of the terms on the right side, except precipitation, are not specified directly, but are estimated from functions involving atmospheric, plant, and soil parameters. WATBAL1 considers the processes represented by the following equation:

$$\Delta SW = P - E - T + F + D \tag{2}$$

The actual representation of these processes is outlined in the schematic process flow diagram in figure 1. The boxes indicate processes modeled by functions and logic steps. Input data are underlined; water losses are indicated by double arrows. The general flow of algorithm operations and data use is shown by the arrows between the boxes. Considerable feedback is indicated.

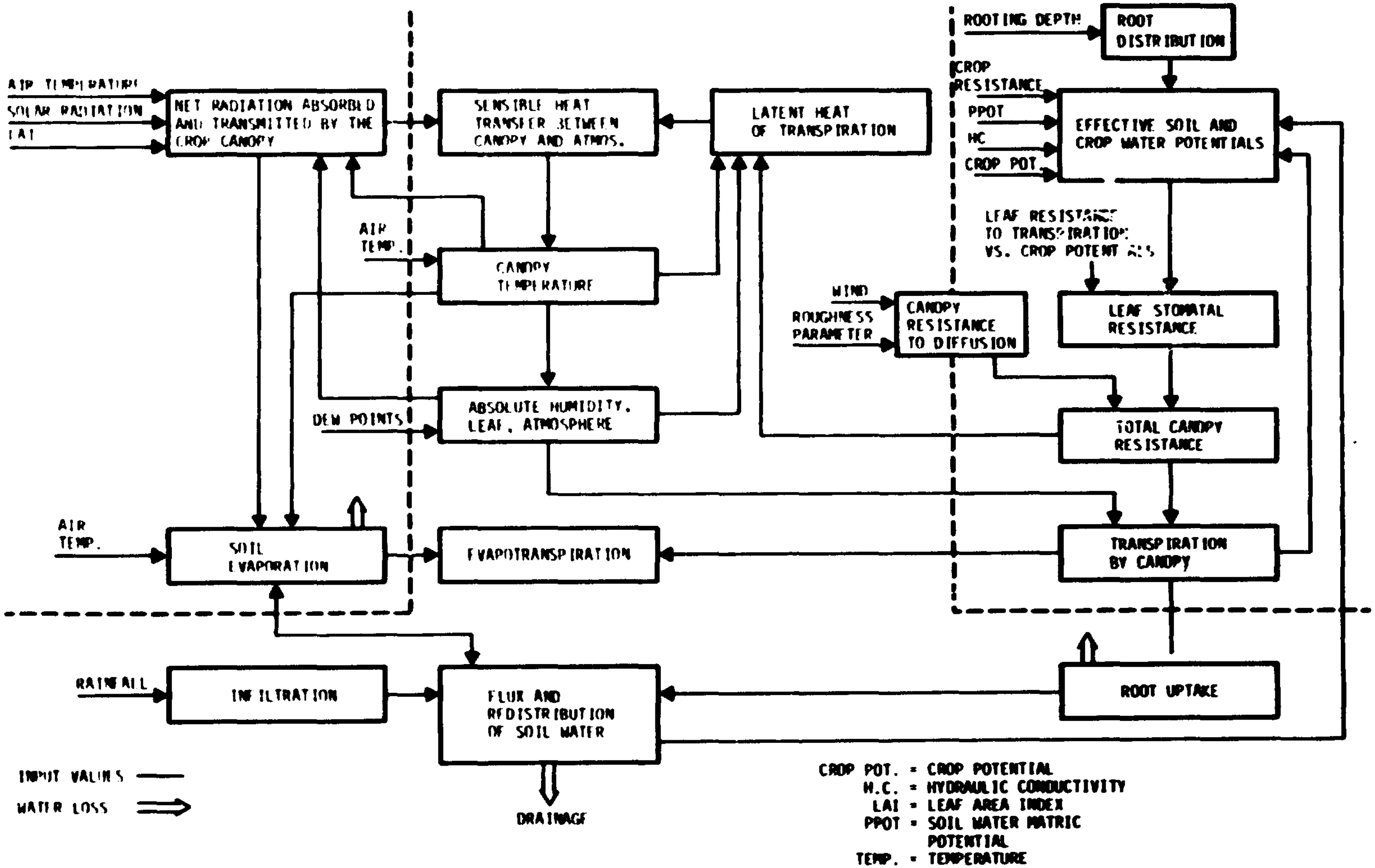

Figure 1.- Flow chart for WATBAL1.

Soil water evaporation is modeled by the processes indicated on the left of the diagram. Transpiration and root uptake are modeled by the processes on the right. The middle section represents intermediate and general calculations. The bottom section represents the processes involved in determining the new soil water distribution. The calculations and operations represented here are discussed in detail below. A listing for the code for the model is presented in Appendix A.

The number of soil layers to be represented by the model and the thicknesses of the layers are arbitrary and can be varied to best represent the depths of interest. The model can also group the layers into larger units which have similar soil hydrologic properties. These properties — moisture release and hydraulic conductivity data — are provided through tables of values.

2.2 SOIL EVAPORATION

The soil evaporation is determined primarily by the net radiation at the ground under the canopy and the amount of water in the surface layer. The calculation is made by the following two equations:

EVS = EVS1*EXP[PPOT(1)]/46.97*TAK (3)

EVS1 = (EPS/EPSH)*NRBS/LH*1000.0 (4)

where

EVS = rate of evaporation from soil surface (m/s)

EPS = ratio of Δ, which is the change in saturation vapor pressure with temperature, to γ, the psychrometer constant

EPSH = (EPS + 1)

LH = latent heat of evaporation (J/kg)

NRBS = net radiation at soil level (W/m^2)

PPOT(1) = matric potential of surface layer (m)

TAK = temperature of the air (K)

PPOT(1) is initially an input datum, but it is then determined from the new water distribution values by the model calculations. TAK is determined from the input data on maximum and minimum Celsius temperatures by using linear interpolation between the appropriate temperatures. Dewpoint values (DPTC) are determined in the same manner from the input maximum and minimum dewpoints. EPS, LH, and NRBS are also computed from the appropriate input data. The functions used are listed in table 1. NRBS is determined from a radiation energy balance calculation which is derived from the incoming solar radiation, the long wave energy balance between air and canopy, the canopy albedo, and transmittance.

2.3 TRANSPIRATION

Transpiration is determined from the input data by the difference between the water vapor potentials of the atmosphere and the leaf, and the canopy resistance to the vapor flow. The following equation shows how this is determined:

$$TRC = (HL - HA)/1000.0*RCW \quad (5)$$

where

TRC = canopy transpiration rate (m/s)

HL = absolute humidity of leaf interior (kg/m^3)

HA = absolute humidity of the atmosphere (kg/m^3)

RCW = total canopy resistance to water vapor diffusion (s/m)

The total canopy resistance, RCW, is made up of two terms: RL, the leaf stomatal resistance (s/m), and RA, the canopy resistance (s/m). The functions determining RL and RA, as well as HL and HA, are presented in table 2. As can be seen from table 2, the leaf stomatal resistance, RL, is determined by the current crop water potential, WPOTCR, from a table relating RL to WPOTCR. RA, the resistance to canopy diffusion, is a function of the daily mean windspeed which is an input datum.

To determine a new WPOTCR, the following relationship is used. (See table 2 for definitions.)

TABLE 1.- FUNCTIONS FOR CALCULATING EVAPORATION PARAMETERS IN EQUATIONS (3) AND (4)

LH	=	$2.49463 \times 10^6 - 2.247 \times 10^3$TL; latent heat of evaporation (J/kg)
EPS	=	0.921 - 0.00262TL + 0.00308TL^2, where TL, interim canopy temperature, is calculated by an implicit CSMPIII routine; i.e., TL = IMPL (TAC, 0.01, FTL) where TAC is the air temperature determined from a linear inter polation between the input data on maximum and minimum temperatures.
FTL	=	TAC - SHCA*(RA/SH); final canopy temperature °C
RA	=	canopy resistance (see table 2)
SH	=	350089.17/TAK; specific heat of air at constant volume (J/m^3)
TAK	=	TAC + 273.16° K; see TAC above
SHCA	=	LTR - NRBC; sensible heat transfer between canopy and atmosphere
NRBC	=	(GR)(ABSC) + (1.0 - FTSR)*(SKL - LWRC); net radiation absorbed by the canopy (W/m^2)
LTR	=	(HL - HA)*LH/RCW; latent heat of transpiration; see table 2 for HL, HA, and RCW
GR	=	(436.33 DGR/DL)*sine[(STIME - 12. + DL/2)*π/DL]
DGR	=	daily total global radiation (mJ/m^2); daily input data
DL	=	day length (hours); daily input data
STIME	=	time of day (hours)
ABSC	=	0.0032 + 0.3084(LAI) - 0.05323(LAI^2) + 0.003667(LAI)^3; canopy absorptance
LAI	=	leaf area index; daily plant input data
FTSR	=	0.9842 - 0.6755(LAI) + 0.1595(LAI)^2 - 0.0124(LAI)^3; view factor of diffuse radiation through the canopy
SKL	=	σ(TAK)^4*(0.605 + 0.039 $\sqrt{1410.0HA}$) = long wave radiation from sky (W/m^2)
HA	=	atmospheric absolute humidity (kg/m^3); see table (2)
σ	=	Stephan - Boltzmann's Constant
LWRC	=	σ(TL + 273.16)^4; long wave radiation from canopy (W/m^2)
NRBS	=	GR*(1.0 - ALBC - ABSC) + FTSR*(SKL - LWRC); = net radiation at soil level (W/m^2)
ALBC	=	0.124 - 0.009988(LAI) + 0.007142(LAI)^2 - 0.000583(LAI)^3, canopy albedo

*indicates multiplication

TABLE 2.- FUNCTIONS FOR CALCULATING TRANSPIRATION

HL	=	1.323 exp[17.27TL/(237.3 + TL)]/(TL + 273.16); absolute humidity of leaf
HA	=	1.323 exp[17.27DPTC/(237.3 + DPTC)]/(273.16 + DPTC); absolute humidity of atmosphere
RCW	=	RL + RA; total canopy resistance (s/m)
RA	=	ALOG$(2.0/z_0)^2$/0.16*SA; canopy resistance to diffusion
SA	=	average daily windspeed (m/s); input
RL	=	1.0/RL'*(LAI); leaf stomatal resistance
RL' is obtained from an input table relating RL to WPOTCR		
WPOTCR	=	WPSEFF + WPCRMN - TRC*SRCR/LAI; crop water potential (m)
WPCRMN	=	crop water potential at zero transpiration and zero soil water potential (m); input
SRCR	=	specific resistance to water uptake (s)
WPSEFF	=	$\sum_{I=1}^{m}$ PPOT(I)*RF(I); effective soil water potential (m)
PPOT(I)	=	soil water matric potential in layer I (m)
RF(I)	=	2.0$[\frac{1}{RD}$ - DEPTH(I)/RD$^2]$*TCOM(I); where RF(I) < 0, RF(I) = 0, root distribution parameter
DEPTH(I)	=	depth of layer I; input
TCOM(I)	=	thickness layer I; input
RD	=	daily root depth (m); input

$$(WPOTCR - WPCRMN) - WPSEFF = TRC*\frac{SRCR}{LAI} \quad (6)$$

This equation relates an effective potential difference on the left side of the equation to the product of the current water flow term (TRC) and a normalized resistance to water uptake. This equation is used to find a new WPOTCR from the current transpiration and the current effective average soil water potential weighted by the root distribution. This latter parameter is determined by the following equation.

$$WPSEFF = \sum_{I=1}^{n} PPOT(I)*RF(I) \quad (7)$$

2.4 ROOT WATER UPTAKE

The root water uptake, RC, is now calculated by using the following equation:

$$RC(I) = [(WPOTCR - WPCRN) - PPOT(I)]*(LAI/SRCR)*RF(I) \quad (8)$$

This equation relates the water uptake from the layer I to a difference in potential which is divided by the specific resistance and weighted by the fraction of total roots in the layer. The difference in potential involves the effective crop potential minus the soil water potential of the layer. The root water uptake is related to the transpiration through the WPOTCR term as given by equation (6).

2.5 RAINFALL AND INFILTRATION

Increases in soil water are determined by the amount of the rainfall that infiltrates the soil. This infiltration is determined partly by the intensity of the rain and partly by the water amount of the near surface and surface layers.

The intensity of the rain at a given time is regulated by the input data: time of beginning, time of ending, and rainfall total for the period. The program determines the midpoint of the period, distributes the rain linearly from zero at the beginning up to a maximum at the midpoint, and then distributes the rain linearly to zero at the end of the period.

The infiltration is determined by the following equations:

$$DETAIN = INTGRL(0.0, Rain - INFILT) \quad (9)$$

$$INCAP = [0.0 - HPOT(1)]*0.5*[SATCON + COND(1)]/DIST(1) \quad (10)$$

where

INTGRL = CMSPIII integration function

INCAP = maximum rate for infiltration (m/s)

HPOT(1) = water potential of surface layer (m)

COND(1) = hydraulic conductivity of surface layer (m/s)

SATCON = saturated conductivity (m/s)

DIST(1) = distance from surface to midpoint of surface layer (m)

DETAIN = amount of rainfall at surface that has not infiltrated the soil

INFILT = amount of rainfall that has infiltrated the soil

The net result of the equations and subsequent logic is that at a given time the infiltration is limited to DETAIN but all the rainfall eventually infiltrates the soil. If the rate is greater than INCAP, the infiltration is spread over a longer time period.

2.6 SOIL WATER PROFILE CHANGE

The total amount of water in the profile or a layer during each time interval is increased by infiltration, and it is decreased by evaporation at the surface, root uptake below the surface, and drainage at the lower boundary. The final step in the time interval is the determination of the net flux in each layer by the following equations (- = upward movement; + = downward movement):

$$FLUX(I) = [HPOT(I-1) - HPOT(I)]*AVCOND(I)/DIST(I) \quad (11)$$

$$FLUX(NLL) = COND(NL) \quad (12)$$

$$FLUX(1) = INFILT - EVS \quad (13)$$

$$NFLUX(I) = FLUX(I) - FLUX(I + 1) + RC(I) \quad (14)$$

where

FLUX(I) = flux across the top boundary of layer I (m/s)

FLUX(I + 1) = flux across the bottom of layer I (m/s)

HPOT(I) = total soil water potential (head) of layer I (m)

AVCOND(I) = average hydraulic conductivity at boundary I (m/s)

DIST(I) = distance between midpoint layer (I - 1) and layer I (m)

COND(NL) = hydraulic conductivity of last layer (m/s)

FLUX(1) = flux at upper boundary

INFILT = infiltration (m/s)

EVS = evaporation (m/s)

NFLUX(I) = net flux in layer I (m/s)

RC(I) = water uptake from layer I (m/s)

These equations show that the surface flux in a given time interval is the infiltration minus the evaporation. The flux at the lower boundary (drainage), as determined by the program algorithm, is equal to the conductivity for the layer and is always downward. The net flux in a layer is equal to the differences in the boundary fluxes minus the water uptake [-RC(I) = water loss]. To get the new soil water profile, the net flux in each layer I is multiplied by the time interval (seconds) and added to the contents of layer I at the beginning of the interval.

2.7 WATER BALANCE COMPUTATIONS

As a check on the many calculations and operations in the model, a net balance value between the initial water amount in the profile, the resulting infiltration, the evapotranspiration, the drainage, and the final water amount is obtained using the following relation:

$$\text{BALANS} = \text{CUMWTR} - (\text{IWATER} + \text{CUMINF} - \text{CUMETR} - \text{CUMDRN}) \qquad (15)$$

where

IWATER = the initial amount of water in the profile (m)

CUMWTR = new water amount in the profile after a given period of time (m)

CUMINF = total amount of infiltration for a given time period (m)

CUMETR = total amount of evapotranspiration for a given time interval (m)

CUMDRN = total amount of drainage in a given time period (m)

In order to appreciate the significance of the BALANS term, it is necessary to analyze the term CUMWTR. This latter term is the water amount in the profile at the beginning of the calculation plus the summation of the fluxes in the layers over the time period. This net flux includes root uptake [-RC(I)] from each layer plus infiltration and evaporation at the upper boundary and drainage at the lower boundary. Relating this definition of CUMWTR to the terms in the BALANS equation above indicates that the BALANS term essentially compares the root uptake in the profile over a time interval (CUMRC) to the transpiration over the same time interval (CUMTR). Also included in the BALANS term are computational uncertainties resulting from the initial computations and the ensuing integrations. If BALANS is a positive number, CUMTR is generally larger than CUMRC; if negative, CUMTR should be smaller than CUMRC. In order to analyze the BALANS values, SUMRC and CUMRC were later added to the program code, and CUMRC was printed along with the other output. These parameters are similar to the other SUM and CUM parameters.

3. VALIDATION AND SENSITIVITY ANALYSES

WATBAL1 is a new, comprehensive model. The model should be tested extensively with field data so it can be used objectively, and the results can be interpreted with a known degree of confidence. However, if the needed field data are not available, which is the case here, a preliminary evaluation can be performed using simulated data. The use of simulated data can provide information on how well the model represents the generally anticipated characteristics of the domain modeled.

If the simulated data are changed in a systematic manner, the variation in the output when compared to the variation in the input will also provide insight into the sensitivity of the output to uncertainties in the input data. These sensitivity analyses can also indicate the accuracy and precision needed in the input data to obtain the desired accuracy and precision in the output. The data simulated represents the atmospheric and soil properties discussed below.

3.1 ENVIRONMENTAL MODEL

In order to perform the validation and sensitivity analyses, a standard data test set is needed that represents typical conditions. In this regard the atmospheric and plant data for the standard data set are similar to the values used by Dr. Van Bavel. The exception is that precipitation was not included in the standard set. The values are listed in tables 3 and 4.

The soil characteristics are, however, different from those considered by Dr. Van Bavel. Basically, the properties of the Keith silt-loam profile near Colby, Kansas, were modeled. The layers were separated into two groups with different hydrologic properties in each group. The data for the hydrologic variable, moisture retention, are derived from three models: (1) regression (ref. 7), (2) Rogowski's (ref. 8), and (3) Ghosh's model (ref. 9). The basic input data for these models were obtained from previous soil surveys (ref. 10) or later in-situ measurements. The hydraulic conductivity data were then

TABLE 3.- STANDARD DATA SET

Weather input data												
JNM INPUT	DL	DGR	TMAX	TMIN	DMAX	DMIN	SA	BEGIN	END	RFT	LAI	RD
121.	14.4	20.0	25.0	10.0	10.0	8.0	3.0	0.0	0.0	0.0	3.0	0.5
122.	14.4	20.0	25.0	10.0	10.0	8.0	3.0	0.0	0.0	0.0	3.1	0.5
123.	14.5	20.0	25.0	10.0	10.0	8.0	3.0	0.0	0.0	0.0	3.2	0.6
124.	14.5	20.0	25.0	10.0	10.0	8.0	3.0	0.0	0.0	0.0	3.3	0.6
125.	14.5	20.0	25.0	10.0	10.0	8.0	3.0	0.0	0.0	0.0	3.4	0.7
126.	14.5	20.0	25.0	10.0	10.0	8.0	3.0	0.0	0.0	0.0	3.4	0.7
127.	14.5	20.0	25.0	10.0	10.0	8.0	3.0	0.0	0.0	0.0	3.5	0.7
128.	14.6	20.0	25.0	10.0	10.0	8.0	3.0	0.0	0.0	0.0	3.6	0.8
129.	14.6	20.0	25.0	10.0	10.0	8.0	3.0	0.0	0.0	0.0	3.7	0.8
130.	14.6	20.0	25.0	10.0	10.0	8.0	3.0	0.0	0.0	0.0	3.8	0.9

where

JNM = day

DL = day length (hours)

DGR = daily global radiation (mJ/m^2)

TMAX = maximum centigrade temperature

TMIN = minimum centigrade temperature

DMAX = maximum dewpoint centigrade temperature

DMIN = minimum dewpoint centigrade temperature

SA = mean daily windspeed (m/sec)

BEGIN = beginning of rainfall (hour)

END = end of rainfall (hour)

RFT = amount of rainfall (m)

LAI = leaf area index

RD = roofing depth (m)

TABLE 4.- PLANT AND PHYSICAL INPUT DATA

(a) Parameters

Sigma	=	5.67×10^{-8}
SATCON	=	0.30×10^{-6}
SRCR	=	1.00×10^{9}
WPCRMN	=	-5.0
WPOTCR (initial)	=	-5.0
FUNCTION RLVSWP	=	(0.0, 0.2), (50.0, .02), (150.0, 0.0002), (500.0, .0002), (20000.0, 0.000002)

(b) Layer thickness and depth at midpoint

Layer no.	Thickness (m)	Depth (m)
1.	0.0254	0.0127
2.	0.0254	0.0381
3.	0.0254	0.0635
4.	0.0254	0.0889
5.	0.0254	0.1143
6.	0.0508	0.1524
7.	0.0508	0.2032
8.	0.1524	0.3048
9.	0.1524	0.4572
10.	0.1524	0.6096
11.	0.1524	0.7620
12.	0.1524	0.9144
13.	0.1524	1.0668
14.	0.1524	1.2192
15.	0.1524	1.3716
16.	0.1524	1.5240
17.	0.1524	1.6764
18.	0.1524	1.8288

TABLE 5.- REGRESSION MODEL

```
****      VOLUMETRIC WATER CONTENT VS. PRESSURE POTENTIAL
FUNCTION TVSP1 =    ( 0.000, -0.7000E+06), ...
                    ( 0.010, -0.4000E+06), ...
                    ( 0.030, -0.7000E+05), ...
                    ( 0.050, -0.1650E+05), ...
                    ( 0.070, -0.9500E+04), ...
                    ( 0.090, -0.5700E+04), ...
                    ( 0.110,   -0.3400E+04), ...
                    ( 0.130,   -0.1950E+04), ...
                    ( 0.150,   -0.1150E+04), ...
                    ( 0.170,     -0.6400E+03), ...
                    ( 0.190,     -0.3800E+03), ...
                    ( 0.210,     -0.2250E+03), ...
                    ( 0.230,       -0.1300E+03), ...
                    ( 0.250,       -0.7500E+02), ...
                    ( 0.270,       -0.430E+02), ...
                    ( 0.290,       -0.2500E+02), ...
                    ( 0.310,       -0.1500E+02), ...
                    ( 0.330,         -0.7700E+01), ...
                    ( 0.350,         -0.5000E+01), ...
                    ( 0.370,         -0.2600E+01), ...
                    ( 0.390,         -0.1200E+01), ...
                    ( 0.410,         -0.3000E+00), ...
                    ( 0.430,         -0.1000E-01), ...
                    ( 1.000,          0.00)
****      VOLUMETRIC WATER CONTENT VS. HYDRAULIC CONDUCTIVITY IN M/S
FUNCTION TVSC1 =    ( 0.000, 0.0000000     ), ...
                    ( 0.020, 0.1556000E-17), ...
                    ( 0.040, 0.5278000E-17), ...
                    ( 0.060, 0.1861000E-16), ...
                    ( 0.080, 0.6389000E-16), ...
                    ( 0.100, 0.2278000E-15), ...
                    ( 0.120, 0.8333000E-15), ...
                    ( 0.140, 0.2917000E-14), ...
                    ( 0.160, 0.1000000E-13), ...
                    ( 0.180, 0.3611000E-13), ...
                    ( 0.200, 0.1250000E-12), ...
                    ( 0.220, 0.4444[illegible]E-12), ...
                    ( 0.240, 0.1500[illegible]E-11), ...
                    ( 0.260, 0.4861[illegible]E-11), ...
                    ( 0.280, 0.1667[illegible]E-10), ...
                    ( 0.300, 0.5278000E-10), ...
                    ( 0.320, 0.1611000E-09), ...
                    ( 0.340, 0.5278000E-09), ...
                    ( 0.360, 0.1722000E-08), ...
                    ( 0.380, 0.5556000E-08), ...
                    ( 0.400, 0.1944000E-07), ...
                    ( 0.420, 0.1111000E-07), ...
                    ( 1.000, 0.1111000E-07)
****      VOLUMETRIC WATER CONTENT VS. PRESSURE POTENTIAL
FUNCTION TVSP2 =    ( 0.000, -0.5000E+06), ...
                    ( 0.010, -0.1000E+06), ...
                    ( 0.030, -0.5000E+05), ...
                    ( 0.050, -0.2450E+04), ...
                    ( 0.070, -0.1550E+04), ...
                    ( 0.090, -0.9800E+03), ...
                    ( 0.110, -0.6400E+03), ...
                    ( 0.130, -0.4100E+03), ...
                    ( 0.150, -0.2600E+03), ...
                    ( 0.170, -0.1700E+03), ...
                    ( 0.190, -0.1070E+03), ...
                    ( 0.210, -0.6800E+02), ...
                    ( 0.230, -0.4200E+02), ...
                    ( 0.250, -0.2600E+02), ...
                    ( 0.270, -0.1600E+02), ...
                    ( 0.290, -0.9600E+01), ...
                    ( 0.310, -0.5600E+01), ...
                    ( 0.330, -0.3300E+01), ...
                    ( 0.350,        -0.1900E+01), ...
                    ( 0.370,        -0.9600), ...
                    ( 0.390,        -0.4200), ...
                    ( 0.410,        -0.1300), ...
                    ( 0.430,        -0.1000E-01), ...
                    ( 1.000,         0.00)
****      VOLUMETRIC WATER CONTENT VS. HYDRAULIC CONDUCTIVITY
FUNCTION TVSC2 =    ( 0.000, 0.0000000     ), ...
                    ( 0.020, 0.1556000E-16), ...
                    ( 0.040, 0.4583000E-16), ...
                    ( 0.060, 0.1306000E-15), ...
                    ( 0.080, 0.3750000E-15), ...
                    ( 0.100, 0.1111000E-14), ...
                    ( 0.120, 0.3194000E-14), ...
                    ( 0.140, 0.9306000E-14), ...
                    ( 0.160, 0.2778000E-13), ...
                    ( 0.180, 0.8333000E-13), ...
                    ( 0.200, 0.2333000E-12), ...
                    ( 0.220, 0.7083000E-12), ...
                    ( 0.240, 0.2000000E-11), ...
                    ( 0.260, 0.5555000E-11), ...
                    ( 0.280, 0.1722000E-10), ...
                    ( 0.300, 0.4583000E-10), ...
                    ( 0.320, 0.1333000E-09), ...
                    ( 0.340, 0.3889000E-09), ...
                    ( 0.360, 0.1111000E-08), ...
                    ( 0.380, 0.3472000E-08), ...
                    ( 0.400, 0.1139000E-07), ...
                    ( 0.420, 0.5139000E-07), ...
                    ( 1.000, 0.5139000E-07)
```

TABLE 6.- GHOSH MODEL

```
****      VOLUMETRIC WATER CONTENT VS. PRESSURE POTENTIAL                VHG00440
FUNCTION TVSP1 =   ( 0.003, -0.7000E+07), ...                            VHG00450
                   ( 0.010, -0.4000E+07), ...                            VHG00460
                   ( 0.030, -0.1000E+07), ...                            VHG00470
                   ( 0.050, -0.7260E+06), ...                            VHG00480
                   ( 0.070, -0.8870E+05), ...                            VHG00490
                   ( 0.090, -0.1880E+05), ...                            VHG00500
                   ( 0.110,  -0.5270E+04), ...                           VHG00510
                   ( 0.130,  -0.1550E+04), ...                           VHG00520
                   ( 0.150,  -0.7580E+03), ...                           VHG00530
                   ( 0.170,   -0.3600E+03), ...                          VHG00540
                   ( 0.190,   -0.1740E+03), ...                          VHG00550
                   ( 0.210,   -0.9000E+02), ...                          VHG00560
                   ( 0.230,     -0.5300E+02), ...                        VHG00570
                   ( 0.250,     -0.3200E+02), ...                        VHG00580
                   ( 0.270,     -0.1950E+02), ...                        VHG00590
                   ( 0.290,     -0.1250E+02), ...                        VHG00600
                   ( 0.310,     -0.7400E+01), ...                        VHG00610
                   ( 0.330,       -0.5500E+01), ...                      VHG00620
                   ( 0.350,       -0.3800E+01), ...                      VHG00630
                   ( 0.370,       -0.2700E+01), ...                      VHG00640
                   ( 0.390,       -0.1420E+01), ...                      VHG00650
                   ( 0.410,       -0.1400E+01), ...                      VHG00660
                   ( 0.430,       -0.1050E+01), ...                      VHG00670
                   ( 0.450,       -0.7400), ...                          VHG00680
                   ( 0.470,       -0.500), ...                           VHG00690
                   ( 0.490,       -0.450), ...                           VHG00700
                   ( 0.500,         0.1000E-01), ...                     VHG00710
                   ( 1.000,         0.00)                                VHG00720
****      VOLUMETRIC WATER CONTENT VS. HYDRAULIC CONDUCTIVITY IN M/S     VHG00730
FUNCTION TVSC1 =   ( 0.000, 0.0000000     ), ...                         VHG00740
                   ( 0.020, 0.1530000E-19), ...                          VHG00750
                   ( 0.040, 0.1110000E-17), ...                          VHG00760
                   ( 0.050, 0.7530000E-17), ...                          VHG00770
                   ( 0.080, 0.5140000E-16), ...                          VHG00780
                   ( 0.100, 0.3470000E-15), ...                          VHG00790
                   ( 0.120, 0.2660000E-14), ...                          VHG00800
                   ( 0.140, 0.1790000E-13), ...                          VHG00810
                   ( 0.160, 0.1390000E-12), ...                          VHG00820
                   ( 0.180, 0.8310000E-12), ...                          VHG00830
                   ( 0.200, 0.4720000E-11), ...                          VHG00840
                   ( 0.220, 0.1960000E-10), ...                          VHG00850
                   ( 0.240, 0.7780000E-10), ...                          VHG00860
                   ( 0.260, 0.2560000E-09), ...                          VHG00870
                   ( 0.280, 0.8510000E-09), ...                          VHG00880
                   ( 0.300, 0.2290000E-08), ...                          VHG00890
                   ( 0.320, 0.6110000E-08), ...                          VHG00900
                   ( 0.340, 0.1560000E-07), ...                          VHG00910
                   ( 0.360, 0.3800000E-07), ...                          VHG00920
                   ( 0.380, 0.8810000E-07), ...                          VHG00930
                   ( 0.400, 0.1800000E-06), ...                          VHG00940
                   ( 0.420, 0.4030000E-06), ...                          VHG00950
                   ( 0.440, 0.8300000E-06), ...                          VHG00960
                   ( 0.460, 0.1610000E-05), ...                          VHG00970
                   ( 0.480, 0.3060000E-05), ...                          VHG00980
                   ( 0.500, 0.5440000E-05), ...                          VHG00990
                   ( 1.000, 0.5440000E-05)                               VHG01000
****      VOLUMETRIC WATER CONTENT VS. PRESSURE POTENTIAL                VHG01010
FUNCTION TVSP2 =   ( 0.000, -0.5000E+07), ...                            VHG01020
                   ( 0.010, -0.1000E+07), ...                            VHG01030
                   ( 0.030, -0.5000E+06), ...                            VHG01040
                   ( 0.050, -0.1350E+06), ...                            VHG01050
                   ( 0.070, -0.1740E+05), ...                            VHG01060
                   ( 0.090, -0.3770E+04), ...                            VHG01070
                   ( 0.110, -0.1110E+04), ...                            VHG01080
                   ( 0.130, -0.4150E+03), ...                            VHG01090
                   ( 0.150, -0.1650E+03), ...                            VHG01100
                   ( 0.170, -0.4200E+02), ...                            VHG01110
                   ( 0.190, -0.4100E+02), ...                            VHG01120
                   ( 0.210, -0.2200E+02), ...                            VHG01130
                   ( 0.230, -0.1360E+02), ...                            VHG01140
                   ( 0.250, -0.7700E+01), ...                            VHG01150
                   ( 0.270, -0.4400E+01), ...                            VHG01160
                   ( 0.290, -0.3050E+01), ...                            VHG01170
                   ( 0.310, -0.2060E+01), ...                            VHG01180
                   ( 0.330, -0.1400E+01), ...                            VHG01190
                   ( 0.350,       -0.9700), ...                          VHG01200
                   ( 0.370,       -0.7000), ...                          VHG01210
                   ( 0.390,       -0.50000), ...                         VHG01220
                   ( 0.410,       -0.3550), ...                          VHG01230
                   ( 0.430,       -0.2750), ...                          VHG01240
                   ( 0.450,       -0.2100), ...                          VHG01250
                   ( 0.470,       -0.1500), ...                          VHG01260
                   ( 0.490,       -0.1240), ...                          VHG01270
                   ( 0.510,         -0.4900E-01), ...                    VHG01280
                   (0.520,          -0.1000E-01), ...                    VHG01290
                   ( 1.000,         0.001)                               VHG01300
****      VOLUMETRIC WATER CONTENT VS. HYDRAULIC CONDUCTIVITY            VHG01310
FUNCTION TVSC2 =   ( 0.000, 0.0000000     ), ...                         VHG01320
                   ( 0.020, 0.5430000E-18), ...                          VHG01330
                   ( 0.040, 0.3050000E-17), ...                          VHG01340
                   ( 0.060, 0.1670000E-16), ...                          VHG01350
                   ( 0.080, 0.8890000E-16), ...                          VHG01360
                   ( 0.100, 0.4440000E-15), ...                          VHG01370
                   ( 0.120, 0.2500000E-14), ...                          VHG01380
                   ( 0.140, [illegible]E-13), ...                        VHG01390
                   ( 0.160, 0.7750000E-13), ...                          VHG01400
                   ( 0.180, 0.4170000E-12), ...                          VHG01410
                   ( 0.200, 0.2110000E-11), ...                          VHG01420
                   ( 0.220, [illegible]E-11), ...                        VHG01430
                   ( 0.240, 0.3330000E-10), ...                          VHG01440
                   ( 0.260, 0.1170000E-09), ...                          VHG01450
                   ( 0.280, 0.3670000E-09), ...                          VHG01460
                   ( 0.300, 0.9860000E-09), ...                          VHG01470
                   ( 0.320, 0.2560000E-08), ...                          VHG01480
                   ( 0.340, 0.6530000E-08), ...                          VHG01490
                   ( 0.360, 0.1530000E-07), ...                          VHG01500
                   ( 0.380, 0.3470000E-07), ...                          VHG01510
                   ( 0.400, 0.7660000E-07), ...                          VHG01520
                   ( 0.420, 0.1610000E-06), ...                          VHG01530
                   ( 0.440, 0.3140000E-06), ...                          VHG01540
                   ( 0.460, 0.6110000E-06), ...                          VHG01550
                   ( 0.480, 0.1140000E-05), ...                          VHG01560
                   ( 0.500, 0.2220000E-05), ...                          VHG01570
                   ( 0.520, 0.4000000E-05), ...                          VHG01580
```

TABLE 7.- ROGOWSKI MODEL

```
****      VOLUMETRIC WATER CONTENT VS. PRESSURE POTENTIAL                  VRR00410
FUNCTION TVSP1 =    ( 0.000, -0.7000E+06), ...                             VRR00420
                    ( 0.010, -0.4000E+06), ...                             VRR00430
                    ( 0.030, -0.1000E+06), ...                             VRR00440
                    ( 0.050, -0.3340E+05), ...                             VRR00450
                    ( 0.070, -0.1570E+05), ...                             VRR00460
                    ( 0.090, -0.7430E+04), ...                             VRR00470
                    ( 0.110,  -0.3510E+04), ...                            VRR00480
                    ( 0.130,  -0.1650E+04), ...                            VRR00490
                    ( 0.150,  -0.7810E+03), ...                            VRR00500
                    ( 0.170,   -0.3800E+03), ...                           VRR00510
                    ( 0.190,   -0.1800E+03), ...                           VRR00520
                    ( 0.210,   -0.8600E+02), ...                           VRR00530
                    ( 0.230,    -0.4150E+02), ...                          VRR00540
                    ( 0.250,    -0.2000E+02), ...                          VRR00550
                    ( 0.270,    -0.9600E+01), ...                          VRR00560
                    ( 0.290,    -0.4500E+01), ...                          VRR00570
                    ( 0.310,    -0.2200E+01), ...                          VRR00580
                    ( 0.330,     -0.1150E+01), ...                         VRR00590
                    ( 0.350,     -0.6500E+00), ...                         VRR00600
                    ( 0.370,     -0.4600E+00), ...                         VRR00610
                    ( 0.390,     -0.3600E+00), ...                         VRR00620
                    ( 0.410,     -0.3000E+00), ...                         VRR00630
                    ( 0.430,     -0.2500E+00), ...                         VRR00640
                    ( 0.450,     -0.2300), ...                             VRR00650
                    ( 0.470,     -0.20), ...                               VRR00660
                    ( 0.490,     -0.12), ...                               VRR00670
                    ( 0.500,      0.1000E-01), ...                         VRR00680
                    ( 1.000,      0.00)                                    VRR00690
****      VOLUMETRIC WATER CONTENT VS. HYDRAULIC CONDUCTIVITY IN M/S       VRR00700
FUNCTION TVSC1 =    ( 0.000, 0.0000000     ), ...                          VRR00710
                    ( 0.020, 0.2444000E-18), ...                           VRR00720
                    ( 0.040, 0.1111000E-17), ...                           VRR00730
                    ( 0.060, 0.5139000E-17), ...                           VRR00740
                    ( 0.080, 0.2300000E-16), ...                           VRR00750
                    ( 0.100, 0.1043000E-15), ...                           VRR00760
                    ( 0.120, 0.5000000E-15), ...                           VRR00770
                    ( 0.140, 0.2361000E-14), ...                           VRR00780
                    ( 0.160, 0.1167000E-13), ...                           VRR00790
                    ( 0.180, 0.5556000E-13), ...                           VRR00800
                    ( 0.200, 0.2500000E-12), ...                           VRR00810
                    ( 0.220, 0.1250000E-11), ...                           VRR00820
                    ( 0.240, 0.5833000E-11), ...                           VRR00830
                    ( 0.260, 0.2861000E-10), ...                           VRR00840
                    ( 0.280, 0.1278000E-09), ...                           VRR00850
                    ( 0.300, 0.6111000E-09), ...                           VRR00860
                    ( 0.320, 0.3056000E-08), ...                           VRR00870
                    ( 0.340, 0.1250000E-07), ...                           VRR00880
                    ( 0.360, [illegible]E-07), ...                         VRR00890
                    ( 0.380, 0.1417000E-06), ...                           VRR00900
                    ( 0.400, 0.3611000E-06), ...                           VRR00910
                    ( 0.420, 0.7222000E-06), ...                           VRR00920
                    ( 0.440, 0.1300000E-05), ...                           VRR00930
                    ( 0.460, 0.2030000E-05), ...                           VRR00940
                    ( 0.480, 0.3750000E-05), ...                           VRR00950
                    ( 0.500, 0.5444000E-05), ...                           VRR00960
                    ( 1.000, 0.5444000E-05)                                VRR00970
****      VOLUMETRIC WATER CONTENT VS. PRESSURE POTENTIAL                  VRR00980
FUNCTION TVSP2 =    ( 0.000, -0.5300E+06), ...                             VRR00990
                    ( 0.010, -0.1000E+06), ...                             VRR01000
                    ( 0.030, -0.5300E+05), ...                             VRR01010
                    ( 0.050, -0.3440E+04), ...                             VRR01020
                    ( 0.070, -0.1800E+04), ...                             VRR01030
                    ( 0.090, -0.1010E+04), ...                             VRR01040
                    ( 0.110, -0.5600E+03), ...                             VRR01050
                    ( 0.130, -0.3000E+03), ...                             VRR01060
                    ( 0.150, -0.1550E+03), ...                             VRR01070
                    ( 0.170, -0.8800E+02), ...                             VRR01080
                    ( 0.190, -0.4400E+02), ...                             VRR01090
                    ( 0.210, -0.2600E+02), ...                             VRR01100
                    ( 0.230, -0.1450E+02), ...                             VRR01110
                    ( 0.250, -0.7000E+01), ...                             VRR01120
                    ( 0.270, -0.4100E+01), ...                             VRR01130
                    ( 0.290, -0.2400E+01), ...                             VRR01140
                    ( 0.310, -0.1400E+01), ...                             VRR01150
                    ( 0.330, -0.8800E+00), ...                             VRR01160
                    ( 0.350,       -0.5600), ...                           VRR01170
                    ( 0.370,       -0.4330), ...                           VRR01180
                    ( 0.390,       -0.3600), ...                           VRR01190
                    ( 0.410,       -0.3090), ...                           VRR01200
                    ( 0.430,       -0.2550), ...                           VRR01210
                    ( 0.450,       -0.2410), ...                           VRR01220
                    ( 0.470,       -0.2210), ...                           VRR01230
                    ( 0.490,       -0.1450), ...                           VRR01240
                    ( 0.510,        -0.9000E-01), ...                      VRR01250
                    (0.520,         -0.1999E-01), ...                      VRR01260
                    ( 1.000,        0.00)                                  VRR01270
****      VOLUMETRIC WATER CONTENT VS. HYDRAULIC CONDUCTIVITY              VRR01280
FUNCTION TVSC2 =    ( 0.000, 0.0000000     ), ...                          VRR01290
                    ( 0.020, 0.1444000E-16), ...                           VRR01300
                    ( 0.040, 0.5278000E-16), ...                           VRR01310
                    ( 0.060, 0.1944000E-15), ...                           VRR01320
                    ( 0.080, 0.7222000E-15), ...                           VRR01330
                    ( 0.100, 0.2667000E-14), ...                           VRR01340
                    ( 0.120, 0.9167000E-14), ...                           VRR01350
                    ( 0.140, 0.3750000E-13), ...                           VRR01360
                    ( 0.160, 0.1333000E-12), ...                           VRR01370
                    ( 0.180, 0.5417000E-12), ...                           VRR01380
                    ( 0.200, 0.2000000E-11), ...                           VRR01390
                    ( 0.220, 0.7083000E-11), ...                           VRR01400
                    ( 0.240, 0.2861000E-10), ...                           VRR01410
                    ( 0.260, 0.1056000E-09), ...                           VRR01420
                    ( 0.280, 0.3750000E-09), ...                           VRR01430
                    ( 0.300, 0.1389000E-08), ...                           VRR01440
                    ( 0.320, 0.4583000E-08), ...                           VRR01450
                    ( 0.340, 0.1444000E-07), ...                           VRR01460
                    ( 0.360, 0.4028000E-07), ...                           VRR01470
                    ( 0.380, 0.9306000E-07), ...                           VRR01480
                    ( 0.400, 0.1944000E-06), ...                           VRR01490
                    ( 0.420, 0.3611000E-06), ...                           VRR01500
                    ( 0.440, 0.6667000E-06), ...                           VRR01510
                    ( 0.460, 0.1043000E-05), ...                           VRR01520
                    ( 0.480, 0.1722000E-05), ...                           VRR01530
                    ( 0.500, 0.2722000E-05), ...                           VRR01540
                    ( 0.520, 0.4000000E-05), ...                           VRR01550
                    ( 1.000, 0.4000000E-05)                                VRR01560
      WRITE(6,1100)                                                        VRR01570
 1100 FORMAT(' TCOM  DEPTH   ITHETA')                                      VRR01580
```

obtained from Jackson's method using moisture retention data as input (ref. 11). The moisture retention and hydraulic conductivity values derived for the three models are presented in tables 5, 6, and 7.

Each simulation run was for a period of 10 days. Ten days were used mainly as a convenience since most of the runs in references 4 and 5 were for 10 days. In addition, a 10-day period is often the interval between soil moisture profile measurements. Simulation runs were made using the three models of the moisture retention and the standard atmospheric and plant data set described above. For each moisture retention model, simulation runs were then made using systematic variations from these standard conditions for a range of constant soil water values with depth (i.e., profiles). These constant profiles generally varied from 0.4 to 0.15 cm^3/cm^3 in 0.05 cm^3/cm^3 increments. A large range of variation for most of the variables was used in conjunction with the regression model; fewer were used for the Rogowski and Ghosh models. Both crop and fallow conditions were simulated.

The results of the simulations discussed above are presented below. The sensitivity characteristic for crops using the regression model will be presented and discussed first, followed by the Rogowski and Ghosh models. Then the responses of the model for fallow conditions are presented.

3.2 CROP SIMULATIONS

3.2.1 REGRESSION MODEL FOR WATER RETENTION

3.2.1.1 Daily E_v, and T, and ET for Standard Conditions

Figures 2, 3, and 4 present the simulated daily values of evaporation (E_v), Transpiration (T), and evapotranspiration (ET) over the 10-day period for wet, intermediate, and dry soils. These figures reproduce the observed three stages of drying, which are the constant rate stages (wet and dry) and the falling rate stage (intermediate). However, it can be seen that this three-stage drying is only present in the wet regime. In the other two regimes, only the falling rate and final constant rate stages are indicated. On the other hand, other simulat ons with lower solar radiation values (data not shown) extend the initial constant rate stage to lower values of the initial soil water profiles. The cumulative evapotranspiration for 10 days compared to initial soil water profiles are shown in figure 5.

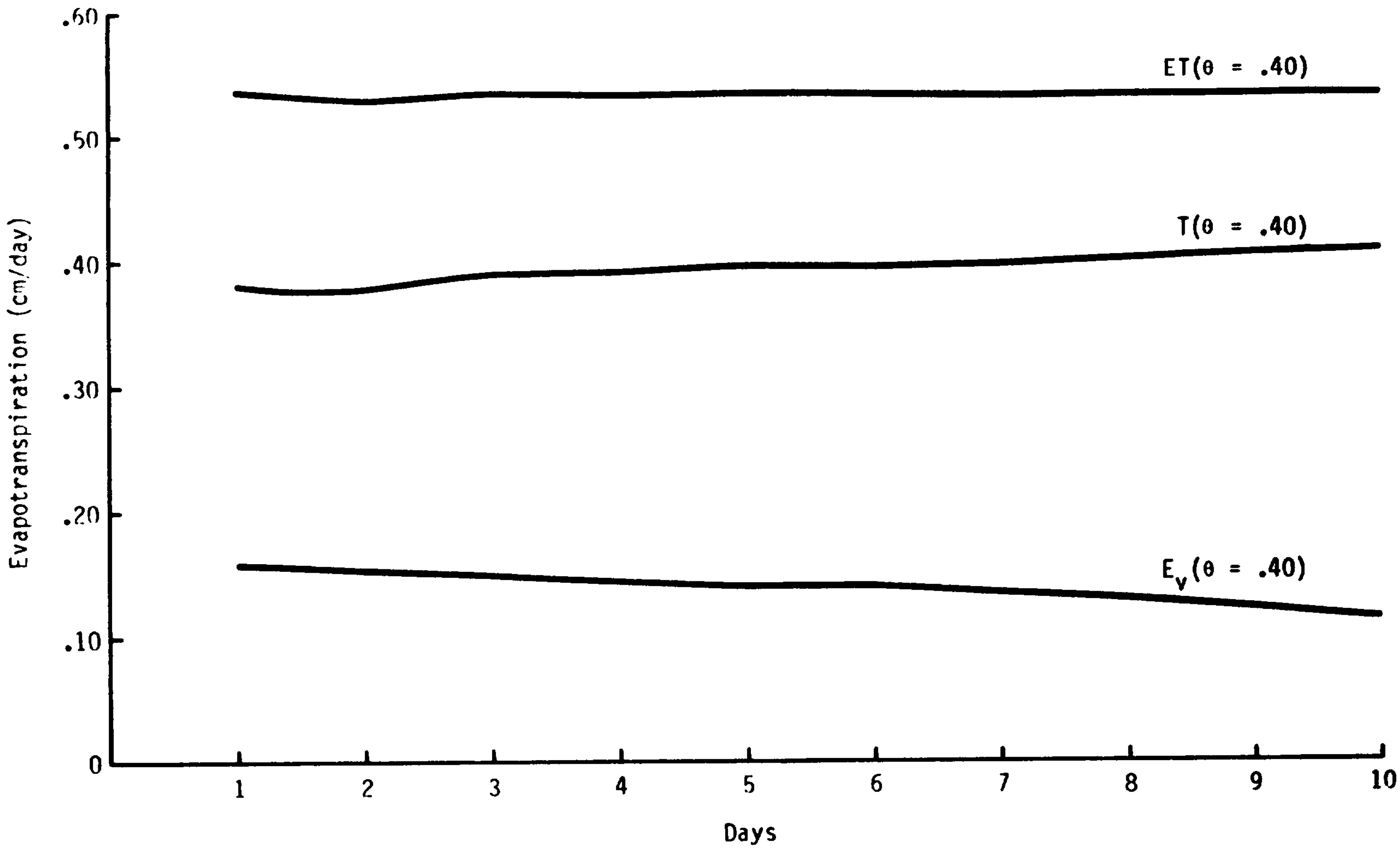

Figure 2.- Daily values of E_v, T, and ET for 10 days for wet soils.

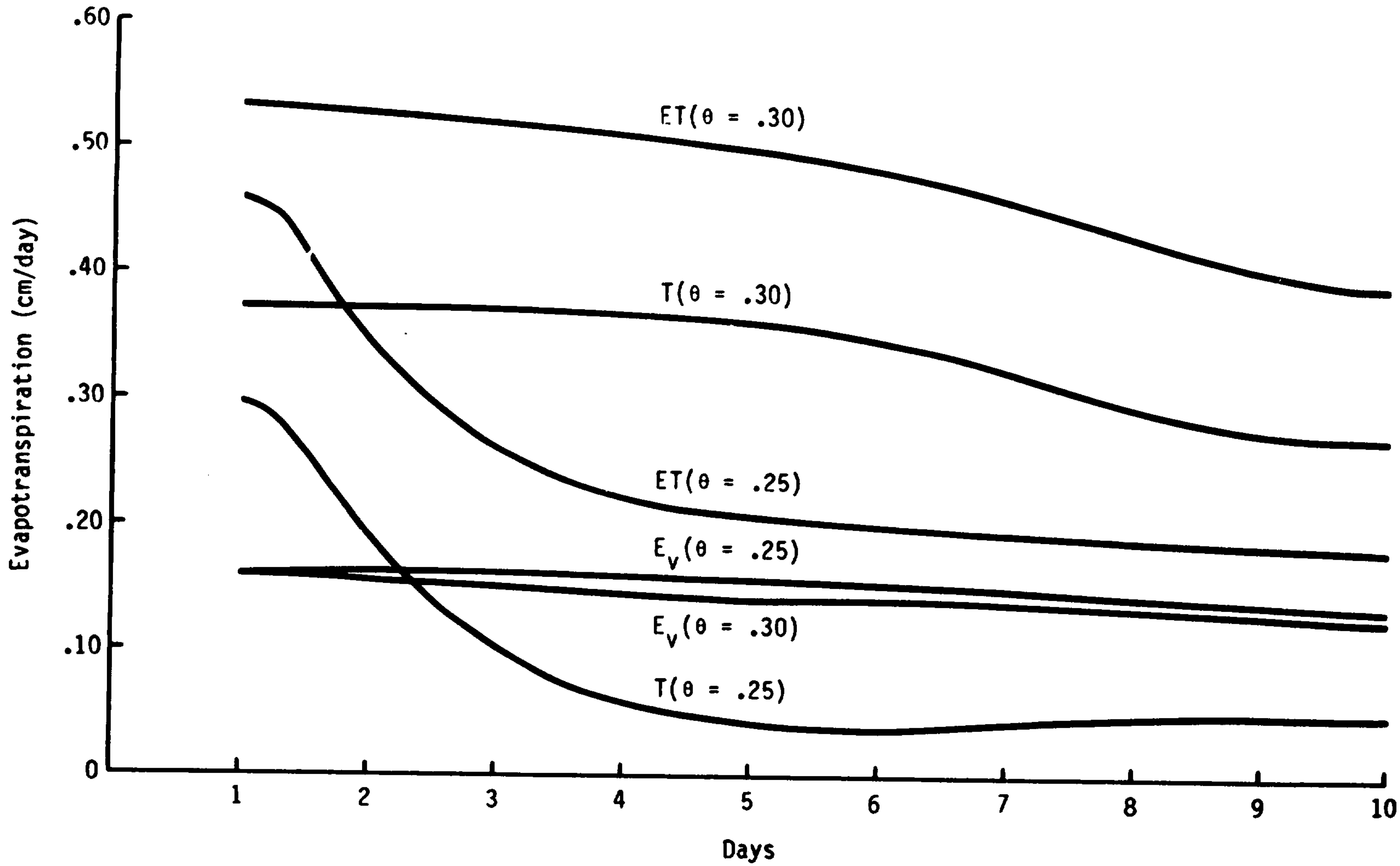

Figure 3.- Daily values of E_v, T, and ET for 10 days for intermediate soils.

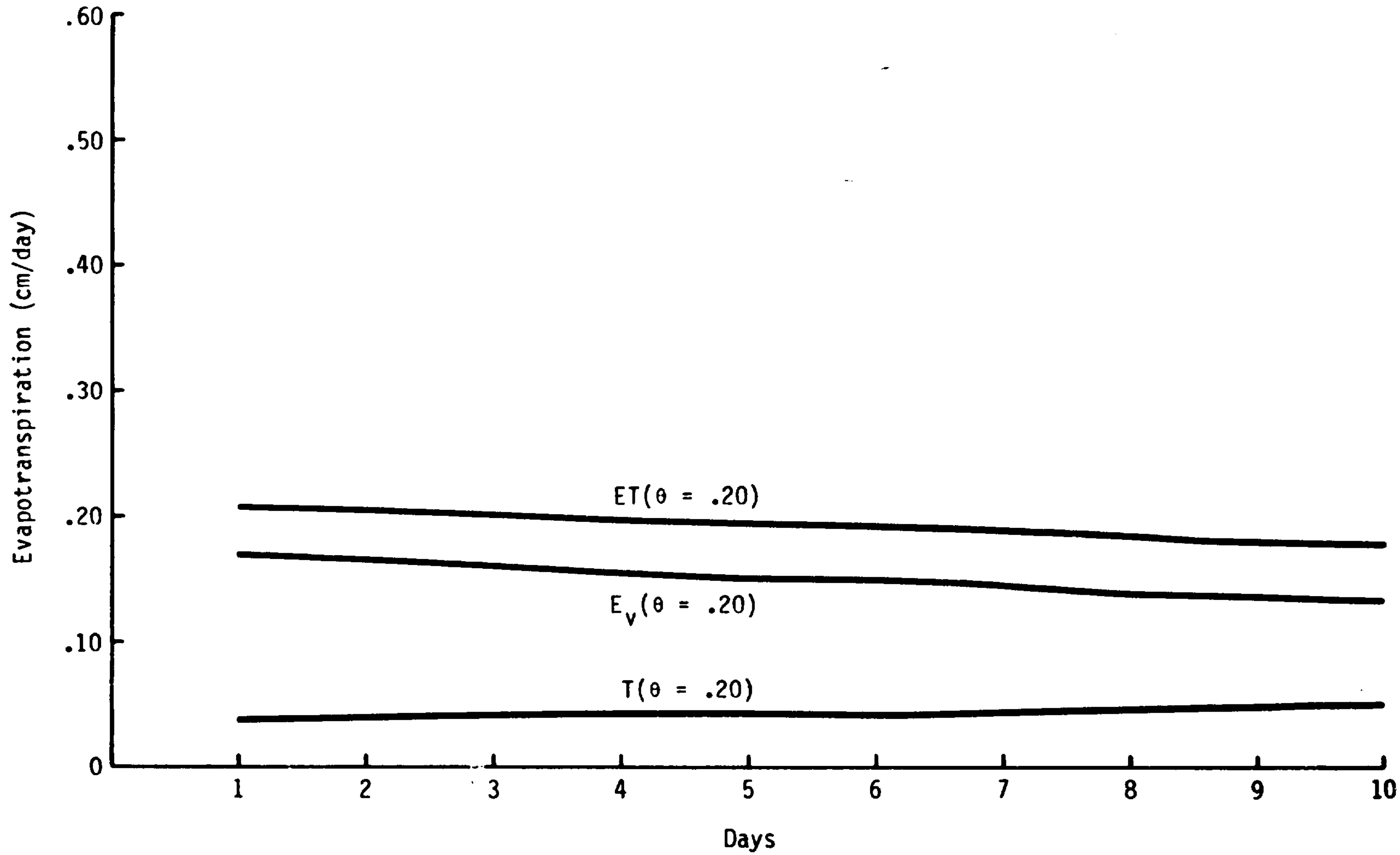

Figure 4.- Daily values of E_v, T, and ET for 10 days for dry soils.

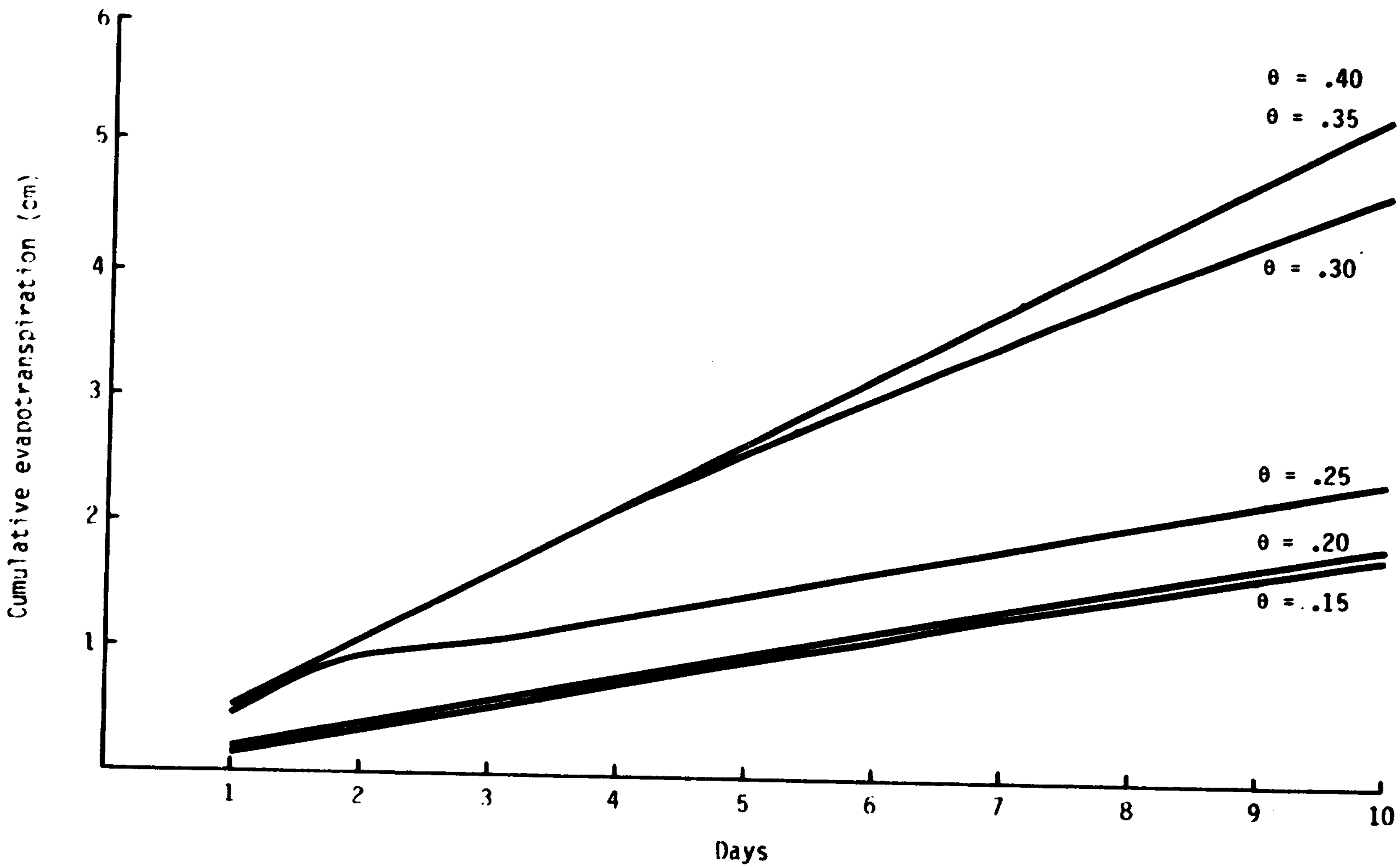

Figure 5.- The cumulative ET for 10 days versus initial soil water profiles.

The 10-day totals of ET, T, E_v, and water loss (IWATER - CUMWTR) for different initial constant soil water profiles are presented in table 8 and figure 6. Total water loss is higher than the ET values in the wet regime because of high drainage values. As the 10-day drainage decreases when θ becomes smaller, the water loss curve becomes nearly identical to the ET curve. It departs from the ET curve at still lower θ values, and it indicates less water loss than would be expected from the ET and drainage values. The amount of departure coincides with an increase in the BALANS value since the model only allows drainage out the bottom boundary.

An investigation of the cause of these high BALANS values has indicated that they are involved with the root uptake [RC(I)] of soil water at intermediate and low soil water values. The probable cause of this is discussed in a later section. The response of E_v, T, and ET to changes in the daily global radiation amount, DGR, is shown in table 3 and figure 7. These results indicate that the model provides a nearly linear response to solar radiation changes over the range studied for the wet and dry boundary regimes. In the intermediate zone, the response is nonlinear.

The curves indicate that for θ = .40, a 10 percent change in the solar radiation at DGR = 20 provides approximately a 7.5 percent change in the 10-day ET. For θ = .15, a 10 percent change in DGR gives approximately a 10 percent change in ET for 10 days. At a value of DGR = 10, the ET for 10-day response is approximately 9 percent for a 10 percent change in DGR at θ = .40. For θ = .15, the response is about 11 percent for a 10 percent change in DGR.

The evapotranspiration on day 10 compared to the profile amount and daily solar radiation value is illustrated in figure 8. These curves show a consistent modified step character.

The variation of ET for 10 days as the daily maximum temperature changes is presented in figure 9. The curves indicate that the response is nearly linear in the wet and dry regimes, but it is somewhat nonlinear in the intermediate regime. In general, the percentage response is less than the DGR response.

TABLE 8.- VAN BAVEL-CROP-REGRESSION STANDARD 10-DAY TEST RESULTS

Cumulative centimeters for 10 days							Centimeters for last day			
θ_v	ET	T	E_v	Drainage	Water loss*	BALANS	ET	T	E_v	Drainage
DGR = 30										
0.40	7.43	5.20	2.20	0.901	8.291	0.036	0.731	0.536	0.191	0.074
.35	7.14	4.91	2.21	0.064	7.141	.059	.666	.469	.194	.006
.30	5.23	2.93	2.31	0.004	5.106	.132	.321	.113	.210	4×10^{-4}
.25	3.39	.96	2.41	3×10^{-4}	3.228	.166	.285	.073	.212	3×10^{-5}
.20	3.02	.63	2.39	2×10^{-5}	2.610	.410	.278	.073	.205	2×10^{-6}
.15	2.83	.61	2.21	2×10^{-6}	1.586	1.23	.257	.069	.188	2×10^{-7}
DGR = 20										
0.40	5.33	3.94	1.39	0.906	6.213	0.026	0.532	0.410	0.121	0.076
.35	5.30	3.91	1.39	0.064	5.325	.039	.522	.401	.121	.006
.30	4.76	3.36	1.41	0.004	4.681	.080	.394	.271	.125	4×10^{-4}
.25	2.43	.92	1.50	3×10^{-4}	2.301	.129	.183	.050	.132	3×10^{-5}
.20	1.93	.44	1.50	2×10^{-5}	1.606	.328	.179	.050	.130	2×10^{-6}
.15	1.82	.42	1.40	2×10^{-6}	.778	1.04	.170	.048	.120	2×10^{-7}
DGR = 10										
0.40	3.35	2.72	0.64	0.913	4.239	0.021	0.337	0.281	0.056	0.079
.35	3.36	2.73	.64	.064	3.402	.019	.337	.281	.055	.006
.30	3.28	2.66	.64	.004	3.242	.039	.320	.266	.055	4×10^{-4}
.25	1.80	1.13	.66	3×10^{-4}	1.678	.121	.106	.047	.059	3×10^{-5}
.20	.95	.28	.67	2×10^{-5}	.616	.272	.089	.031	.059	2×10^{-6}
.15	.90	.27	.64	2×10^{-6}	.017	.887	.085	.030	.055	2×10^{-7}
DGR = 1										
0.40	1.64	1.61	0.031	0.920	3.255	0.010	0.166	0.163	0.003	0.082
.35	1.64	1.61	.031	.064	1.694	.011	.166	.163	.003	.006
.30	1.64	1.61	.031	.004	1.617	.027	.165	.163	.003	4×10^{-4}
.25	1.37	1.34	.030	3×10^{-4}	1.280	.086	.122	.119	.0025	3×10^{-5}
.20	.18	.16	.025	2×10^{-5}	-.05	.233	.020	.017	.0022	2×10^{-6}
.15	.18	.15	.024	2×10^{-6}	-.611	.789	.019	.017	.0021	2×10^{-7}

*IWATER - CUMWTR

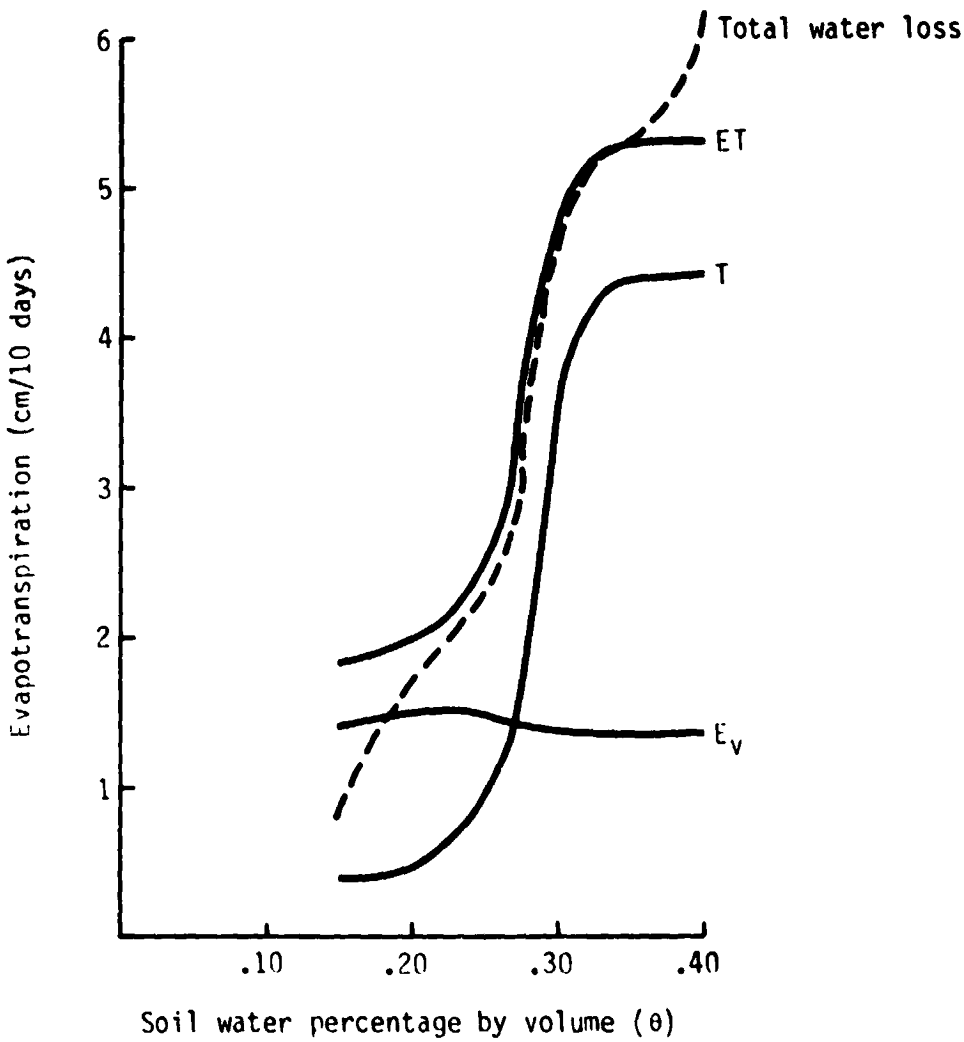

Figure 6.- The 10-day totals of ET, T, E_v, and water loss versus the initial soil water profile.

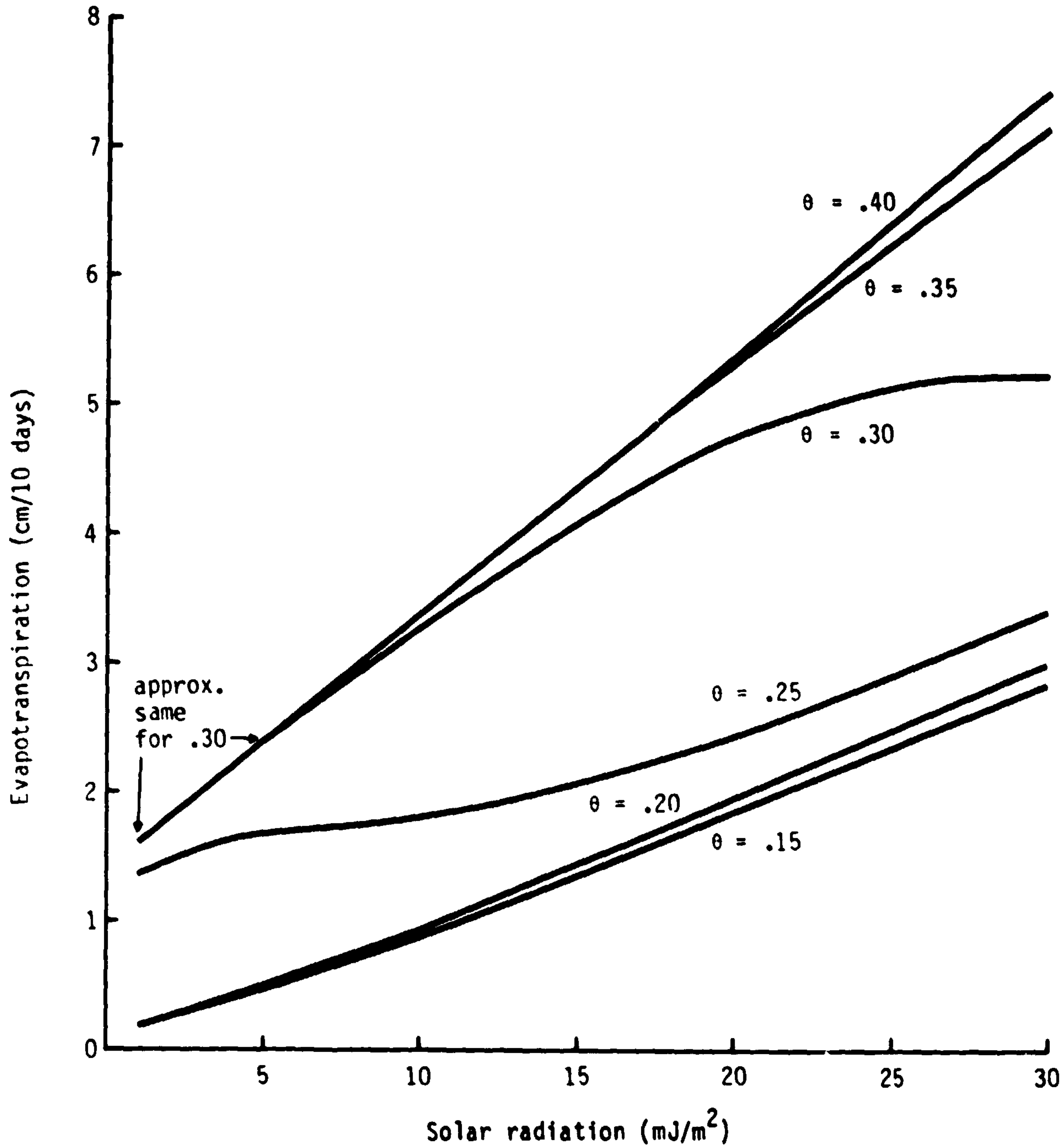

Figure 7.- The response of ET for 10 days versus the daily global radiation amount (DGR) and initial soil water profile.

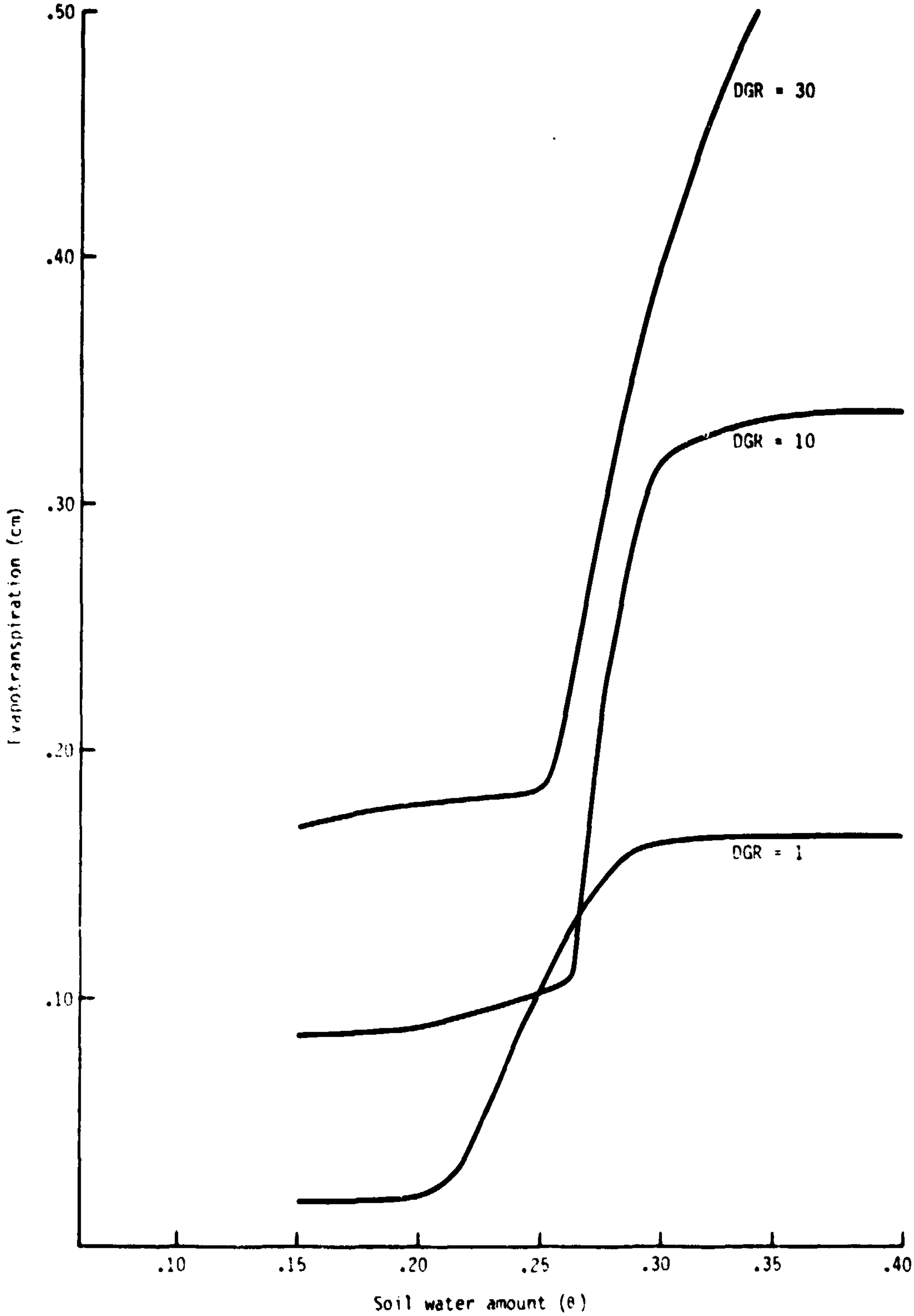

Figure 8.- The ET on the 10th day versus the profile amount and the daily solar radiation value.

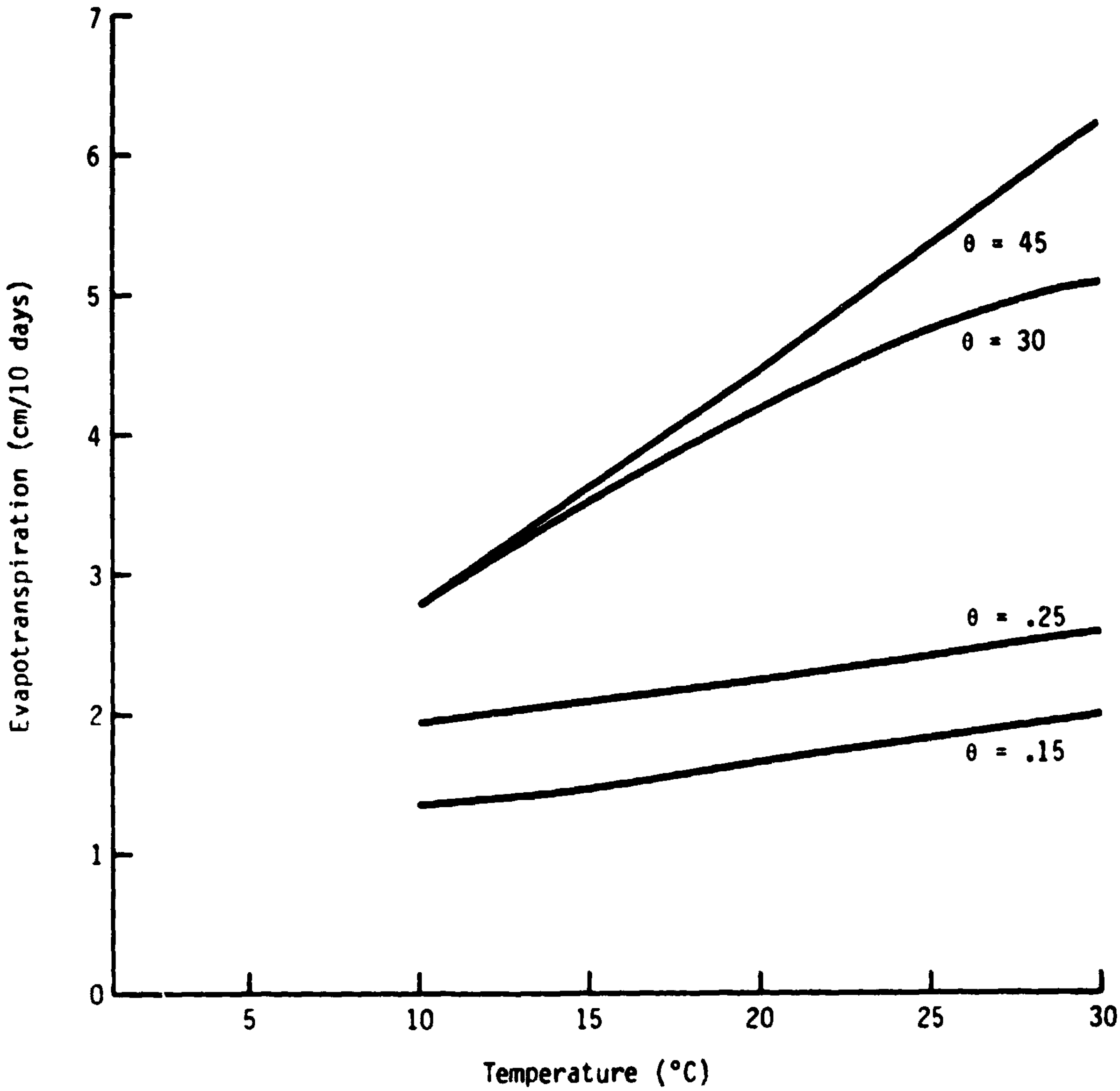

Figure 9.- The variation of ET for 10 days versus the maximum temperature and initial soil water profile.

The response for changes in minimum temperature is similar. The effects of changing the dewpoint are presented in figure 10. This simulation was accomplished by lowering the minimum dewpoint. Changes in dewpoint result in considerably less response of ET for 10 days than changes in the temperature.

The ET for 10-day response to daily mean windspeed changes is shown in figure 11. These curves indicate a nonlinear response for wet conditions and very little response for dry conditions. The decrease of ET for 10 days with increase of windspeed when $\theta = .15$ is unexpected and may reflect the RC inconsistency. Over most of the range of windspeeds, a 10 percent change in wind speed indicates a 4 to 5 percent change in ET for 10 days for the wet boundary. Dryer soil conditions provide less of a change.

The simulation response obtained for ET for 10 days from varying the LAI and RD in unison as a percentage of the standard values is depicted in figure 12. These curves indicate that from small values of LAI and RD (i.e., shortly after emergence to an LAI/RD of 15 percent) a 10 percent increase in LAI/RD gives about a 13 percent change in ET for 10 days for the wet regime. The percent response in the drier regimes is progressively larger. For progressively larger values of LAI/RD, the percent change in the ET response for a given change in LAI/RD progressively decreases in the wet regime. In the dry regime, the ET for 10 days actually decreases with further LAI/RD increases, another unexpected response.

The variation in ET for 10 days with the variation in the plant constant SRCR (the specific resistance to water uptake) is illustrated in figure 13. These curves indicate that the ET response to a given change in SRCR is very small. In addition, other simulations indicate that if SRCR is decreased sufficiently at a given soil water amount the ET for the 10-day value changes sign, a very unrealistic situation (not shown on figure 3). Furthermore, increasing the SRCR value above standard reduces the BALANS values for the drier regimes.

Figures 14 and 15 show the response of two other plant constants, RLVSWP and WPCRM. The curves indicate negligible changes in the model reponse. The soil

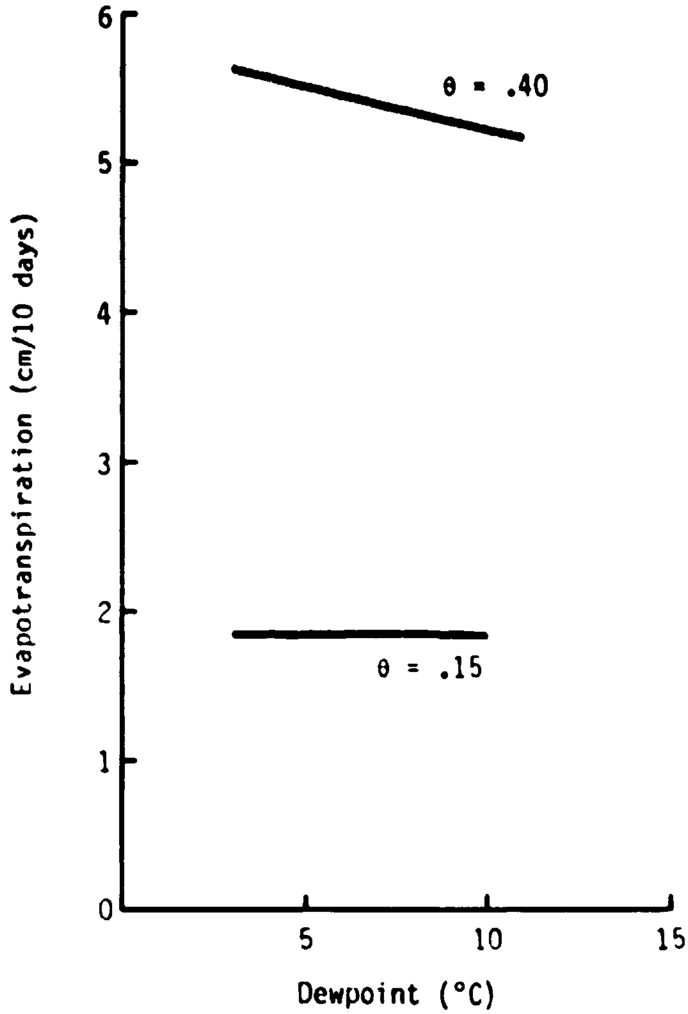

Figure 10.- The response of ET for 10 days versus the dewpoint and initial soil water profile.

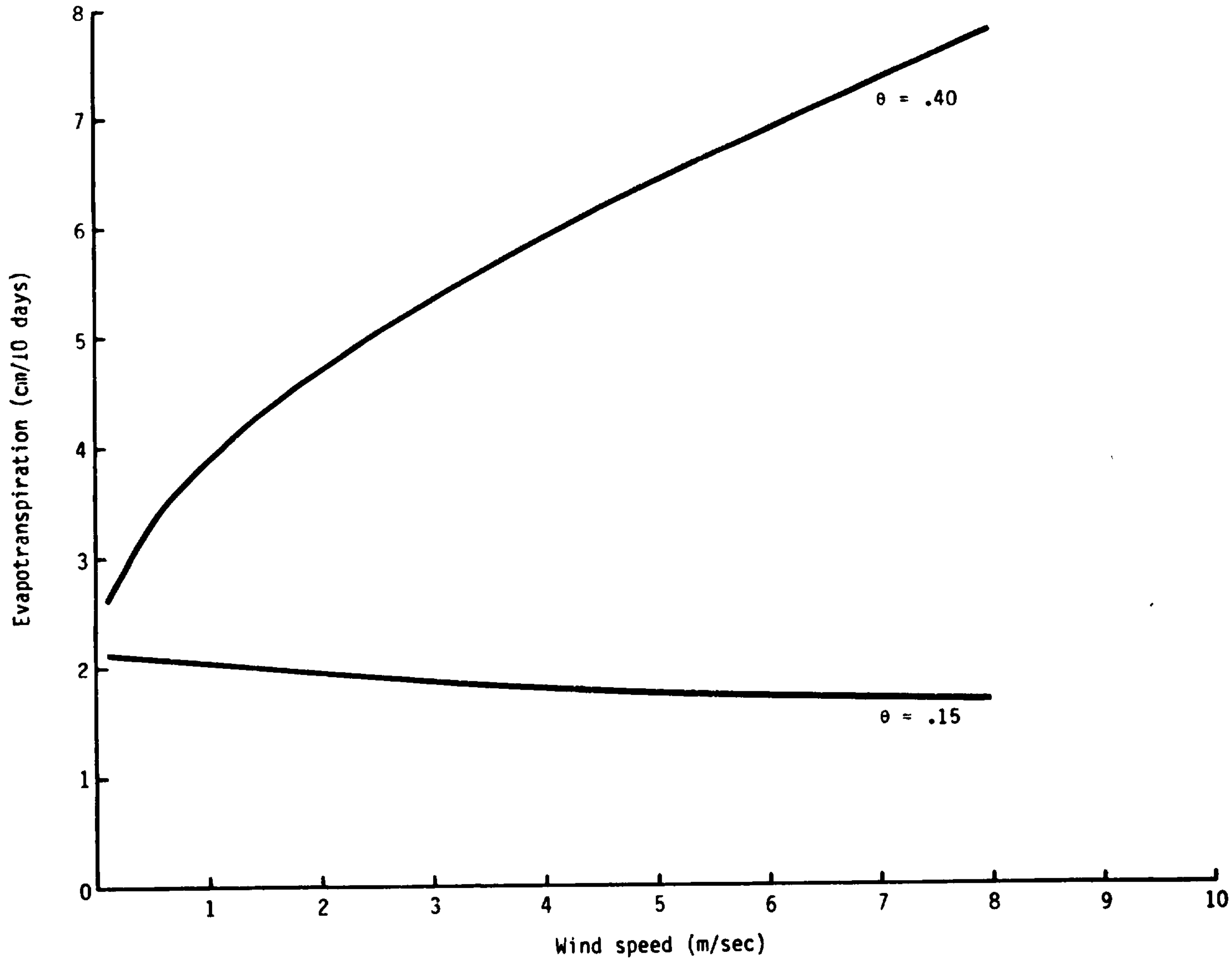

Figure 11.- The response of ET for 10 days to mean wind speed and initial soil water profile.

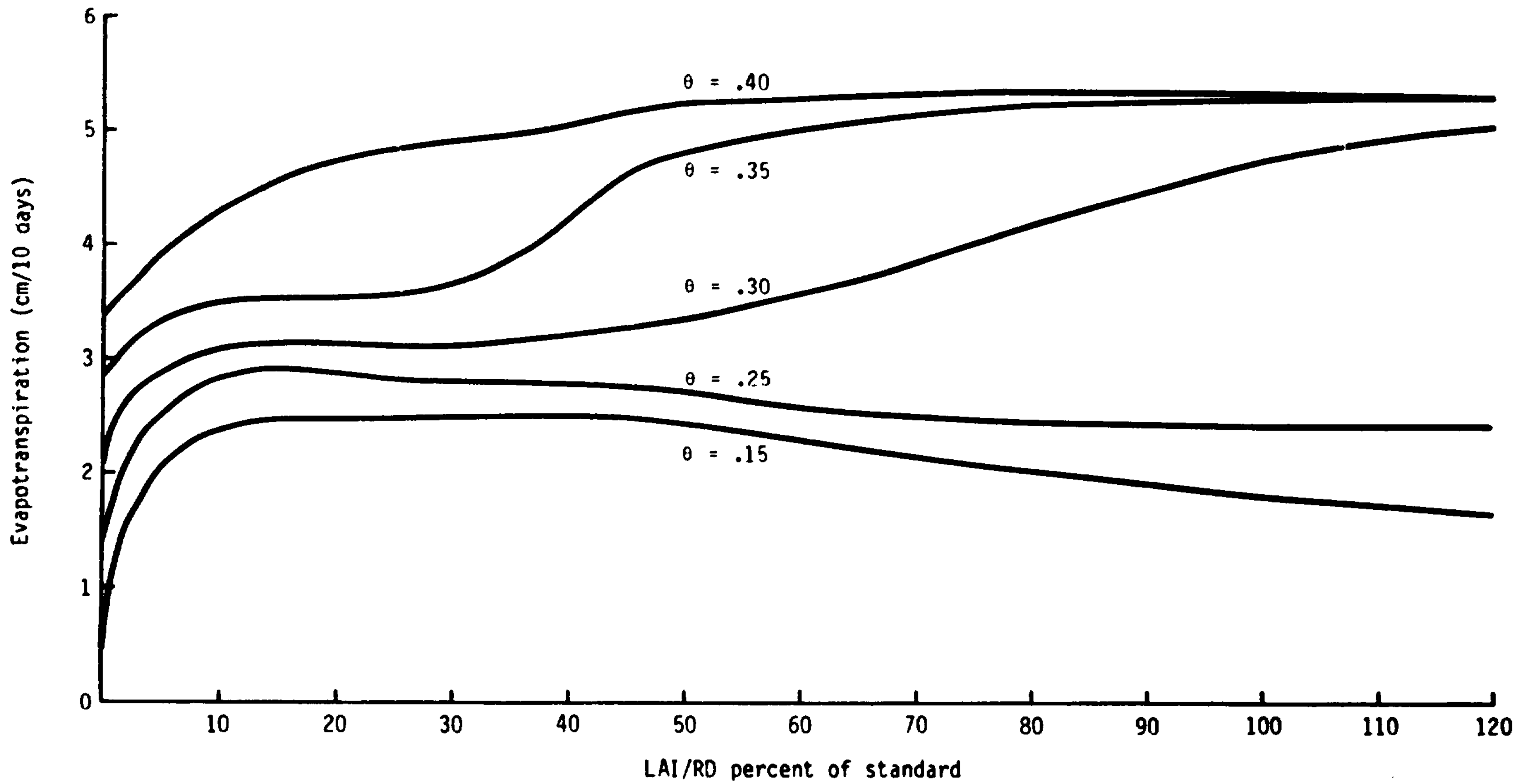

Figure 12.- The response of ET for 10 days from varying the LAI and RD in unison as a percentage of the standard values versus initial soil water profile.

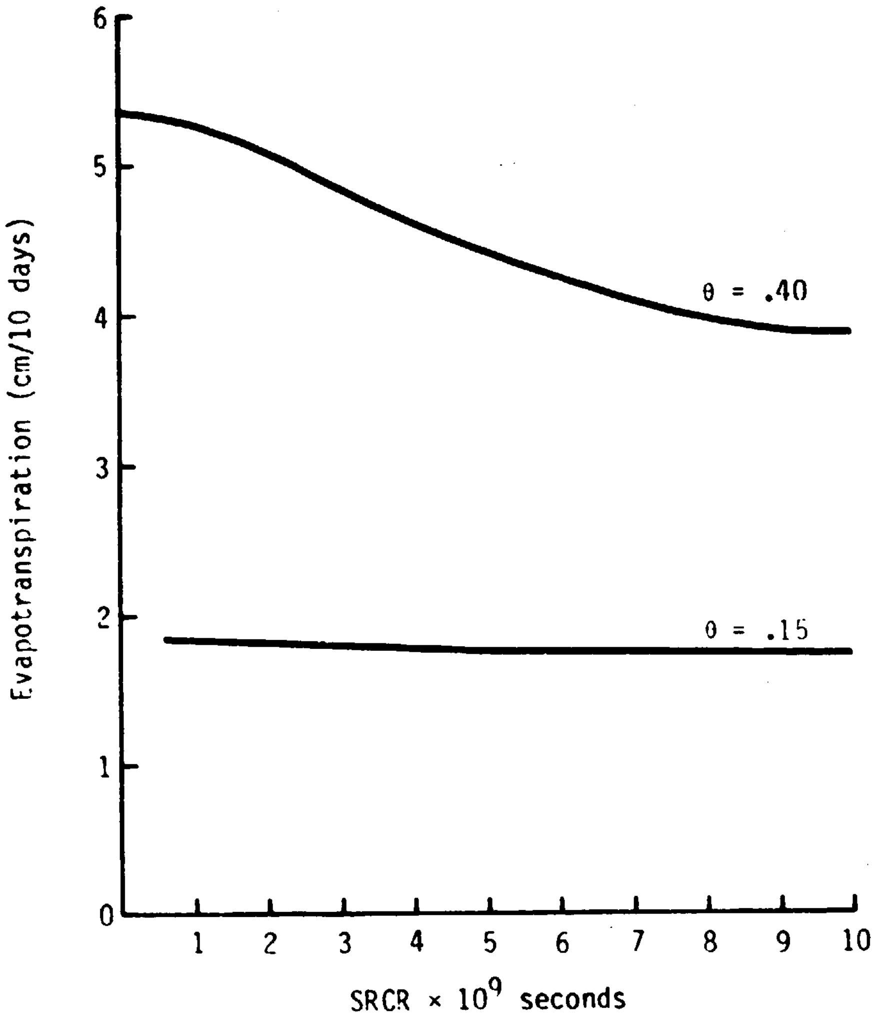

Figure 13.- The variation in ET for 10 days versus constant specific resistance to water uptake (SRCR) and initial soil water profile.

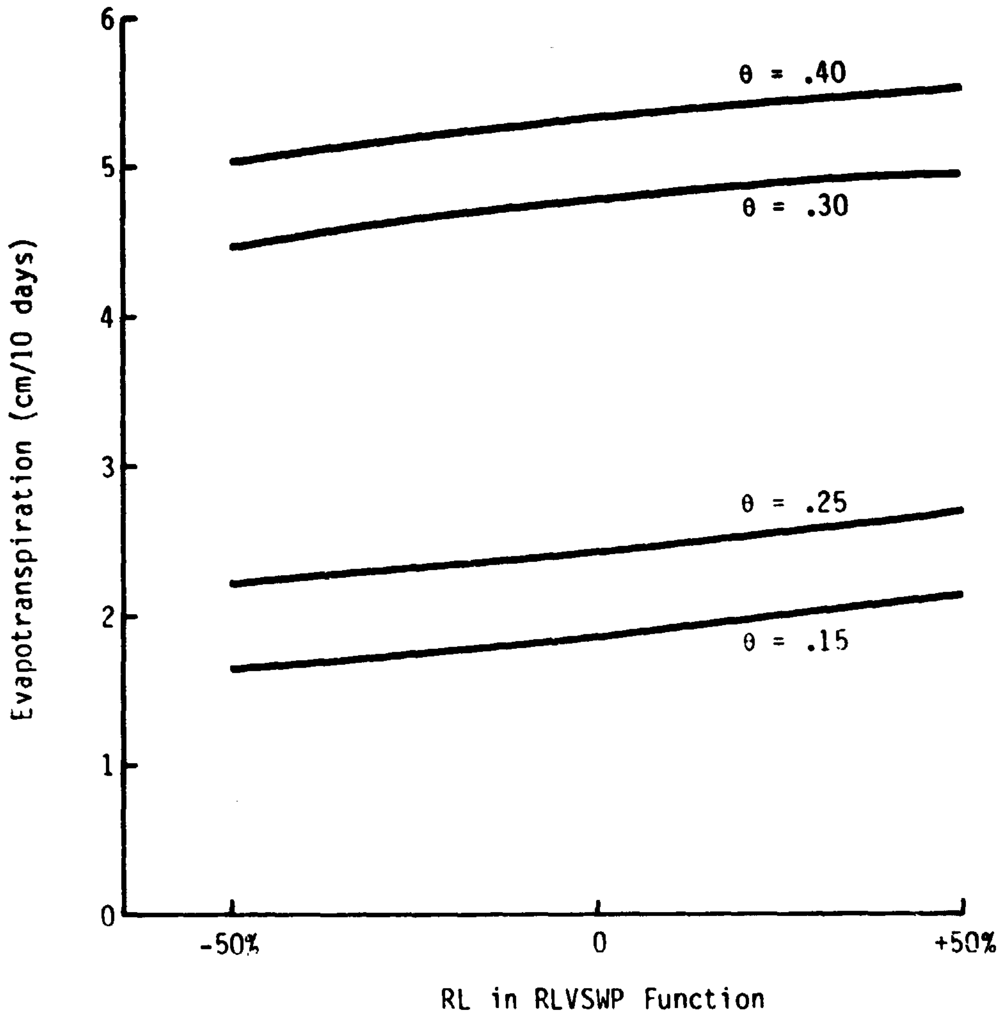

Figure 14.- The response of ET for 10 days versus a change in the RLVSMP function as a percentage of standard values and intiial soil water profile.

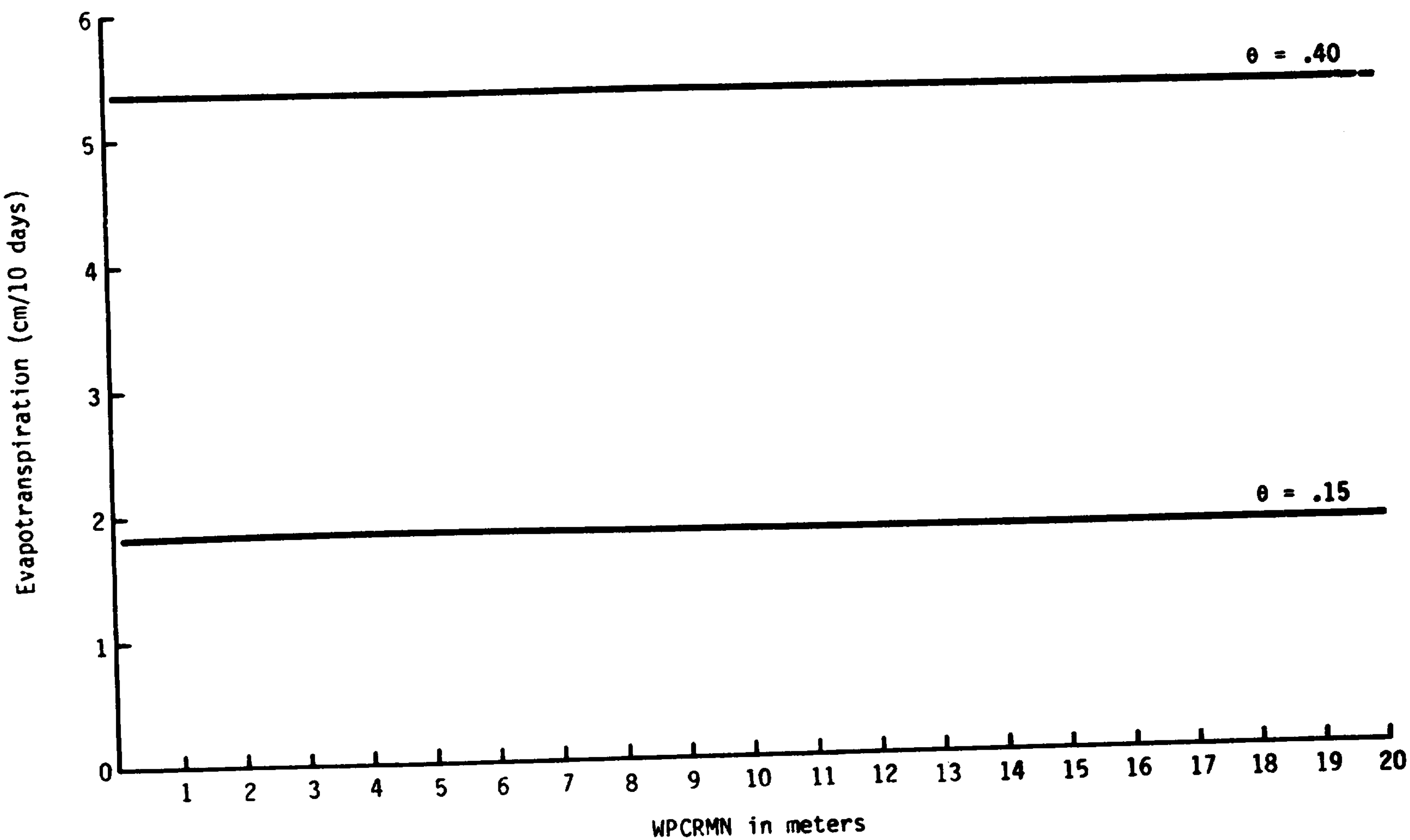

Figure 15.- The response of ET for 10 days versus a change in the WPCRM as a percentage of standard values and initial soil water profile.

water depth profiles on the 10th day are shown in figure 16. The wet profiles look realistic but become increasingly unrealistic toward the dry regime. The profiles are unrealistic because the near-surface water values appear too high.

3.2.1.2 Output Values Versus Hydraulic Conductivity

Errors can occur in the hydraulic conductivity (h.c.) values since they are not measured, but calculated from the moisture release data by Jackson's method. To test responses to these errors, all the h.c. values were increased and decreased by 20 percent. The results of simulations using these changes, but otherwise standard inputs, indicate negligible effects on E_v and T, but a definite effect is noted on drainage and water loss in the wet regime.

3.2.2 ROGOWSKI AND GHOSH MODELS FOR WATER RETENTION

The results of simulations for a variety of conditions using Rogowski's model are presented in table 9 and figures 17 and 18, and the results for Ghosh's model are shown in table 10 and figures 19 and 20. Inspection of these curves allows the following comments.

The daily values for E_v show very little difference from the regression model under similar environmental conditions. T values, however, are similar in the wet and dry regime, but remain high for a few more days before falling in the intermediate regime.

The E_v for 10 days as a function of θ changes very little between the models for any of the environmental conditions simulated. On the other hand, the T changes are very small in the wet and dry regimes, but are considerable in the intermediate regimes; in some cases, changes of at least 200 percent occur. The shape of the ET curves, however, are similar to the regression model curves.

Other significant differences in the output provided by the different water retention models occur in the values of the drainage and total water loss. As can be seen from table 8, 9, and 10, the regression model allows the least drainage and water loss, while the Rogowski model allows the most drainage and

TABLE 9.- VAN BAVEL-CROP-GHOSH STANDARD 10-DAY TEST RESULTS

Cumulative centimeters for 10 days							Centimeters for last day			
θ_v	ET	T	E_v	Drainage	Water loss	BALANS	ET	T	E_v	Drainage
DGR = 30										
0.40	7.38	5.19	2.19	2.63	9.907	0.104	0.734	0.543	0.191	0.101
.35	7.39	5.19	2.20	.668	8.044	.017	.742	.547	.192	.043
.30	7.23	5.01	2.21	.084	7.230	.088	.694	.497	.193	.008
.25	4.55	2.16	2.36	.006	4.410	.150	.300	.079	.214	6×10^{-4}
.20	3.08	.659	2.42	2×10^{-4}	2.838	.243	.282	.073	.209	2×10^{-5}
.15	2.84	.611	2.23	4×10^{-6}	1.745	1.10	.257	.069	.188	4×10^{-7}
DGR = 20										
0.40	5.26	3.88	1.38	2.68	7.922	0.017	0.525	0.405	0.120	0.109
.35	5.28	3.89	1.38	.670	5.965	-.020	.529	.409	.120	.043
.30	5.30	3.91	1.39	.084	5.323	.056	.526	.404	.121	.008
.25	4.21	2.74	1.43	.006	4.088	.130	.321	.184	.128	6×10^{-4}
.20	1.98	0.46	1.52	2×10^{-4}	1.794	.182	.182	.050	.132	2×10^{-5}
.15	1.85	0.43	1.43	4×10^{-6}	.991	.857	.170	.048	.122	4×10^{-7}
DGR = 10										
0.40	3.27	2.64	0.634	2.73	6.014	-0.010	0.328	0.273	0.055	0.118
.35	3.29	2.66	.635	.672	3.968	-.004	.329	.274	.055	.044
.30	3.35	2.72	.638	.084	3.417	.014	.337	.281	.056	.008
.25	3.18	2.56	.640	.006	3.132	.059	.306	.252	.056	6×10^{-4}
.20	.983	.328	.682	2×10^{-4}	.855	.128	.090	.031	.059	2×10^{-5}
.15	.920	.273	.650	4×10^{-6}	.272	.649	.086	.031	.056	4×10^{-7}
DGR = 1										
0.40	1.62	1.59	0.030	2.79	4.567	-0.157	0.164	0.161	0.003	0.127
.35	1.63	1.60	.030	.674	2.349	-.045	.164	.161	.003	.045
.30	1.64	1.61	.031	.084	1.661	.062	.165	.163	.003	.008
.25	1.62	1.59	.031	.006	1.588	.039	.163	.160	.003	6×10^{-4}
.20	.346	.322	.027	2×10^{-4}	.234	.112	.024	.021	.002	2×10^{-5}
.15	.181	.156	.024	4×10^{-6}	-.359	.540	.019	.017	.002	4×10^{-7}

TABLE 10.- VAN BAVEL-CROP-ROGOWSKI STANDARD 10-DAY TEST RESULTS

Cumulative centimeters for 10 days							Centimeters for last day			
θ_v	ET	T	E_V	Drainage	Water loss	BALANS	ET	T	E_V	Drainage
DGR = 30										
0.40	7.40	5.18	2.20	9.71	17.03	0.032	0.727	0.533	0.190	0.269
.35	7.37	5.15	2.20	1.97	9.28	.051	.720	.526	.191	.136
.30	6.76	4.51	2.22	.119	6.79	.091	.551	.351	.199	.012
.25	4.36	2.01	2.35	.006	4.25	.117	.286	.073	.213	6×10^{-4}
.20	3.07	.65	2.42	2×10^{-4}	2.81	.258	.282	.073	.209	2×10^{-5}
.15	2.86	.61	2.25	7×10^{-6}	1.82	1.03	.259	.070	.190	7×10^{-7}
DGR = 20										
0.40	5.33	3.94	1.39	9.83	15.16	0.003	0.532	0.410	0.121	0.283
.35	5.34	3.95	1.39	1.99	7.28	.05	.531	.410	.120	.141
.30	5.26	3.88	1.39	.12	5.34	.05	.513	.392	.121	.012
.25	3.85	2.40	1.44	.006	3.75	.103	.248	.123	.131	6×10^{-4}
.20	1.97	.46	1.52	2×10^{-4}	1.79	.183	.181	.050	.132	2×10^{-5}
.15	1.85	.43	1.43	7×10^{-6}	1.02	.834	.170	.048	.122	7×10^{-6}
DGR = 10										
0.40	3.35	2.71	0.64	9.98	13.34	0.013	0.337	0.281	0.056	0.300
.35	3.36	2.73	.64	2.02	5.364	.008	.337	.281	.056	.148
.30	3.35	2.73	.64	.119	3.46	.016	.334	.281	.054	.012
.25	3.17	2.54	.64	.006	3.12	.052	.291	.236	.056	6×10^{-4}
.20	.98	.30	.68	2×10^{-4}	.853	.131	.091	.031	.059	2×10^{-5}
.15	.92	.27	.65	7×10^{-6}	.266	.654	.097	.031	.056	7×10^{-7}
DGR = 1										
0.40	1.64	1.61	0.031	10.13	11.90	0.019	0.166	0.163	0.003	0.317
.35	1.64	1.61	.031	2.05	3.684	.009	.166	.163	.003	.158
.30	1.64	1.61	.031	.119	1.751	.010	.166	.163	.003	.012
.25	1.63	1.60	.031	.006	1.607	.031	.163	.161	.003	2×10^{-4}
.20	.305	.281	.026	2×10^{-4}	.101	.104	.020	.018	.002	2×10^{-5}
.15	.181	.156	.024	7×10^{-6}	-.375	.556	.019	.017	.002	7×10^{-7}

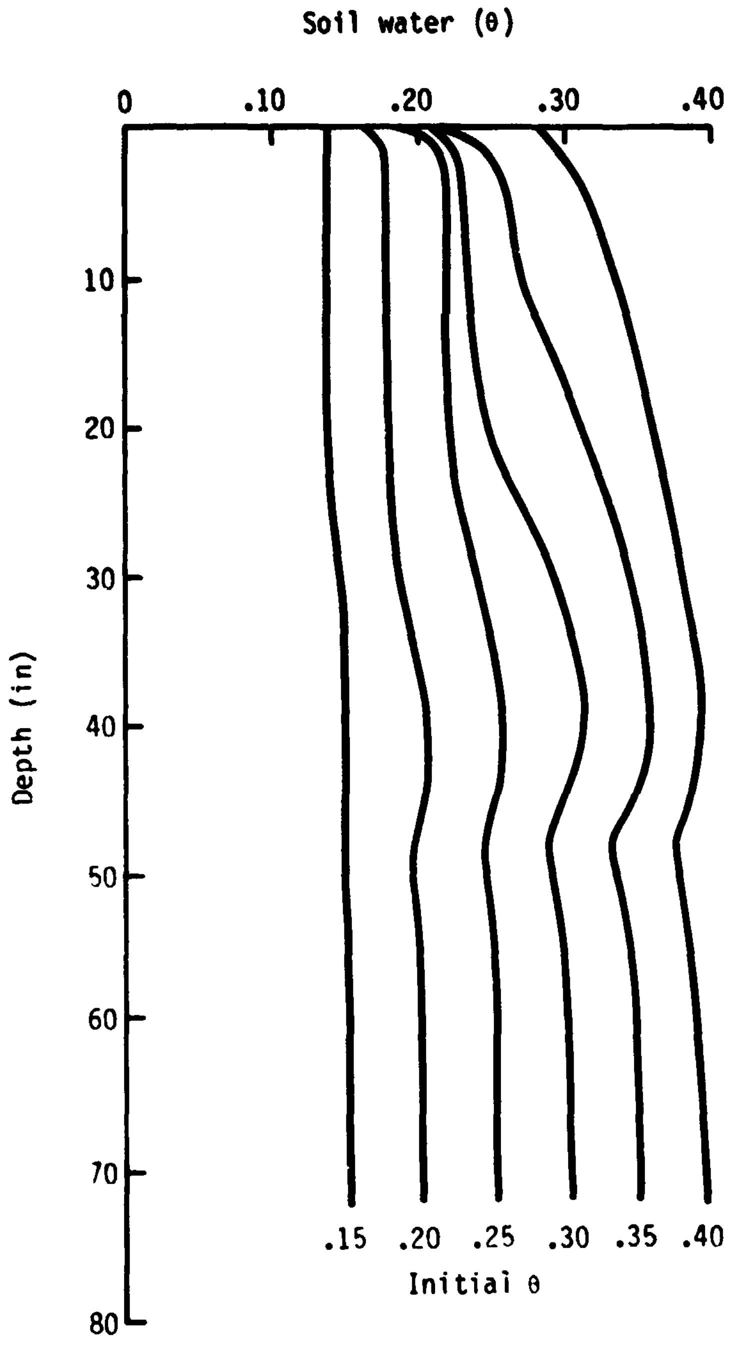

Figure 16.- The soil water depth profiles on the 10th day.

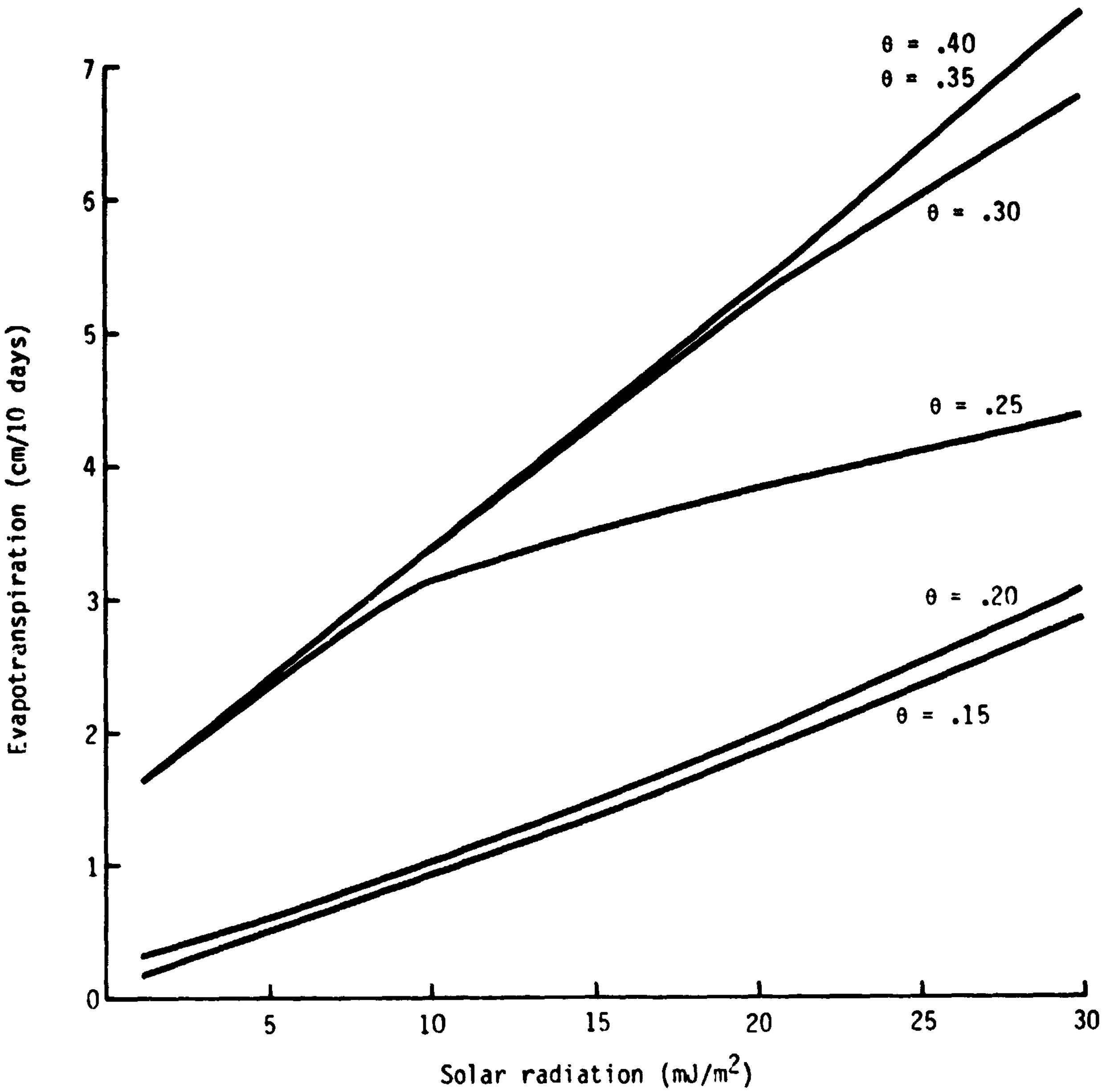

Figure 17.- The variation of ET for 10 days versus the solar radiation and soil water profile using Rogowski's model for soil water characteristics.

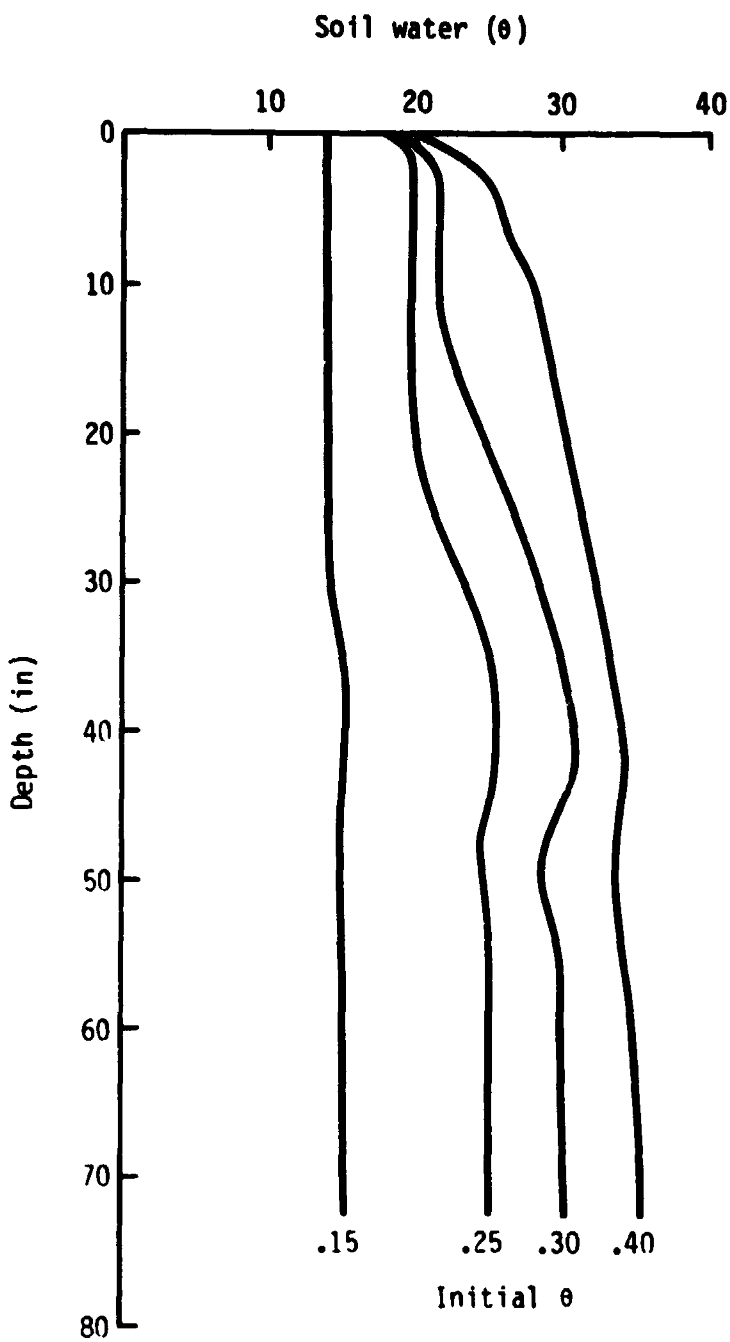

Figure 18.- The soil water profile on the 10th day using the Rogowski model for soil water characteristics.

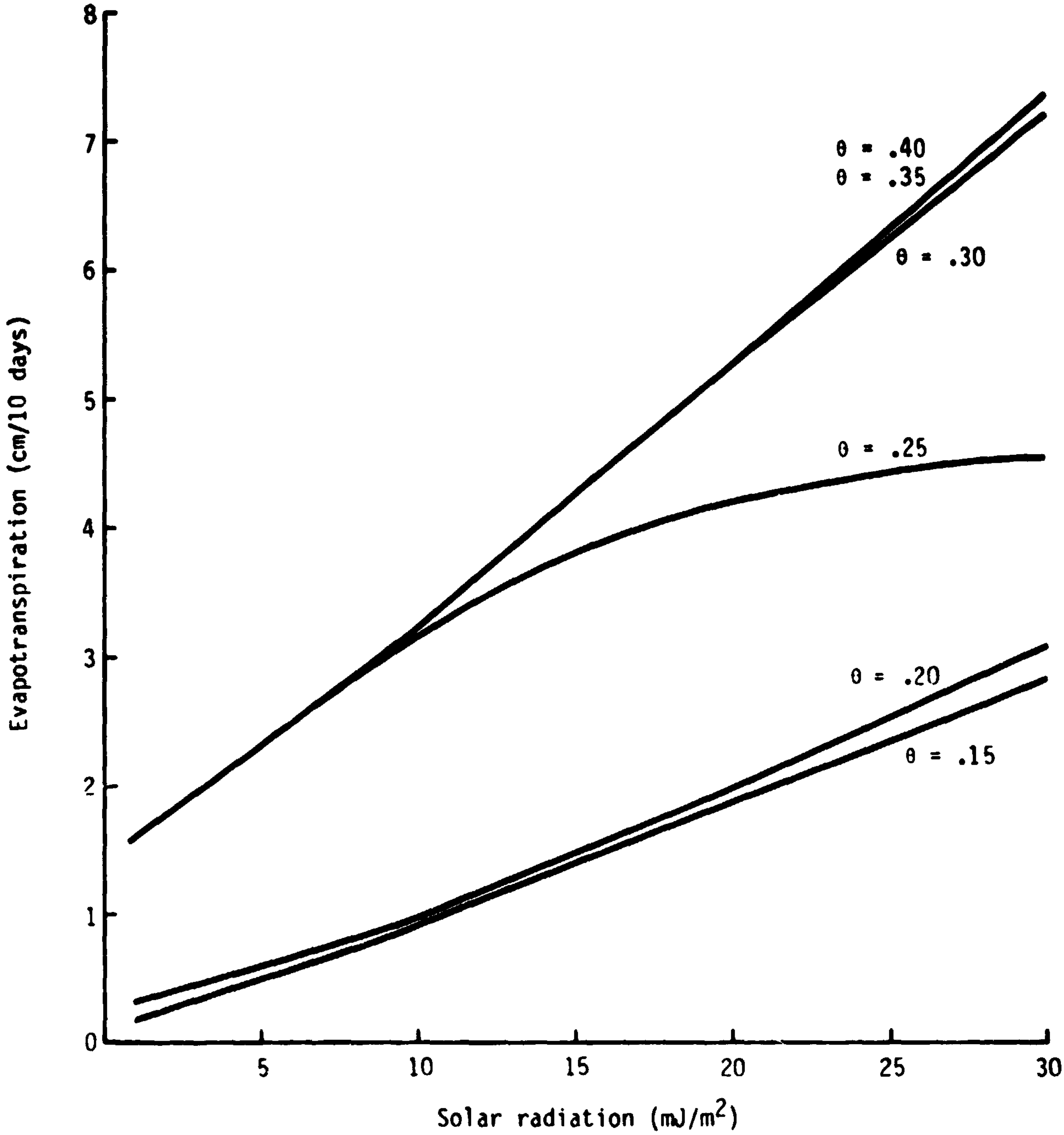

Figure 19.- The variation of ET for 10 days versus the solar radiation and initial soil water profile using Ghosh's model for soil water characteristics.

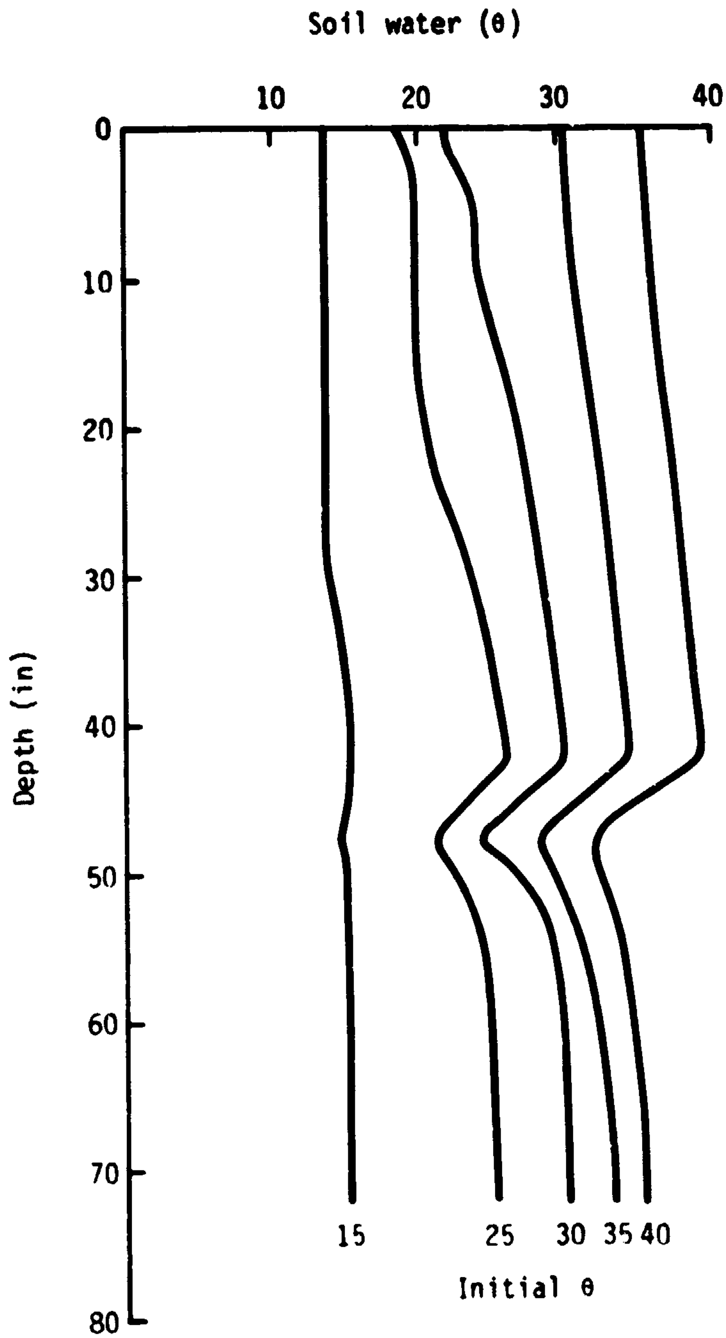

Figure 20.- The soil water profile on the 10th day using the Ghosh model for soil water characteristics.

water loss. In addition, the BALANS values are smaller for the Rogowski model and largest for the regression model.

3.3 FALLOW SIMULATIONS

Fallow conditions were also simulated. This was accomplished by deleting from the program some of the terms involving the crop and by setting LAI and RD to zero. The resulting daily evaporation for the 10-day period for the different initial conditions using the regression model are shown in figure 21. The cumulative evaporation for the 10-day period is shown in figure 22. These simulation results indicate that the three stages noted earlier for ET are also present for evaporation alone. A basic difference in the simulated evaporation under a good crop cover (LAI = 3.5) and for fallow condition is that under crop cover the E_v is nearly always constant, while for fallow conditions it starts higher and ends lower.

The changes in the E_v for 10-day values as the solar radiation (DGR) is increased or decreased is indicated in figure 23. These results are similar to those given for ET shown in figure 6. However, for comparable DGR, the E_v for 10 days is lower. Also, the response differs since the E_v approaches a maximum value as DGR increases. The evaporation on day 10 for different DGR and θ values is shown in figure 24. This response differs significantly from that for ET which is illustrated in figure 8. The 10-day soil water profiles are presented in figure 25. These profiles look more realistic than do the profiles under crops (see figs. 16, 19, and 20).

3.4 THE BALANS EVALUATION AND RC(I) INCONSISTENCY

To investigate the reason the BALANS values increase as the soil becomes dryer, the program code was modified to print out the RC(I) values and CUMRC along with the other output information. Inspection of these values for various simulations indicated that, as the initial profile was made drier, the absolute value of CUMRC became progressively smaller than the value of CUMTR, and it finally became positive for the dry regime. This positive value suggests that the crop was taking water from the air and putting it in the soil. In addition, as the

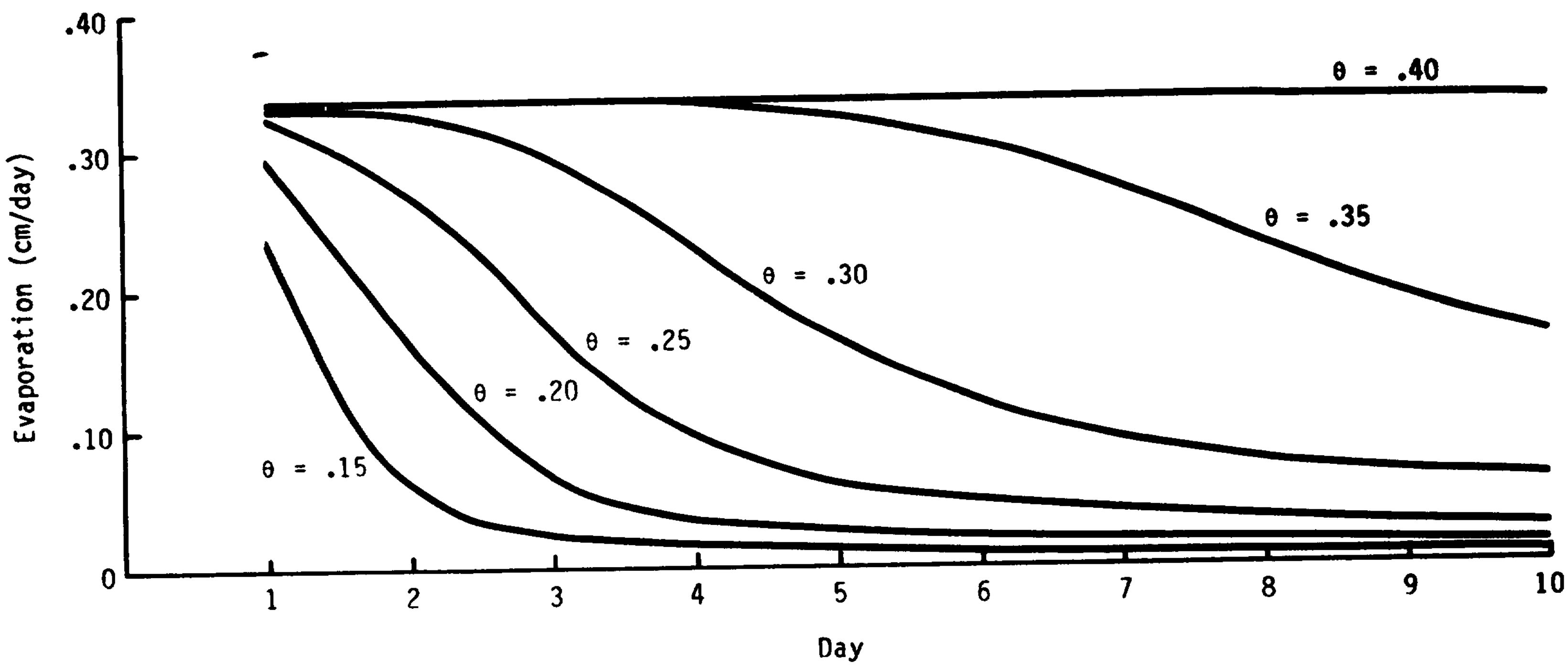

Figure 21.- The daily E_v for the 10-day period for different initial soil water profiles for fallow fields and standard atmospheric conditions.

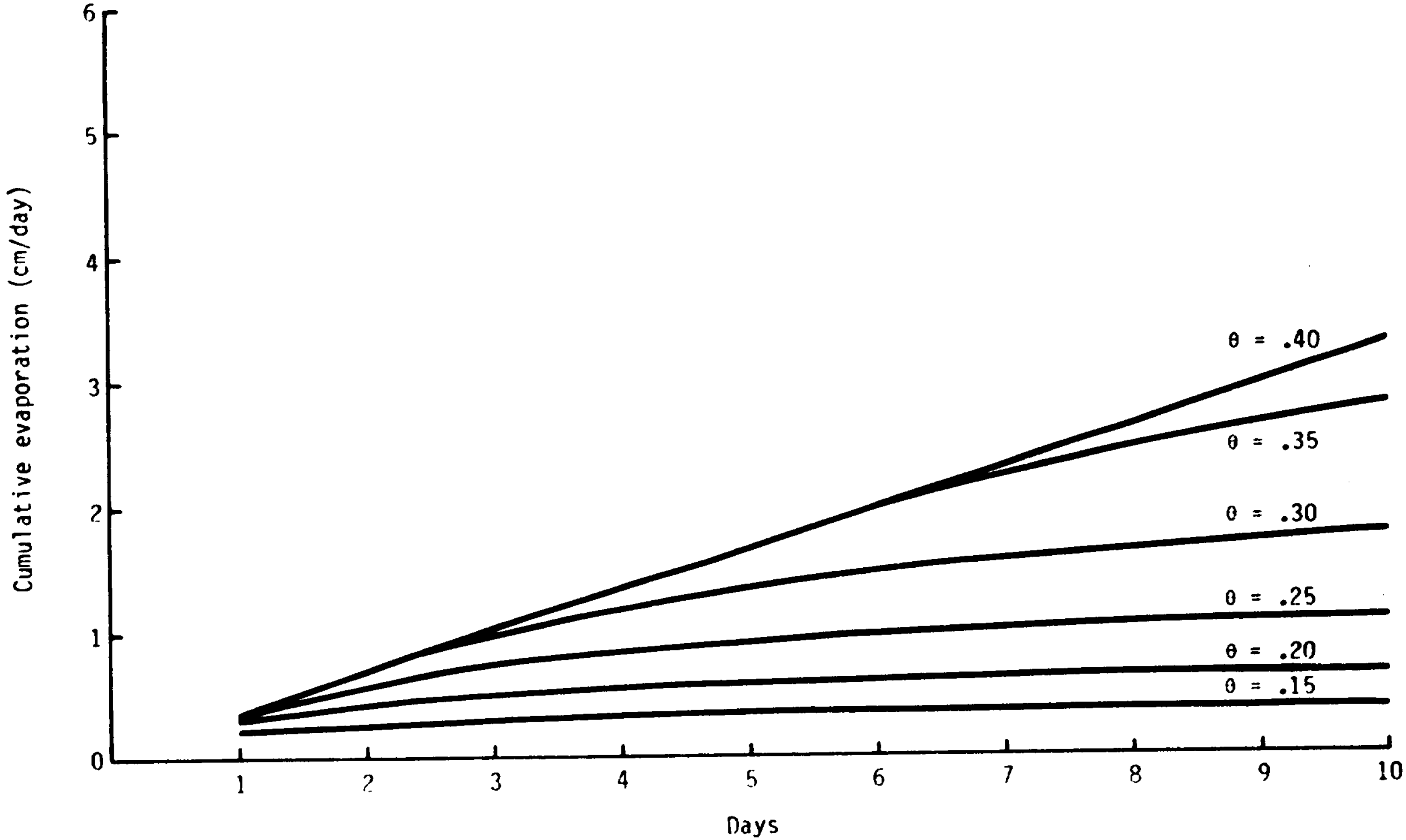

Figure 22.- The cumulative E_v for the 10-day period versus the initial soil water profile for fallow fields and standard atmospheric conditions.

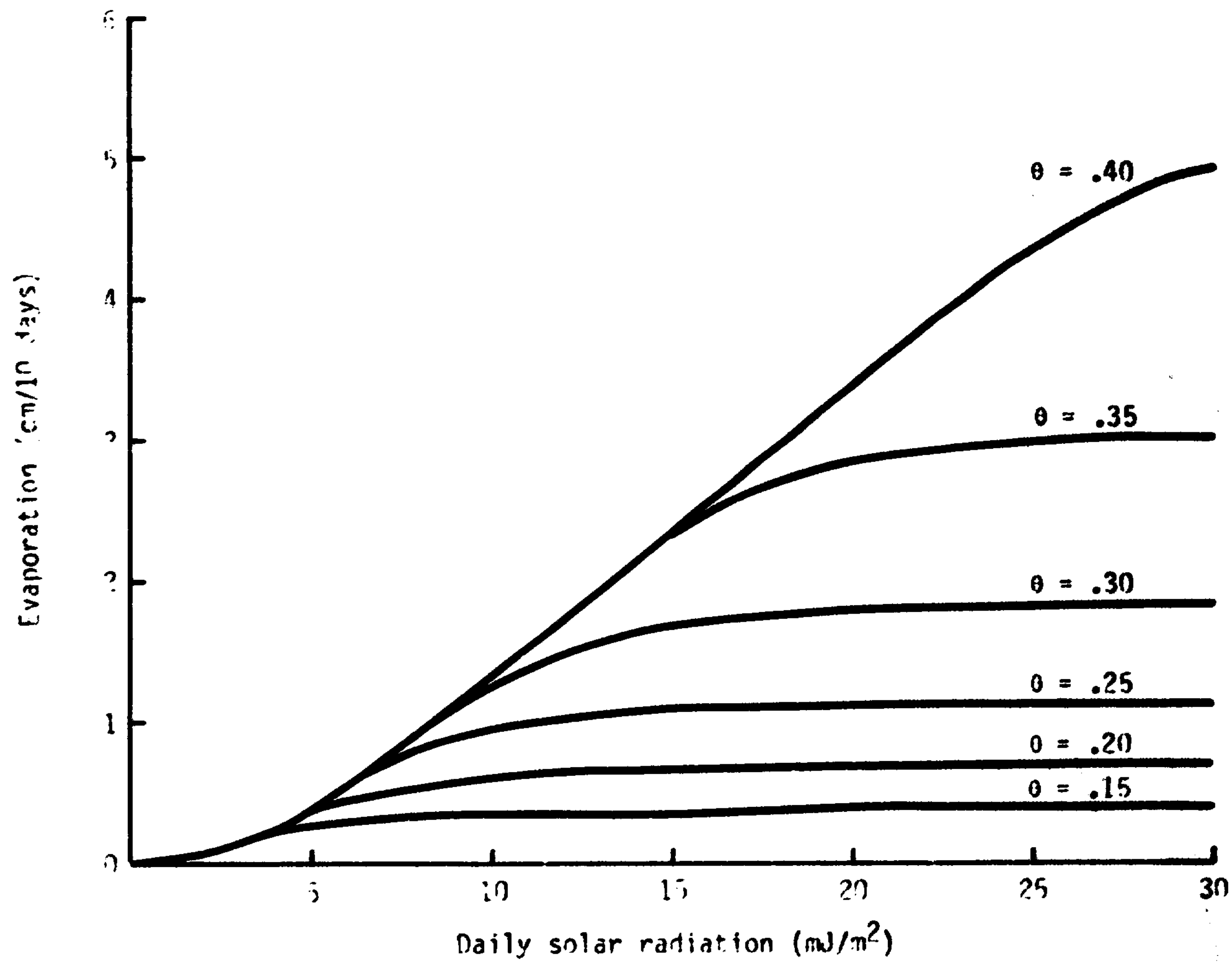

Figure 23.- The changes in the E_v for the 10-day period versus the solar radiation (DGR) and initial water profile for fallow fields.

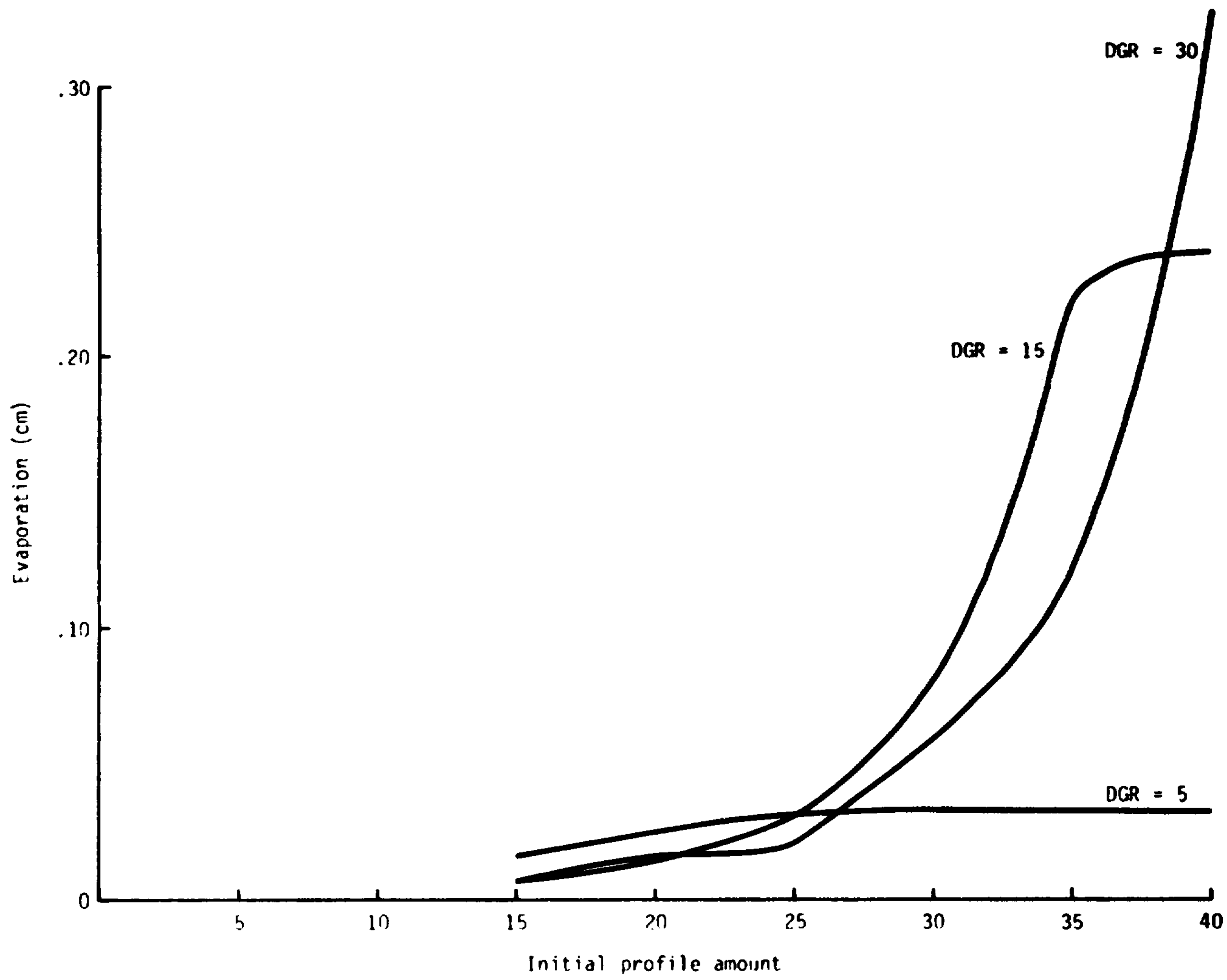

Figure 24.- The E_v on the 10th day versus the initial soil water profile and different solar radiation amounts for fallow fields.

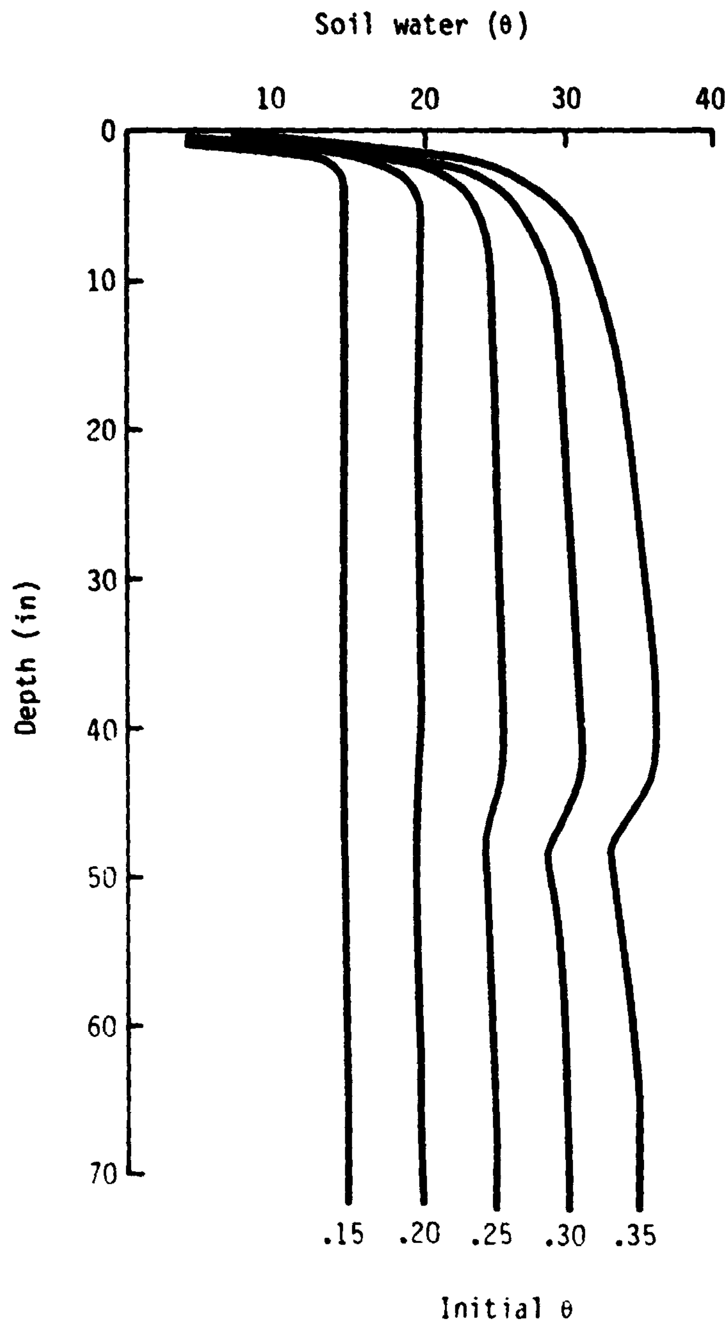

Figure 25.- The soil water profiles on the 10th day for fallow fields using the regression model.

soil profile became drier, positive values for RC(I) began appearing near the surface and became larger as drier initial profiles were used. This behavior of RC(I) is inconsistent with what is expected to occur, which is negative RC(I) values and absolute CUMRC values always nearly equal to absolute CUMTR values. An analysis of the mathematical equations (4), (5), and (6), which determine the RC(I) values, indicates that it is possible for RC(I) to be positive, especially when TRC is small. The term involving TRC is multiplied by SRCR; so, in order to test this hypothesis, SRCR was increased and further simulation performed. These runs indicated that CUMRC and BALANS values were progressively improved as SRCR was made larger.

In order to further evaluate the nature of the RC(I) inconsistency, the program code was modified so that positive RC(I) values were set to zero, and the model was run for the range of θ values under standard conditions. The simulation results showed that, at the wet boundary, CUMRC was nearly equal to CUMTR, and the values were nearly the same as those provided by the original code. However, as drier initial conditions were simulated, the BALANS values became progressively larger, reaching a maximum value at $\theta = .30$ of - 21.3 cm with CUMRC the greater. As a further check, the relation below was substituted for the original code.

$$RC(I) = RF(I)*TRC \tag{16}$$

As expected, this equation provided values of CUMRC just about equal to CUMTR. In addition, the BALANS values became small for all θ. Examples of the model response using equation (16) are presented in Appendix B.

One conclusion that can be drawn from the above results is that the original program provides positive values of RC(I) in some layers and negative values in other layers. Furthermore, the positive values become progressively greater than the negative values for progressively drier conditions with the largest positive values near the surface. The interpretation here is that the model simulates plant root uptake of water in some layers (negative values), and it simulates a loss of water to the soil in other layers (positive values). The overall result, at a given time, is that the soil water in the profile near the surface is too much when compared to the amount it would be if the RC were in balance with the ET (i.e., small BALANS value).

4. SUMMARY OF SIMULATION RESULTS

WATBAL1 is a computer model that predicts the evapotranspiration and the soil water profile as a function of time. The computer program solves the nonlinear partial differential water transport equation numerically using the CSMPIII. This latter program is easy to program and use.

Although the model is quite complicated with a number of empirical equations and coefficients, the output obtained from the sensitivity study appears quite reasonable and realistic. A number of the response curves agree with the results of empirical studies.

The sensitivity analysis did indicate several unrealistic responses in the intermediate and dry regimes in both the ET for 10 days and the BALANS values. The cause of these responses were located in the algorithm that determines the water uptake by the roots. At low-water amounts, this algorithm took water from the soil at deep layers and put water in the soil in the near-surface layers; the drier the soil the more pronounced this effect. For extremely dry conditions, water was essentially taken from the air and put into the soil.

Simulations using an algorithm that equated the root uptake to the ET provided responses that were similar in the wet regime but more realistic in the intermediate and dry regimes. Presented below are the specific responses of the model to parameter or atmospheric changes:

1. The model simulates the diurnal variation in soil moisture, the amplitude of which decreases with depth as expected.
2. In general, the model responses to changes in atmospheric evaporativity appear reasonable and realistic.
3. Both crop and fallow cases reproduce three-stage drying.
4. Total water loss becomes progressively less than ET as drier initial profiles are simulated, an unrealistic occurrence.

5. BALANS values become progressively greater as drier initial conditions are simulated, and they eventually become much too large.

6. The response to increases in windspeed and LAI/RD in the dry regimes do not appear realistic.

7. The response in the wetter regimes to increases in LAI/RD are small over most of the range of values.

8. The response to percentage changes in SRCR are small. Decreasing the value in the drier regime can change the sign of the ET indicating that water is taken from the air and forced into the soil. Increasing the value of SRCR decreases the transpiration, but it also decreases the BALANS value.

9. Responses to changes in RLVSWP gives very little change.

10. Responses to changes of WPCRM are negligible.

11. Soil water profile changes are negligible in the drier regimes and provide unrealistic profiles.

12. Changes in hydrologic properties were investigated by using three models: regression, Ghosh, and Rogowski.

    a. The T, E_v, and ET values for the wet and dry soil cases show little differences among the models; however, in the intermediate regimes, the values vary quite significantly.

    b. Drainage and water loss are least for the regression model and greatest for the Rogowski model. The values are large at the wet boundary and then become progressively less for increasingly drier conditions. Although the drainage becomes insignificant in the intermediate and dry regimes in all three models, a large difference exists between models in wet regime.

    c. The 10-day soil water profiles are in general similar, but none of them show realistic water losses near the surface in the dry regime.

13. The response of E_v for 10 days to changes in solar radiation for fallow conditions are similar to the ET changes in the crop case in wet regimes but somewhat less in the intermediate and dry regimes.

14. The 10-day soil water profiles for the fallow case show large surface drying with final surface values of the different profiles very close together with steep gradients.

15. As a function of soil water amount and solar radiation values daily E_v values for the fallow case have responses similar to those found by Denmead and Shaw.

16. The three-stage drying response is also provided by the modified model.

17. The ET for 10-day response in the modified model to changes in DGR as a function of θ are similar in character to the fallow response, but larger in value.

18. The ET for 10-day response to changes in LAI/RD are more realistic than the original model.

19. The 10-day profiles show surface layer drying in the modified model which are more realistic than the profiles from the original model.

5. CONCLUSIONS AND RECOMMENDATIONS

The responses of the model have been tested for a range of values for most of the atmospheric, crop, and soil parameters. In particular, the response to rainfall was not investigated systematically, but it appears to be realistic in general use. Most of the responses to the tests appear to be realistic; however, it was determined that the logic that was related to the root uptake of soil water did not appear to give reasonable responses in the intermediate and dry regimes. When the logic was modified to relate total root uptake directly to transpiration, the model provided more realistic responses.

In general, the ratio of the percent change in response to percent change in input is one or less than one. None of the cases investigated provided an unreasonably large percent change in the response. However, LAI, RD, RL, and SA cannot be allowed to be zero because they occur in the denominator of a mathematical term.

Because the positive and favorable aspects of the model surpass the negative aspects, it is recommended that it be tested with field data along with the other models. In particular, the model language CSMPIII is flexible, easy to modify, and easy to use.

6. REFERENCES

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APPENDIX A
WATBAL1 MODEL LISTING

APPENDIX A

WATBAL1 MODEL LISTING

```
****       VOLUMETRIC WATER CONTENT VS. PRESSURE POTENTIAL
FUNCTION TVSP1 =    ( 0.000, -0.7000E+06), ...
                    ( 0.010, -0.4000E+06), ...
                    ( 0.030, -0.7000E+05), ...
                    ( 0.050, -0.1650E+05), ...
                    ( 0.070, -0.9500E+04), ...
                    ( 0.090, -0.5700E+04), ...
                    ( 0.110,  -0.3400E+04), ...
                    ( 0.130,  -0.1950E+04), ...
                    ( 0.150,  -0.1150E+04), ...
                    ( 0.170,    -0.6400E+03), ...
                    ( 0.190,    -0.3800E+03), ...
                    ( 0.210,    -0.2250E+03), ...
                    ( 0.230,      -0.1300E+03), ...
                    ( 0.250,      -0.7500E+02), ...
                    ( 0.270,      -0.430E+02), ...
                    ( 0.290,      -0.2500E+02), ...
                    ( 0.310,      -0.1500E+02), ...
                    ( 0.330,        -0.7700E+01), ...
                    ( 0.350,        -0.5000E+01), ...
                    ( 0.370,        -0.2600E+01), ...
                    ( 0.390,        -0.1200E+01), ...
                    ( 0.410,        -0.3000E+00), ...
                    ( 0.430,        -0.1000E-01), ...
                    ( 1.000,         0.00)
****       VOLUMETRIC WATER CONTENT VS. HYDRAULIC CONDUCTIVITY IN M/S
FUNCTION TVSC1 =    ( 0.000, 0.0000000    ), ...
                    ( 0.020, 0.1556000E-17), ...
                    ( 0.040, 0.5278000E-17), ...
                    ( 0.060, 0.1861000E-16), ...
                    ( 0.080, 0.6389000E-16), ...
                    ( 0.100, 0.2278000E-15), ...
                    ( 0.120, 0.8333000E-15), ...
                    ( 0.140, 0.2917000E-14), ...
                    ( 0.160, 0.1000000E-13), ...
                    ( 0.180, 0.3611000E-13), ...
                    ( 0.200, 0.1250000E-12), ...
                    ( 0.220, 0.4444000E-12), ...
                    ( 0.240, 0.1500000E-11), ...
                    ( 0.260, 0.4861000E-11), ...
                    ( 0.280, 0.1667000E-10), ...
                    ( 0.300, 0.5278000E-10), ...
                    ( 0.320, 0.1611000E-09), ...
                    ( 0.340, 0.5278000E-09), ...
                    ( 0.360, 0.1722000E-08), ...
                    ( 0.380, 0.5556000E-08), ...
                    ( 0.400, 0.1944000E-07), ...
                    ( 0.420, 0.1111000E-07), ...
                    ( 1.000, 0.1111000E-07)
****       VOLUMETRIC WATER CONTENT VS. PRESSURE POTENTIAL
FUNCTION TVSP2 =    ( 0.000, -0.5000E+06), ...
                    ( 0.010, -0.1000E+06), ...
                    ( 0.030, -0.5000E+05), ...
                    ( 0.050, -0.2450E+04), ...
                    ( 0.070, -0.1550E+04), ...
                    ( 0.090, -0.9800E+03), ...
                    ( 0.110, -0.6400E+03), ...
                    ( 0.130, -0.4100E+03), ...
                    ( 0.150, -0.2600E+03), ...
                    ( 0.170, -0.1700E+03), ...
                    ( 0.190, -0.1070E+03), ...
                    ( 0.210, -0.6800E+02), ...
```

```
                                  ( 0.230, -0.4200E+02), ...
                                  ( 0.250, -0.2600E+02), ...
                                  ( 0.270, -0.1600E+02), ...
                                  ( 0.290, -0.9600E+01), ...
                                  ( 0.310, -0.5600E+01), ...
                                  ( 0.330, -0.3300E+01), ...
                                  ( 0.350,      -0.1900E+01), ...
                                  ( 0.370,      -0.9600), ...
                                  ( 0.390,      -0.42000), ...
                                  ( 0.410,      -0.1300), ...
                                  ( 0.430,      -0.1000E-01), ...
                                  ( 1.000,       0.00)
****      VOLUMETRIC WATER CONTENT VS. HYDRAULIC CONDUCTIVITY
FUNCTION TVSC2 =    ( 0.000, 0.0000000      ), ...
                                  ( 0.020, 0.1556000E-16), ...
                                  ( 0.040, 0.4583000E-16), ...
                                  ( 0.060, 0.1306000E-15), ...
                                  ( 0.080, 0.3750000E-15), ...
                                  ( 0.100, 0.1111000E-14), ...
                                  ( 0.120, 0.3194000E-14), ...
                                  ( 0.140, 0.9306000E-14), ...
                                  ( 0.160, 0.2778000E-13), ...
                                  ( 0.180, 0.8333000E-13), ...
                                  ( 0.200, 0.2333000E-12), ...
                                  ( 0.220, 0.7083000E-12), ...
                                  ( 0.240, 0.2000000E-11), ...
                                  ( 0.260, 0.5555000E-11), ...
                                  ( 0.280, 0.1722000E-10), ...
                                  ( 0.300, 0.4583000E-10), ...
                                  ( 0.320, 0.1333000E-09), ...
                                  ( 0.340, 0.3889000E-09), ...
                                  ( 0.360, 0.1111000E-08), ...
                                  ( 0.380, 0.3472000E-08), ...
                                  ( 0.400, 0.1139000E-07), ...
                                  ( 0.420, 0.5139000E-07), ...
                                  ( 1.000, 0.5139000E-07)
            WRITE(6,1100)
       1100 FORMAT('0 I      TCOM     DEPTH      ITHETA')
            DO 40 I=1,NLL
         40 WRITE(6,1200) I,TCOM(I),DEPTH(I),ITHETA(I)
       1200 FORMAT(1H ,I2,3F10.5)
            HTIME=TIME/3600.
            STIME=AMOD(HTIME,24.)
            Y=IMPULS(86400.,86400.)
            IF(Y.LT.0.5) GO TO 22
            DNUM = DNUM + 1
         22 CONTINUE
            XDNUM=FLOAT(DNUM)
            JDNUM = WINPUT (1,DNUM)
            DO 50 I=1,13
            THETA(I) = VOLW(I)/TCOM(I)
            COND(I)=AFGEN( TVSC1,THETA(I))
            PPOT(I)=AFGEN( TVSP1,THETA(I))
            HPOT(I)=PPOT(I)-DEPTH(I)
         50 CONTINUE
            DO 60 I=14,NL
            THETA(I) = VOLW(I)/TCOM(I)
            COND(I)=AFGEN( TVSC2,THETA(I))
            PPOT(I)=AFGEN( TVSP2,THETA(I))
            HPOT(I)=PPOT(I)-DEPTH(I)
         60 CONTINUE
            DO 80 I = 2,NL
            AVCOND(I)=(COND(I-1)*TCOM(I-1)+COND(I)*TCOM(I))/...
                      (TCOM(I-1)+TCOM(I))
         80 CONTINUE
            FLUX(NLL)= COND(NL)
```

```
      DO 90 I = 2,NL
      FLUX(I)=(HPOT(I-1)-HPOT(I))*AVCOND(I)/DIST(I)
   90 CONTINUE
      BEGIN = WINPUT(9,DNUM)
      END = WINPUT(10,DNUM)
      RFT = WINPUT(11,DNUM)
      RAIN=0.0
      IF(RFT.EQ.0.0) GO TO 33
      UPSLOP=(4.0*RFT)/((END-BEGIN)**2)
      DWSLOP=-UPSLOP
      MDPNT=(BEGIN+END)/2.0
      HEIGHT=(2.0*RFT)/(END-BEGIN)
      IF(STIME.GE.BEGIN.AND.STIME.LE.MDPNT)RAIN=...
      (UPSLOP*(STIME-BEGIN))/3600000.0
      IF(STIME.GT.MDPNT.AND.STIME.LE.END)RAIN=...
      (DWSLOP*(STIME-END))/3600000.0
   33 CONTINUE
      DL=WINPUT(2,DNUM)
****  DGR/86400.*1.E06*24./DL*PI/2.=436.33*DGR/DL
      GR=436.33*WINPUT(3,DNUM)/DL*SIN((STIME-12.+DL/2.)...
         *3.141/DL)
      IF (GR.LE.0.0) GO TO 160
      IF(HTIME.LE.12.) SA=WINPUT(8,DNUM)
      IF(HTIME.LE.12.) GO TO 44
      IF(STIME.LE.12.)SA=WINPUT(8,DNUM-1)+(STIME+12.)/24.* ...
      (WINPUT(8,DNUM)-WINPUT(8,DNUM-1))
      IF(STIME.LE.12.) GO TO 44
      SA=WINPUT(8,DNUM)+(STIME-12.)/24.*(WINPUT(8,DNUM+1)-...
      WINPUT(8,DNUM))
   44 CONTINUE
      RA = (ALOG(2.0/Z0)**2.0)/(0.16*SA)
      DPMAX=WINPUT(6,DNUM)
      DPMIN=WINPUT(7,DNUM)
      DPTC=DPMIN+(DPMAX-DPMIN)*(STIME-5.)/10.
      IF(STIME.GT.15.)DPMIN=WINPUT(7,DNUM+1)
      IF(STIME.GT.15.)DPTC=DPMAX-(DPMAX-DPMIN)*(STIME-15.)/14.
      IF(STIME.LT.5.AND.DNUM.GE.2.)DPMAX=WINPUT(6,DNUM-1)
      IF(STIME.LT.5.)DPTC=DPMAX-(DPMAX-DPMIN)*(STIME+9.)/14.
      HA = 1.323*EXP(17.27*DPTC/(237.3+DPTC))/(273.16+DPTC)
      TAMAX=WINPUT(4,DNUM)
      TAMIN=WINPUT(5,DNUM)
      TAC=TAMIN+(TAMAX-TAMIN)*(STIME-5.)/10.
      IF(STIME.GT.15.)TAMIN=WINPUT(5,DNUM+1)
      IF(STIME.GT.15.)TAC=TAMAX-(TAMAX-TAMIN)*(STIME-15.)/14.
      IF(STIME.LT.5.AND.DNUM.GE.2.)TAMAX=WINPUT(4,DNUM-1)
      IF(STIME.LT.5.)TAC=TAMAX-(TAMAX-TAMIN)*(STIME+9.)/14.
      TAK=TAC+273.16
      SH=(1154.8*303.16)/(TAK)
      SKL=(SIGMA*TAK**4)*(0.605+0.039*SQRT(1410.*HA))
      RD=WINPUT(13,DNUM)
      DO 500 I=1,NL
      RF(I)=2.0*(1/RD-DEPTH(I)/RD**2)*TCOM(I)
      IF(RF(I).LT.0.0) RF(I)=0.0
  500 CONTINUE
      WPSEFF=0.0
      DO 501 I=1,NL
      WPSEFF=WPSEFF+PPOT(I)*RF(I)
  501 CONTINUE
      LAI=WINPUT(12,DNUM)
      ALBC=0.1240-0.009988*LAI+0.007142*LAI**2-0.000583*LAI**3

      ABSC=0.0032+0.3084*LAI-0.05323*LAI**2+0.003667*LAI**3
      FTSR=0.9842-0.6755*LAI+0.1595*LAI**2-0.01241*LAI**3
      WPOTCR=-WPOTCR
      RL=AFGEN(RLVSWP,WPOTCR)
```

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```
      RL=1.0/(RL*LAI)
      RCW=RL+RA
      TL=IMPL(TAC,0.01,FTL)
      LWRC=SIGMA*(TL+273.16)**4
      NRBC=GR*ABSC+(1.0-FTSR)*(SKL-LWRC)
      HL=1.323*EXP(17.27*TL/(237.3+TL))/(273.16+TL)
      LH=2.49463E06-2.247E03*TL
      LTR =(HL-HA)*LH/RCW
      SHCA=-NRBC+LTR
      FTL=TAC-SHCA*RA/SH
      TRC=(HL-HA)/(RCW*1000.0)
      NRBS=GR*(1.0-ALBC-ABSC)+FTSR*(SKL-LWRC)
      EPS=0.921-0.00262*TL+0.00308*TL**2
      EVS=(EPS/(EPS+1.0))*NRBS/(LH*1000.0)
      EVS=EVS*EXP(PPOT(1)/(46.97*TAK))
      IF(TRC.LT.0.0) TRC=0.0
      IF(EVS.LT.0.0) EVS=0.0
      WPOTCR=WPSEFF+WPCRMN-TRC*SRCR/LAI
      DO 502 I=1,NL
      RC(I)=(WPOTCR-WPCRMN-PPOT(I))*RF(I)*LAI/SRCR
  502 CONTINUE
      EVTR=EVS+TRC
      GO TO 170
  160 CONTINUE
      EVS=0.0
      TRC=0.0
      EVTR=0.0
      DO 161 I=1,NL
      RC(I)=0.0
  161 CONTINUE
  170 CONTINUE
      DETAIN = INTGRL (0.0, RAIN-INFILT)
      INCAP = (0.-HPOT(1))*0.5*(SATCON+COND(1)) / DIST(1)
      IF (RAIN.GT.0.0) GO TO 55
      IF (DETAIN.LE.0.0) GO TO 66
      INFILT=INCAP
      GO TO 77
   66 CONTINUE
      DETAIN = 0.0
      INFILT=0.0
      GO TO 77
   55 CONTINUE
      INFILT = INCAP
      IF (RAIN. LT. INCAP. AND. DETAIN. LE. 0.)INFILT=RAIN
   77 CONTINUE
      FLUX(1)=INFILT-EVS
      DO 100 I = 1,NL
      NFLUX(I)=FLUX(I)-FLUX(I+1)+RC(I)
  100 CONTINUE
      VOLW=INTGRL(IVOLW,NFLUX,18)
      CUMRN = INTGRL  (0.0 , RAIN)
      CUMINF = INTGRL ( 0.0 , INFILT )
      CUMEV = INTGRL ( 0.0 , EVS )
      CUMTR=INTGRL(0.0,TRC)
      CUMETR=INTGRL(0.0,EVTR)
      CUMDRN = INTGRL ( 0.0 , FLUX(NLL))
      CUMWTR = 0.0
      DO 110 I=1,NL
      CUMWTR= CUMWTR + VOLW(I)
  110 CONTINUE
      ZBHJS=IMPULS( 86400., 86400.)
      IF(ZBHJS.LT.0.5) GO TO 88
      INF(DNUM-1)=CUMINF
      RN(DNUM-1)=CUMRN
      EV(DNUM-1)=CUMEV
      TR(DNUM-1)=CUMTR
      ETR(DNUM-1)=CUMETR
```

```
            DRAIN(DNUM-1)=CUMDRN
            DINF=CUMINF-INF(DNUM-2)
            DRN=CUMRN-RN(DNUM-2)
            DEV=CUMEV-EV(DNUM-2)
            DTR=CUMTR-TR(DNUM-2)
            DETR=CUMETR-ETR(DNUM-2)
            DDRN=CUMDRN-DRAIN(DNUM-2)
         88 CONTINUE
            BALANS = CUMWTR - IWATER - CUMINF + CUMETR + CUMDRN
            Z=IMPULS(  10800.0,10800.0)
            IF(Z.LT.0.5) GO TO 99
        222 CONTINUE
            WRITE(6,1300) WINPUT(1,DNUM),TIME, XDNUM,STIME,TL
       1300 FORMAT(' JULIAN DAY NUMBER = ',F4.0,' TIME = ',F10.1,
     $     ' XDNUM = ',F11.0,' STIME = ',F7.4,'    TL= ',F4.1)
            WRITE(6,1400)
       1400 FORMAT('0 I ',5X,'DEPTH',10X,'THETA',11X,'PPOT',11X,
     $     'FLUX',9X,'NET FLUX',10X,'ROUTF',10X,'ROOTUPTAKE')
            DO 150 I=1,NLL
        150 WRITE(6,1500) I,DEPTH(I),THETA(I),PPOT(I),FLUX(I),
            NFLUX(I),RF(I),RC(I)
       1500 FORMAT( I3,7E15.4)
            WRITE(6,1600)
       1600 FORMAT(1H ////)
         99 CONTINUE
TIMER FINTIM= 864000.,PRDEL= 86400.,OUTDEL=7200.0  ,DELT=10.
PRINT JDNUM, XDNUM, DRN, DINF, DEV,DTR,DETR, DDRN, CUMWTR,...
   BALANS, CUMRN,CUMDRN,CUMINF,CUMEV,...
            CUMTR,CUMETR,DELT

PAGE SHADE = (0.15,0.35)
OUTPUT THETA(13),THETA(12),THETA(11),THETA(10),THETA(9),...
       THETA(8),THETA(6),THETA(2)
METHOD STIFF
      END
*   WEATHER INPUT DATA, STORED IN ARRAY WINPUT(13,37)
* JNM   DL    DGR TMAX TMIN DMAX DMIN   SA BEGIN END   RFT LAI  RD
INPUT
 121. 14.4  20.0 25.0 10.0 10.0  8.0  3.0  0.0  0.0  0.0  3.0  0.5
 122. 14.4  20.0 25.0 10.0 10.0  8.0  3.0  0.0  0.0  0.0  3.1  0.5
 123. 14.5  20.0 25.0 10.0 10.0  8.0  3.0  0.0 00.0 00.0  3.2  0.6
 124. 14.5  20.0 25.0 10.0 10.0  8.0  3.0  0.0  0.0  0.0  3.3  0.6
 125. 14.5  20.0 25.0 10.0 10.0  8.0  3.0  0.0  0.0  0.0  3.4  0.7
 126. 14.5  20.0 25.0 10.0 10.0  8.0  3.0  0.0  0.0  0.0  3.4  0.7
 127. 14.5  20.0 25.0 10.0 10.0  8.0  3.0  0.0  0.0  0.0  3.5  0.7
 128. 14.6  20.0 25.0 10.0 10.0  8.0  3.0  0.0  0.0  0.0  3.6  0.8
 129. 14.6  20.0 25.0 10.0 10.0  8.0  3.0  0.0  0.0  0.0  3.7  0.8
 130. 14.6  20.0 25.0 10.0 10.0  8.0  3.0  0.0  0.0  0.0  3.8  0.9
   0. 14.6  20.0 25.0 10.0 10.0  8.0  3.0
ENDINPUT
      STOP
ENDJOB
```

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APPENDIX B

MODIFIED WATBAL1

APPENIDX B

MODIFIED WATBAL1

This appendix presents the results of further simulations that were made in order to better evaluate the effects of the root uptake function inconsistency on the previous simulation results. These simulations were made using the equation:

$$RC(I) = RF(I)^{*}TRC \qquad (B-1)$$

which equates the root uptake with the transpiration. The simulation results are presented in figures B-1 through B-7. The daily values of T, E_v, and TR are shown in figures B-1 through B-3. These figures correspond to figures 2 through 4 for the original model. Comparing these figures indicates that the results are similar and that the two drying stages are evident in the new simulations. However, in the latter curves, the falling stage commences sooner and the drop in ET and T are quicker and larger. Another difference is that E_v eventually falls below the T value in the modified rersults. The cumulative ET response curves are presented in figure B-4.

The change of ET for 10 days with the daily radiation amount is shown in figure B-5 which corresponds to figure 7. Comparing the results of the two models shows that the modified model has a different response in the intermediate and dry moisture regimes. In particular, the dry boundary does not increase as rapidly with increasing DGR values. In the intermediate zone, the ET for days increases up to a certain value and then remains more or less constant above that DGR value. The humps on the curves for θ = .30, .35, and .40 appear to reflect the rapid falloff from the constant stage. Increases of DGR beyond 30 mJ/m^2 should result in the ET for 10 days eventually increasing again. This is suggested by the curves in figures B-6 and B-7.

The manner in which ET is divided into T and E_v is shown in figures B-5 and B-6 (note change of scale in figure B-6). The response curves in these figures indicate that the E_v increases regularly with increasing DGR. T increases up to a certain value of DGR, and then it increases in DGR, apparently reflecting the change from the constant to the falling transpiration stage. The indications are that it should increase again for further increases of DGR (see figure B-7). The evapotranspiration on the 10th day, as related to DGR

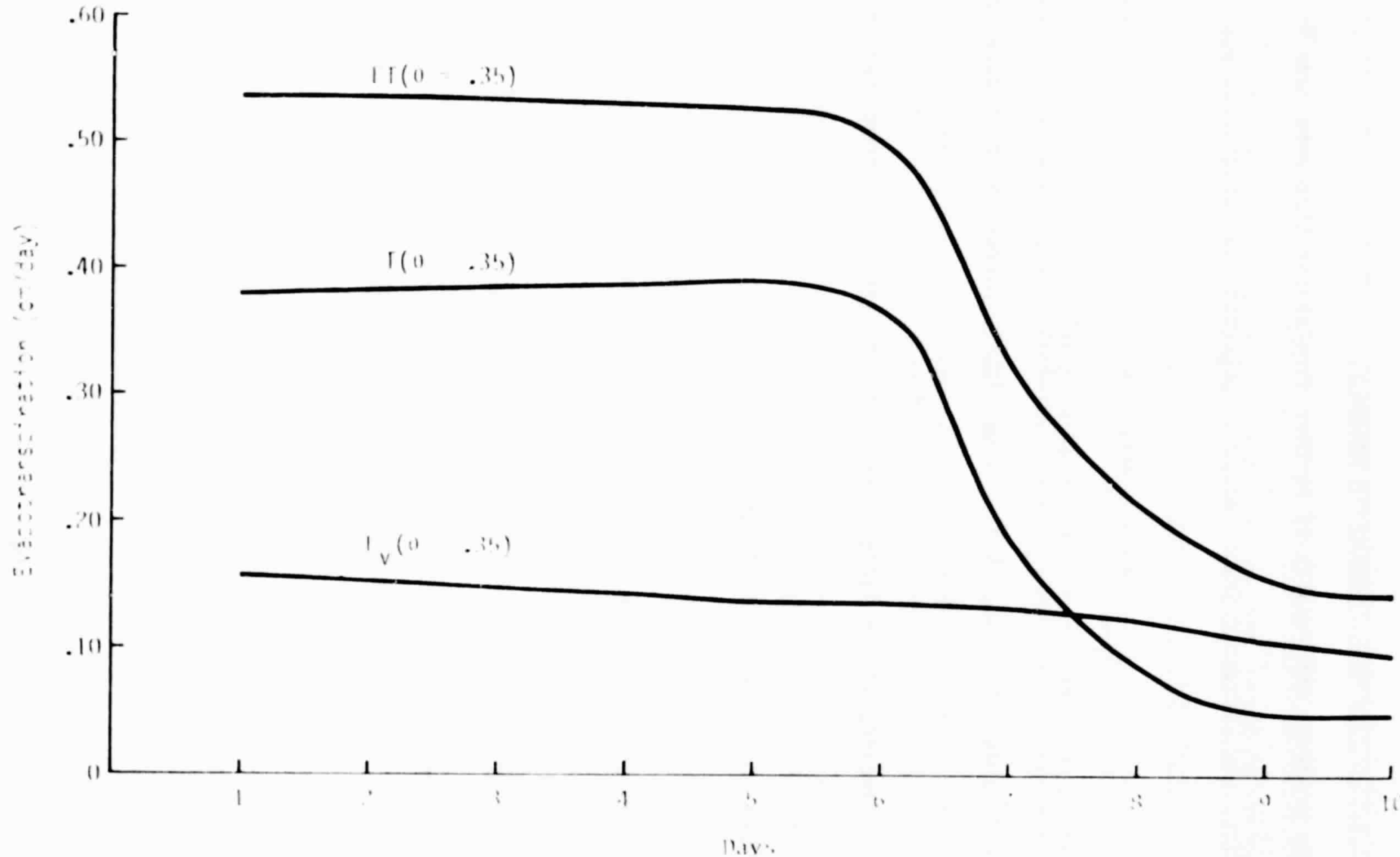

Figure B.1. The daily ET, T, and E_V for wet soil water conditions using the modified Van Bavel model.

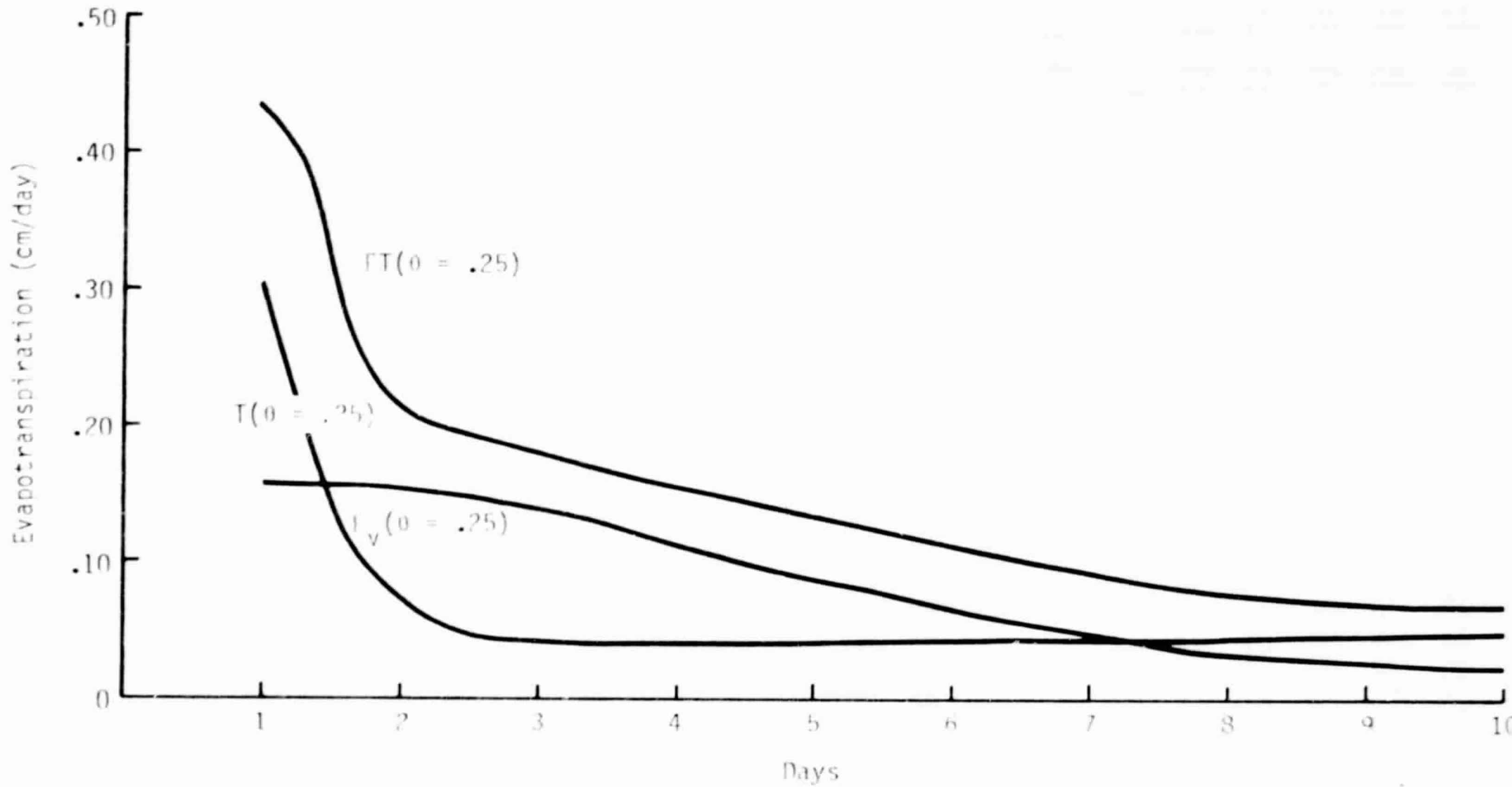

Figure B-2.- The daily ET, T, and E_v for intermediate soil water conditions using the modified Van Bavel model.

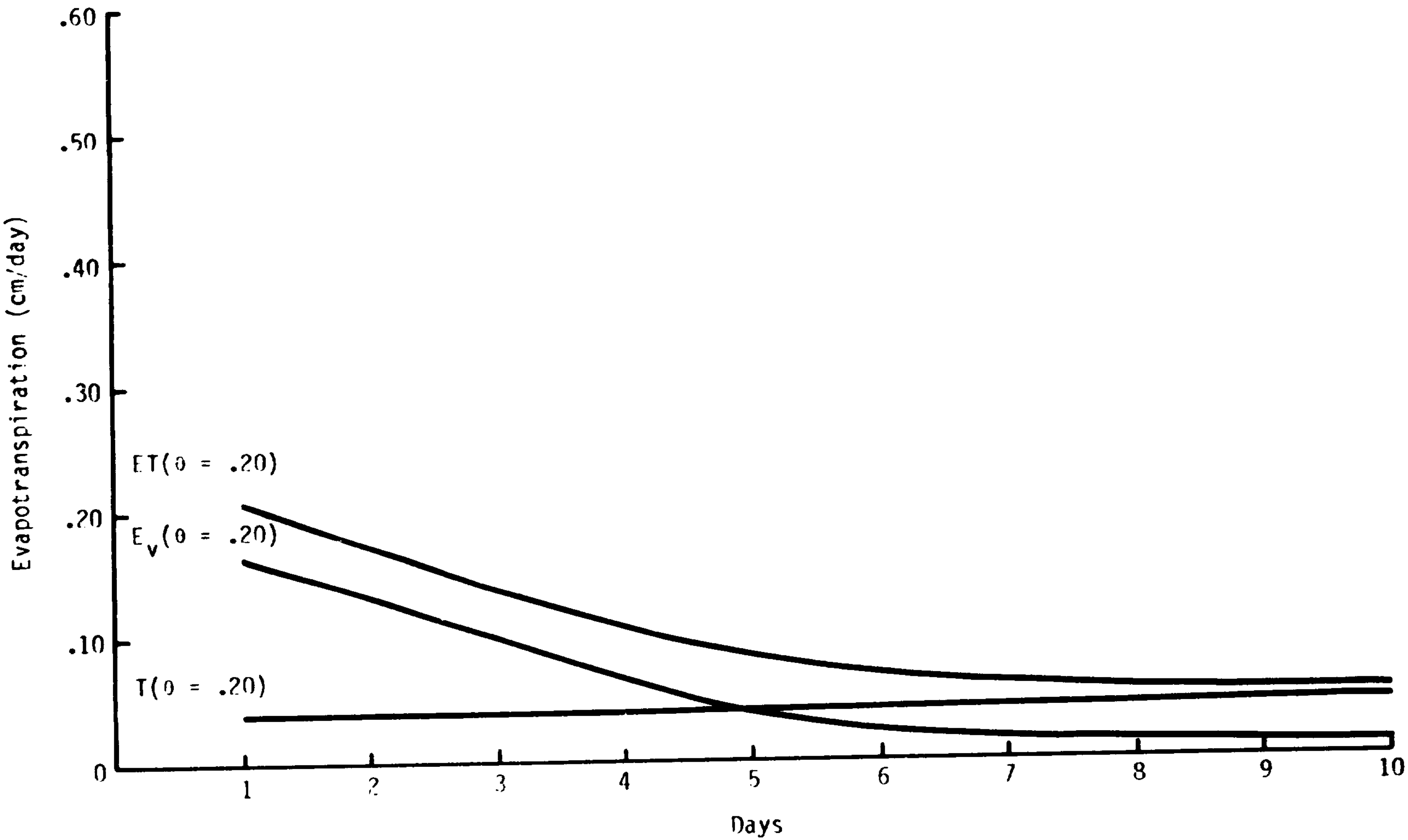

Figure B-3.- The daily ET, T, and E_v for dry soil water conditions using the modified Van Bavel model.

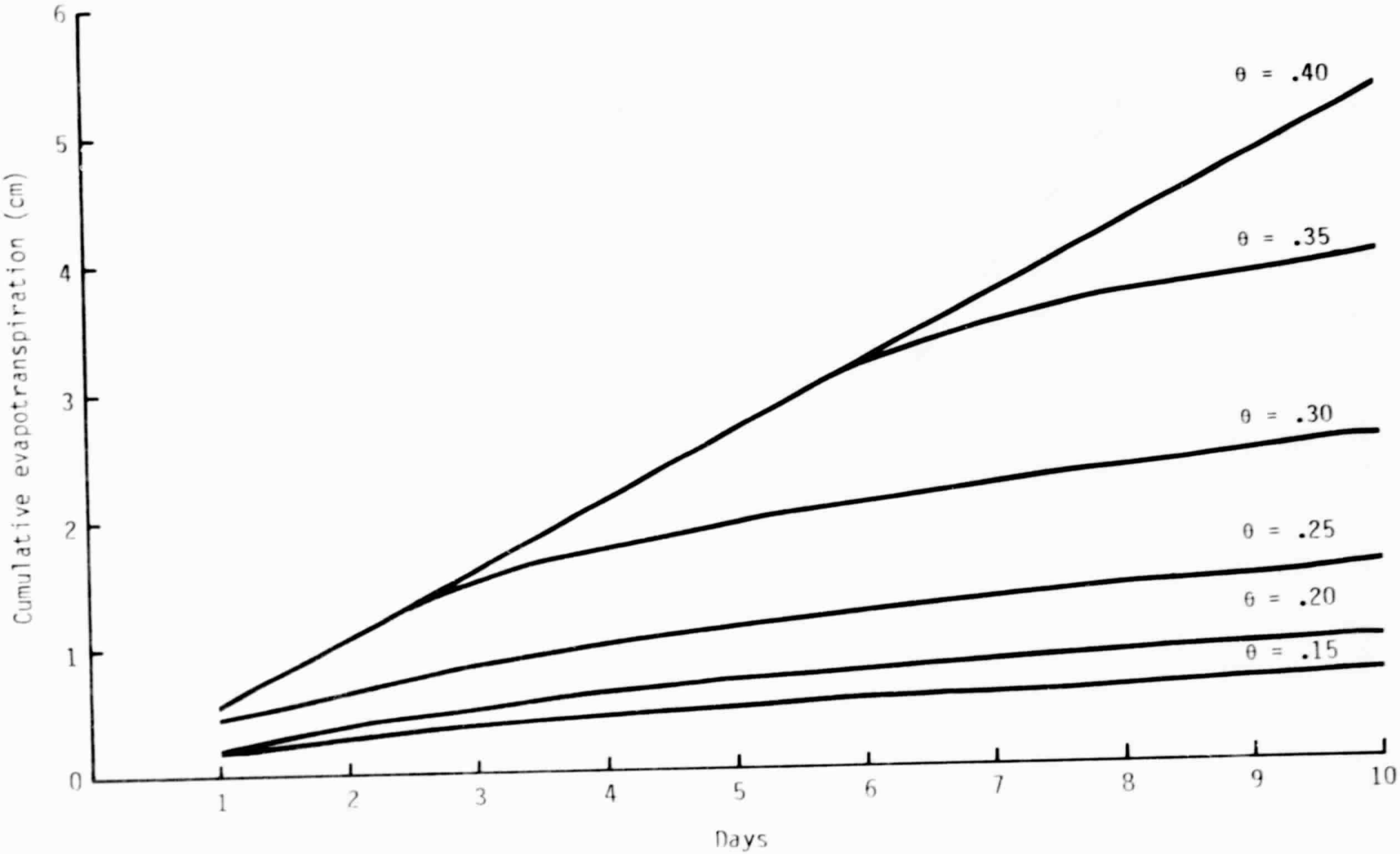

Figure B-4.- The cumulative ET versus the initial soil water profile using the modified Van Bavel model.

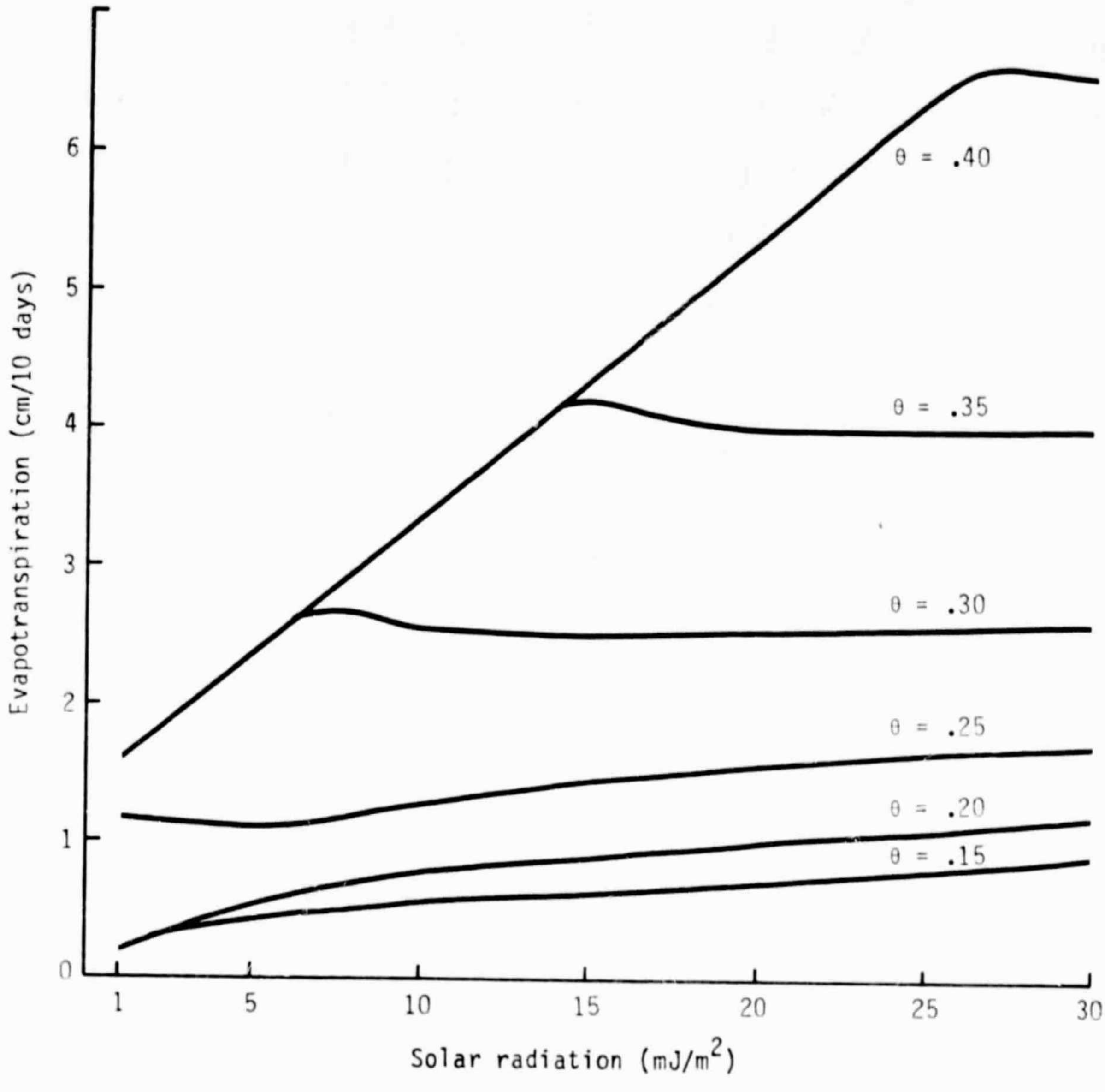

Figure B-5.- The change of ET for 10 days versus the daily radiation amount and the initial soil water profile using the modified Van Bavel model.

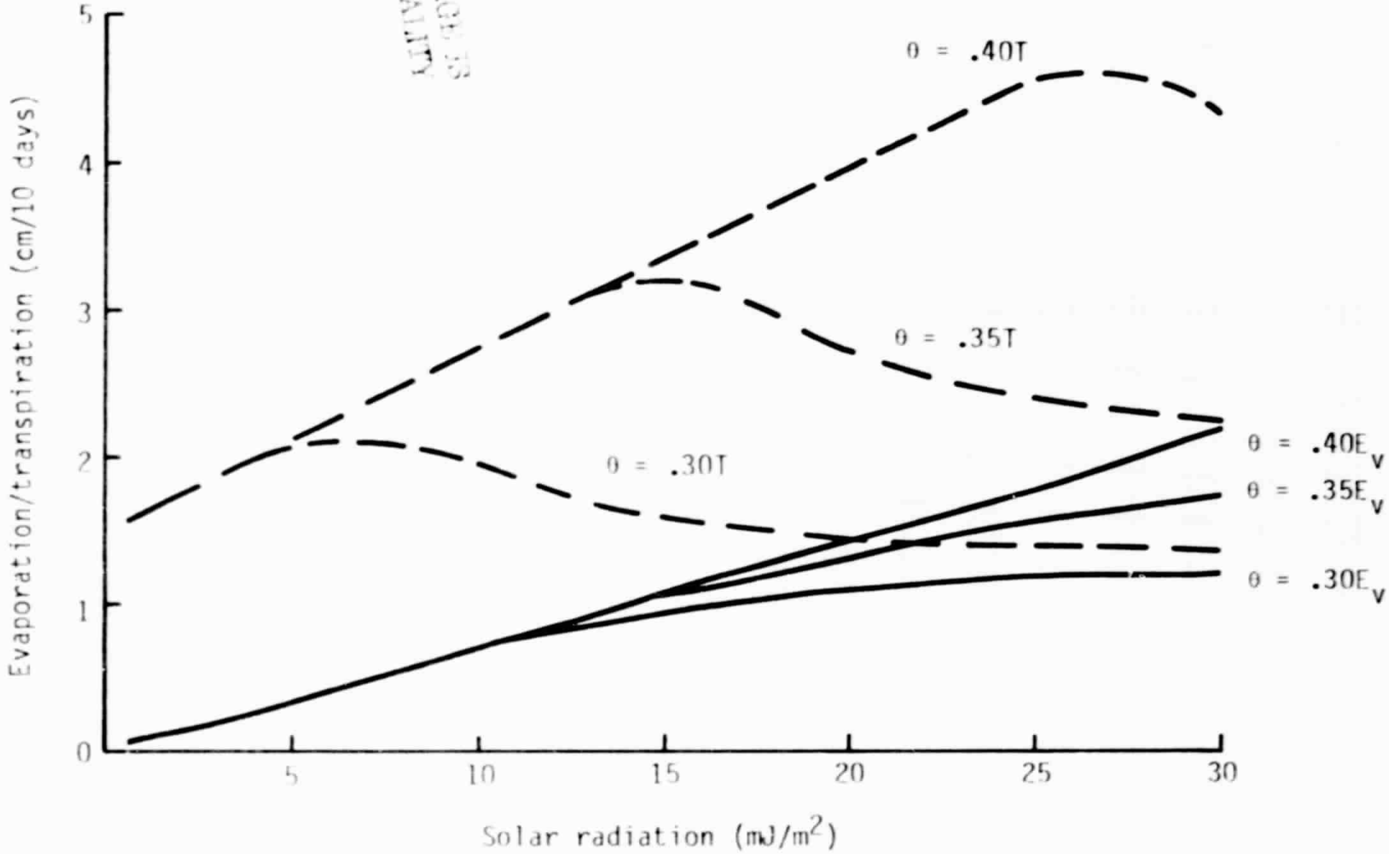

Figure B-6.- The variation of the E_v and T for 10 days versus solar radiation for θ = .40, .35, and .30 using the modified Van Bavel model.

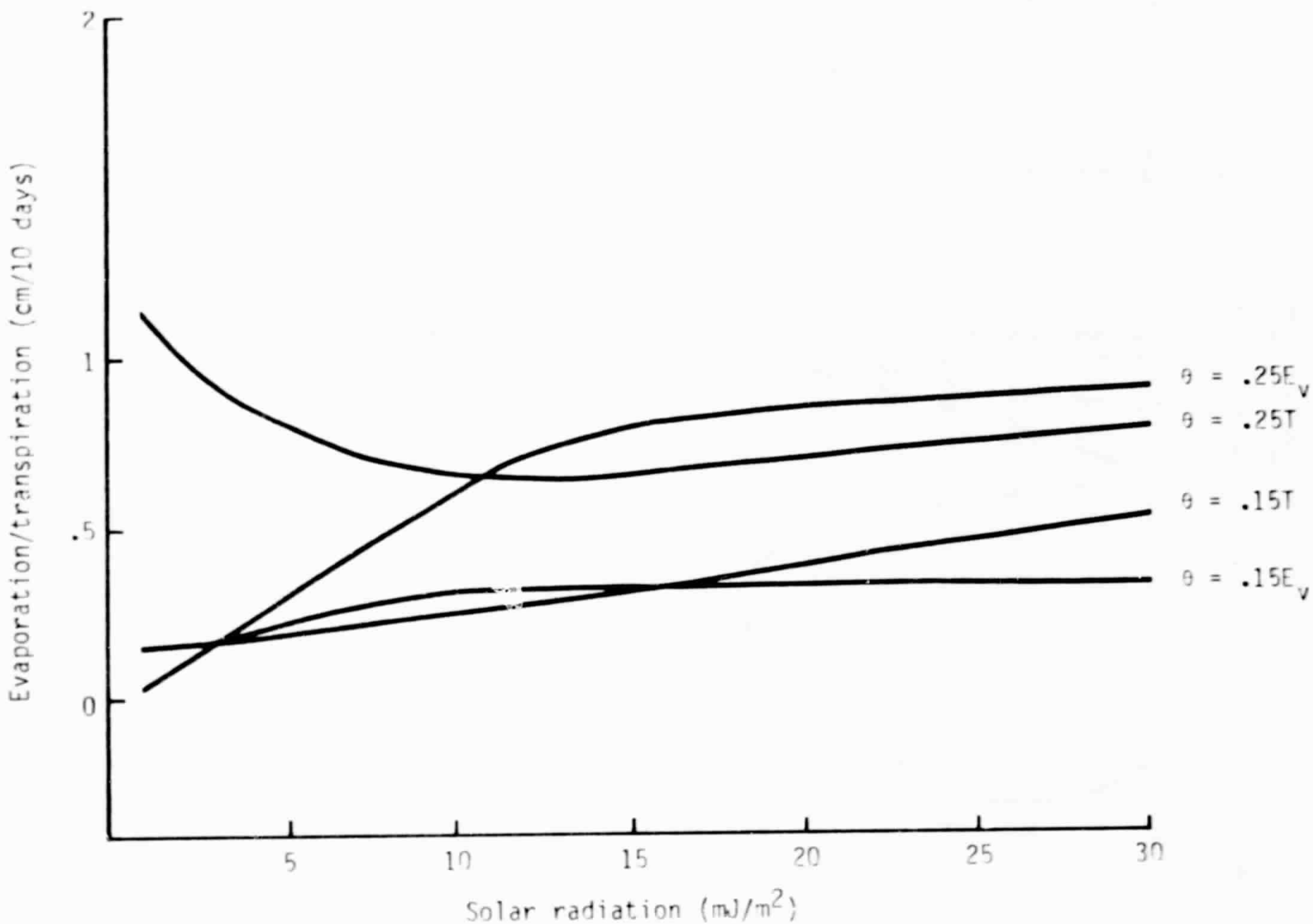

Figure B-7.- The variation of the E_v and T for 10 days versus solar radiation for θ = .25 and .15 using the modified Van Bavel model.

and θ, is illustrated in figure B-8. The curves are similar to those presented by Denmead and Shaw (ref. 12) which were obtained from experiments with corn grown in large pots.

The ET for 10 days for different LAI/RD values are shown in figure B-9. Comparing these results with those in figure 12 indicates that the dry regime response is now more logical. The intermediate regime has also changed, and progressively higher ET for 10-day values occur as the LAI/RD values increase. How these values are divided into T and E_v are shown in figure B-10. As would be expected, T increases with increasing LAI/RD, while E_v decreases.

The final comparison is in the 10-day profiles. These are shown, for the regression model, in figures 16 and B-11. The model profiles in figure B-11 are more realistic than those presented in figure 16. These latter profiles reflect the fact that water is apparently simulated as being taken from lower soil layers and transferred to surface layers by the root system. Comparing figure B-12 for the Ghosh model with the similar conditions in figure 20 indicates that the same types of changes are indicated.

These comparisons of the simulation results of the modified Van Bavel model with the results of the original model show that some significant differences are indicated in the output. These differences become greater as drier regimes are simulated, and they generally appear to reflect the indications that water in the original model is simulated as being extracted from the soil by the lower parts of the root system and returned to the soil in the near surface layers.

In addition, the results from the modified Van Bavel model appear more realistic in the drier regimes than the original model when the experimental field data are considered.

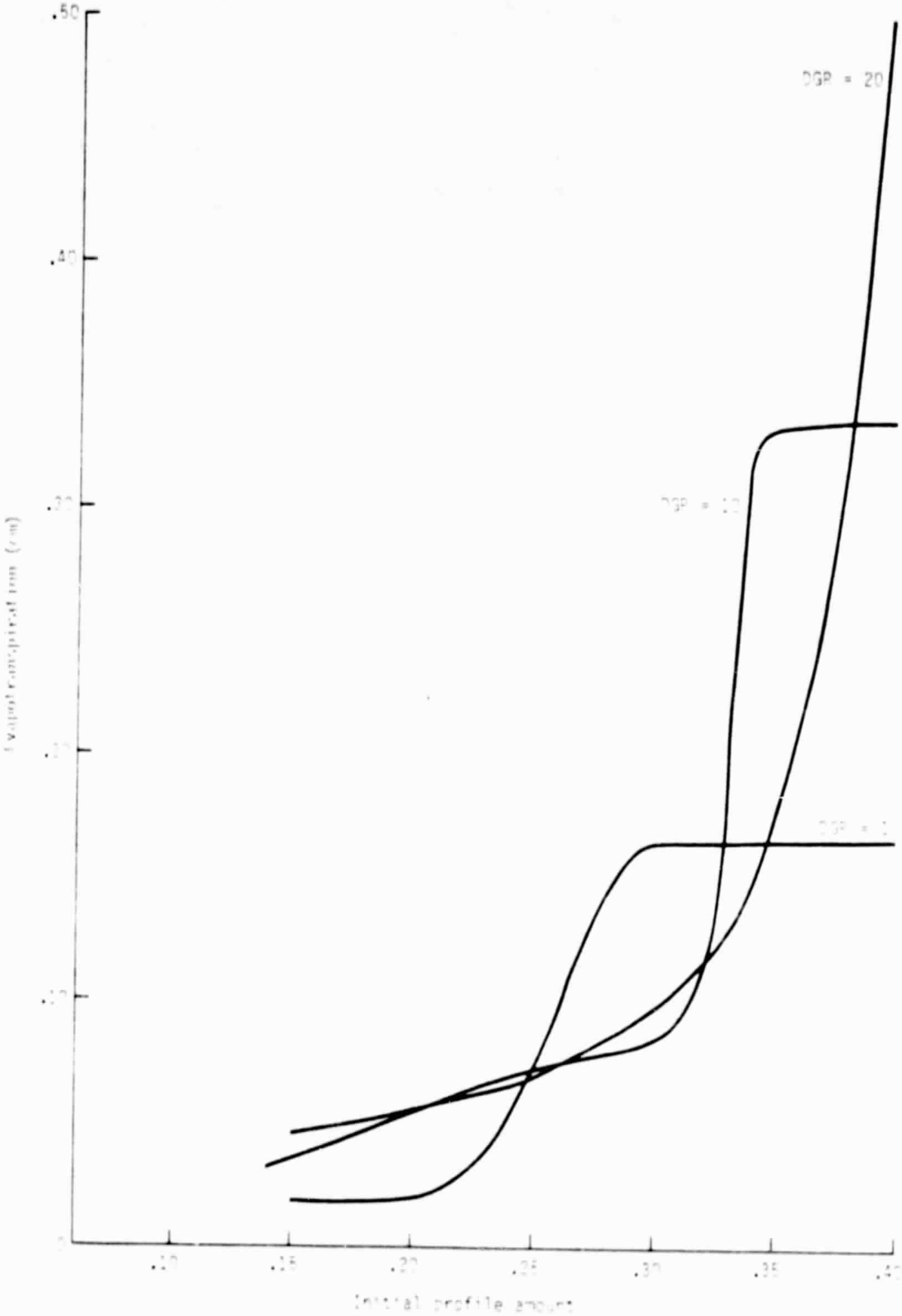

Figure B-8.- The ET on the 10th day versus solar radiation and initial soil water profile using the modified Van Bavel model.

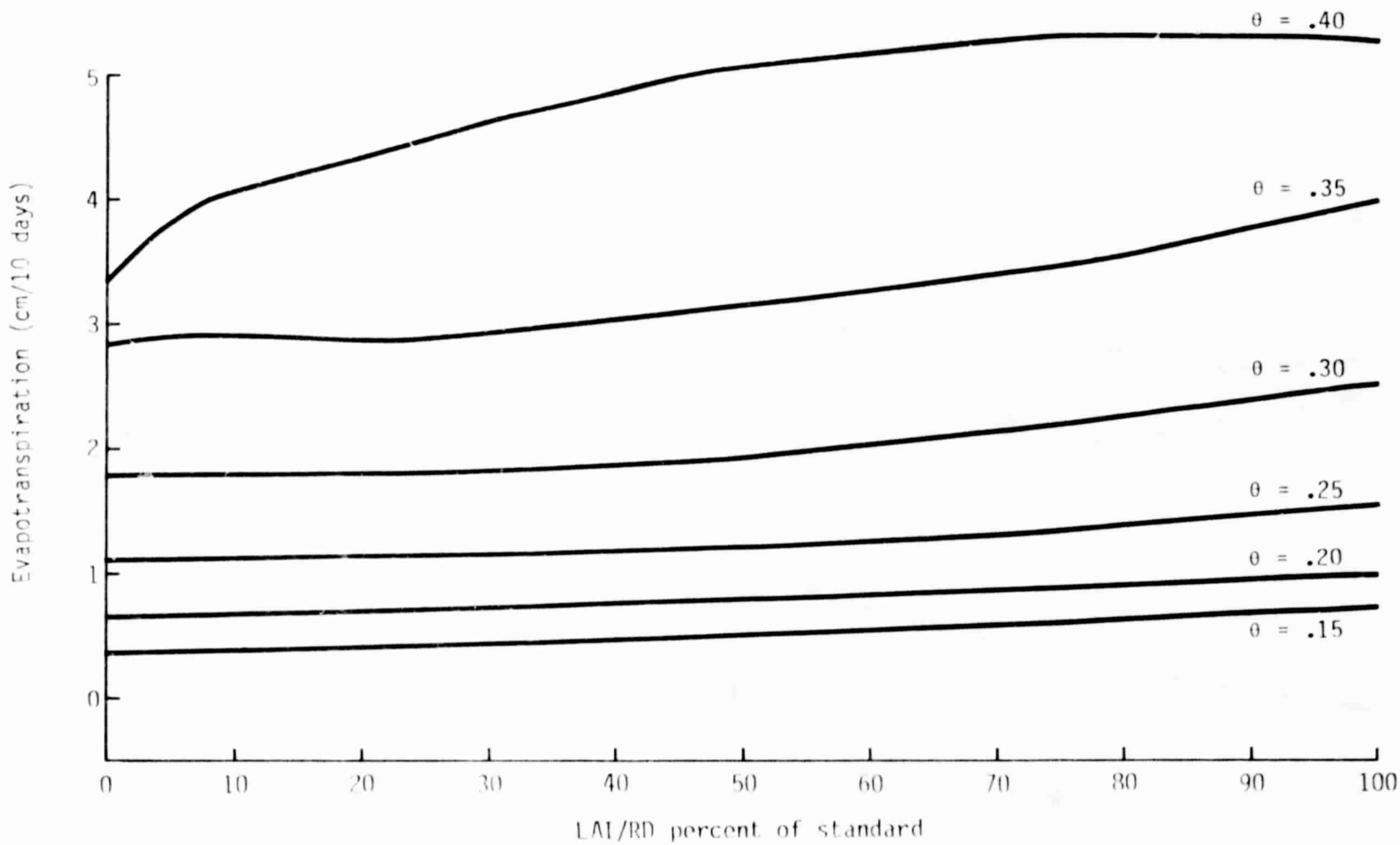

Figure B-9.- The ET for 10 days for different LAI/RD values as a percentage of the standard and initial soil water profile using the modified Van Bavel model.

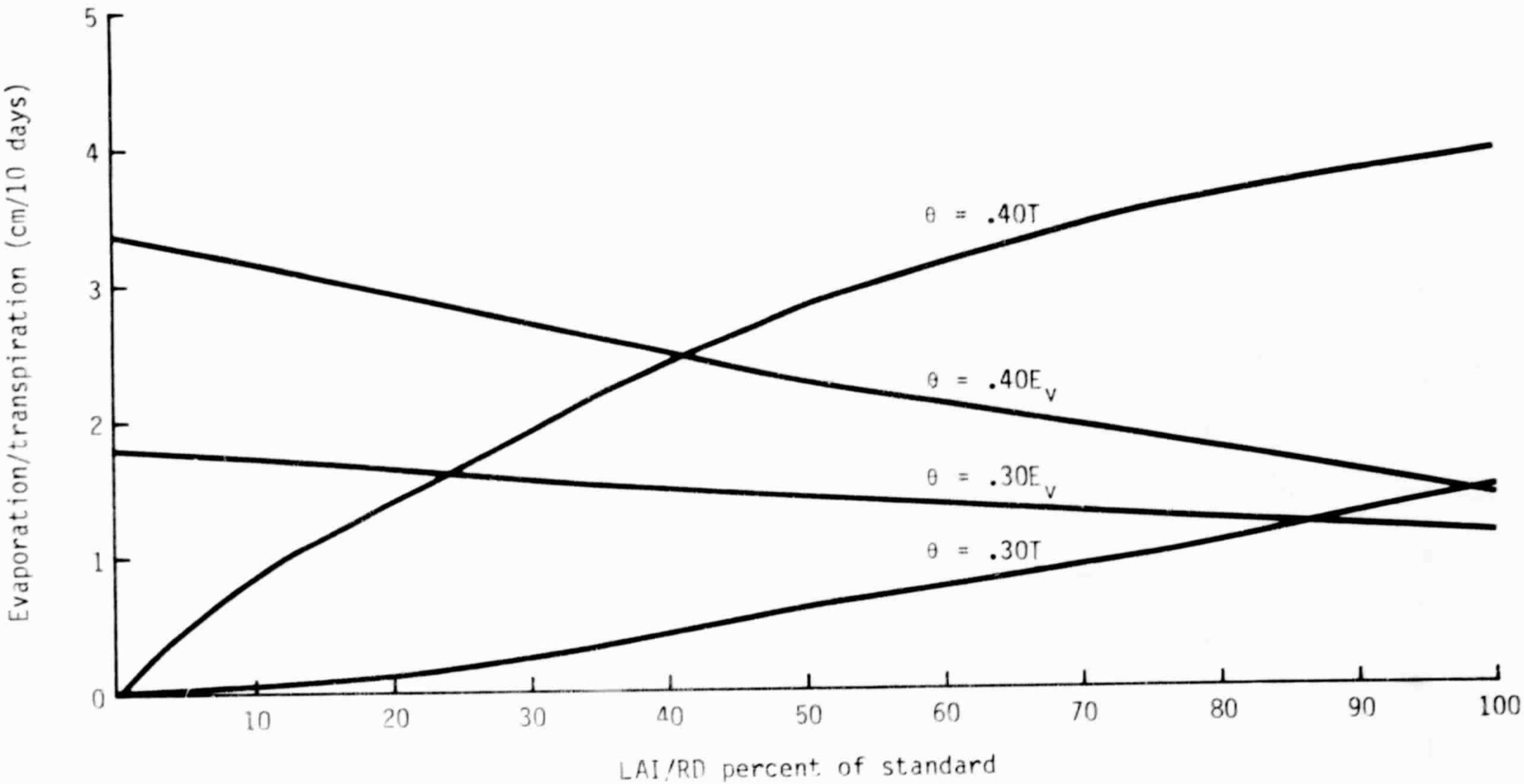

Figure B-10.- The E_v and T for the 10-day period versus the LAI and RD as a percentage of the standard for θ = .40 and .30 using the modified Van Bavel model.

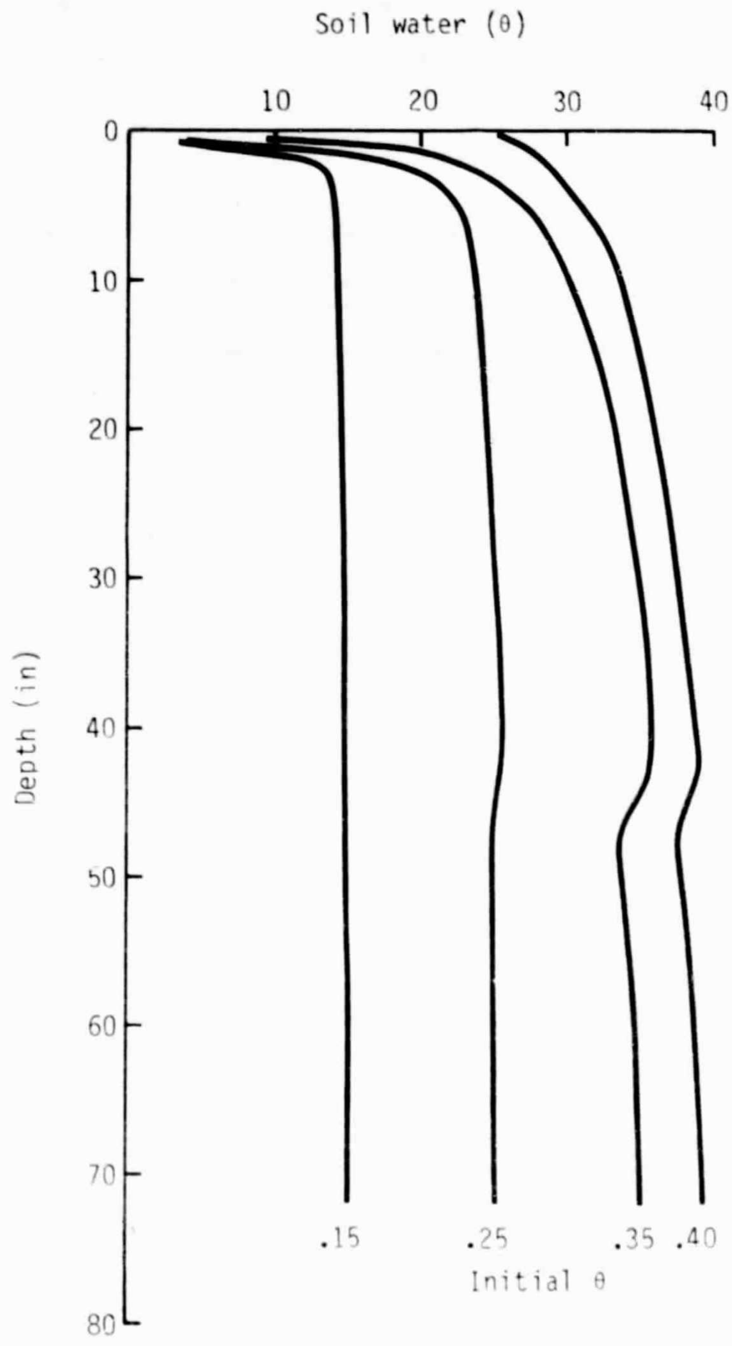

Figure B-11.- The soil water profile using the modified Van Bavel model on the 10th day.

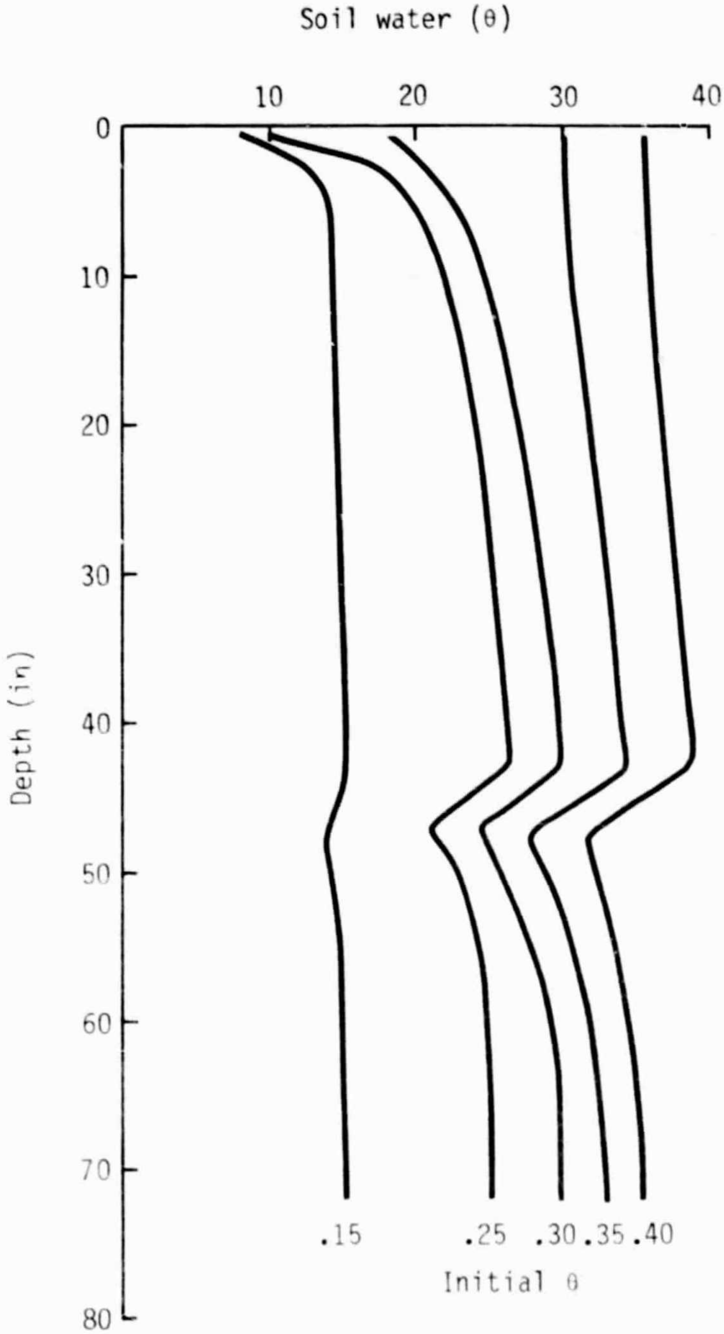

Figure B-12.- The soil water profile characteristics on the 10th day using the modified Van Bavel model and Ghosh's model for soil water.

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