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MODEL FOR ESTIMATING SOIL WATER FLOW, WATER CONTENT, EVAPOTRANSPIRATION AND ROOT EXTRACTION

by

Musa N. Nimah

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Department of Soil Science and Biometeorology

in

Soil Physics

Approved:

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Musa Nimah

Musa N. Nimah

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NOTATION

A	= Area over which the weight of lysimeter is distributed (L^2)
A_1	= Area of the bottom of the lysimeter (L^2)
$A(z)$	= Root extraction term (L/T)
a	= Root radius (L)
D	= Soil water diffusivity = $K\ dh/d\theta$. (L^2/T)
E_a	= Evapotranspiration or precipitation rate (L/T)
E_f	= Potential evaporation rate (L/T)
E_p	= Potential evapotranspiration rate (L/T)
H	= Hydraulic head (L)
H_{root}	= Effective root water potential at the soil surface ($z = 0$). (L)
h	= Soil matric potential (L)
h_0	= Initial soil matric potential (L)
h_{plant}	= Water potential within the plant root (L)
h_{soil}	= Total soil water potential (L)
$h(z)$	= Soil matric potential at depth (z). (L)
i	= Subscript for depth increment; usually appears along with j
I_0	= Radiation count with no interference
j	= Subscript for time increment
K	= Hydraulic conductivity (L/T)
K_c	= Crop factor
q	= Flux of water at the root surface (L^3/T)
r	= Radial distance from the axis of the root (L)
R	= Resistance to water movement in the soil (T/L)

R	=	Also ratio of neutron counts in soil to standard count
R	=	Also total incoming solar radiation ($Cal/L^2/T$)
R_c	=	Flow coefficient
R_L	=	Net longwave back radiation ($cal/L^2/T$)
R_n	=	Net radiation ($Cal/L^2/T$)
$RDF(z)$	=	Proportion of total active roots in depth increment Δz (M/M)
RRES	=	Root Resistance = $(1 + R_c)$
$S(z)$	=	Water extraction rate (L/T)
$S(z)$	=	Also salt (osmotic) potential at depth z (L)
T	=	Average transpiration rate (L/T)
T_{max}, T_{min}	=	Maximum and minimum air temperature, respectively. (°C)
t	=	Time (T)
V	=	Vertical length of root system (L)
W	=	Rate of water uptake/unit volume of soil (L/T)
z	=	Vertical distance (L)
Δh	=	Matric potential difference (L)
Δh	=	Also corrected change in height of fluid (L)
Δz	=	Depth increment (L)
θ	=	Volumetric water content (Fraction). (L^3/L^3)
θ_0	=	Initial volumetric water content (Fraction. (L^3/L^3)
ρ	=	Bulk density of material (M/L^3)
ρ	=	Also reflection coefficient
ρf	=	Density of the fluid (M/L^3)
ρw	=	Density of the water (M/L^3)
γ	=	Euler's constant = 0.57722 ...

μ = Mass absorption coefficient

μ_s = Mass absorption coefficient of dry soil

μ_w = Mass absorption coefficient of water

ABSTRACT

Model for Estimating Soil Water Flow,

Water Content, Evapotranspiration

And Root Extraction

by

Musa N. Nimah, Doctor of Philosophy

Utah State University, 1972

Major Professor: Dr. R. J. Hanks
Department: Soil Science and Biometeorology

A mathematical model was developed to predict water content profiles, evapotranspiration, water flow from or to the water table, root extraction and root water potential at the surface as functions of time under unsteady state conditions.

The model was tested in the field at The Hullinger Farm near Vernal, Utah, in 1970 and 1971. Comparison of water content-depth profiles show excellent agreement at the end of a 9-day run in 1970 on oats seeded to alfalfa. In 1971 with alfalfa as the crop, the data show best agreement, between predicted and computed water content-depth profiles, 48 hours after any water addition. The poorest agreement for both crops was right after irrigation.

The computed cumulative ET was 4.9 cm which was 0.4 cm less than actual (measured) ET, during the 9-day period in 1970. In 1971, the actual and measured ET were the same for the whole season. This agreement may be partially due to the "forcing" of the water removal by ET to be the same as measured.

In 1970, the computed cumulative upward flow from the water table was 2.20 cm which was 0.1 cm greater than the actual for the 9-day period. In 1971, the cumulative upward water flow from the water table was 4.80 cm which was 3.20 cm greater than the calculated for the whole season of 116 days.

(131 pages)

INTRODUCTION

The water quality problems associated with irrigation return flow are of special concern, because irrigated agriculture is the largest consumer of public water supplies in western United States. Of the water applied to the field for irrigation, a large portion is stored in the root zone and transpired by the crop or evaporated from the soil. The water not stored may percolate below the root zone, and/or may run off the land surface during irrigation. Deep percolating and runoff water constitute the irrigation return flow from an irrigated field.

The evapotranspiration rate of a crop plays an important role in determining the quality and quantity of irrigation return flow. The most important factor, in the relationship of evapotranspiration to irrigation return flow, is that the water consumed by the crop is relatively pure, the dissolved salts being left behind in the soil. Thus, the process of evapotranspiration has the effect of concentrating the total salt load in the fraction of the water returned to the stream as return flow.

During evapotranspiration water moves from the soil through the plant to the atmosphere along a path of continuously decreasing potential. The movement of water along this path is affected by a complex set of interactions and processes which occur simultaneously at different rates. This path is a continuum involving soil, plant and atmosphere (SPAC) and includes a number of distinct segments, each of which can be described in terms of a flow equation. The first segment is the flow of water in the unsaturated soil surrounding the root.

The second segment is the flow of water in the plant to the evaporative surface. The third segment is the flow of water from the evaporative surface to the atmosphere, in vapor form. The flow of water in any segment is influenced by properties of the other segment.

Evapotranspiration and evaporation from a free water surface have been related to each other through many empirical formulas. Due to the development of the crop and to a possible lack of water, evapotranspiration has, under many conditions, little direct relation with the evaporation from a free water surface. It is therefore necessary to take all the factors governing evapotranspiration from a crop, into account to estimate water uptake by the plant. The most important factors can be grouped under soil properties, plant properties and climatological properties.

1. Soil properties: These include the matric potential, hydraulic conductivity, diffusivity and water capacity relations to the water content.
2. Plant properties: These include the plant root distribution as a function of depth plus percent plant cover.
3. Climatological properties: These properties govern the evaporation rate from soil and transpiration rate by plant. They include radiation, temperature, wind velocity and humidity.

Each of the factors may act as a limiting factor to the water movement through the soil-plant-atmosphere continuum (SPAC). For example, when the soil is dry, although other factors are favorable, water movement from the soil to the root is hindered due to the low soil water potential. Similarly for plants, if the stomata are closed

water movement is stopped. At night, where there is no radiation, water movement stops because there is no demand at the evaporative surface.

The overall objective of this study is to manage water in the SPAC, taking into consideration all related factors. This is closely related to a similar study by Gupta (1972) on salt flow in the soil because salt and water flow are so closely linked. Both studies are a part of a general study on the control of quantity and quality of irrigation return flow from irrigated fields.

Objectives

The specific objectives of this study were:

1. To develop a mathematical model to determine the relation of soil water and root distribution to water uptake, soil water content profiles, drainage, evapotranspiration and soil water flow under irrigated and non-irrigated conditions.
2. To develop a computer program to solve the mathematical model. The program should predict evaporation, transpiration, soil moisture change, runoff, infiltration, drainage and water content profiles as a function of time.
3. To test the developed model under field conditions, where the appropriate soil, plant, and atmosphere components have been measured.

REVIEW OF LITERATURE

A current approach to the field soil water cycle is based on recognition that the field and all its components--soil, plant, and atmosphere taken together--form a physically unified and dynamic system (Gardner, 1960; Cowan, 1965) in which various flow processes occur sequentially like links in a chain. This unified system has been called "SPAC" (for "soil-plant-atmosphere-continuum") by J. R. Philip (1966). In this system, flow takes place from higher to lower potential, with the concept "water potential" equally valid and applicable in soil, plant, and atmosphere alike.

To characterize the SPAC physically, therefore, it is necessary to evaluate the potential of water and its change with distance and time along the entire path of water movement (Hillel, 1971). The flow rate is everywhere inversely proportional to an appropriate resistance. The flow path includes the water movement in the soil toward the roots, absorption into the roots, transport in the roots to the stems through the xylem to the leaves, evaporation in the intercellular air spaces of the leaves, vapor-diffusion through the stomatal cavities and openings to the quiescent air layer in contact with the leaf surface and through it to the turbulent boundary layer, whence the vapor is finally transported to the external atmosphere.

Soil water flow to plant root has been studied by a number of investigators. The studies of Philip (1957), Gardner (1960), and Molz et al. (1968) consider the radial flow of water to a single root. However, other studies (Ogata, Richards, and Gardner, 1960; Gardner,

1964; Whistler, Klute, and Millington, 1968; Molz and Remson, 1970, 1971; and Molz, 1971) deal with the removal of moisture by the root zone as a whole without considering explicitly the effects of individual roots. For convenience, the term "microscopic" is used for the flow process in the vicinity of a single root, and "macroscopic" for the overall moisture extraction process in an entire root zone.

Models for Root Extraction

Soil water potential decreases as soil water content decreases. The soil will deliver water to the root as long as the water potential in the root is maintained less than in the soil. However, as a root extracts water from the soil in contact with it, the water potential in the soil contact zone may decrease, as well as the hydraulic conductivity. Water uptake may decrease, assuming the root water potential stays constant, unless additional water can move in from the farther reaches of the soil in direct contact with the root. In order for this additional water to become available to the plant, not only must the soil water potential be greater than the root water potential, but the hydraulic conductivity of the soil must be large enough so that water will move toward and into the root at a rate sufficient to compensate the plant for its own loss of water to the atmosphere by transpiration.

These principles have been applied on both a microscopic and a macroscopic scale. These two approaches will now be discussed in detail.

Microscopic Approach or Single Root Model

In this approach the details of the flow about a single root are examined. On the assumption that a typical root can be represented by an infinitely long, narrow cylinder of constant radius and water - absorbing characteristic (effectively a line sink), and that soil water movement toward the root is radial, the appropriate form of the flow equation is:

$$\frac{\partial\theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(rD\frac{\partial\theta}{\partial r}) \qquad [1]$$

where θ is volumetric soil water content, D is diffusivity, t is time, and r is radial distance from the axis of the root. Assuming constant flux at the surface, Gardner (1960) solved this equation subject to the following initial and boundary conditions:

$$\theta = \theta_0 \qquad h = h_0 \qquad t = 0$$

$$q = 2\pi aK\frac{\partial h}{\partial r} = 2\pi aD\frac{\partial\theta}{\partial r} \qquad r = a, \qquad t > 0 \qquad [2]$$

where a is the root radius, h is matric potential, K is hydraulic conductivity, and q is the rate of water uptake by the root or the flux of water at the root surface expressed as volume of water per unit length of root per unit time. The solution of equation [1] subject to equation [2] for constant D and K and sufficiently long time is:

$$h - h_0 = \Delta h = \frac{q}{4\pi K}(\ln\frac{4Dt}{r^2} - \gamma) \qquad [3]$$

where γ is Euler's constant = 0.57722 ... . From this equation, it is possible to calculate the gradient Δh that will develop at any time

between the soil at a distance (r-a) from the root (i.e., the initial soil water potential h_0) and the matric potential h at the root-to-soil contact zone. Since diffusivity, time, and radius at the root occur in a logarithmic term in equation [3], Δh is much less sensitive to these three factors than to q and K. Gardner (1960) showed that a ten thousand-fold variation in D would cause only about a nine-fold variation in Δh, hence the assumption of an average constant value of D does not introduce a serious error. Similarly, Gardner showed that root size is not extremely important; the root diameter should be important only when resistance to water entry in the root is large compared with resistance to water movement in the soil. This is probably the case only in wet soils. Moreover, the variation in K, due to Δh, was considered to be no larger than the uncertainties in determination of K, so that the assumption of a constant K was valid for not too large K. Equation [3] shows that the gradient Δh, or the increase of soil water potential above the initial value, is directly proportional to the rate of water uptake and inversely proportional to the hydraulic conductivity of the soil. The root water potential can, therefore, be expected to depend on these two factors as well as on the average soil water potential. Hence, when soil water potential is high and conductivity high, Δh is small and the potential in the root will not differ markedly from the potential in the soil. When soil water potential decreases and soil hydraulic conductivity decreases, the potential difference (or gradient) needed to maintain the same flow rate must increase correspondingly. As long as the transpiration of the plant is not too high, and as long as the hydraulic conductivity of the soil is adequate and the density of the roots is sufficient, the

plant can extract water from the soil at the rate needed to maintain normal activity. However, the moment the rate of extraction drops below the rate of transpiration (either because of high evaporative demand by the atmosphere, and/or because of low soil conductivity, and/or because the root system is too sparse), the plant necessarily loses water, and if it cannot adjust its root water potential or its root density so as to increase the rate of soil water uptake, the plant may suffer from loss of turgor. This situation will sooner or later cause the plant to wilt.

Limitations of the Microscopic Approach

The limitations of the microscopic approach are:

1. The diffusivity, D, and hydraulic conductivity, K, of the soil were assumed constant (Gardner, 1960), while they change as soil water and salt concentration change with time and depth.
2. The model has been based on the assumption that the roots are uniformly distributed in the rooting zone, and that the average soil water potential is similarly uniform within the rooting zone (Gardner, 1960; Molz et al., 1968). In actual fact, root systems in the field are seldom, if ever, uniform with depth.
3. Another limitation of the microscopic approach is the determination of the correct boundary condition at the root surface. Most authors have used either a constant flux condition (Gardner, 1960) or a constant head condition (Molz et al., 1968). The correct condition would probably be some combination of both that varied temporally (Molz and Remson, 1970).

Moreover, if an attempt is made to treat realistically more than one root at a time, it becomes very difficult to specify the geometry correctly. An added difficulty is measuring the necessary variables with macroscopic instruments.

Based on the microscopic approach, the usual method for studying the composite soil-plant system has been to consider flow to a single "typical root." The results are then multiplied by an "average" root density to obtain generalizations concerning the entire root-plant system (Gardner, 1960; Cowan, 1965).

Macroscopic Approach or Bulk Root Model

In this model the flow to individual roots is ignored and the overall root system is assumed to extract moisture from each differential volume of the root zone at some rate. At a given point, this rate can depend on position in a coordinate system, water content, soil conductivity, time, etc. The water-removing roots may then be represented as an extraction (sink) term in the soil water flow equation.

Ogata, Richards, and Gardner (1960); Gardner (1964); Whistler et al. (1968); Molz and Remson (1970, 1971); and Molz (1971) have considered the macroscopic approach. Gardner (1964) modified equation [3] from single root system to an entire root system:

$$W = (h_{plant} - h_{soil})/R \qquad [4]$$

where W is the rate of water uptake per unit volume of soil, h_{plant} is water potential within the plant root, h_{soil} is the total water potential in the soil, and R is the resistance to water movement in the soil, R_s, and the plant, R_p. In specifying R one can assume that the soil

and the plant resistance can be added in series so that $R = R_p + R_s$. Gardner and Ehlig (1962) suggested that R_p may be small compared to R_s; therefore, it is assumed to be negligible. According to this, Gardner (1964) assumed that the water potential is uniform throughout the entire root system at any one time. On the other hand, Molz and Remson (1970) devised an extraction term that depended only on depth and transpiration rate. They used an empirical rule, given by Danielson (1967) that 40 percent, 30 percent, 20 percent and 10 percent of the total transpiration requirements comes from each successively deeper quarter of the root zone. Molz and Remson (1970) considered these numbers 40, 30, 20, and 10 of no special significance but they regarded them as "reasonable" quantities to write their root extraction term:

$$S(z) = -\frac{1.6T}{v^2} z + \frac{1.8T}{v} \qquad 0 \leq z \leq v \qquad [5]$$

where S(z) is the water extraction rate per unit volume of soil, z is the vertical distance positive downward, v is the vertical length of the root system, T is the transpiration rate per unit area of soil surface. In some cases, T is interpreted as an "average" transpiration rate.

The total water extraction rate from a volume of soil of unit cross section bounded by the horizontal planes $z = z_1$ and $z = z_2$ where $z_1 < z_2$ is:

$$\int_{z_1}^{z_2} S(z)dz \qquad [6]$$

Because the extraction rate from the root zone equals the transpiration rate, then:

$$T = \int_0^v S(z)dz = -\frac{1.6T}{v^2}\frac{z^2}{2}\Big|_0^v + \frac{1.8Tz}{v}\Big|_0^v. \qquad [7]$$

It can be verified that [5] meets the stated percentage requirements by integrating over the appropriate portions of the root zone. To account for root systems that are growing so that $v = v(t)$, Molz and Remson (1970) generalized equation [5] to:

$$S(z,t) = -\left(\frac{1.6T}{(v(t))^2}\right)z + \left(\frac{1.8T}{v(t)}\right). \qquad [8]$$

Combining equation [8] with the general flow equation in one dimension, and assuming steady state conditions, they got the partial differential equation:

$$0 = \frac{\partial}{\partial z}\left(D\frac{\partial\theta}{\partial z}\right) - \frac{\partial K}{\partial z} - (az - b) \qquad [9]$$

where D is diffusivity = $K\ \partial h/\partial\theta$, h is matric potential, θ is volumetric water content, $a = -1.6T/v^2$, and $b = 1.8T/v$. Equation 9 was applied to the data from an experiment of Gardner and Ehlig (1962) and yielded reasonable results.

Limitations of the Macroscopic Approach

The macroscopic approach has been studied under controlled experiments, but it has not been widely used and knowledge of its utility and behavior is limited under field conditions. Other limitations of the macroscopic models that have been studied are:

1. A uniform root distribution and water potential were assumed throughout the root system at any one time (Gardner, 1964). These assumptions rarely exist under field conditions. It was also assumed that the plant resistance to water movement was negligible compared to the soil resistance to water-movement (Gardner, 1964), but roots are not uniformly permeable to moisture (Slayter, 1960).
2. Steady state was assumed to solve the model (Whistler, Klute and Millington, 1968; Molz and Remson, 1970). Steady state rarely occurs in the field.
3. A constant "average" transpiration rate and an initial uniform moisture content of approximately field capacity were used to solve the macroscopic model by Molz and Remson (1970 and 1971) and Molz (1971) utilizing controlled column experimental data collected by Gardner and Ehlig (1962) and Gardner (1964).

Moreover, extraction models such as [5] and [8] may give reasonable qualitative results for higher moisture contents, but it is doubtful if they will agree in detail with experimental results. One reason for this is that as the upper layers of soil dry, more of the transpiration requirements comes from deeper roots in the wetter soil (Van Bavel, Stirk, and Brust, 1968). This is not accounted for in [5] and [8]. However, for a steady state, the moisture extraction pattern is static and a model as [8] and [9] can yield reasonable results (Molz and Remson, 1970).

The macroscopic approach has significant advantages over the microscopic approach. The geometry for a one-dimensional model is

quite simple. The boundary conditions are easy to identify and apply compared with those that occur at the root surface in the microscopic treatment. The upper boundary conditions are usually taken at the soil surface; thus evaporation, rainfall, or zero flow conditions can be accounted for. The lower boundary might be an impermeable layer or water table. Moreover, any results obtained from the macroscopic model apply directly to the SPAC as a whole.

DERIVATION OF A NEW MACROSCOPIC APPROACH

This study was a part of a general problem that dealt with quality of irrigation return flow. The overall objective of this study was to determine the salt and water content within a soil and in the drainage water as a function of time and depth for saturated and unsaturated soil water flow. None of the previous models, as mentioned before, have been applied to field conditions. For these reasons, and in order to encounter more variables as they exist under field conditions, a new macroscopic approach has been developed and tested under field conditions.

The bulk root model developed herein is a modification of the soil water flow model of Hanks, Klute and Brestler (1969). The principle modification involves the consideration of extraction by plant roots. The general flow equation without root extraction for one dimension given by Hanks, Klute, and Brestler (1969) is:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(K(\theta)\frac{\partial H}{\partial z}\right) \qquad [10]$$

where θ is volumetric water content, t is time, z is depth, K is hydraulic conductivity, H is hydraulic head (sum of pressure head h and gravity head z). The modification of the above equation by a plant root extraction term, A(z), gives:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(K(\theta)\frac{\partial H}{\partial z}\right) + A(z). \qquad [11]$$

A(z) is the root extraction term or the sink term and depends on the root density function (the fraction of total active roots per unit volume of soil), soil conductivity, and the difference between pressure potential of water in the plant root and the pressure potential of soil water. Thus, the source term is defined as:

$$A(z) = \frac{[Hroot + (RRES \cdot z) - h(z) - S(z)] \cdot RDF(z) \cdot K(z)}{\Delta z} \quad [12]$$

where Hroot is an effective water potential in the root at the soil surface where z is considered zero, RRES = $(1 + R_c)$. R_c is a flow coefficient. When RRES is multiplied by z, the product will account for the gravity term and friction loss in the root water potential, so that root water potential at depth z is higher than the root water potential at the surface (Hroot) by a gravity term and friction loss term, (assuming that the friction loss in the root is independent of flow), h(z) is the soil matric potential at depth z, S(z) is the salt (osmotic) potential at depth z, RDF(z) is the proportion of total active roots in depth increment Δz, and K(z) is the hydraulic conductivity at depth z and it is a function of θ. The soil matric potential, h(z) and the hydraulic conductivity, K(z), are assumed to be unique functions of soil water content (hysteresis ignored). The validity of the assumption that a unique relation of hydraulic conductivity to a volumetric water content $K(\theta)$ exists is affected by hysteresis to a much lesser degree than is the K(h) function (Topp and Miller, 1966; Poulovassilis, 1969). The Hroot term is dependent on plant, climatic and soil conditions. The value of Hroot will depend on plant conditions since they govern the root distribution function, RDF(z). Hroot will depend on climatic conditions since they define potential transpiration, discussed in

detail later. The value of Hroot will depend on soil conditions since h(z), K(z), S(z) will be soil properties (which will vary greatly from wet to dry soil). In the model, a value of Hroot is "hunted" for until the plant root extraction over the total profile is equal to potential transpiration provided the value of Hroot is higher than the value of plant water potential below which the plant will not go and thus wilting will occur (Hwilt). Thus, in the model Hroot is bounded on the wet end by (Hroot = 0.0) and the dry end by (Hroot = Hwilt).

The basic input data needed for the solution of the model are:

1. Soil properties h - θ and K - θ curves covering the range of water content to be encountered in the problem. The value of θ-saturated and θ-air dry must also be known.
2. θ vs z and S vs z at the beginning, or at t = 0.
3. Plant properties, root distribution function RDF(z) and the value of Hwilt.
4. Boundary and climatic properties--these include the potential evapotranspiration and potential transpiration (from which potential evaporation can be deduced) as a function of time. These data will come basically from climatic variables of solar or net radiation, air temperature, air humidity, and wind speed and the proportion of ground covered by actively transpiring plants, or measurements of actual evapotranspiration. Potential infiltration, and precipitation as a function of time, are also needed.
5. Presence or absence of water table or layer restricting water flow at the lower boundary.

The output data that the solution of the model will give are:

1. Cumulative evapotranspiration, transpiration and evaporation as functions of time.
2. Volumetric soil water content, θ, soil water potential, h, as functions of time and depth.
3. Cumulative water flow (upward or downward) through the lower boundary as a function of time.
4. The value of Hroot as a function of time.

Theory and Basis for the Model Development

Equation [10] results from combining Darcy's law for flow in an unsaturated soil with the continuity equation. The assumptions underlying this development are:

1. The fluid of interest, water, is continuously connected throughout the flow region.
2. Inertial forces are not significant as compared to viscous forces.
3. The fluid of interest, water, is incompressible.
4. Flow is isothermal, vertical and one-dimensional.
5. The chemical nature of water does not change with time or position.
6. Biological phenomena have no effect on soil water flow.
7. Air freely and instantaneously escapes from the system as water accumulates in it.
8. Soil does not shrink or swell as water content changes.
9. Water content either increases or decreases monotonically, thus avoiding the effects of hysteresis of soil properties.

Equation [11] is a modification of equation [10], so the following assumptions were imposed for its development.

1. The roots are considered to be distributed in a continuous (but not necessarily uniform) manner.
2. No water is stored or consumed by the plant itself.

Equation [10] is a second-order, non linear, partial differential equation of parabolic type. Hanks and Bowers (1962) solved equation [10] and developed an implicit-type finite-difference model for infiltration in layered soil. Hanks, Klute and Brestler (1969) modified the solution to estimate infiltration, redistribution, drainage, and evaporation as they occur under field conditions. Since the present model, equation [11], is a modification of equation [10], the generalized numerical solution is presented herein.

The one-dimensional vertical flow or equation [11] is:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial H}{\partial z}\right) + A(z). \qquad [13]$$

This equation needs to be transformed so that there is only one variable. Rubin (1966) mentioned three possible ways of doing this transformation. The transformation used was developed by Richards (1931) involving the left-hand side of equation [13]:

$$C(\theta) = \frac{\partial\theta}{\partial h} \qquad [14]$$

where $C(\theta)$ is the soil water differential capacity. By the chain rule of calculus:

$$\frac{\partial\theta}{\partial t} = \frac{\partial\theta}{\partial h}\frac{\partial h}{\partial t} = C(\theta)\frac{\partial h}{\partial t}. \qquad [15]$$

The substitution of equation [15] into equation [13] yields:

$$C(\theta)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta)\frac{\partial H}{\partial z}\right) + A(z) \qquad [16]$$

where the hydraulic head ($H = h + z$) is the only dependent variable.

The finite-difference form of the left-hand side term of equation [16] is:

$$C(\theta)\frac{\partial h}{\partial t} = \left(\frac{C_i^j + C_i^{j-1}}{2}\right)\left(\frac{h_i^j - h_i^{j-1}}{\Delta T}\right) = C_i^{j-\frac{1}{2}}\left(\frac{h_i^j - h_i^{j-1}}{\Delta t}\right) \qquad [17]$$

where the subscript i represents the depth of a node, and the superscript j represents time.

The first step in finite differencing the first term on the right of equation [16] is:

$$\frac{\partial}{\partial z}\left(K(\theta)\frac{\partial H}{\partial z}\right) = \frac{1}{\Delta z_3}\left(K\frac{\partial H}{\partial z}\bigg|_1 - K\frac{\partial H}{\partial z}\bigg|_2\right) \qquad [18]$$

where the identifier 1 is the mesh increment between nodes i-1 and i, the identifier 2 is the mesh increment between nodes i and i+1, and the identifier 3 is the mesh increment between nodes i-1 and i+1. Solving for the second and third term on the right-hand side of equation [18] yields:

$$K\frac{\partial H}{\partial z}\bigg|_1 = \left(\frac{K_1}{\Delta z_1}\right)\left(\frac{H_{i-1}^{j-1} + H_{i-1}^j}{2} - \frac{H_i^{j-1} + H_i^j}{2}\right) \text{ and}$$

$$K\frac{\partial H}{\partial z}\bigg|_2 = \left(\frac{K_2}{\Delta z_2}\right)\left(\frac{H_i^{j-1} + H_i^j}{2} - \frac{H_{i+1}^{j-1} + H_{i+1}^j}{2}\right) \qquad [19]$$

where K_1 is the average of the K values corresponding to the θ values at nodes (i-1, j-1), (i-1, j), (i, j-1) and (i, j), and K_2 is

similarly associated with nodes (i, j-1), (i, j), (i+1, j-1) and (i+1, j). Another way of defining K_1 and K_2 that has been used is:

$$K_1 = K_{i-\frac{1}{2}}^{j-\frac{1}{2}} \quad \text{and} \quad K_2 = K_{i+\frac{1}{2}}^{j-\frac{1}{2}} \qquad [20]$$

The substitution of equations [19] and [20] into equation [18] yields:

$$\frac{\partial}{\partial z}\left(K\frac{\partial H}{\partial z}\right) = \frac{1}{\Delta z_3}\left(\left(\frac{H_{i-1}^{j-1} + H_{i-1}^{j}}{2} - \frac{H_i^{j-1} + H_i^j}{2}\right)\frac{K_{i-\frac{1}{2}}^{j-\frac{1}{2}}}{\Delta z_1} - \left(\frac{H_i^{j-1} + H_i^j}{2} - \frac{H_{i+1}^{j-1} + H_{i+1}^j}{2}\right)\frac{K_{i+\frac{1}{2}}^{j-\frac{1}{2}}}{\Delta z_2}\right) \qquad [21]$$

Hanks and Bowers (1962), and Hanks, Klute and Bresler (1969) assumed constant depth increments, therefore, having:

$$\Delta z_1 = \Delta z_2 = \Delta z_3.$$

In this model variable depth increments are considered, hence Δz_1, Δz_2, and Δz_3 are not equal and are defined by:

$$\Delta z_1 = z_i - z_{i-1};\ \Delta z_2 = z_{i+1} - z_i;\ \Delta z_3 = (z_{i+1} - z_{i-1})/2. \qquad [22]$$

Finally, the finite difference for the last term of equation [16] is:

$$A_i^j = \frac{(hp_i^j - hs_i^j)K_i^{j-\frac{1}{2}} \times RDF_i}{\Delta z_3} \qquad [23]$$

where $hp_i^j = Hroot_0^j + RRES \times z_i$; and $hs_i^j = h_i^{j-1} + S_i^{j-1}$ [24]

Substituting equation [17], [21], and [23] into equation [16], and substituting for H = h + z, yields:

$$\left(\frac{h_i^j - h^{j-1}}{\Delta t}\right) C_i^{j-\frac{1}{2}} = \frac{1}{\Delta z_3} \left(\left(\frac{h_{i-1}^{j-1} + h_{i-1}^j - h_i^{j-1} - h_i^j + 2z}{2\Delta z_1} \right) K_{i-\frac{1}{2}}^{j-\frac{1}{2}} - \right.$$

$$\left. \left(\frac{h_i^{j-1} + h_i^j - h_{i+1}^{j-1} - h_{i+1}^j + 2z}{2\Delta z_2} \right) K_{i+\frac{1}{2}}^{j-\frac{1}{2}} + \left(hp_i^j - hs_i^j\right) K_i^{j-\frac{1}{2}} \times RDF_i \right. \quad [25]$$

Equation [25] was the basic linear equation used to solve the model. This equation was programmed and solved by computer (IBM 360 and/or UNIVAC 1108) using Crank-Nicholson or Laosonen approximation, from a knowledge of appropriate boundary and initial conditions. Detailed explanation of the computer program and the solution of equation [25] will be presented later.

General Program Description

The general flow diagram for the computer program (Appendix A, Program A) is shown in Figure 1. The input and boundary data necessary for the program must be obtained for the specific crop and field condition for which the study is to be done. The program calculates the different variables for any time period and prints the output at any time interval required.

A step by step description of the program (details in Appendix A) follows:

Step 1. The program reads and prints all the input and boundary data. These data include tables of conductivity and soil water pressure head as functions of water content, and root distribution as functions of depth. The potential water and salt flux at the surface, as well as potential evaporation and evapotranspiration as functions of time are also input data as are the maximum and minimum plant water potential. Other input information needed is the initial time increments Δt to be used, the upper and lower limits on pressure head and water content (that is, saturation and air dry), the length of time the computation is to run, and the condition of the lower boundary (two conditions, a constant pressure head or no flux are provided).

Step 2. The diffusivity as a function of water content is computed and printed, as well as the pressure head as a function of water content at the different depth increments.

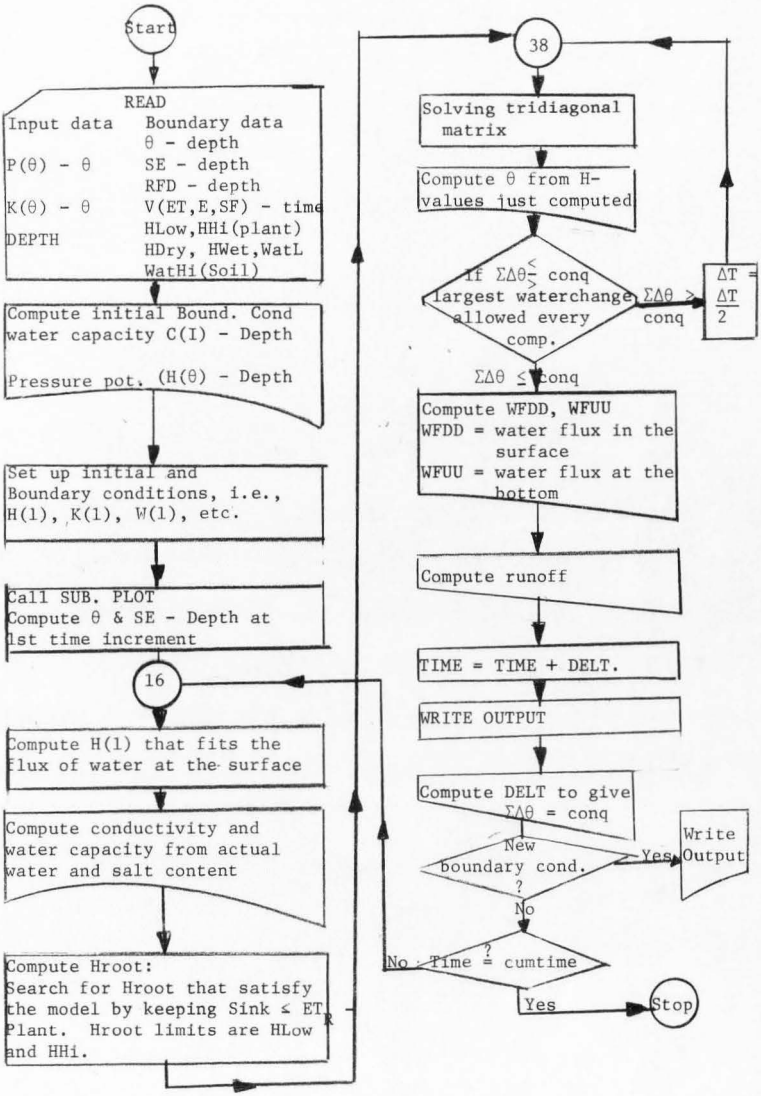

Figure 1. General flow diagram of the program.

Step 3. The subroutine "plot" is called and water and salt content versus depth are plotted for the first time increment.

Step 4. From the initial water content as a function of depth, values of hydraulic conductivity as a function of depth are computed by the procedure outlined by Hanks and Bowers (1962). Values of the specific water capacity ($C = \frac{\Delta\theta}{\Delta h}$) as function of depth are computed from the water content and the pressure head-water content relations. A surface pressure head is computed to give the estimated flux at the surface in conformance with boundary conditions applying at the time using the following equation:

$$ER = \frac{(h_0^{J+1} + h_0^J - h_1^{J+1} - h_1^J + \Delta z)K_{\frac{1}{2}}^{J+\frac{1}{2}}}{2\ \Delta z} \qquad [26]$$

where ER is the flux at the surface, h_0^{J+1} and h_0^J are the pressure heads at the surface at the end and beginning of the time interval, h_1^{J+1} and h_1^J are the pressure heads at depth Δz from the surface at the beginning and end of the time interval and $K_{\frac{1}{2}}^{J+\frac{1}{2}}$ is the hydraulic conductivity assumed constant over the time interval and applying between the surface and $z = \Delta z$. The surface pressure head is allowed to vary only between limits (that is, saturation or air dry). So the computed flux may be different from the potential flux. To solve equation [26] a value of h_0^{J+1} is assumed (h_0^{J+1} = Hdry, if it is evaporation, h_0^{J+1} = Hwet if it is precipitation) since it has not been computed yet.

Step 5. A value of Hroot is hunted for that satisfies the condition (Sink $\leq$ potential ET of the plant, Sink is the cumulative root extraction). Hroot is allowed to vary only between limits (i.e., Hlow $\leq$ Hroot $\leq$ Hhi). A value of Hroot is assumed (Hroot = h_1^J) to start with since it is not computed yet. If precipitation is taking place, root extraction is assumed zero. If evaporation is taking place, then the cumulative root extraction is printed using equation [23].

Step 6. The tridiagonal matrix which approximates the original flow equation [21] is solved for the pressure head at the end of the time interval at each depth increment as described by Hanks and Bowers (1962). The only difference is Δz is variable in the model used herein.

Step 7. The water content at each depth increment is computed from a knowledge of pressure head at each depth increment and water capacity as function of depth and pressure head-water content relations, using the following formula:

$$\theta_i^{J+1} = C_i^J \, [h_i^{J+1} - h_i^J] + \theta_i^J \qquad [27]$$

The values of h_i^{J+1} and h_i^J are computed in Step 6.

Step 8. The program tests the total change in water content ($\Sigma/\Delta\theta/ \overset{?}{\leq}$ ConQ, where ConQ is the largest total water content change allowed every computation). If $\Sigma/\Delta\theta/>$ConQ, then the time is reduced by half ($\Delta t = \frac{\Delta t}{2}$) and the program goes back to Step 6. If $\Sigma/\Delta\theta/ \leq$ ConQ the program proceeds to Step 9.

Step 9. The program computes the water flux at the surface and at

the bottom boundaries. The cumulative water flow through the surface and lower boundary, and runoff.

Step 10. Cumulative values of various variables are computed, desired output is printed, a new Δt is chosen that satisfies the condition $\Sigma\Delta\theta = ConQ$, and the values of h_i^{J+1} and θ_i^{J+1} taken as the new initial conditions h_i^j, θ_i^J.

Step 11. The cumulative time is checked to adjust the potential boundary conditions if necessary. The process is repeated from Step 4 above until the time required for the entire program is reached.

EXPERIMENTAL PROCEDURE

The field work for this study was carried out at the Hullinger Farm near Vernal, Utah. Actual evapotranspiration was measured by means of lysimeters. Potential evapotranspiration (E_p) was calculated from a combination equation developed by Penman (1963) using daily values of a minimum number of meteorological paramerers. The basic meteorological data required consist of:

1. Daily maximum and minimum air temperatures.
2. Daily solar radiation.
3. Average dew point temperature
4. Daily wind run at a known height.

The combination equation is:

$$E_p = \frac{\Delta}{\Delta + \gamma} (Rn) + \frac{\gamma}{\Delta + \gamma} (15.36)(1 + 0.01\ w)(e_s - e_a) \qquad [28]$$

where Δ is the slope of the saturation vapor pressure-temperature curve, γ is the psychrometric constant equal to 0.57 for Vernal conditions, w is the total daily wind run in miles, e_s is the mean saturation vapor pressure in mb, e_a is the saturation vapor pressure at mean dew point temperature in mb, Rn is the daily net radiation in cal-cm^{-2}-T^{-1}. The parameters $\Delta/(\Delta + \gamma)$ and $\gamma/(\Delta + \gamma)$ are mean air temperature sensitive factors whose sum is 1.0 (Jensen, 1966). It was assumed that soil heat flow was negligible.

The net radiation (Rn) was calculated from

$$Rn = (1 - \rho)\ R - R_L \qquad [29]$$

where ρ (albedo) is reflection coefficient assumed equal to 0.20, and R is total incoming solar radiation in cal $cm^{-2}T^{-1}$. R_L, the net long wave back radiation in cal $cm^{-2}T^{-1}$ was calculated from:

$$R_L = [0.98 - (0.67 + 0.044e_a^{1/2})] \times 0.5855 \times 10^{-7} [(T_{max} + 273)^4 + (T_{min} + 273)^4] \quad [30]$$

where T_{max} and T_{min} are maximum and minimum air temperature, °C, respectively. The data for actual and potential evapotranspiration were measured periodically twice a day.

Potential evapotranspiration for a given agricultural crop can be related to potential evaporation from free surface:

$$E_p = K_c \quad E_F \quad [31]$$

where E_p is potential evapotranspiration, K_c is crop factor (dimensionless), and E_F is potential evaporation from free water surface. Equation [29] is applicable when soil water is not limiting.

Soil water content profiles were arrived at by measuring the water content of the soil at different depths before and after each irrigation using neutron and gamma scattering devices. Details of these measurements are given later.

The field work was carried out in 1970 and 1971. In 1970 the field was planted to oats and seeded to alfalfa. In 1971 alfalfa was grown. The field was irrigated by a solid-set automated sprinkler system. Excess water was drained by tiles already installed in the field or by natural drainage. The field layout is shown in Figure 2.

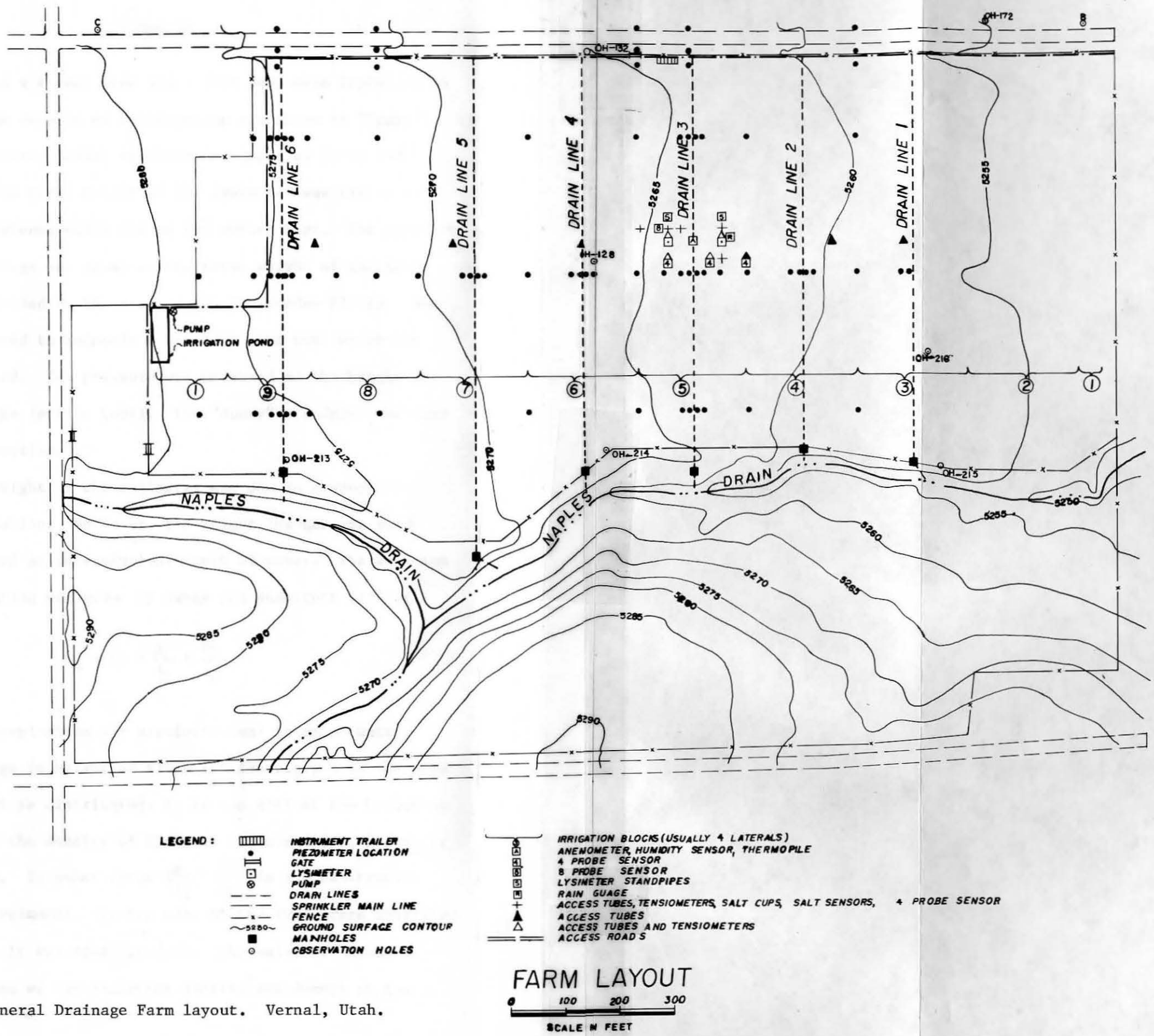

Figure 2. General Drainage Farm layout. Vernal, Utah.

Lysimeters

Two lysimeters 4 x 4 feet wide and 4 feet deep were installed in the Vernal farm. The details of construction are shown in Figure 3. The lysimeters used were similar to those developed by Hanks and Shawcroft (1965). The total weight of the lysimeter was distributed over the two wooden blocks which sat on two rubber bags. The pressure of the water in the bags was equal to the total weight of the inner tank and contents divided by the area of the two wooden blocks. The wooden blocks were used to maintain a constant area over which the weight was distributed. The pressure was measured as the height of water in the standpipe (active tube). The "dummy" standpipe was used for temperature correction.

The change in weight of the lysimeter was due to evapotranspiration or precipitation. Moreover, the weight changes are most conveniently expressed as an equivalent depth of water. The equation expressing this relation was given by Hanks and Shawcroft (1965):

$$E_a = \Delta h \times \frac{A}{A_1} \times \frac{\rho_f}{\rho_w} \qquad [32]$$

where E_a is evapotranspiration (or precipitation) in cm of water, Δh is corrected change in height of fluid in standpipe, A is the area over which the weight is distributed, A_1 is the area of the bottom of the lysimeter, ρ_f is the density of fluid in the standpipe, and ρ_w is the density of water. In other words $(\frac{A}{A_1} \times \frac{\rho_f}{\rho_w})$ is the calibration coefficient of the lysimeter. In the case of the lysimeters installed for this experiment, it was equal to 0.53. The value of Δh was measured from readings of the standpipe (active and dummy) at two

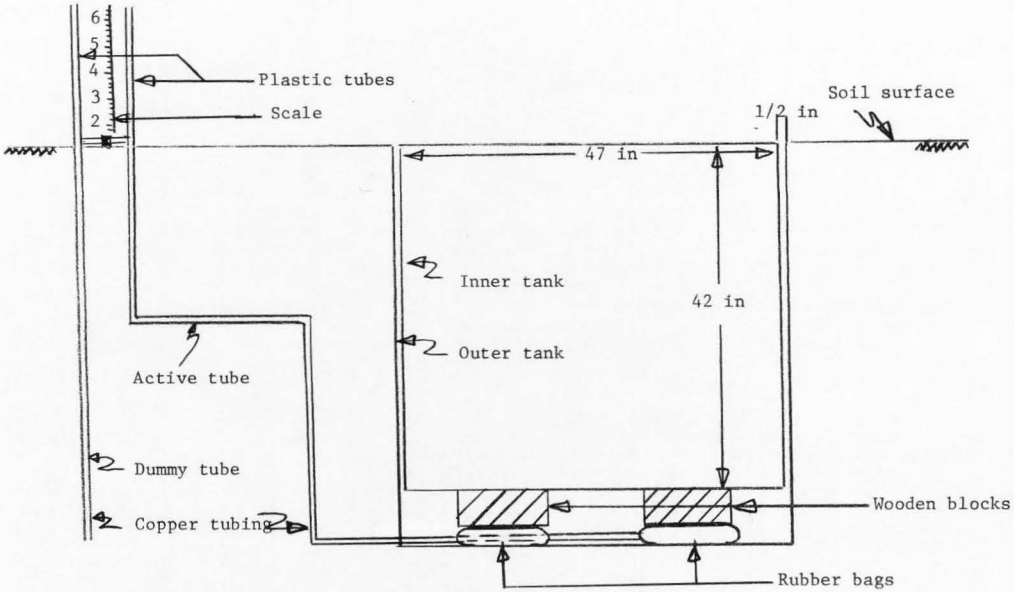

Figure 3. Schematic diagram of the lysimeter installation.

different times. Hence for the lysimeters used in the field experiment, equation [32] becomes:

$$E_a = 0.53\ [(A_1 - A_2) - (D_1 - D_2)] \qquad [33]$$

where A_1 and D_1 are readings of active and dummy standpipes at first period, and A_2 and D_2 are readings of active and dummy standpipes at second period, respectively. The data collected is presented in Appendix B, Table 9.

Neutron Probe

Soil moisture determinations were made by the neutron scattering method. Equipment manufactured by Troxler Electronic Laboratories of Raleigh, North Carolina was utilized. The probe was model 104A, 1.865 inches in diameter with americuim-beryllium as a fast neutron source, and with a nominal activity level of three millicuries. The detector utilized boron trifloride (BF_3) enriched with B^{10} isotope which respond only to relatively slow neutrons. The scaler was Model 2651 with count indicators and was battery operated.

Moisture content on a volume basis was determined by taking neutron counts at the desired depths, comparing them to the neutron counts through the standard and then applying the calibration equation. Readings at various depths were made by inserting the neutron probe into access tubes penetrating the root zone to a depth of 7.0 feet. These access tubes were made of two-inch outside diameter aluminum pipes, placed vertically in the soil by augering. While not in use each tube was closed by a rubber stopper to prevent the tube from filling with water while irrigation was taking place.

The probe was calibrated. The purpose of this calibration was to compare results with a general calibration supplied by the manufacturer.

One metal barrel 46 cm in diameter and 56 cm high was filled up to 45 cm with air dry soil; another barrel was filled with field moist soil and another barrel was filled with field moist soil brought to saturation and then drained for 48 hours. The moisture contents of the soil were determined gravimetrically and counts per minute of the neutron probe were taken at 20, 23, and 25 cm depth in each of the barrels and the average count computed. The ratio of the counts per minute in the soil to the shield standard for each soil was calculated. The results are tabulated in Table 1.

Table 1. Results of calibration of the neutron probe.

Sample	Relative counts R	Water content by weight	Bulk density $gm\text{-}cm^{-3}$	Water content by volume
Air dry soil	0.062	0.013	1.482	0.019
Field moist soil	0.562	0.159	1.354	0.216
Field moist soil (before saturation)	0.601	0.137	1.548	0.212
Field moist soil (after drainage)	1.089	0.239	1.548	0.370

Figure 4 shows the calibration curve and the calibration curve supplied by the manufacturer. The latter gives negative water content for low counts. The calibration resulted in the formula:

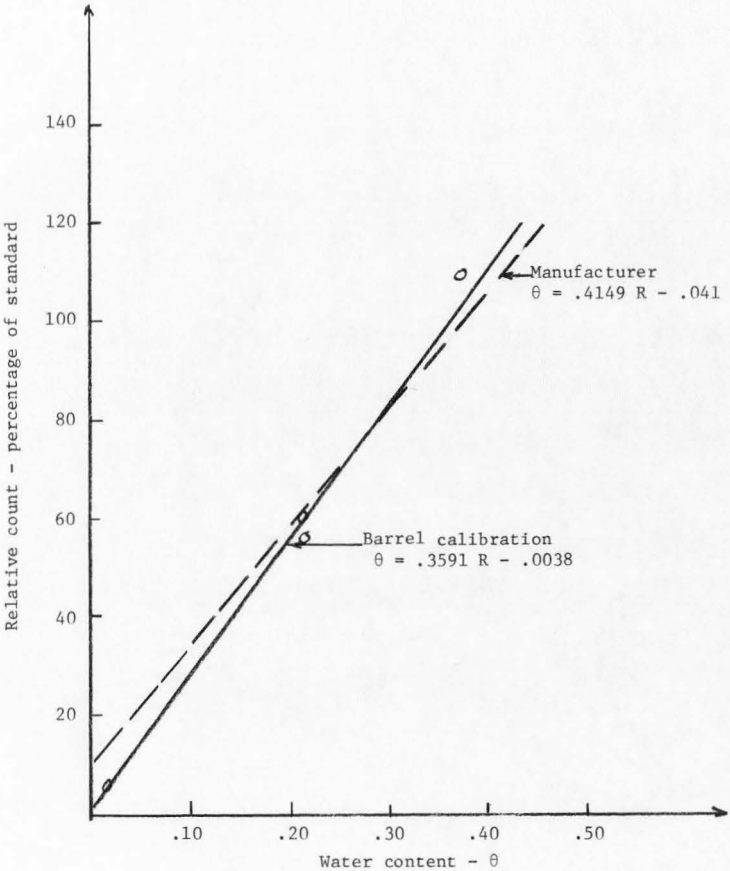

Figure 4. Barrel calibration curve of the neutron probe as compared to manufacturer calibration curve.

$$\theta = 0.3591\ R - 0.0038 \qquad [34]$$

as compared to

$$\theta = 0.4149\ R - 0.0410 \qquad [35]$$

supplied by the manufacturer. θ is water content by volume and R is the ratio of soil count rate to shield standard count rate. The differences between the calibration curves do not allow drawing a conclusion as to whether different soils require separate calibration curves as recommended by Mortier and Deboodt (1956), McGuinnes, Driebelbio, and Harold (1961), and Nimah (1968) or whether one calibration is enough, as reported by Gardner and Kirkham (1952). The calibration curve as developed in Figure 3 and equation [34] was used for moisture determination throughout this study. Tables 10 and 11, Appendix B, summarize the data collected during the 1971 growing season.

Gamma Probe

The two-probe gamma density gauge used in this study was manufactured by Troxler Electronics Laboratories of Raleigh, North Carolina. The two-probe density gauge was Model 2376 and used cesium 137 as a source of gamma photons of 661 Kev energy with a nominal activity level of five millie-curies. The detector utilized thalium activated sodium iodide crystal. The system used a pulse height analyzer which rejects all radiation above and below a 661 Kev energy level. The attenuation of monoenergetic gamma radiation for a fixed source-detector distance is described by:

$$I - I_0 \exp\ (-\mu\rho\chi) \qquad [36]$$

where I_0 is radiation intensity with no interference, μ the mass absorption coefficient (cm^2/g) of the absorber for the quantum energy of radiation, ρ the density of the material (g/cm^3) and χ the thickness of the sample (cm). Accurate values of the mass absorption coefficients of the soil and the water are needed if equation [36] is to be used for determining density and water content of the soil, (Davidson, Biggar, and Nielsen, 1963). With these mass absorption coefficients, equation [36] can be written as

$$I = I_0 \left[\exp\left(- (\mu_s \rho + \mu_w \theta)\ \chi\right)\right] \qquad [37]$$

where ρ is the bulk density (g/cm^3) of the soil, θ is the water content (g/cm^3), and μ_s and μ_w are the mass absorption coefficients of oven dry soil and water, respectively. As the water content increases, the radiation passing through the sample decreases. It is apparent from equation [37] that changes in the bulk density of the soil cause corresponding variation in the radiation intensity passing through the soil water system. If the bulk density is constant, changes in I from one period to the next are due to changes in water content. Although this is a major assumption of the method, it offers no limitation for many agricultural soils. Equation [37] requires a knowledge of I_0, μ_s, μ_w and ρ to calculate θ from detector count rate reading, I.

The attenuation coefficient or mass absorption of oven dry soil and water were determined for Mesa fine sandy loam and water. The procedure for determining them was essentially the same as given by Davidson, Biggar and Nielsen (1963). The attenuation coefficients for soil and water were measured as 0.065 and 0.067, respectively. These results are lower than those reported by Davidson, Biggar and Nielsen

(1963) which were 0.077 (soil) and 0.082 (water). The reason for these differences is not known. Measurements on the other soils yielded almost identical lower results. Therefore, the values 0.065 (soil) and 0.067 (water) were used throughout this study. The processed data is shown in Appendix B, Tables 12 and 13.

Climatic Data

A weather station was located on the farm, as shown in Figure 2. Measurements of global radiation, wind velocity, and wet and dry bulb temperatures were taken during the experiment.

Global radiation was measured by a radiometer sold by Science Associates, 230 Nassau St., Box 230, Princeton, N. J. It was Model No. 633 solarimeter and consists of weather protected thermopile, a pyranometer (180° pyrheliometer, for the measurements of total sun and sky radiation and is the Moll Gorezynski-type). It has a sensitivity of about 3 millivolts per cal/cm^2-min, with an effective wavelength range of 0.3 to 2.0 microns (3,000/20,000 Angstroms). The measurements were recorded on an integrator using this formula:

$$R = 2.7775\ [(0.1016\ Dx) - (I \times min)] \qquad [38]$$

where R is total radiation in cal/cm^2 - period, Dx is the difference in integrator readings at two different times, I is the average "zero" current intensity during the time interval, and min is the lapsed period in minutes between the time of measurements. The net radiation was calculated from the total radiation using equation [29]. Data of R and computed R_n and R_L are shown in Table 14, Appendix B.

Wind velocity was measured at 200 cm above the soil surface by an anemometer purchased from Science Associates, (U. S. Weather Bureau Specification Number 450.6103). The anemometer consists of three conical cups of 2.75 inches in diameter mounted on a rotor with a turning diameter of 12.5 inches with a starting speed of 3 mph and an accuracy of ± 1.5 mph to 70 mph. The measurements were taken by a totalizing remote electrical counter that was read twice daily. The data collected is tabulated in Table 14, Appendix B.

The wet and dry bulb temperatures were measured at about 200 cm by a sling psychrometer, purchased from Science Associates, (U. S. Weather Bureau Specification Number 450.1016). It utilized two matched thermometers, 9.5 inches long, accurate to ± 0.3°F above 0°F and ± 0.5°F below 0°F, mounted on a stainless steel backing. The measurements were made twice a day. Table 14, Appendix B, shows all data collected.

Daily maximum and minimum temperatures were measured at the weather station located at Vernal Airport about 1500 feet to the east of the research farm.

The values of e_s and e_a were estimated from the following equations:

$$e_s = 6.10127 + 0.4538\ DB + 0.01217\ DB^2 + 0.004156\ DB^3 \qquad [39]$$

and

$$e_a = e_s - 0.57288(1 + 0.00115\ WB)(DB - WB) \qquad [40]$$

where DB and WB are dry and wet bulb temperatures in °C. The data are tabulated in Table 14, Appendix B.

RESULTS AND DISCUSSION

The developed mathematical model, equation [25], and the computer program (Program A, Appendix A) were used to predict evapotranspiration, soil water flow, and soil water content profiles as a function of time in the Vernal project. The crops used were oats in 1970, and alfalfa in 1971. Predicted values were compared to the actual as measured in the field.

The program predictions covered nine days of the 1970 growing season, and the entire growing season in 1971 for a fixed irrigation frequency of ten and one-half days. The results show the soil water profiles, evapotranspiration, drainage, and plant root potential as a function of time.

Input Data Used in 1970 and 1971

The input data used for the computation are tabulated in Appendix A, Tables 6, 7 and 8. Figures 5 and 6 show the soil properties as determined by Andrade (1971) for the soil *in situ*. The data were extrapolated to cover the whole range of the soil water content. The initial soil water content as a function of depth, for the different crops, is shown in Figure 7, for the years 1970 and 1971.

Figure 8 shows the plant properties for the two crops. Figure 8a shows the relative root distribution assumed for oats. No measurements were made. Figure 8b shows the root distribution of alfalfa as measured in the field during the growing season.

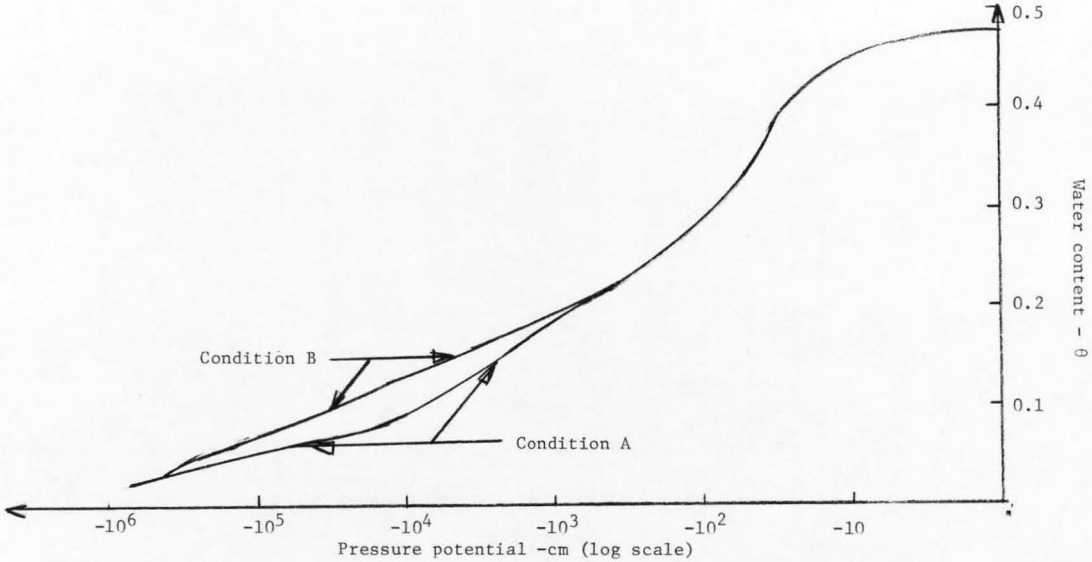

Figure 5. Pressure potential vs water content for Vernal sandy loam soil. Condition A was used in the computation. Condition B was used to test the sensitivity of the model.

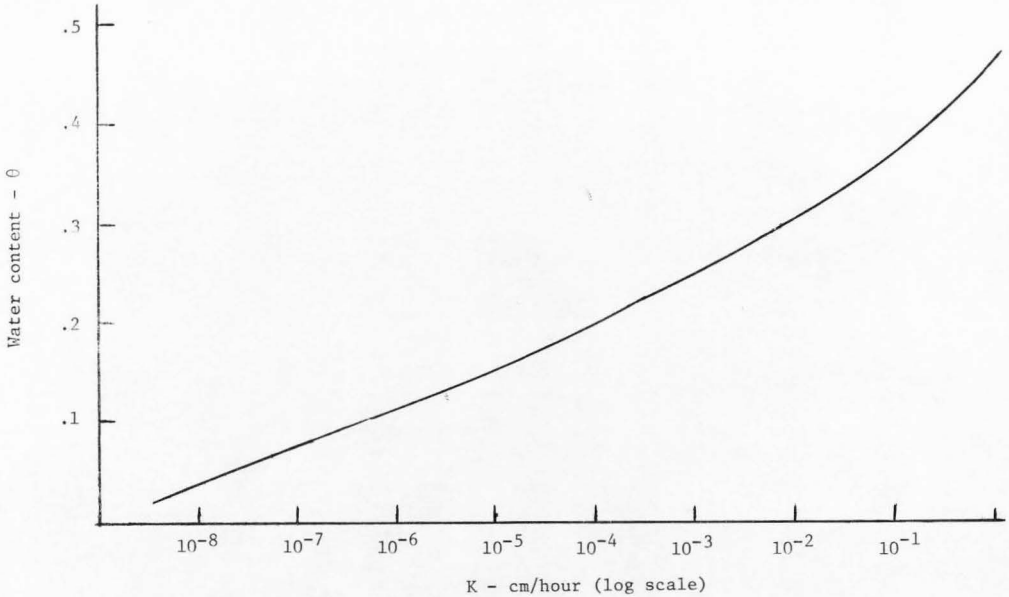

Figure 6. Water content vs hydraulic conductivity for Vernal sandy loam soil.

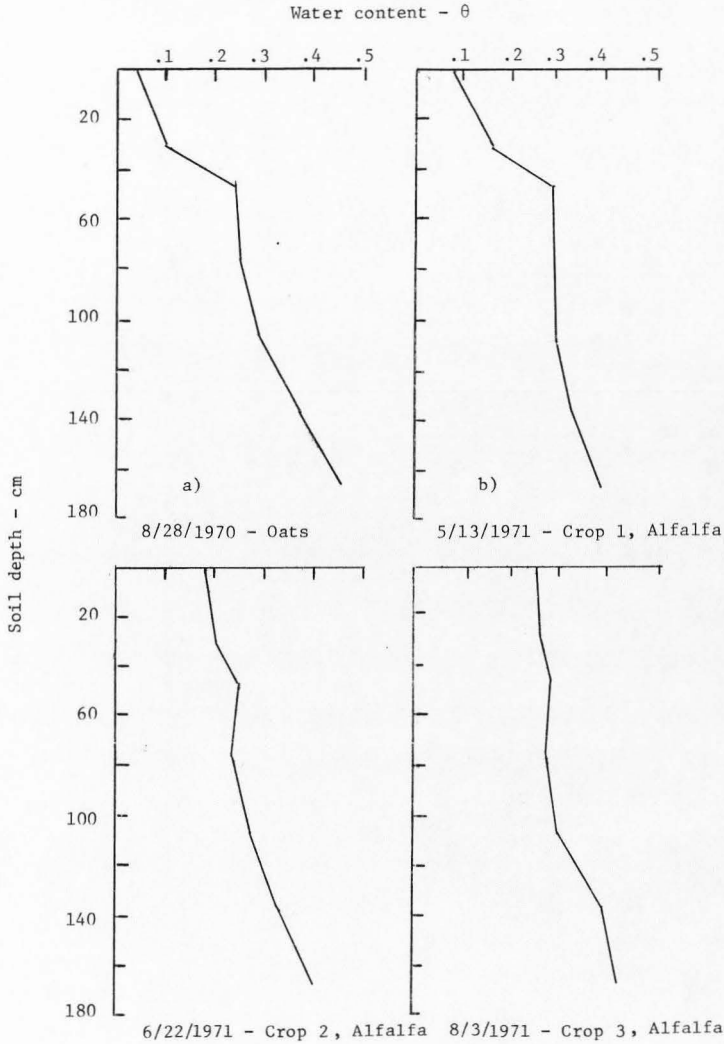

Figure 7. Water content profiles vs depth input data, a) for oats in 1970, b) alfalfa crop 1 in 1971, c) alfala crop 2 in 1971, d) alfalfa crop 3 in 1971.

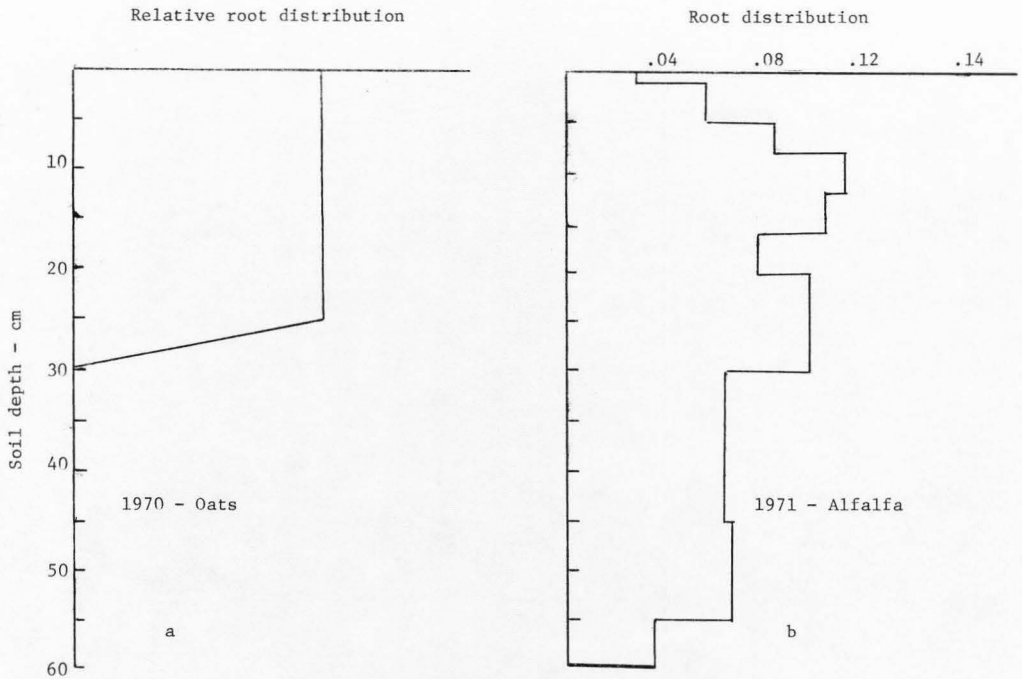

Figure 8. Root distribution for a) oats in 1970 and b) alfalfa in 1971.

Figures 9 and 10 show the potential flux at the surface for the different crops in 1970 and 1971, respectively. The fluxes include the rate of potential evapotranspiration and precipitation (rain and/or irrigation) as functions of time for the total time of computation. These data are the surface boundary conditions needed for the computation. The bottom boundary condition was a constant pressure head at 165 cm (the water table).

Results

The program was run for one irrigation interval during 1970 due to the lack of continuous field data for comparison of actual versus computed data. The computed results of 1970 and 1971 as compared to the actual measurements are shown in the following order:

1. Soil water profiles at different times of season.
2. Evapotranspiration as a function of time.
3. Water flow through the lower boundary as a function of time.
4. Plant root potential as a function of time.

Soil Water Profiles

Figure 11 shows the actual and computed water content profiles for oats in 1970. Water contents were measured by the neutron probe at 30, 45, 75, 105, 135, and 165 cm depth. A linear relation was assumed to exist between any two depths. For the top 30 cm the water content at 75 and 30 cm was extrapolated linearly. This was done because the effective diameter of the neutron probe was more than 30 cm, so no points could be measured between 0 and 30 cm. The

Figure 9. Water flux at the surface (evapotranspiration and precipitation cm/hr) vs time for oats in the 9-day interval in 1970.

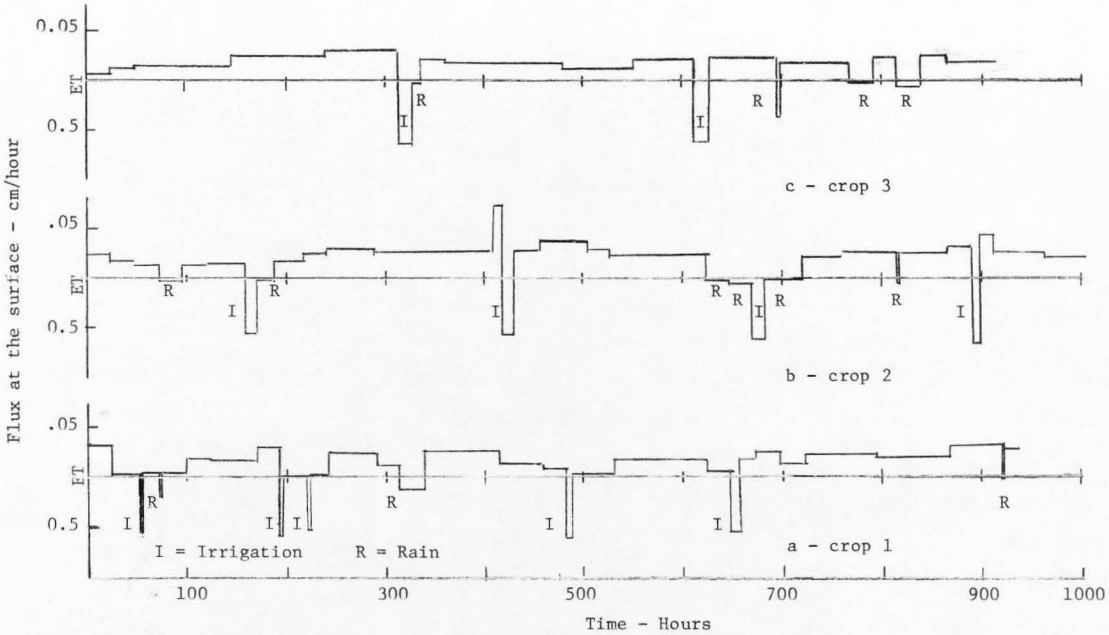

Figure 10. Water flux at surface (evapotranspiration and precipitation cm/hour) vs time for alfalfa in 1971, a) crop 1; b) crop 2; c) crop 3.

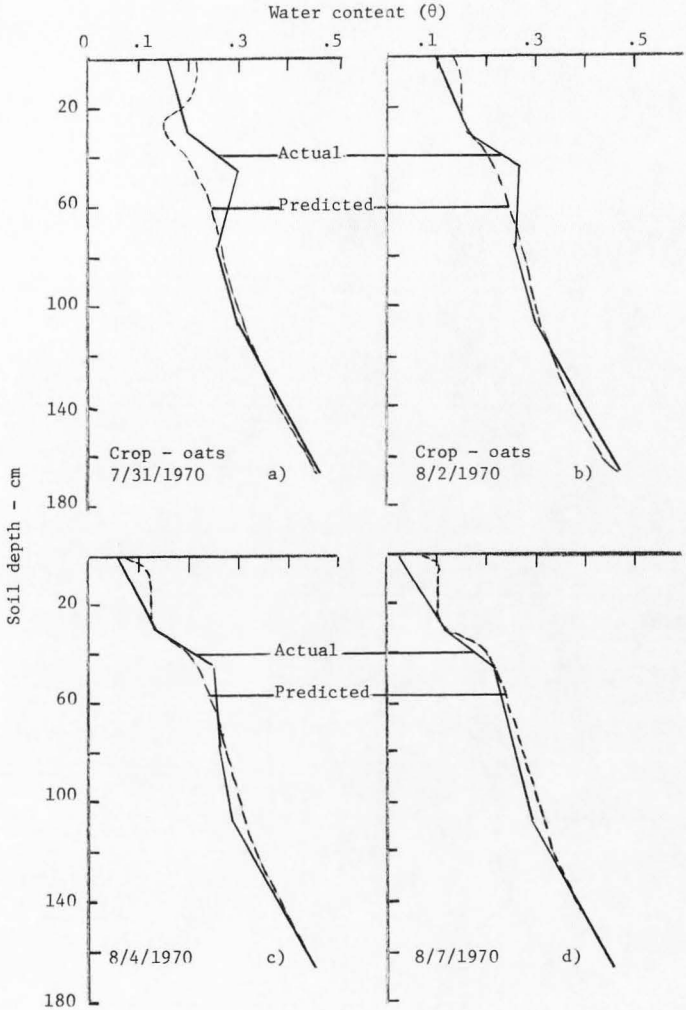

Figure 11. Comparison of the water content profiles as predicted and measured for oats in 1970. a) 48 hrs, b) 96 hrs, c) 144 hrs, d) 216 hrs.

comparison was better when the redistribution stage reached an end as shown in Figures 11b, 11c, and 11d.

For alfalfa in 1971, similar results were reached as shown in Figure 12 for the first crop, Figures 13 and 14 for the second crop, and Figures 15 and 16 for the third crop. The results of computed and actual soil water content showed excellent agreement, especially after 48 hours of irrigation or heavy rain.

Figure 17 shows water content with respect to time for the nine days interval in 1970 (oats) at 30, 70 and 100 cm depth, as compared to the measured water content during that interval. The agreement is good except for the period 24 hours after irrigation where at the 30 cm depth the measured water content was higher than the computed. Figure 18 shows the same comparison for alfalfa in 1971 for the entire season of 116 days. The computed values agree very well at all depths with the measured. The greatest difference was at 30 cm depth. The disagreements at 30 cm occurred mostly after irrigation in the redistribution stage. This might be due to the assumption that there was no hysteresis effect on the soil properties, and/or due to the non-uniform field soil.

Evapotranspiration

Figure 19 shows a comparison among the computed, actual and Penman cumulative evapotranspiration (ET). The actual ET was measured from daily readings of two lysimeters installed in the field, the Penman ET was calculated using equation [28] using measured field data. The model computed 4.9 cm cumulative ET in 1970 which was 0.4 cm less than the actual ET. This might be due to two factors:

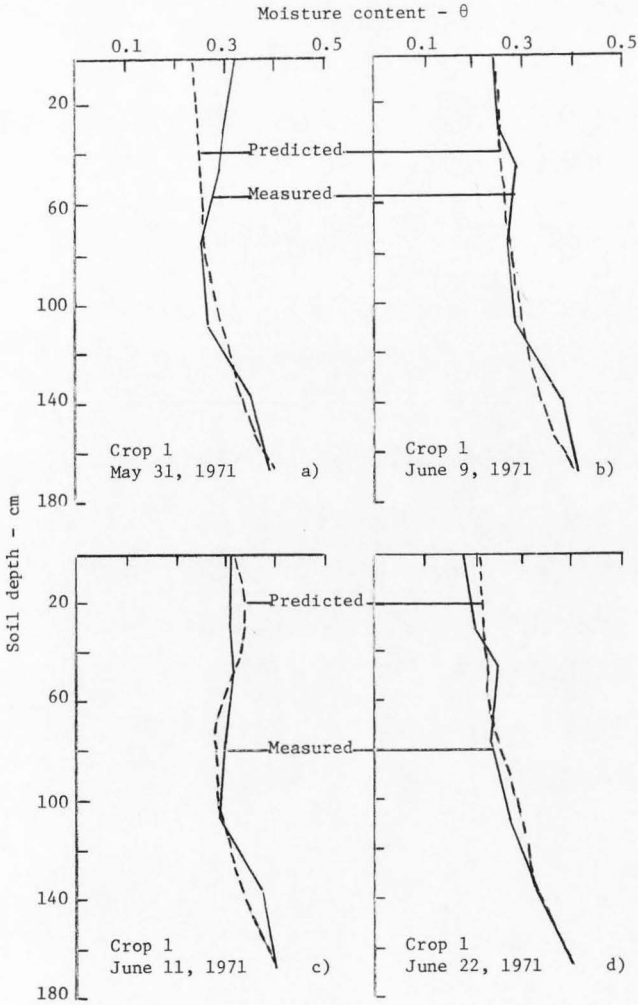

Figure 12. Comparison of water content profiles as measured and predicted for crop 1 alfalfa in 1971 (a,c) 24 hrs after precipitation, (b,d) end of irrigation interval.

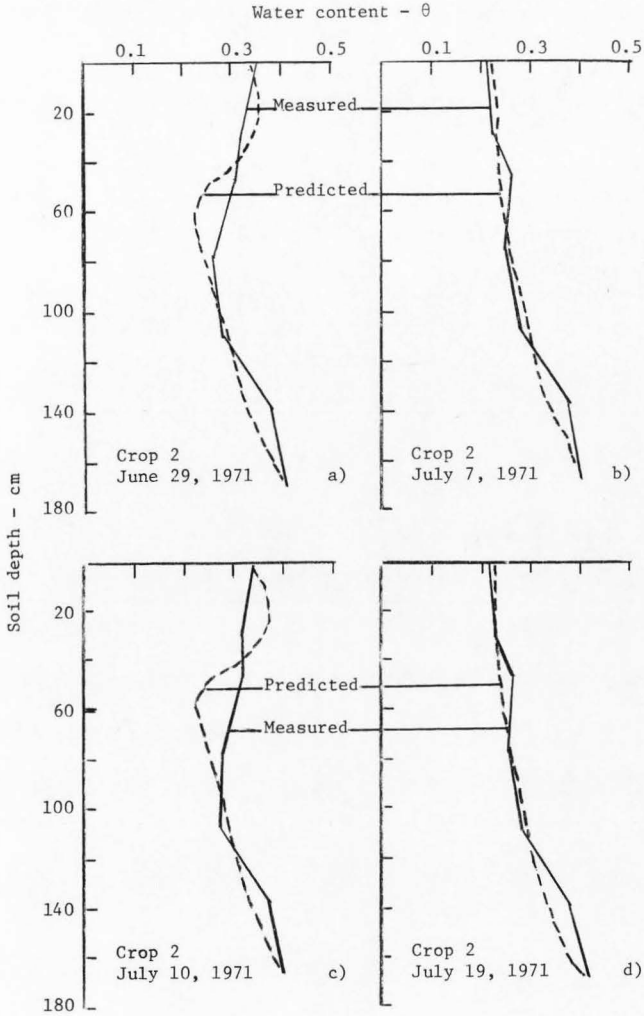

Figure 13. Comparison of water content profiles as measured and predicted for crop 2 alfalfa in 1971. (a,c) 24 hours after irrigation, (b,d) end of irrigation interval.

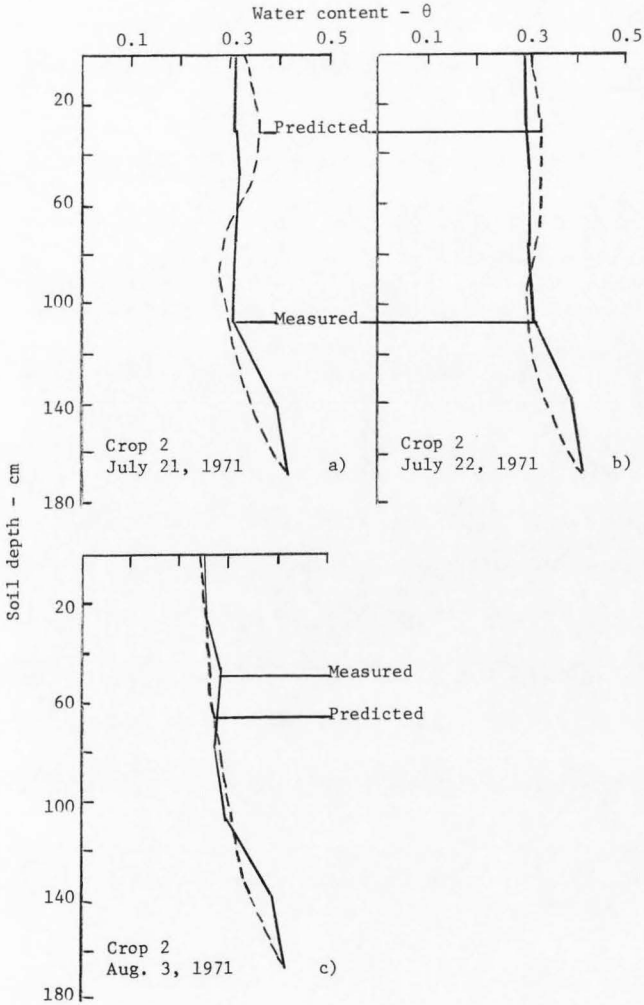

Figure 14. Comparison of water content profiles as measured and predicted for crop 2, alfalfa, in 1971. a) 24 hrs after irrigation, b) 48 hours, c) end of irrigation interval.

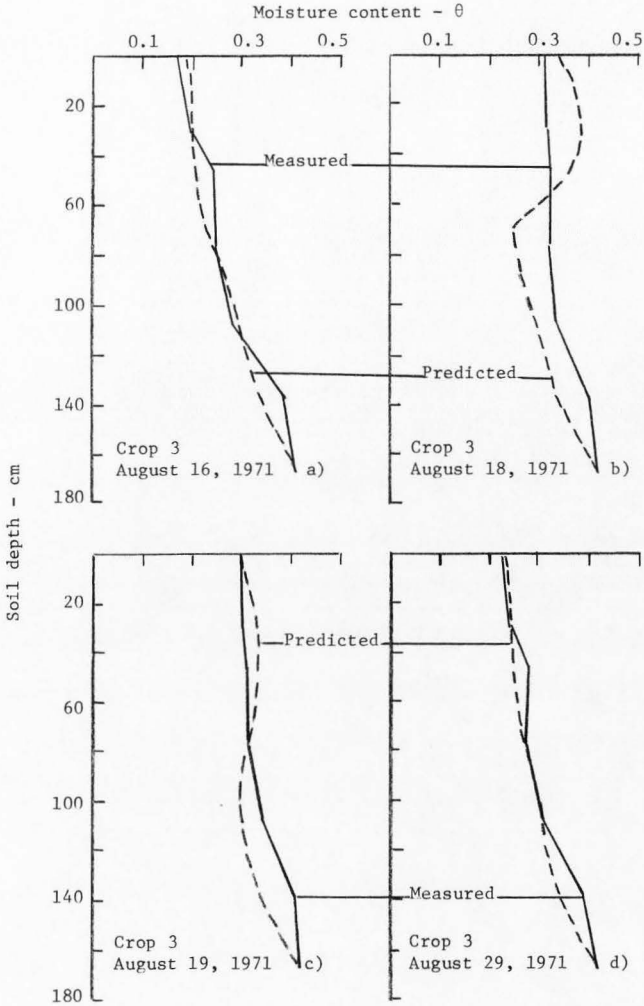

Figure 15. Comparison of water content profiles as measured and predicted for crop 3, alfalfa, in 1971. a) end of irrigation interval, b) 24 hrs after irrigation, c) 48 hrs after irrigation, d) end of irrigation interval.

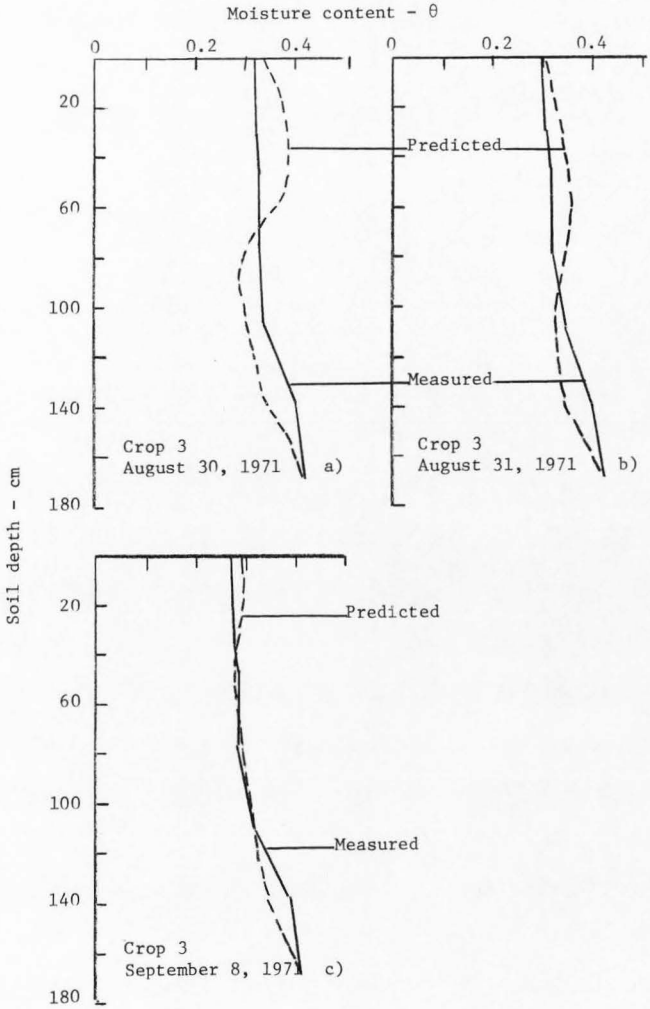

Figure 16. Comparison of water content profiles as measured for crop 3, alfalfa, in 1971. a) after irrigation, b) 48 hrs, c) end of season.

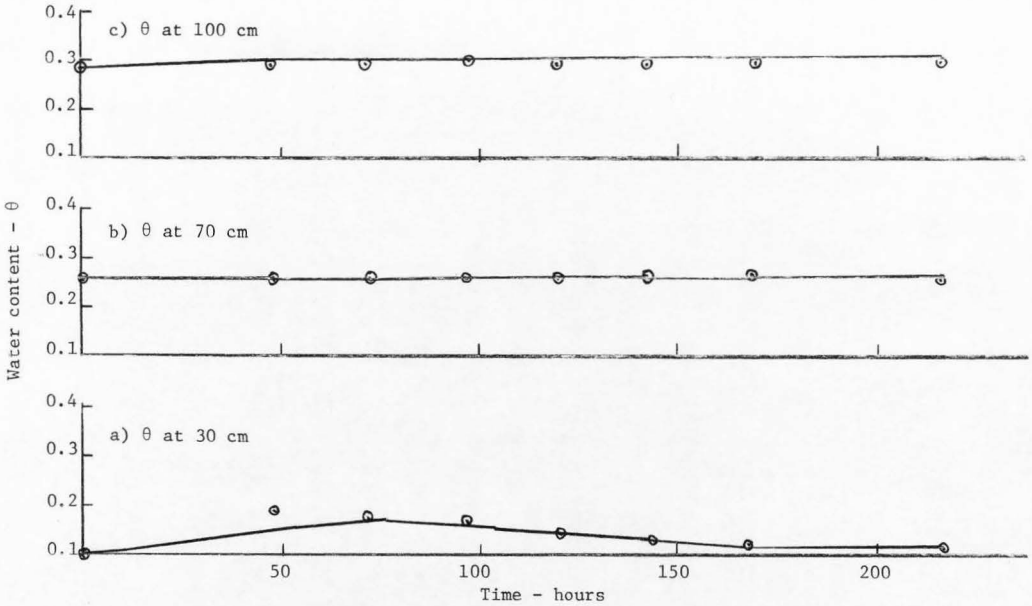

Figure 17. Comparison of predicted (solid lines) and measured (dots) water content at three depths for oats in 1970. a) 30 cm, b) 70 cm, c) 100 cm depth.

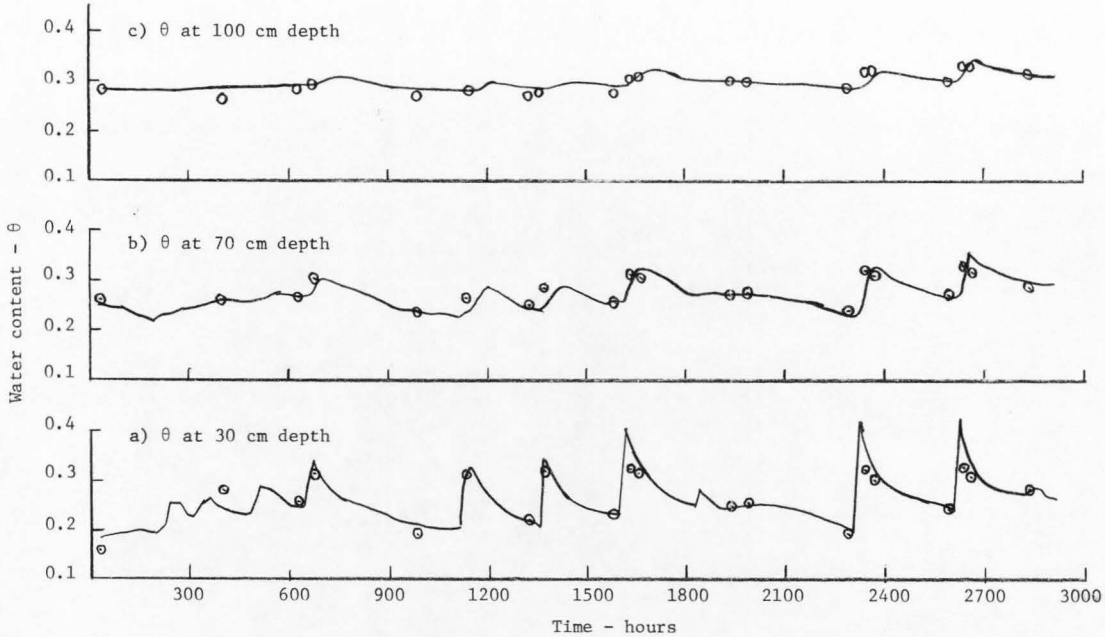

Figure 18. Comparison of measured and predicted water content profiles for alfalfa in 1971. a) 30 cm, b) 70 cm, c) 100 cm depth.

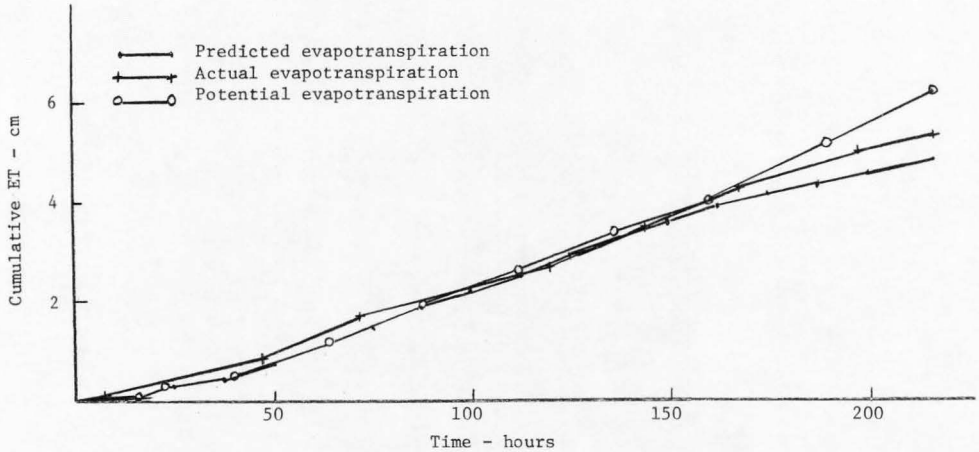

Figure 19. Comparison of actual, predicted, and potential evapotranspiration during the 9-day period with that predicted for oats in 1970.

1. The root distribution was assumed uniformly distributed to a depth of 30 cm, which is generally not true.
2. At such depth the Hroot reached the minimum allowable (-15 bars) at the 155 hour, where the cumulative computed ET started to become less than the cumulative actual ET, as shown in Figure 19. The minimum value allowed for Hroot, -15 bars, was chosen arbitrarily. Lower values of Hroot -20 or -40 bars would have decreased the difference between cumulative computed ET and cumulative actual ET. This condition was considered and details of its effect are discussed in a later section.

In the 1971 growing season the cumulative actual and computed ET were almost the same. This is due to the intentional high irrigation regime. If the value of Hroot is greater than the minimum allowed, computed ET is equal to the actual ET as shown in Figure 20. The comparison with Penman ET depends on the stage of growth of the crop. At the early growth stages the ET demand was less, hence Penman ET was usually greater than the actual or predicted ET. At the later growth stages the relation was reversed as shown in Figures 20b and 20c. In Figure 20a, the cumulative actual and computed ET were less than the Penman ET for the first alfalfa crop.

Figure 21 shows the variation of the ratio of actual ET to Penman ET, and the ratio of predicted ET to Penman ET during the nine-day interval in 1970. The ratio reached a maximum of 1.2 for the actual ET/Penman ET (ETact/ETpen) and .99 for the predicted ET/Penman ET (ETpre/ETpen). Both ratios dropped at the sixth and seventh day of the interval, at that time the program predicted an Hroot = -15 bar, which was the minimum allowable. In the 1971 growing season, although

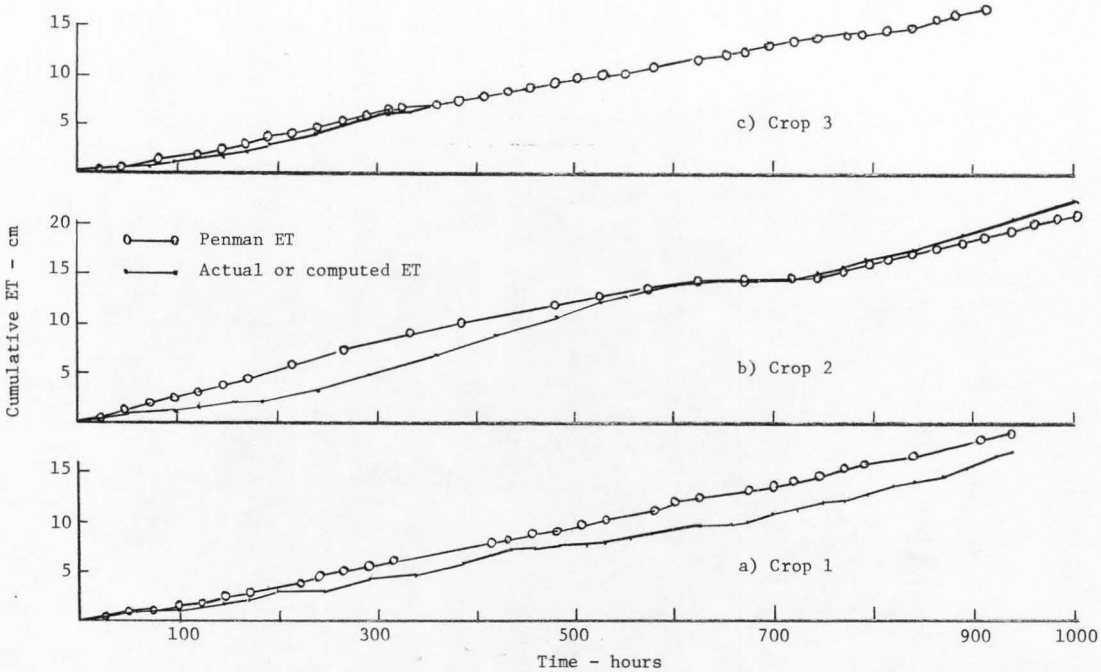

Figure 20. Comparison of actual, predicted, and potential evapotranspiration for alfalfa in 1971.

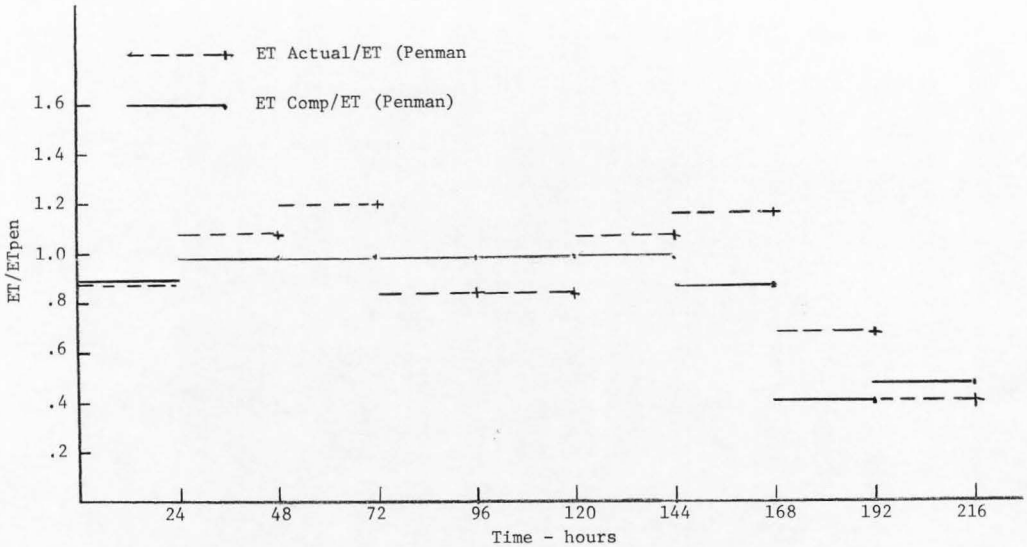

Figure 21. Comparison of ratio of actual ET/Penman ET, computed ET/Penman ET for oats in 1970.

the Hroot did not reach the minimum allowable, the ratio of actual or predicted ET to Penman ET seemed to vary with the irrigation cycle or the change in Hroot value, as shown in Figure 22. At 938 hours and 1995 hours the decrease in the ratio of ETact/ETpen was due to cutting of the alfalfa crop. The discontinuity in Figure 22 between 1395 and 1995 hours was due to lack of climatological data to calculate Penman ET.

Flow from/to the Water Table

In the 1970 growing season, only upward flow from the water table occurred in the nine days test interval. Figure 23 shows that the computed cumulative upward flow added up to 2.2 cm which was 0.1 cm greater than the actual. The actual upward flow was measured by measuring the right hand side components of equation [41],

$$FLOW = \Delta M_0 - I + ET \qquad [41]$$

where ΔM_0 is the change in moisture content in the field, as measured by the neutron probe, I is irrigation or precipitation, ET is evapotranspiration as measured by the lysimeters, and FLOW is flow through the lower boundary. If FLOW is positive, the flow through the lower boundary is upward, otherwise it is downward.

Figure 24 shows the cumulative flow through the bottom boundary as compared to the actual for 1971. The actual upward flow was consistently greater than the predicted except at the end of the first crop. The total actual upward flow was 4.8 cm as compared to 0.0 cm predicted for the entire growing season (116 days). This difference might be due to the uncertainty of measurement of water content in the top 30 cm of

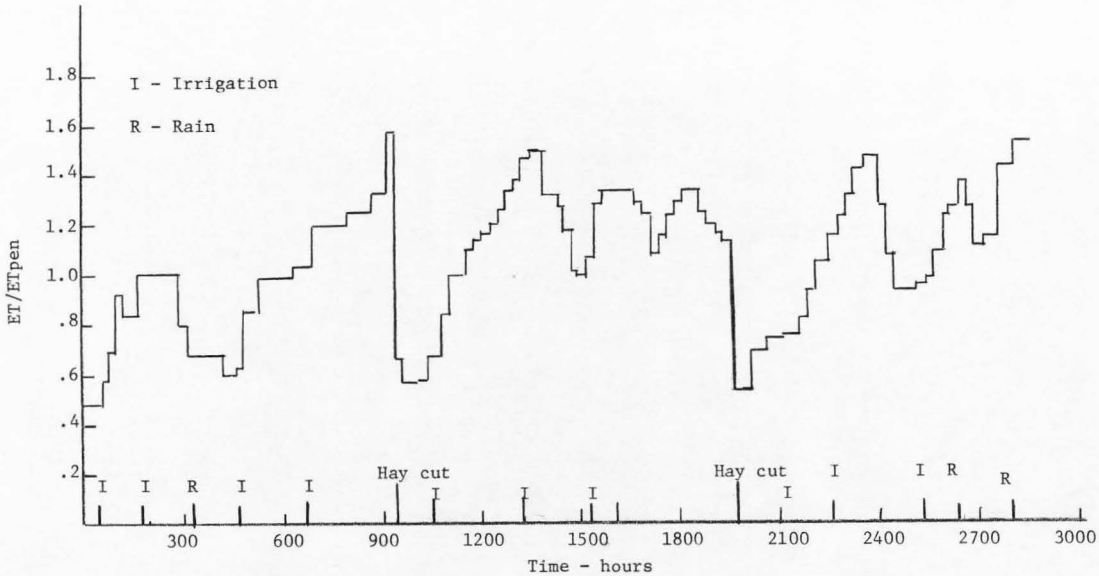

Figure 22. Variation of actual ET/Penman ET for alfalfa in 1971.

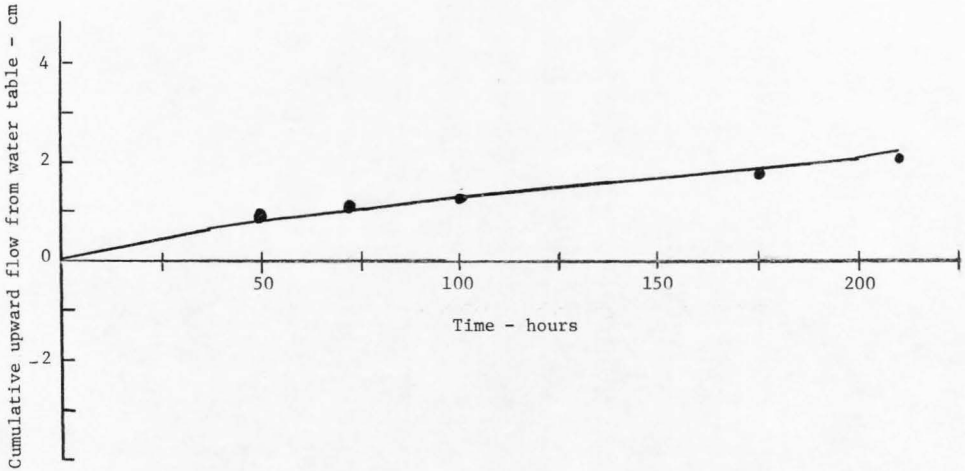

Figure 23. Comparison of actual (dots) and predicted (solid line) upward flow from the water table for oats during the 9-day interval in 1970.

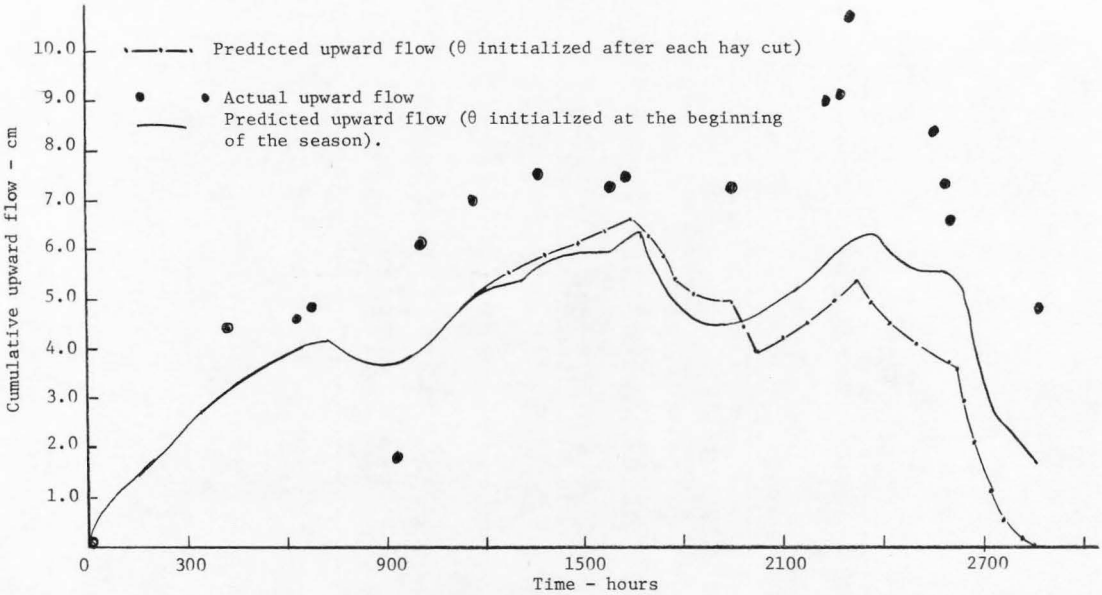

Figure 24. Comparison of actual (dots) and predicted (solid line) upward flow of water from water table for alfalfa in 1971.

depth was the average for that depth. Figure 24 shows that late in the season, or at 2400 hours, 19 days before the cut of the third crop, downward flow to the water table started. This was due to the larger amount of water applied to induce downward flow. The predicted and actual data agree in general during this period.

Root Water Potential (Hroot) at the Surface

Figure 25 shows the variation of Hroot during the nine-day interval for oats. The Hroot reached -15 bars, which is the minimum allowable beyond which wilting occurs at 155 hours. Figures 25 and 26 show that Hroot increased when precipitation occurred, and decreased when the water content decreased toward the end of the irrigation cycle. In 1971, as shown in Figure 26, Hroot rarely reached -1 bar; this might be due in part to the greater depth of the root system for alfalfa as compared to oats in 1970, but it was primarily due to increased addition of water. In both years, the average conditions over the day were used as a boundary condition. Consequently, predicted changes of Hroot valued with time during the day did not occur. It would be more realistic, but cost more field and computer time, if the potential ET was varied with time during the day for both seasons. If this was allowed the program would be expected to predict the variations in Hroot values during the day, since it predicted the variations during the whole season.

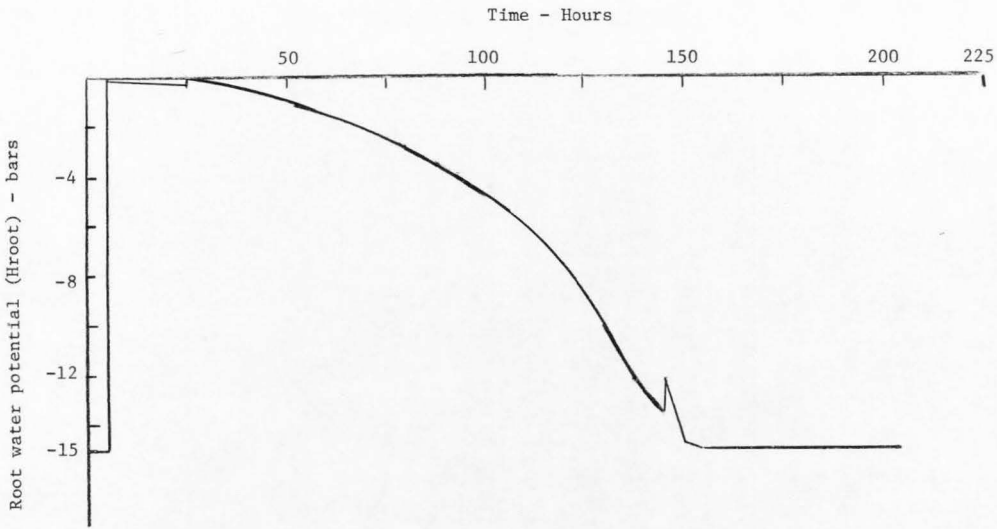

Figure 25. Variation of root water potential (Hroot) of oats during the 9-day interval in 1970. The increase in Hroot is due to precipitation.

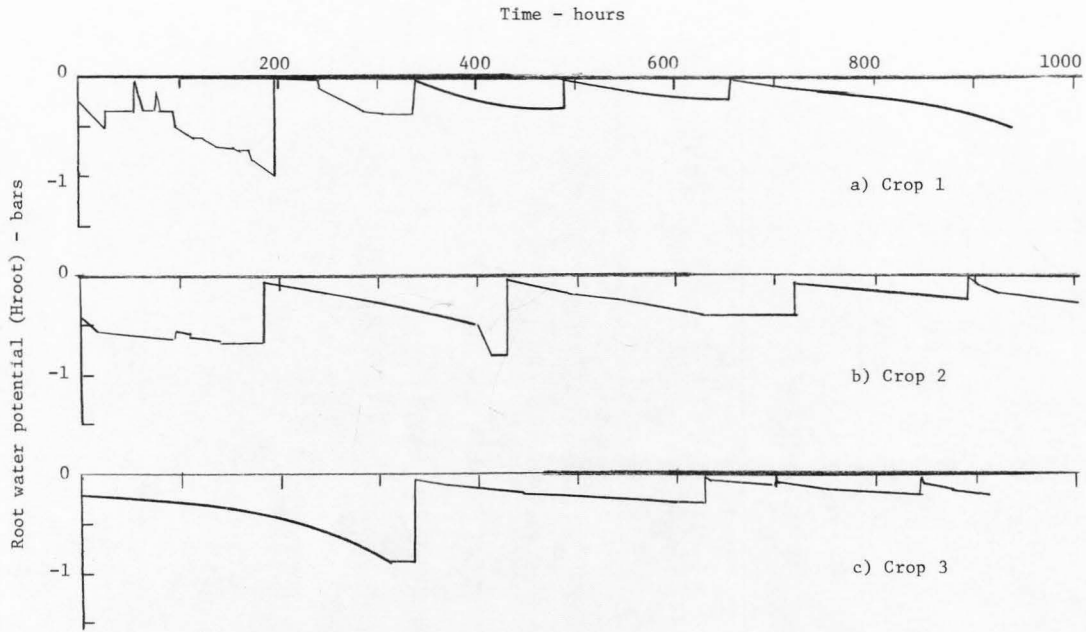

Figure 26. Variation of root water potential of alfalfa in 1971. The increase in Hroot is due to precipitation. a) crop 1, b) crop 2, c) crop 3.

SENSITIVITY OF THE MODEL

The sensitivity of the model to various parameters was tested. Most of the tests were conducted for the data from the nine-day interval in 1970. Two soil conditions A and B were compared. The pressure potential was varied in these two conditions as tabulated in Table 3 and shown in Figure 5. Condition A caused evapotranspiration and transpiration to be greater than condition B while the reverse was true for evaporation and upward water flow. The comparison is tabulated in Table 2.

Table 2. Comparison of predicted evapotranspiration, evaporation, transpiration, and water flow as influenced by different soil properties for a nine-day period starting July 28, 1970 at Vernal, Utah (no precipitation)

	Condition A 45 cm root depth	Condition B 45 cm root depth
Evapotranspiration	6.01 cm	5.79 cm
Evaporation	0.64 cm	0.77 cm
Transpiration	5.37 cm	5.02 cm
Water flow from the water table	2.44 cm	2.58 cm

The water content profiles were quite different in the active root extraction zone. At the end of the period the water content at 30 cm depth was about 0.10 for condition A and about 0.12 for condition B, Figure 27 shows these data. For these computations Hroot fell to -15 bars one day earlier for condition B than for condition A.

Table 3. Soil properties used for computations made. Vernal sandy clay loam. A and B are different conditions assumed.

Water content	Hydraulic conductivity	Pressure potential A	Pressure potential B
0.02	3.4×10^{-9} cm hr	$-8.5 \times 10^{+5}$ cm	$-8.5 \times 10^{+5}$ cm
.04	1.7×10^{-8}	$-2.2 \times 10^{+5}$	$-3.6 \times 10^{+5}$
.06	5.4×10^{-8}	$-5.8 \times 10^{+4}$	$-1.5 \times 10^{+5}$
.08	1.7×10^{-7}	$-1.5 \times 10^{+4}$	$-6.4 \times 10^{+4}$
.10	4.8×10^{-7}	$-8.0 \times 10^{+3}$	$-2.7 \times 10^{+4}$
.12	1.5×10^{-6}	$-4.9 \times 10^{+3}$	$-1.5 \times 10^{+4}$
.14	4.5×10^{-6}	$-3.0 \times 10^{+3}$	$-7.8 \times 10^{+3}$
.16	1.4×10^{-5}	$-1.85 \times 10^{+3}$	$-3.8 \times 10^{+3}$
.18	4.5×10^{-5}	$-1.12 \times 10^{+3}$	$-1.5 \times 10^{+3}$
.20	1.1×10^{-4}	$-6.7 \times 10^{+2}$	$-7.7 \times 10^{+2}$
.22	2.7×10^{-4}	$-4.1 \times 10^{+2}$	$-4.1 \times 10^{+2}$
.24	6.1×10^{-4}	$-2.5 \times 10^{+2}$	$-2.5 \times 10^{+2}$
.26	1.5×10^{-3}	$-1.65 \times 10^{+2}$	$-1.65 \times 10^{+2}$
.28	3.5×10^{-3}	$-1.15 \times 10^{+2}$	-1.15×10^{2}
.30	9.0×10^{-3}	$-8.5 \times 10^{+1}$	-8.5×10^{1}
.32	2.1×10^{-2}	$-6.6 \times 10^{+1}$	-6.6×10^{1}
.34	3.5×10^{-2}	$-4.8 \times 10^{+1}$	-4.8×10^{1}
.36	6.0×10^{-2}	$-4.13 \times 10^{+1}$	-4.13×10^{1}
.38	1.0×10^{-1}	$-3.44 \times 10^{+1}$	-3.44×10^{1}
.40	1.7×10^{-1}	$-2.73 \times 10^{+1}$	-2.73×10^{1}
.42	3.1×10^{-1}	$-2.10 \times 10^{+1}$	-2.10×10^{1}
.44	5.4×10^{-1}	$-1.34 \times 10^{+1}$	-1.34×10^{1}
.46	8.8×10^{-1}	-6.98	-6.98
.48	1.3	0	0

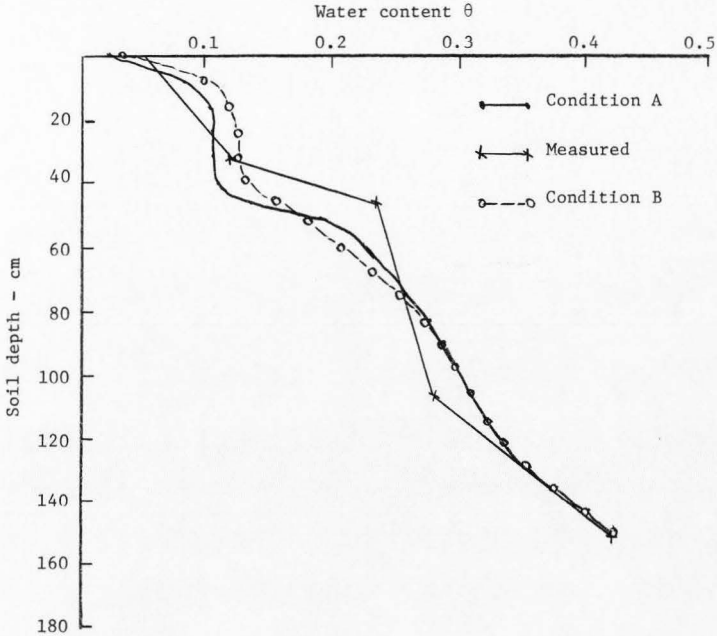

Figure 27. Comparison of measured water content profiles for soil condition A and B at the end of the 9-day period in 1970, oats.

Another test of sensitivity of the model was made using different root extraction depths 30, 45, and 60 cm for oats in 1970. Evapotranspiration and upward flow from the water table for the 45 and 60 cm root extraction were higher than the actual and the 30 cm root extraction. The results are tabulated in Table 4.

Table 4. Comparison of evapotranspiration, upward flow of water from the water table and Hroot at the end of the 9-day interval in 1970.

Root depth	Evapotranspiration cm	Upward water flow cm	Hroot-bars (end of interval)
30 cm	4.9	3.2	-15
45 cm	5.8	2.3	-11
60 cm	5.8	2.7	- 2
Actual	5.3	2.1	-

The water content profiles varied from the measured with the 30 cm root extraction giving best results compared to the measured as shown in Figure 28.

In this test the flux at the surface was varied. Potential evaporation was assumed to be 10 percent and 50 percent of potential evapotranspiration. The program was run for these two conditions and for the three root depths. The results are tabulated in Table 5.

A sensitivity test was run on the data of the 1971 growing season. In this test the initial moisture content was reinitialized at the beginning of each crop as compared to one initial moisture content at the beginning of the season. The results were the same, the water

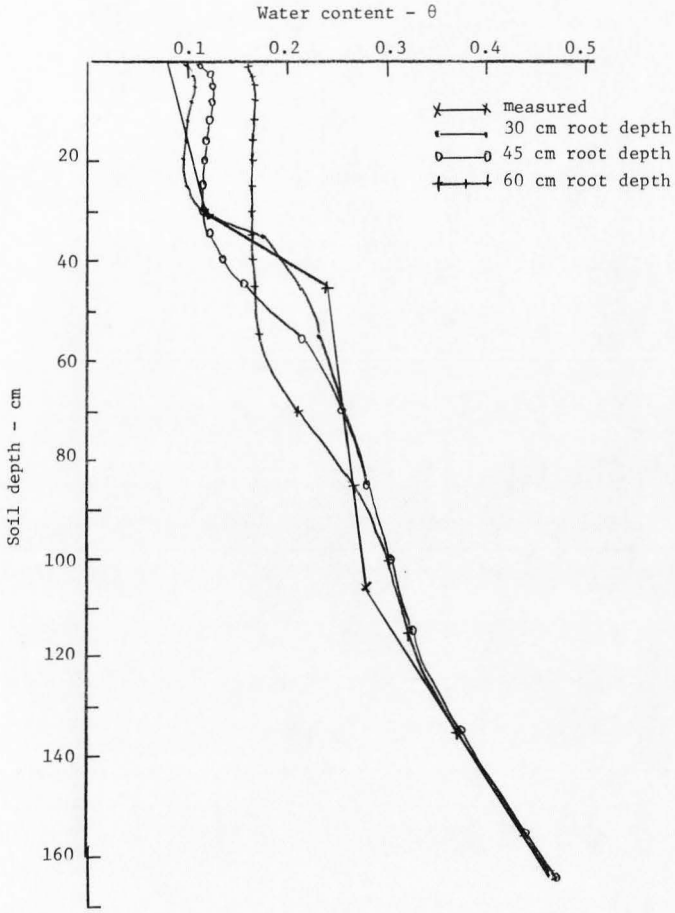

Figure 28. Comparison of measured and predicted water content profiles at the end of a 9-day period in 1970 assuming root distribution 30, 45 and 60 cm.

content profiles were about the same, especially after the first irrigation after cutting in both cases, as shown in Figure 29. Figure 24 shows the difference in upward flow for both cases.

Table 5. Effect of change in upper boundary condition and root depth on evaporation, transpiration and upward water flow (11 days)

Surface flux	E = 0.1 ET			E = 0.5 ET		
Root depth - cm	30	45	60	30	45	60
Evaporation	.62	.62	.62	2.68	2.99	2.99
Transpiration	5.70	6.37	6.37	3.26	3.58	3.58
ET	6.32	6.99	6.99	5.94	6.57	6.57
Upward water flow	5.43	6.35	7.76	5.38	5.94	6.78

Another test of sensitivity of the model was made using data from a desert soil,[1] where the lower limit for Hroot was varied. The original soil water content was high simulating spring conditions. Figure 30 shows cumulative ET where the lower limit was allowed to drop to -20 and -40 bars as well as cumulative potential ET. The data show that cumulative ET at 48 days was 7.6 cm for the -20 bar limit compared to 8.3 for the -40 bar limit. The computed data indicated that the lower limit of Hroot was reached at 24 days for -20 bars and 30 days for -40 bars.

From the last two tests it appears that under irrigated conditions one initial water content profile is needed at the beginning of the growing season. And, it appears also that the value chosen for the

[1]Personal communication with Dr. R. J. Hanks, Utah State University.

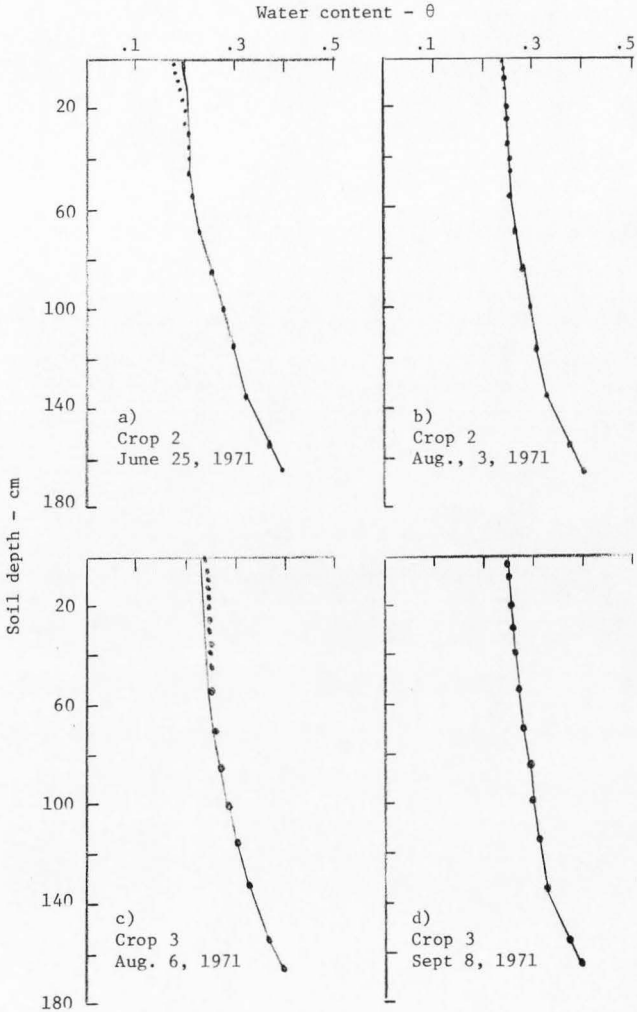

Figure 29. Comparison of water content profiles as predicted, (dots) θ was initialized after each hay cut, (solid lines) θ was initialized at the beginning of the season: (a,c) three days after hay cut, (b,d) at the end of the crop.

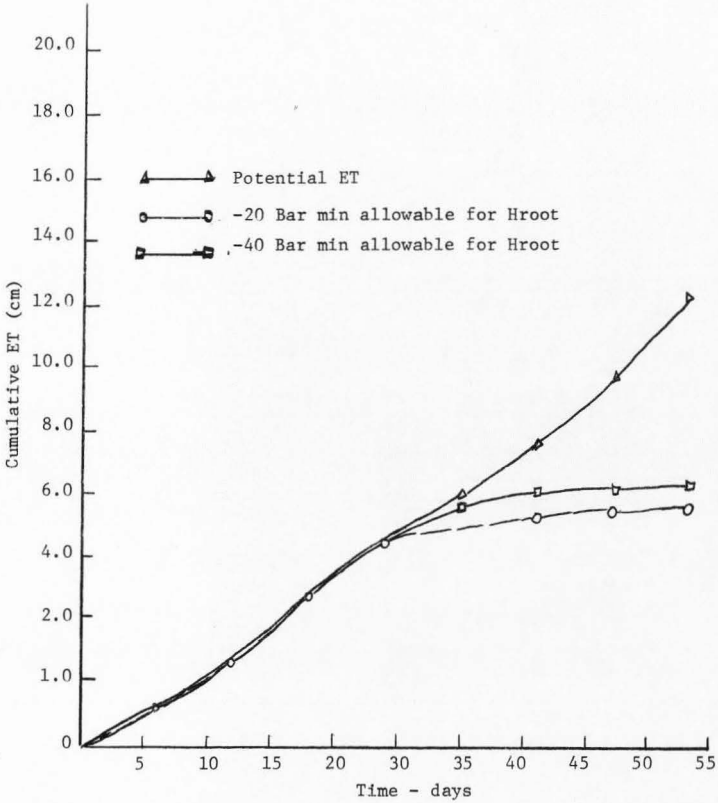

Figure 30. Cumulative evapotranspiration versus time compared with predicted evapotranspiration where the lower limit of Hroot was -40 bars and -20 bars (data for desert soils--from Curlew Valley, Utah).

lower limit does not make very large differences in ET. Other than these, exact field conditions and soil properties are needed for the program to compute comparable results.

SUMMARY AND CONCLUSIONS

A mathematical model was developed to predict soil water profiles, evaporation, transpiration, drainage and root potential at the surface in a cropped field as functions of time. The model is for one dimensional unsteady state flow conditions, and can be applied to irrigated and non-irrigated crops.

The model consists of a second-order, non-linear partial differential equation of a parabolic type with a plant extraction term:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}[K(\theta)\frac{\partial H}{\partial z}] + A(z) \qquad [42]$$

where A(z) is the root extraction term which depends on root density function, soil conductivity and plant water potential and soil water potential difference. The solution for equation [42] was obtained by using a numerical method solution using a digital computer to solve the above equation. The basic input data needed for the solution of the model are:

1. Soil properties: $h - \theta$ and $K - \theta$ curves covering the range of water content to be encountered in the problem. $\theta - z$ and $S - z$ relation at $t = 0$, as well as θ saturated and θ air dry of the soil.
2. Plant properties: Root distribution function RDF - z and the minimum and maximum values that Hroot can reach.
3. Boundary and climatic properties; these include: potential ET and potential transpiration and evaporation as function of time. These can be calculated from climatic parameters,

potential infiltration and precipitation as function of time, and presence or absence of water table or layer restricting water flow at the lower boundary.

Soil, plant, and climatic parameters were determined in the field.

The total study included two years of field experiments. The crops were oats seeded to alfalfa in 1970 and alfalfa in 1971. Two lysimeters were used to measure actual ET. A neutron and gamma probe were used to measure soil water content profiles. Climatic data were collected from a weather station installed in the field.

The computed soil water content-depth profiles agreed very well with measured soil water content-depth profiles for both crops in 1970 and 1971.

The cumulative computed ET was 4.9 cm which was 0.4 cm less than the actual (measured) ET during the 9-day interval in 1970. In 1971 actual and computed ET were the same for the whole season. This agreement may be partially due to the "forcing" of the water removal by evapotranspiration to be the same as measured.

Computed cumulative upward water flow from the water table was 2.2 cm which was 0.10 cm greater than measured in the 9-day period in 1970. The computed cumulative upward flow from the water table was 4.8 cm as compared to 1.6 cm measured upward flow for the whole season (116 days) in 1971.

FURTHER RESEARCH

This study provides a basic framework for solving problems that involve water quality and quantity in irrigation return flow, since salt movement in the soil depends primarily on water movement. Moreover, this study provides a basic step in irrigation water management, as to how much and when to irrigate.

Some of the weaknesses of this model are that it didn't consider hysteresis or layered soil although both of these have been considered earlier. Further assumptions were made that the soil properties, primarily the hydraulic conductivity-water content relation, do not change with time. Moreover, this model requires some assumption regarding the partioning of potential evapotranspiration into potential transpiration and potential evaporation directly from the soil. At present, this partition is done rather crudely based on an estimate of percent of cover of the plant.

Therefore, further research for the development of this program should be pursued. The suggested research is:

1. Development of the program to account for the variation of parameters with time, therefore increasing the accuracy of computed values.
2. Simplification of the model to reduce computer time and input data needed since the accuracy of the computed values is fair enough for many practical purposes.

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APPENDIXES

Appendix A

Program A

The FORTRAN program to solve equation [25] by the implicit method using Crank-Nicholson or Laosonen approximation.

```
C*********************************************************************
              SALT AND WATER FLOW. 1972
@FOR,I  MAIN,MAIN
C       PROGRAM-SOIL WATER,SALT,FLOW WITH PLANT UPTAKE.
C       PROGRAM OF FEB. 29,1972
C       CONQ IS  LARGEST WATERCONTENT CHANGE ALLOWED EACH COMPUTATION
C       HWET IS PRESSURE OF HIGHEST POSSIBLE WATER CONTENT
C       V IS BOUNDARY CONDITIONS AT TOP AND TIMES CONDITIONS APPLY
C       DETT IS TIME INCREMENT TO START WITH AND LOWEST TO USE
C       CONQ IS SMALLEST WATERCONTENT CHANGE ALLOWED EACH COMPUTATION
C       GRAVY IS GRAVITY COMPONENT USUALLY THE SAME AS DELX
C       DELW IS WATER CONTENT DIFFERENCE CORRESPONDING TO TABLE INCREMENTS
C       T IS WATER CONTENT TABLE  HAS EQUAL SPACED INCREMENTS
C       TIME IS CUMULATIVE TIME AT START OF COMPUTATION
C       TT IS 1.0 FOR LAASONEN AND 0.5 FOR CRANK NICHOLSON
C       CUMT IS TIME AT END OF COMPUTATION
C----TAA=1. FOR ZERO FLUX AT BOTTOM,TAA=0 FOR H(KK) CONSTANT              A    5
C         FROM G(I) OR H(I)=G(I)
C       CTM IS LOWEST VALUE OF DELT PERMITTED--IF AS LOW STOPS
C       HDRY IS PRESSURE OF LOWEST POSSIBLE WATER CONTENT
C       PP IS PRESSURE TABLE(WETTING)STARTING WITH LOWEST PRESSURE
C       D IS CONDUCTIVITY TABLE STARTING WITH LOWEST WATER CONTENT VALUE
C       DD SAME AS ABOVE EXCEPT STARTS FROM WETTING
C       C IS WATER CAPACITY AS A FUNCTION OF DEPTH  BEGINNING AT TOP
C       DELX IS DEPTH INCREMENT
C       W IS WATER CONTENT  AS A FUNCTION OF DEPTH  BEGINNING AT TOP
C       H IS WATER PRESSURE AS A FUNCTION OF DEPTH  BEGINNING AT TOP
C       WATL IS LOWEST POSSIBLE WATER CONTENT
C       WATH IS HIGHEST POSSIBLE WATER CONTENT
C       CB IS A CONSTANT TO MULTIPLY D ARRAY BY--USUALLY 1.0
C----K IS NO. OF DELX INCREMENTS,MM NO. OF TIMES H+W PRINTED+KIT NO.OF    A   12
C-----START HERE FOR A NEW PROGRAM                                        A   13
C-----MI IS TO PRINT H,W ARRAYS EACH ITER..ITER NO. OF V ELEMENTS         A   14
C       HROOT IS THE ACTUAL ROOT WATER POTENTIAL
C       BB REPRESENTS PLANT UPTAKE ADDITIONS
C       HLOW IS THE MINIMUM ROOT POTENTIAL ALLOWED
C       HHI IS THE MAXIMIM  ROOT POTENTIAL ALLOWED
C       ET IS THE POTENTIAL EVAPOTRANSPIRATION,ALWAYS NEGATIVE
C       WFOD IS THE WATER FLOW RATE AT THE SURFACE
C       ETPL IS THE POTENTIAL TRANSPIRATION,ALWAYS NEGATIVE
C       TET IS THE BOUNDARY POTENTIAL ET,ALWAYS NEGATIVE,LTV ARRAY
C******DD,H,G*Y*W*RDF*A(SE(SS*SD*ARRAYS ARE OF SAME DIMENSIONS AT LEAST=KK
C******SF*TET*V ARRAYS ARE OF SAME DIMENSIONS AT LEAST=ITER
C******P*D*T*ARE OF EQUAL DIMENSIONS,=60 AT MOST
C*********************************************************************
      DIMENSION DD(25),H(25),G(25),Y(25),W(25),RDF(25),A(25),SE(25)
      DIMENSION SS(25),SD(25),C(25),B(25),E(25),F(25)
      DIMENSION SF(65),TET(65),V(65)
      DIMENSION P(50),D(50),T(50)
      WRITE(6,8765)
 8765 FORMAT(1H1,25X,61('*'))
      WRITE(6,8766)
 8766 FORMAT(1H ,25X,**ROOT DEPTH NORMALT.. EVAPRATION =0.1 EVAPOTRANSP
     1IRATION.  **)
      WRITE(6,9999)
9999  FORMAT(1H,25X,**$TAA=0.0    UPWARD WATER FLOW..FIELD DATA
```

```
     1HLOW=-15 BARS. CROP 1.1971')
      WRITE(6,8767)
 8767 FORMAT(1H ,25X,61('*'))
C*****************************************************************
      READ 163, ML                                                  A   9
      LMM=0                                                         A  11
1     LMM=LMM+1                                                     A  10
      READ(5,163)K,MM,IER,NB,ND
      KK=K+1                                                        A  18
      READ(5,165) (TET(I),I=1,IER)
      READ(5,165) (RDF(I),I=1,KK)
      KC=1
      WFDD=-.009
      ET=TET(1)
      LL=MM                                                         A  19
      READ(5,165)(P(I),I=1,ND)
      READ(5,165)(DD(I),I=1,ND)
      READ 165, (W(I),I=1,KK)                                       A  25
      READ 165, (V(I),I=1,IER)                                      A  26
      READ 165, DELX,DETT,GRAVY,CONQ,DELW,TTME
      READ 165, TT,CUMT,TAA,HLOW,HHI,RRES
      READ 165, HDRY,HWET,WATL,WATH,CB
      READ 165,(SF(I),I=1,IER)
      READ 165, (SE(I),I=1,KK)
      WRITE (6,169)
      WRITE(6,163) K,MM,IER,NB,ND
      P(1)=P(1)*1.0E+03
      T(1)=0.0                                                      A  38
      DO 900 I=2,ND
      T(I)=DELW+T(I-1)
 900  P(I)=P(I)*1.0E+03
      READ 165,(DD(I),I=1,KK)
      SE(1)=SF(1)
      SMAX=5.0
      CWELX=0.0
      EOR=V(1)                                                      A  74
      DELT=DETT
      TM=1.0-TT                                                     A  76
      TBB=1.0-TAA                                                   A  77
      YMAX=WATH                                                     A  82
      DO 14 I=1,KK
      SS(I)=SE(I)
      SD(I)=SE(I)*W(I)
14    Y(I)=W(I)                                                     A  87
      PIT=0.0                                                       A  89
      DO 15 I=2,K
   15 PIT=W(I)*(DD(I+1)-DD(I-1))/2.+PIT
      WRITE (6,170)
      TW=D(1)
      D(1)=(D(1)*(P(2)-P(1)))*CB                                    A  39
      J=(W(1)-T(1))/DELW+1.0
      H(1)=(P(J+1)-P(J))*(W(1)-T(J))/DELW+P(J)
      G(1)=H(1)
      C(1)=DELW/(P(J+1)-P(J))
      WRITE ( 6,166) T(1),P(1),TW,D(1),C(1),DD(1),W(1),H(1),RDF(1),SF(1)
      DO 3 I=2,KK
```

```
      TW=D(I)
      D(I)=D(I)*(P(I)-P(I-1))*CB+D(I-1)
      J=(W(I)-T(1))/DELW+1.0
      H(I)=(P(J+1)-P(J))*(W(I)-T(J))/DELW+P(J)
      C(I)=DELW/(P(J+1)-P(J))
      G(I)=H(I)
      WRITE ( 6,166) T(I),P(I),TW,D(I),C(I),DD(I),W(I),H(I),RDF(I),SE(I)
3     CONTINUE
      N=KK+1
      DO 7 I=N,ND
      TW=D(I)
      D(I)=D(I)*(P(I)-P(I-1))*CB+D(I-1)
7     WRITE (6,166) T(I),P(I),TW,D(I)
C*****************************************************************
C     D IS NOW DIFFUSIVITY TIMES DELW NOT CONDUCTIVITY
      WRITE (6,179)
      DO 5 I=2,IER,2
5     WRITE (6,166) V(I),V(I-1),TFT(I-1),SF(I-1)
      WRITE (6,180)
      WRITE (6,166) DELX,DFTT,GRAVY,CONO,DELW,TIME
      WRITE (6,181)
      WRITE (6,166) TT,CUMT,TAA,HLOW,HHI,RRES
      WRITE (6,172)
      WRITE (6,166) HDRY,HWET,WATL,WATH,CB
      KCK=1
      HROOT=G(2)
      RUNOF=0.0
      CUMS=0.0
      CUMB=0.0
      CUMM=0.0
      SUMA=0.0
      CALL PLOT (KK,WATH,W,DD,SMAX,SD)
      WRITE(6,166) TIME
C*****************************************************************
C----COMPUTATION OF CONDUCTIVITY (B) AND WATER CAPACITY (C)
16    TOP=WATH
      BOT=WATL
      HKP=H(1)
      WKP=W(1)
      IF (FOR-0.0) 17,19,18
17    W(1)=WATL
      H(1)=HDRY
      GO TO 19
18    W(1)=WATH
      H(1)=HWET
19    TWW=(W(1)+Y(1))*0.5
      J=(TWW-T(1))/DELW+1.0
      BB=(TWW-T(J))/DELW
      DIFFA=(D(J+1)-D(J))*BB+D(J)
      HI=(P(J+1)-P(J))*BB+P(J)
      DO 37 I=1,K
      TW=(W(I+1)+Y(I+1))*0.5
      J=(TW -T(1))/DELW+1.0
      BB=(TW-T(J))/DELW
      DIFFB=(D(J+1)-D(J))*BB+D(J)
      GI=(P(J+1)-P(J))*BB+P(J)
```

```
  219 IF(HI-GI)20,32,20
20    B(I)=(DIFFA-DIFFB)/(HI-GI)                                    A 120
      IF (I-1) 21,21,33                                             A 121
21    IF (EOR-0.0) 22,33,22
  22  ER=(R(1)*(H(1)*TT-H(2)*TT-G(2)*TM+G(1)*TM+DD(2)))/DD(2)
      IF (ABS(1.1*EOR-ER)-ABS(0.1*EOR)) 236,236,23
23    IF(KCK.EQ.1) GO TO 220
      IF (KCK-20)305,236,236
  236 H(1)=(1.1*EOR*DD(2)/R(1)+H(2)*TT-G(1)*TM+G(2)*TM-DD(2))/TT
      IF(H(1).LT.HDRY) H(1)=HDRY
      IF (H(1).GT.HWET) H(1)=HWET
      GO TO 33
220   H(1)=HKP
      W(1)=WKP
      KCK=KCK+1
      GO TO 19
305   KCK=KCK+1
      IF (ER-EOR) 24,33,26
24    IF (W(1)-WATH) 25,33,33                                       A 126
25    BOT=W(1)                                                      A 127
      W(1)=(W(1)+TOP)*0.5                                           A 128
      GO TO 28                                                      A 129
26    IF (W(1)-WATL) 33,33,27                                       A 130
27    TOP=W(1)                                                      A 131
      W(1)=(W(1)+BOT)*0.5                                           A 132
  28  J=(W(1)-T(1))/DELW+1.0
      BB=(W(1)-T(J))/DELW                                           A 134
      IF(EOR-0.0)30,33,30
30    H(1)=(P(J+1)-P(J))*BB+P(J)                                    A 138
  218 TWW=(W(1)+Y(1))*0.5
      J=(TWW-T(1))/DELW+1.0
      BB=(TWW-T(J))/DELW                                            A 140
      DIFFA=(D(J+1)-D(J))*BB+D(J)                                   A 141
      HI=(P(J+1)-P(J))*BB+P(J)                                      A 142
      GO TO 219
32    B(I)=(D(J+1)-D(J))/(P(J+1)-P(J))                              A 142
      IF (I-1) 33,21,33                                             A 143
33    TWW=TW                                                        A 144
      HI=GI                                                         A 145
      DIFFA=DIFFB                                                   A 146
      TW=(W(I+1)+Y(I+1))*0.5                                        A 147
      J=(TW -T(1))/DELW+1.0
35    C(I+1)=DELW/(P(J+1)-P(J))                                     A 151
37    CONTINUE                                                      A 154
      KCK=1
      IF(EOR.GT.0.0.AND.ET.GE.0.0) GO TO 6666
      IF(EOR.GT.0.0.AND.ET.LT.0.0) GO TO 5555
 6666 ETPL=ET-EOR
      IF(ET.GE.0.0) GO TO 39
      IF(ETPL-0.0) 365,39,39
 5555 ETPL=ET
C*****************************************************************
C     SEARCHING FOR THE PROPER HROOT VALUE
365   HHOLD=HROOT
      HROOT=HLOW                                                    BP
      SINK=0.0
```

```
      DO 250 I=2,K
  250 F(I)=G(I)-0.5715*SF(I)-DD(I)*RRES
      DO 420 I=2,K
      IF(HROOT-E(I).GT.0.0) GO TO 420
      SINK=B(I)*RDF(I)*(HROOT-E(I))+SINK
  420 CONTINUE
      IF(SINK-ETPL.GT.0.0) GO TO 402
      HROOT=HHOLD
  410 HROOT=1.2*HROOT
      SINK=0.0
      DO 421 I=2,K
      IF(HROOT-E(I).GT.0.0) GO TO 421
      SINK=B(I)*RDF(I)*(HROOT-E(I))+SINK
  421 CONTINUE
      IF(SINK-ETPL)411,402,410
  411 HRLO=HROOT
      HROOT=HHOLD
      LCOUNT=0
  412 HROOT=0.8*HROOT
      LCOUNT=LCOUNT+1
      IF(LCOUNT.EQ.5) GO TO 490
      SINK=0.0
      DO 422 I=2,K
      IF(HROOT-E(I).GT.0.0) GO TO 422
      SINK=B(I)*RDF(I)*(HROOT-E(I))+SINK
  422 CONTINUE
      IF(SINK-ETPL)412,402,413
  413 HRHI=HROOT
      GO TO 491
  490 HRHI=HHI
  491 LCOUNT=0
      HROOT=HHOLD
  405 SINK=0.0                                                          BB
      DO 400 I=2,K                                                      BB
      IF(HROOT-E(I).GT.0.0) GO TO 400
      SINK=B(I)*RDF(I)*(HROOT-E(I))+SINK
  400 CONTINUE                                                          BB
      LCOUNT=LCOUNT+1                                                   BB
      IF(LCOUNT.EQ.20) GO TO 402
      IF(ABS(SINK-ETPL)-0.002)402,402,401
  401 IF(SINK-ETPL)403,402,404                                          BB
  403 HRLO=HROOT                                                        BB
      HROOT=0.5*(HROOT+HRHI)                                            BB
      GO TO 405                                                         BB
  404 HRHI=HROOT
      HROOT=0.5*(HROOT+HRLO)                                            BB
      GO TO 405                                                         BB
   79 DO 251 I=2,K
      SINK=0.0
  251 A(I)=0.0
      GO TO 38
C     A IS THE DEL WATER/DELT CAUSED BY PLANT EXTRACTION
  402 DO 406 I=2,K
      IF(HROOT-E(I).GT.0.0) GO TO 407
      A(I)=B(I)*(HROOT-E(I))*2.0*RDF(I)/(DD(I+1)-DD(I-1))
      GO TO 406
```

```
 407  A(I)=0.0
405   CONTINUE
C*****************************************************************
C----COMPUTATION OF TRIDIAGONAL MATRIX MAIN BODY                    A 158
38    DO 42 I=2,K                                                   B 159
      POT=(DD(I+1)-DD(I-1))/(2.0*DELT)                              B 160
      DLXA=(DD(I)-DD(I-1))                                          B 161
      DLXB=(DD(I+1)-DD(I))                                          B 162
      BB=C(I)*POT/TT+B(I)/DLXB+B(I-1)/DLXA                          B 162 1
      DA=(C(I)*POT*G(I)+(B(I)/DLXB)*(TM*(G(I+1)-G(I))-DLXB)+(B(I-1)/DLXA  B 162 2
     1)*(TM*(G(I-1)-G(I))+DLXA)+A(I)*(DD(I+1)-DD(I-1))*0.5)/TT
      IF(I-2)390,390,40
  390 IF(H(1).GE.HWET.OR.H(1).LE.HDRY) GO TO 394
      DA=DA-((B(I-1)/DLXA)*(TM*(G(I-1)-G(I))+DLXA))/TT+FOR/TT
      BB=BB-B(I-1)/DLXA
      GO TO 393
  394 DA=DA+H(I-1)*B(I-1)/DLXA
  393 F(I)=DA/BB
      E(I)=(B(I)/DLXB)/BB                                           B 166 1
      GO TO 42                                                      A 167
40    IF (I-K) 41,43,43                                             A 168
41    E(I)=(B(I)/DLXB)/(BB-(B(I-1)/DLXA)*E(I-1))                    B 169
      F(I)=(DA+(B(I-1)/DLXA)*F(I-1))/(BB-(B(I-1)/DLXA)*E(I-1))      B 170
  42  CONTINUE
43    BB=BB-TAA*B(I)/DLXB                                           B 172
      DA=DA+TAA*(B(I)/DLXB)*((G(I)-G(I+1))*TM+DLXB)/TT+TPB*B(I)/DLXB*H(  B 173
     1KK)                                                           B 174
      H(I)=(DA+(B(I-1)/DLXA)*F(I-1))/(BB-(B(I-1)/DLXA)*E(I-1))      B 174 1
44    I=I-1                                                         A 175
      H(I)=E(I)*H(I+1)+F(I)                                         A 176
      IF (I-2) 45,45,44                                             A 177
45    IF(TAA-1.0)47,46,46
46    H(KK)=H(K)+DD(KK)-DD(K)                                       B 178
47    DO 60 I=2,KK
300   IF (H(I)-HWET-DD(I)) 60,60,55
55    H(I)=HWET+DD(I)
60    CONTINUE                                                      A 197
C*****************************************************************
C----COMPUTATION OF WATER CONTENTS AS A FUNCTION OF PRESSURES JUST COMP  A 199
      IF(H(1).GE.HWET.OR.H(1).LE.HDRY) GO TO 1005
      WFDD=FOR
      H(1)=(FOR*DD(2)/B(1)+H(2)*TT-G(1)*TM+G(2)*TM-DD(2))/TT
      GO TO 134
1005  WFDD=B(1)*((H(1)-H(2))*TT+(G(1)-G(2))*TM+DD(2))/DD(2)         B 189
134   I=1
62    IF (H(I)-G(I)) 65,116,65
65    NHI=54                                                        A 206
      NLO=1                                                         A 207
      J=25                                                          A 208
66    IF (H(I)-P(J)) 67,72,68                                       A 209
67    NHI=J                                                         A 210
      GO TO 69                                                      A 211
68    NLO=J                                                         A 212
69    JT=J                                                          A 213
      J=(NHI-NLO)/2+NLO                                             A 214
      IF (J-JT) 66,70,66                                            A 215
```

```
70      IF (H(I)-P(J)) 71,72,72                                          A 21F
71      J=J-1                                                            A 217
72      WAT=(H(I)-P(J))*DELW/(P(J+1)-P(J))+T(J)                          A 218
        W(I)=WAT
        GO TO 117
11F     W(I)=Y(I)                                                        A 300
  117   DO 268 I=2,KK
268     W(I)=C(I)*(H(I)-G(I))+Y(I)
        GO TO 269
269     SUM3=0.0
        SUM2=0.0                                                         A 326
        SUM1=0.0
        DO 131 I=2,K                                                     A 327
        SUM1=W(I)+SUM1                                                   A 328
        SUM2=Y(I)+SUM2                                                   A 329
        IF (ABS(SUM1-SUM2)-ABS(SUM3)) 131,131,130                        A 330
130     SUM3=SUM1-SUM2                                                   A 331
131     CONTINUE                                                         A 332
        IF(ABS(SUM3)-ABS(CONQ))63,63,132
 132    IF(DELT-DETT*0.1)63,63,133
 133    DELT=0.5*DELT
        GO TO 38                                                         A 33F
  63    SUM1=0.0
        SUM2=0.0
        DO 800 I=2,K
        SUM1=W(I)*(DD(I+1)-DD(I-1))/2.+SUM1
 800    SUM2=Y(I)*(DD(I+1)-DD(I-1))/2.+SUM2
        CWF=SUM1-PIT
        WFRDD=(SUM1-SUM2)/DELT
        WFDUU=B(NB)*((H(NB)-H(NB+1))*TT+(G(NB)-G(NB+1))*TM*DD(NB+1)-DD(NB))
       1/(DD(NB+1)-DD(NB))
        CUMS=WFDD*DELT+CUMS                                              A 341
        CUMB=WFUU*DELT+CUMB
        SUMA=SUMA+STNK*DELT
        CWFLX=(SUM1-SUM2)                                               A 34 3A
C*****************************************************************
        KB=K-1
        DO 999 I=1,KB
        DELX=(DD(I+2)-DD(I))/2.0
        WFRU=(B(I)*((H(I)-H(I+1))*TT+(G(I)-G(I+1))*TM+DD(I+1)-DD(I))*DELT)  B 34 4
       1/(DD(I+1)-DD(I))
        WFRD=(B(I+1)*((H(I+1)-H(I+2))*TT+(G(I+1)-G(I+2))*TM+DD(I+2)-DD(I+1  B 345 1
       1))*DELT)/(DD(I+2)-DD(I+1))
        WFRU=WFRU/DELX
        WFRD=WFRD/DELX
        A(I+1)=A(I+1)*DELT
        IF(ABS(WFRU-WFRD).LT.0.0001)GO TO 200
        IF(I.EQ.1)GO TO 201
        IF(WFRU.GE.0.0.AND.WFRD.GE.0.0)GO TO 205
        IF(WFRU.LE.0.0.AND.WFRD.LE.0.0)GO TO 209
        IF(WFRU.GE.0.0.AND.WFRD.LE.0.0)GO TO 208
        IF(WFRU.LE.0.0.AND.WFRD.GE.0.0)GO TO 210
 205    SE(I+1)=(SS(I+1)*Y(I+1)+SS(I)*WFRU-SS(I+1)*WFRD)/W(I+1)
        GO TO 200
 201    IF(EOR-0.0)203,204,202
 202    IF(WFRD.GT.0.0)GO TO 206
```

```
  207   SE(2)=(SS(2)*Y(2)-SS(3)*WFRD)/W(2)
        GO TO 200
  206   SE(2)=(SS(2)*Y(2)-SS(2)*WFRD)/W(2)
        GO TO 200
  204   IF(WFRD.LT.0.0)GO TO 207
        GO TO 206
  202   IF(WFRD.GT.0.0)GO TO 205
  208   SE(I+1)=(SS(I+1)*Y(I+1)+SS(I)*WFRU-SS(I+2)*WFRD)/W(I+1)
        GO TO 200
  209   SE(I+1)=(SS(I+1)*Y(I+1)+SS(I+1)*WFRU-SS(I+2)*WFRD)/W(I+1)
        GO TO 200
  210   SE(I+1)=(SS(I+1)*Y(I+1)+SS(I+1)*WFRU-SS(I+1)*WFRD)/W(I+1)
  210   IF(SF(I+1).LT.0.0) SF(I+1)=SS(I+1)
  999   CONTINUE
        DO 704 I=1,KK
 704    SD(I)=SE(I)*W(I)                                                R 3 85 4
 705    IF(EOR-0.0)136,136,135
 135    RUNOF=(EOR-WFRD)*DELT+RUNOF                                     A 3 45
 136    TIME=TIME+DELT                                                  A 3 46
        IF (LL-MM) 138,137,137                                          A 3 47
  137   CALL PLOT (KK,WATH,W,DD,SMAX,SD)
        WRITE (6,166) (H(I),I=1,KK)                                     A 3 49
        WRITE(6,166)(SE(I),I=1,KK)
        WRITE(6,166)(A(I),I=2,K)
        LL=0                                                            A 3 52
        WRITE (6,184)
  138   WRITE (6,166) TIME,CWF,EOR,WFRD,HROOT,CUMS,CUMP,SUMA,WFRDD,WFUU,SE
       1(K)
        IF (SUM3-0.0) 139,301,139
  301   DELT=2.0*DELT
        GO TO 145
 139    TW=ABS(CONO*DELT/SUM3)                                          A 3 57
 140    IF (TW-0.1*DETT) 141,142,142                                    A 3 59
  141   TW=0.1*DETT
        GO TO 144
  142   IF(TW-1000.0*DETT)144,144,143
 143    TW=1000.0*DETT
  144   IF(TW.GT.2.0*DELT) GO TO 301
        DELT=TW
C*****************************************************************
C-----TEST TO SEE IF EVAP OR RAIN INTENSITY (EOR) HAS CHANGED          A 3 65
 145    IF(TIME-V(KC+1))148,147,148
 147    CALL PLOT (KK,WATH,W,DD,SMAX,SD)
        WRITE (6,166) (H(I),I=1,KK)                                     A 3 71
        WRITE(6,166)(SF(I),I=1,KK)
        WRITE(6,166)(A(I),I=2,KK)
        WRITE(6,184)
        WRITE (6,166) TIME,CWF,EOR,WFRD,HROOT,CUMS,CUMP,SUMA,WFRDD,WFUU,SE
       1(K)
        DELT=DETT                                                       A 3 75
        EOR=V(KC+2)
        SE(1)=SF(KC+2)
        ET=TET(KC+2)
        KC=KC+2
        GO TO 151                                                       A 3 79
 148    IF(TIME+DELT-V(KC+1))151,151,149
 149    DELT=V(KC+1)-TIME
 151    LL=LL+1                                                         A 3 84
```

```
      IF (TIME-CUMT) 153,152,152                                        A 3.85
152   IF (ML-LMM) 162,162,1                                             A 3.86
153   Y(1)=(W(1)+Y(1))*0.5                                              A 3.87
      J=(Y(1)-T(1))/DELW+1.0
      BB=(Y(1)-T(J))/DELW                                               A 3.89
      IF (FOR-0.0) 155,156,155                                          A 3.90
155   G(1)=(P(J+1)-P(J))*BB+P(J)                                        A 3.93
156   DO 161 I=2,KK                                                     A 3.94
      J=(W(I)-T(1))/DELW+1.0
      BB=(W(I)-T(J))/DELW
      G(I)=(P(J+1)-P(J))*BB+P(J)
      TW=(W(I)-Y(I))+W(I)                                               A 3.95
      IF (TW-WATH) 157,157,159                                          A 3.96
157   IF (TW-WATL) 158,160,160                                          A 3.97
158   TW=WATL                                                           A 3.98
      GO TO 160                                                         A 3.99
159   TW=WATH                                                           A 4.00
160   Y(I)=W(I)                                                         A 4.01
      W(I)=TW                                                           A 4.02
      SS(I)=SE(I)
161   CONTINUE                                                          A 4.04
      SS(1)=SE(1)
      GO TO 16                                                          A 4.07
162   STOP                                                              A 4.08
C*****************************************************************
163   FORMAT (20I3)                                                     A 4.11
165   FORMAT (7E10.4)                                                   A 4.13
166   FORMAT (11F11.4)
169   FORMAT (14H  K   MM IFP NB)
170   FORMAT (119H    WATER     POTENTIAL    CONDUCTIVITY DIFFUSIVITY
     1C(I)       DEPTH        W-DEPTH      H-DEPTH      PDF-DEPTH    SE-DEPTH)
172   FORMAT (53H    HDRY          HWET          WATL          WATH          CB)
179   FORMAT (54H  TIME END    SOIL FLUX    FT FLUX      SALT CONC.          )
180   FORMAT (66H   DELX          DETT          GRAVY         CONQ          DELW
     1         TIME)
181   FORMAT (66H    TT           CUMT          TAA           HLOW          HHI
     1         PRES)
184 FORMAT(1H ,*  TIME          CWF          FOR          WFDD         HROOT
     1   CUMS          CUMB         TRANS.       WFRDD        WFUU         SE(K)*)
      END                                                               A 4.17-
```

```
@FOR,I  SUB1,SUB1
      SUBROUTINE PLOT(N,WMAX,WVALUE,XVALUE,TMAX,TVALUE)
      DIMENSION ALINE(101),WVALUE(25),XVALUE(25),TVALUE(25)
      DATA FILL,AXIS,CHAR,CHAB,SAME/1H .1H.,1HW,1HS,1H*/
      WRITE (6,7) WMAX,TMAX
      DO 1 J=1,101
1     ALINE(J)=AXIS
      WRITE (6,8) (ALINE(K),K=1,101)
      DO 2 J=1,101
2     ALINE(J)=FILL
      ALINE(1)=AXIS
      DO 4 L=1,N
      J=100.0*(WVALUE(L)/WMAX)+1.5
      JJ=100.0*(TVALUE(L)/TMAX)+1.5
      IF(J.LT.1) J=1
      IF(J.GT.101) J=101
      IF(JJ.LT.1) JJ=1
      IF(JJ.GT.101) JJ=101
      IF (J-JJ)10,11,10
11    ALINE (J)=SAME
      GO TO 12
10    ALINE (J)=CHAR
      ALINE(JJ)=CHAB
12    WRITE(6,9) XVALUE(L),WVALUE(L),TVALUE(L),(ALINE(K),K=1,101)
      ALINE(JJ)=FILL
      ALINE(J)=FILL
   55 ALINE(1)=AXIS
4     CONTINUE
      DO 5 J=1,101
5     ALINE(J)=AXIS
      WRITE (6,8) (ALINE(K),K=1,101)
      RETURN
    7 FORMAT (24H  X VALUE WVALUE  SVALUE,5X,17H  MAX WAT CONT IS,F7.4,'
     1  MAX SALT CONCENTRATION IS',F6.2,1H )
8     FORMAT (31X,101A1)
    9 FORMAT(1H ,F6.1,F9.4,F8.2,7H         ,101A1)
      END
```

Table 6. Soil properties used for computations made. Vernal sandy clay loam soil

Water content θ	Hydraulic conductivity K in cm/hour^{-1}	Pressure head h in cm
.00	1.0×10^{-9}	-2×10^{6}
.01	2.0×10^{-9}	-1.3×10^{6}
.02	3.4×10^{-9}	-8.5×10^{5}
.03	1.0×10^{-8}	-4.2×10^{5}
.04	1.7×10^{-8}	-2.2×10^{5}
.05	3.0×10^{-8}	-1.15×10^{5}
.06	5.4×10^{-8}	-5.8×10^{4}
.07	9.2×10^{-8}	-3.0×10^{4}
.08	1.6×10^{-7}	-1.5×10^{4}
.09	2.7×10^{-7}	-1.1×10^{4}
.10	4.8×10^{-7}	-8.0×10^{3}
.11	7.5×10^{-7}	-6.2×10^{3}
.12	1.5×10^{-7}	-4.9×10^{3}
.13	2.5×10^{-6}	-4.0×10^{3}
.14	4.5×10^{-6}	-3.0×10^{3}
.15	8.7×10^{-6}	-2.35×10^{3}
.16	1.4×10^{-5}	-1.85×10^{3}
.17	2.5×10^{-5}	-1.45×10^{3}
.18	4.5×10^{-5}	-1.12×10^{3}
.19	7.5×10^{-5}	-8.7×10^{3}
.20	1.1×10^{-4}	-6.7×10^{2}
.21	1.7×10^{-4}	-5.3×10^{2}
.22	2.7×10^{-4}	-4.1×10^{2}

Table 6. Continued

Water content θ	Hydraulic conductivity K in cm/hour^{-1}	Pressure head h in cm
.23	4.0×10^{-4}	-3.2×10^{2}
.24	6.1×10^{-4}	-2.5×10^{2}
.25	9.5×10^{-4}	-2.0×10^{2}
.26	1.5×10^{-3}	-1.65×10^{2}
.27	2.4×10^{-3}	-1.35×10^{2}
.28	3.5×10^{-3}	-1.15×10^{2}
.29	5.5×10^{-3}	$- .99 \times 10^{2}$
.30	9.0×10^{-3}	$- .85 \times 10^{2}$
.31	1.4×10^{-2}	$- .74 \times 10^{2}$
.32	2.1×10^{-2}	$- .55 \times 10^{2}$
.33	2.8×10^{-2}	$- .56 \times 10^{2}$
.34	3.5×10^{-2}	$- .48 \times 10^{2}$
.35	4.6×10^{-2}	$- .45 \times 10^{2}$
.36	6.0×10^{-2}	$- .41 \times 10^{2}$
.37	7.9×10^{-2}	$- .38 \times 10^{2}$
.38	1.0×10^{-1}	$- .34 \times 10^{2}$
.39	1.3×10^{-1}	$- .3112 \times 10^{2}$
.40	1.7×10^{-1}	$- .2731 \times 10^{2}$
.41	2.3×10^{-1}	$- .2413 \times 10^{2}$
.42	3.1×10^{-1}	$- .2096 \times 10^{2}$
.43	4.1×10^{-1}	$- .1715 \times 10^{2}$
.44	5.4×10^{-1}	$- .1335 \times 10^{2}$
.45	6.9×10^{-1}	$- .1016 \times 10^{2}$

Table 6. Continued

Water content θ	Hydraulic conductivity K in cm/hour^{-1}	Pressure head h in cm
.46	8.8×10^{-1}	$-.6985 \times 10$
.47	1.03	$-.3175 \times 10$
.48	1.30	-.0000

Table 7. Root distribution (RDF), salt content (SE) for alfalfa in 1971 and initial water content for alfalfa crop 1 (θ_1), crop 2 (θ_2), crop 3 (θ_3) versus depth used for the computations ~~made~~

Depth cm	RDF	SE mmhos	θ_1	θ_2	θ_3
0	.0000	.000	.080	.180	.242
1	.0280	.475	.085	.180	.2425
3	.0560	.505	.090	.181	.2435
5	.0560	.5113	.095	.183	.2445
8	.0840	.5200	.100	.185	.2455
12	.1118	.5325	.110	.189	.2465
16	.1042	1.0000	.120	.1915	.2475
20	.0766	1.3500	.130	.195	.2485
25	.0967	1.7750	.144	.198	.2500
30	.0967	2.2000	.155	.202	.2520
35	.0637	2.6250	.195	.215	.2600
40	.0633	3.0250	.225	.230	.2680
45	.0633	3.4620	.265	.245	.2760
55	.0666	3.1750	.267	.244	.2740
70	.0344	2.7250	.268	.240	.2675
85	.0000	2.4000	.273	.265	.2740
100	.0000	2.1000	.275	.285	.2870
115	.000	1.8000	.285	.301	.3175
135	.0000	1.4120	.305	.326	.3780
155	.0000	1.0500	.365	.370	.4035
165	.0000	.6250	.400	.400	.4140

Table 8. Flux at the surface for alfalfa in 1971, evapotranspiration (ET), soil surface flux (WF), +ve value is precipitation, -ve value is evaporation, and salt concentration (SF) versus time

Time hours	ET cm/hr	WF cm/hr	SF mmhos
		Crop 1	
25	$-.336 \times 10^{-1}$	$-.336 \times 10^{-2}$	.000
52	$-.25 \times 10^{-2}$	$-.25 \times 10^{-3}$	.000
55	-.000	.5433	.635
74	$-.41 \times 10^{-2}$	$-.41 \times 10^{-3}$	.000
75	-.000	.20	.000
98	$-.43 \times 10^{-2}$	$-.43 \times 10^{-3}$	.000
122	$-.20 \times 10^{-1}$	$-.20 \times 10^{-2}$	.000
169	$-.175 \times 10^{-1}$	$-.175 \times 10^{-2}$	.000
193	$-.30 \times 10^{-1}$	$-.30 \times 10^{-2}$	.000
196	-.000	.59	.635
220	$-.40 \times 10^{-4}$	$-.40 \times 10^{-4}$	.000
223	.000	.5233	.635
242	$-.50 \times 10^{-3}$	$-.50 \times 10^{-4}$	.000
290	$-.254 \times 10^{-1}$	$-.254 \times 10^{-2}$	.000
313	$-.139 \times 10^{-1}$	$-.139 \times 10^{-2}$	.000
337	.000	.1162	.000
414	$-.2766 \times 10^{-1}$	$-.2766 \times 10^{-2}$	.000
457	$-.145 \times 10^{-1}$	$-.145 \times 10^{-2}$	.000
482	$-.96 \times 10^{-2}$	$-.96 \times 10^{-3}$	.000
487	.000	.598	.635
530	$-.375 \times 10^{-2}$	$-.375 \times 10^{-3}$	.000
626	$-.192 \times 10^{-1}$	$-.192 \times 10^{-2}$	.000

Table 8. Continued

Time hours	ET cm/hr	WF cm/hr	SF mmhos
648	$-.72 \times 10^{-2}$	$-.72 \times 10^{-3}$	.000
657	.000	.5366	.635
672	$-.193 \times 10^{-1}$	$-.193 \times 10^{-2}$	.000
698	$-.326 \times 10^{-1}$	$-.326 \times 10^{-2}$	.000
722	$-.154 \times 10^{-1}$	$-.154 \times 10^{-2}$	.000
793	$-.241 \times 10^{-2}$	$-.241 \times 10^{-2}$	.000
868	$-.224 \times 10^{-1}$	$-.224 \times 10^{-2}$	.000
919	$-.320 \times 10^{-2}$	$-.320 \times 10^{-2}$	.000
920	.000	.030	.000
938	$-.30 \times 10^{-1}$	$-.30 \times 10^{-2}$	.000
	Crop 2		
22	$-.246 \times 10^{-1}$	$-.246 \times 10^{-2}$	.000
48	$-.181 \times 10^{-1}$	$-.181 \times 10^{-2}$	.000
73	$-.146 \times 10^{-1}$	$-.146 \times 10^{-2}$	.000
96	.000	$.565 \times 10^{-2}$	.000
120	$-.134 \times 10^{-1}$	$-.134 \times 10^{-2}$	.000
157	$-.141 \times 10^{-1}$	$-.141 \times 10^{-2}$	.000
169	.000	.5041	.635
187	.000	.015	.000
216	$-.177 \times 10^{-1}$	$-.177 \times 10^{-2}$	.000
241	$-.249 \times 10^{-1}$	$-.249 \times 10^{-2}$	.000
288	$-.30 \times 10^{-1}$	$-.30 \times 10^{-2}$	.000
408	$-.275 \times 10^{-1}$	$-.275 \times 10^{-2}$	.000
417	$-.749 \times 10^{-1}$	$-.749 \times 10^{-2}$	.000

Table 8. Continued

Time hours	ET cm/hr	WF cm/hr	SF mmhos
429	.000	.5608	.635
456	$-.281 \times 10^{-1}$	$-.281 \times 10^{-2}$	.000
504	$-.383 \times 10^{-1}$	$-.383 \times 10^{-2}$	.000
528	$-.289 \times 10^{-1}$	$-.289 \times 10^{-2}$	.000
576	$-.241 \times 10^{-1}$	$-.241 \times 10^{-2}$	.000
626	$-.251 \times 10^{-1}$	$-.251 \times 10^{-2}$	.000
648	.000	$.363 \times 10^{-2}$	.000
671	.000	$.435 \times 10^{-2}$	.000
683	.000	.6033	1.775
719	.000	.000	.000
769	$-.234 \times 10^{-1}$	$-.234 \times 10^{-2}$	.000
816	$-.259 \times 10^{-1}$	$-.259 \times 10^{-2}$	.000
817	.000	.03	.000
865	$-.264 \times 10^{-1}$	$-.264 \times 10^{-2}$	.000
889	$-.323 \times 10^{-1}$	$-.323 \times 10^{-2}$	.000
893	.000	.6425	.635
912	$-.456 \times 10^{-1}$	$-.456 \times 10^{-2}$	.000
963	$-.277 \times 10^{-1}$	$-.277 \times 10^{-2}$	.000
1005	$-.226 \times 10^{-1}$	$-.226 \times 10^{-2}$	.000
	Crop 3		
24	$-.625 \times 10^{-2}$	$-.625 \times 10^{-3}$	.000
48	$-.127 \times 10^{-1}$	$-.127 \times 10^{-2}$	.000
144	$-.142 \times 10^{-1}$	$-.142 \times 10^{-2}$	.000
240	$-.243 \times 10^{-1}$	$-.243 \times 10^{-2}$	.000

Table 8. Continued

Time hours	ET cm/hr	WF cm/hr	SF mmhos
312	$-.30 \times 10^{-1}$	$-.30 \times 10^{-2}$	.000
328	.000	.6362	1.0920
336	.000	.000	.000
360	$-.211 \times 10^{-1}$	$-.211 \times 10^{-2}$	.000
480	$-.187 \times 10^{-1}$	$-.187 \times 10^{-2}$	.000
552	$-.135 \times 10^{-1}$	$-.135 \times 10^{-2}$	.000
612	$-.219 \times 10^{-1}$	$-.219 \times 10^{-2}$	.000
627	.000	.6166	.839
696	$-.224 \times 10^{-1}$	$-.224 \times 10^{-2}$	.000
698	.000	.37	.000
768	$-.190 \times 10^{-1}$	$-.190 \times 10^{-2}$	.000
792	.000	.0021	.000
816	$-.226 \times 10^{-1}$	$-.226 \times 10^{-2}$	.000
840	.000	.0504	.000
864	$-.227 \times 10^{-1}$	$-.227 \times 10^{-2}$	.000
888	$-.198 \times 10^{-1}$	$-.198 \times 10^{-2}$	.000
915	$-.191 \times 10^{-1}$	$-.191 \times 10^{-1}$	.000

Appendix B

Table 9. Rain, irrigation and actual evapotranspiration data for alfalfa in 1971. Rain and irrigation data were measured by rain gage, evapotranspiration data were measured by the lysimeter

Date	Rain cm	Irrigation cm	ET-cm East lysimeter	ET-cm West lysimeter	Average ET-cm	Cumulative cm
May 15, 1971			.84	.84	.84	.84
May 16, 1971		1.63	.38	-.25	.07	.91
May 17, 1971	.20		.05	.09	.07	.98
May 18, 1971			.04	.15	.10	1.08
May 19, 1971			.53	.42	.48	1.56
May 20, 1971			.48	.42	.45	2.01
May 21, 1971			.32	.42	.37	2.38
May 22, 1971		1.77	1.01	.42	.72	3.10
May 23, 1971		1.57	.37	-.35	.01	3.11
May 24, 1971			.09	-.07	.01	3.12
May 25, 1971			.53	.64	.58	3.70
May 26, 1971			.85	.42	.64	4.34
May 27, 1971			.16	.48	.32	4.66
May 28, 1971	2.79		.00	.00	.00	4.66
May 29, 1971			.65	.65	.65	5.31
May 30, 1971			.71	.71	.71	6.02
May 31, 1971			.77	.77	.77	6.75
June 1, 1971			.16	.37	.26	7.05
June 2, 1971			.48	.26	.37	7.42
June 3, 1971		2.99	.32	.16	.24	7.66
June 4, 1971			.08	.08	.08	7.74
June 5, 1971			.08	.08	.08	7.82
June 6, 1971			.53	.37	.45	8.27
June 7, 1971			.53	.37	.45	8.72
June 8, 1971			.48	.37	.42	9.14
June 9, 1971			.53	.37	.45	9.59
June 10, 1971		4.83	.27	.05	.16	9.75
June 11, 1971			.59	.00	.29	10.04
June 12, 1971			1.27	.42	.85	10.89
June 13, 1971			.24	.50	.37	11.26
June 14, 1971			.71	.45	.58	11.84
June 15, 1971			.58	.48	.53	12.37
June 16, 1971			.58	.64	.61	12.98
June 17, 1971			.53	.42	.48	13.46
June 18, 1971			.64	.58	.61	14.07
June 19, 1971			.90	.85	.87	14.94
June 20, 1971			.90	.60	.75	15.69
June 21, 1971	.03		.90	.73	.81	16.50
June 22, 1971			.54	.54	.54	17.04
June 23, 1971			.54	.54	.54	17.58
June 24, 1971			.47	.47	.47	18.05
June 25, 1971			.27	.47	.37	18.42
June 26, 1971	.13		.00	.00	.00	18.42

Table 9. Continued

Date	Rain cm	Irrigation cm	ET-cm East lysimeter	ET-cm West lysimeter	Average ET-cm	Cumulative cm
June 27, 1971			.26	.37	.32	18.74
June 28, 1971			.42	.62	.52	19.06
June 29, 1971		6.05	.00	.00	.00	19.06
June 30, 1971	.27		.00	.00	.00	19.06
July 1, 1971			.51	.51	.51	19.57
July 2, 1971			.62	.62	.62	20.19
July 3, 1971			.70	.70	.70	20.89
July 4, 1971			.72	.72	.72	21.61
July 5, 1971			.67	.67	.67	22.28
July 6, 1971			.64	.64	.64	22.92
July 7, 1971			.67	.67	.67	23.59
July 8, 1971			.65	.65	.65	24.24
July 9, 1971			.67	.67	.67	24.91
July 10, 1971		6.73	.67	.67	.67	25.58
July 11, 1971			.76	.76	.76	26.34
July 12, 1971			.90	.98	.94	27.28
July 13, 1971			.87	.93	.90	28.18
July 14, 1971			.64	.74	.69	28.87
July 15, 1971			.55	.55	.55	29.42
July 16, 1971			.36	.84	.60	30.02
July 17, 1971			.48	.68	.58	30.60
July 18, 1971			.15	1.17	.66	31.26
July 19, 1971	.08		.00	.00	.00	31.26
July 20, 1971		7.24	.00	.00	.00	31.26
July 21, 1971	.10		.00	.00	.00	31.26
July 22, 1971			.00	.00	.00	31.26
July 23, 1971			.53	.80	.62	31.88
July 24, 1971			.47	.64	.55	32.43
July 25, 1971			.46	.80	.63	33.06
July 26, 1971	.03		.45	.73	.59	33.65
July 27, 1971			.45	.73	.59	34.24
July 28, 1971			.52	.85	.68	34.92
July 29, 1971		2.57	.86	.70	.78	35.70
July 30, 1971			.72	1.02	.87	36.57
July 31, 1971			.64	.95	.79	37.86
Aug. 1, 1971			-	-	.63	37.99
Aug. 2, 1971			-	-	.56	38.55
Aug. 3, 1971			.36	.50	.43	38.98
Aug. 4, 1971			-.21	.53	.16	39.14
Aug. 5, 1971			-	-	.15	39.29
Aug. 6, 1971			.26	.35	.31	39.60
Aug. 7, 1971			.05	.66	.36	39.96
Aug. 8, 1971			.26	.37	.32	40.28
Aug. 9, 1971			.22	.38	.30	40.58
Aug. 10, 1971			.32	.46	.39	40.97
Aug. 11, 1971			.32	.66	.49	41.46

Table 9, Continued

Date	Rain cm	Irrigation cm	ET-cm East lysimeter	ET-cm West lysimeter	Average ET-cm	Cumulative cm
Aug. 12, 1971			.48	.69	.58	42.04
Aug. 13, 1971			.53	.67	.60	42.64
Aug. 14, 1971			.41	.90	.66	43.30
Aug. 15, 1971			.58	.90	.74	44.04
Aug. 16, 1971			.58	.88	.73	44.77
Aug. 17, 1971			-	-	.69	45.46
Aug. 18, 1971		10.18	-	-	.00	45.46
Aug. 19, 1971			-	-	.51	45.97
Aug. 20, 1971			.16	.74	.45	46.42
Aug. 21, 1971			.18	.69	.43	46.85
Aug. 22, 1971			.27	.65	.46	47.31
Aug. 23, 1971			-	-	.45	47.76
Aug. 24, 1971			-	-	.46	48.22
Aug. 25, 1971			-	-	.35	48.57
Aug. 26, 1971			.33	.33	.33	48.90
Aug. 27, 1971			.29	.29	.29	49.19
Aug. 28, 1971			.46	.46	.46	49.65
Aug. 29, 1971			.55	.55	.55	50.20
Aug. 30, 1971		9.25	.28	.28	.28	50.48
Aug. 31, 1971			.50	.50	.50	50.98
Sept. 1, 1971			.49	.49	.49	51.47
Sept. 2, 1971	.74		.56	.53	.55	52.02
Sept. 3, 1971			.42	.42	.42	52.44
Sept. 4, 1971			.43	.43	.43	52.87
Sept. 5, 1971			.48	.48	.48	53.35
Sept. 6, 1971	.05		.00	.00	.00	53.35
Sept. 7, 1971			.54	.54	.54	53.89
Sept. 8, 1971	1.21		.00	.00	.00	53.89
Sept. 9, 1971			.18	.92	.55	54.44
Sept. 10, 1971			.48	.48	.48	54.92
Sept. 11, 1971			.52	.52	.52	55.44

Table 10. Average soil water content (θ) of six sites in the field, as measured by the neutron probe, and equivalent depth of water in the soil profile for alfalfa in 1971, and for oats in 1970

Date	Depth - cm						Equiv. water depth
	30	45	75	105	135	165	
							cm
May 13, 1971	.153	.268	.267	.276	.308	.373	46.407
May 31, 1971	.290	.284	.247	.262	.350	.388	52.556
June 9, 1971	.259	.283	.264	.281	.378	.408	53.766
June 11, 1971	.312	.314	.294	.289	.375	.403	57.456
June 22, 1971	.202	.248	.238	.273	.327	.396	47.947
June 29, 1971	.315	.303	.260	.283	.382	.413	56.600
July 8, 1971	.223	.259	.246	.277	.377	.405	51.121
July 10, 1971	.321	.322	.280	.275	.371	.400	56.990
July 19, 1971	.231	.266	.253	.279	.380	.413	52.128
July 21, 1971	.313	.318	.310	.307	.386	.414	59.255
July 22, 1971	.301	.305	.302	.311	.386	.412	58.286
Aug. 3, 1971	.252	.276	.264	.294	.385	.414	54.116
Aug. 16, 1971	.197	.244	.246	.285	.381	.413	50.304
Aug. 18, 1971	.316	.322	.320	.334	.402	.419	61.151
Aug. 19, 1971	.302	.310	.311	.343	.404	.421	60.386
Aug. 29, 1971	.244	.279	.272	.308	.389	.420	54.845
Aug. 30, 1971	.321	.325	.325	.335	.400	.419	61.540
Aug. 31, 1971	.306	.314	.316	.343	.398	.420	60.641
Sept. 8, 1971	.275	.288	.280	.313	.389	.411	56.370
July 31, 1970	.197	.295	.257	.295	.378	.462	
Aug. 2, 1970	.163	.273	.262	.295	.380	.463	
Aug. 4, 1970	.127	.250	.257	.290	.377	.455	
Aug. 8, 1970	.112	.233	.247	.288	.378	.462	

Table 11. Average soil water content (θ) of two sites in two lysimeters as measured by the neutron probe, and equivalent depth of water in the soil profile for alfalfa in 1971

Date	Depth - cm					Equivalent water depth cm
	30	45	60	75	82.5	
May 13, 1971	.205	.262	.279	.302	.325	22.433
May 31, 1971	.283	.283	.292	.312	.333	26.109
June 9, 1971	.256	.277	.301	.326	.337	25.310
June 11, 1971	.311	.314	.332	.344	.353	28.765
June 22, 1971	.207	.250	.278	.311	.322	22.362
June 29, 1971	.315	.308	.294	.304	.307	27.369
July 8, 1971	.204	.233	.258	.280	.287	21.020
July 10, 1971	.325	.317	.302	.281	.280	27.500
July 19, 1971	.204	.226	.249	.265	.264	20.371
July 21, 1971	.309	.316	.327	.332	.328	28.283
July 22, 1971	.299	.295	.308	.323	.325	27.155
Aug. 3, 1971	.221	.226	.239	.257	.257	20.704
Aug. 16, 1971	.154	.162	.177	.189	.185	14.826
Aug. 18, 1971	.311	.311	.318	.272	.252	26.767
Aug. 19, 1971	.290	.291	.300	.298	.284	25.957
Aug. 29, 1971	.212	.224	.232	.237	.228	19.765
Aug. 30, 1971	.318	.323	.329	.327	.314	28.585
Aug. 31, 1971	.296	.296	.310	.320	.315	26.972
Sept. 8, 1971	.255	.250	.258	.277	.273	23.041

Table 12. Average soil water content (θ) of four sites in the field, as measured by the gamma probe, for alfalfa, 1971

Date	Depth - cm												
	7.5	15	22.5	30	37.5	45	52.5	60	67.5	75	90	105	120
May 14, 1971	.260	.264	.236	.240	.264	.271	.269	.281	.241	.252	.264	.273	.305
May 31, 1971	.319	.297	.252	.230	.241	.255	.241	.244	.225	.220	.255	.267	.293
June 9, 1971	.231	.234	.205	.216	.238	.261	.249	.244	.220	.230	.257	.283	.325
June 11, 1971	.333	.290	.284	.264	.275	.298	.274	.293	.249	.246	.263	.294	.317
June 22, 1971	.165	.202	.149	.163	.202	.228	.223	.223	1224	.228	.265	.299	.328
June 30, 1971	.299	.299	.252	.250	.246	.263	.224	.237	.217	.229	.269	.306	.347
July 8, 1971	.211	.246	.226	.234	.249	.269	.258	.264	.257	.254	.287	.324	.366
July 10, 1971	.361	.342	.302	.291	.287	.316	.278	.380	.229	.235	.258	.296	.336
July 19, 1971	.192	.231	.191	.209	.234	.257	.258	.248	.234	.241	.273	.305	.339
July 21, 1971	.325	.313	.267	.277	.289	.314	.309	.312	.280	.301	.304	.333	.364
July 21, 1971	.327	.326	.289	.292	.293	.339	.328	.329	.294	.304	.324	.351	.378
July 22, 1971	.309	.302	.265	.271	.276	.3.8	.300	.318	.285	.288	.311	.356	.379
Aug. 3, 1971	.241	.251	.220	.233	.250	.269	.268	.277	.265	.265	.293	.344	.364
Aug. 16, 1971	.159	.186	.171	.192	.226	.244	.237	.253	.228	.247	.289	.334	.361
Aug. 18, 1971	.298	.271	.260	.233	.236	.289	.279	.295	.264	.276	.274	.320	.376
Aug. 19, 1971	.329	.330	.274	.280	.282	.332	.324	.345	.306	.309	.334	.379	.417
Aug. 29, 1971	.208	.228	.196	.208	.250	.263	.268	.281	.247	.293	.291	.359	.366
Aug. 30, 1971	.353	.346	.303	.290	.304	.334	.334	.363	.321	.322	.320	.395	.403
Aug. 31, 1971	.322	.322	.282	.265	.277	.312	1316	.354	.310	.319	.322	.400	.421
Sept. 8, 1971	.287	.285	.240	.244	.264	.276	.277	.292	.291	.283	.290	.368	.366

Table 13. Average soil water content (θ) of two sites in two lysimeters as measured by the gamma probe, for alfalfa in 1971

Date	Depth - cm										
	7.5	15	22.5	30	37.5	45	52.5	60	67.5	75	82.5
May 14, 1971	.270	.265	.262	.280	.286	.300	.324	.326	.332	.346	.346
May 31, 1971	.312	.311	.283	.294	.284	.287	.311	.307	.306	.333	.330
June 9, 1971	.226	.248	.238	.256	.273	.281	.316	.311	.317	.352	.350
June 11, 1971	.326	.319	.315	.336	.305	.330	.348	.356	.347	.363	.370
June 22, 1971	.161	.181	.184	.218	.238	.242	.262	.275	.290	.313	.323
June 30, 1971	.289	.294	.274	.307	.288	.296	.301	.312	1283	.321	.325
July 8, 1971	.220	.236	.239	.253	.265	.274	.297	.312	.295	.327	.325
July 10, 1971	.351	.340	.351	.339	.371	.334	.293	.280	.287	.225	.296
July 19, 1971	.180	.186	.183	.206	.240	.232	.255	.270	.243	.285	.274
July 21, 1971	.297	.307	.315	.324	.325	.315	.338	.332	.317	.327	.355
July 21, 1971	.290	.304	.285	.311	.323	.311	.335	.325	.331	.342	.372
July 22, 1971	.281	.304	.272	.300	.296	.296	.312	.311	.319	.352	.372
Aug. 3, 1971	.220	.223	.209	.272	.233	.240	.244	.263	.258	.285	.269
Aug. 16, 1971	.141	.158	.156	.180	.174	.175	.186	.190	.174	.205	.203
Aug. 18, 1971	.287	.296	.295	.322	.311	.309	.345	.326	.306	.258	.245
Aug. 19, 1971	.290	.309	.302	.324	.314	.328	.331	.331	.313	.326	.270
Aug. 29, 1971	.168	.184	.191	.208	.219	.220	.225	.233	.235	.242	.223
Aug. 30, 1971	.327	.311	.324	.361	.339	.343	.360	.356	.341	.361	.325
Aug. 31. 1971	.310	.312	.308	.311	.318	.315	.342	.347	.334	.354	.341
Sept. 8, 1971	-	-	-	-	-	-	-	-	-	-	-

Table 14. Climatic data and potential evapotranspiration as calculated by Penman modified method for alfalfa in 1971

Date	Radiation			Wind	Temperature			Vapour Pressure		ET-Pen	ET-cum.
	Total ly/min	Net ly/min	Long ly/min	miles/day	Dry Bulb °C	Wet Bulb °C	Soil °C	Saturated MB	Actual MB	cm/day	cm
May 15, 1971	.27	.14	.07	71.9	18.61	11.67	9.50	21.44	17.41	.30	.30
May 16, 1971	.50	.33	.08	84.1	16.11	10.83	9.50	18.31	15.25	.59	.89
May 17, 1971	.22	.08	.09	160.6	11.11	6.67	10.00	13.21	10.65	.19	1.08
May 18, 1971	.43	.25	.10	62.8	6.11	2.50	10.75	9.42	7.35	.37	1.45
May 19, 1971	.49	.30	.09	74.2	8.20	4.30	9.65	10.86	8.61	.47	1.92
May 20, 1971	.60	.43	.08	90.0	12.30	6.39	9.25	14.40	10.90	.51	2.43
May 21, 1971	.39	.22	.09	77.7	10.00	5.56	8.50	12.27	9.71	.36	2.79
May 22, 1971	.57	.38	.08	173.0	15.40	7.08	8.00	17.50	12.70	.74	3.53
May 23, 1971	.43	.25	.10	76.4	9.44	5.83	7.75	11.82	9.74	.40	3.93
May 24, 1971	.51	.33	.09	67.6	9.44	6.94	8.25	11.82	10.38	.49	4.42
May 25, 1971	.45	.27	.09	64.4	11.70	7.78	8.00	13.71	11.46	.45	4.87
May 26, 1971	.50	.31	.09	5.7	14.40	9.17	9.50	16.45	13.39	.53	5.40
May 27, 1971	.42	.29	.07	.3	18.75	10.55	8.63	21.60	16.89	.49	5.89
May 28, 1971	.40	.23	.09	84.8	14.86	9.44	10.00	16.89	13.76	.43	6.32
May 29, 1971	.40	.23	.08	84.8	14.86	9.44	10.00	16.89	13.76	.43	6.75
May 30, 1971	.40	.23	.09	84.8	14.86	9.44	10.00	16.89	13.76	.43	7.18
May 31, 1971	.40	.23	.08	84.8	14.86	9.44	10.00	16.89	13.76	.43	7.61
June 1, 1971	.31	.17	.08	86.4	16.53	10.00	8.50	18.80	15.02	.35	7.96
June 2, 1971	.38	.22	.08	66.5	15.00	8.89	10.75	17.05	13.51	.41	8.37
June 3, 1971	.35	.24	.08	59.5	17.64	10.95	10.87	20.10	16.30	.50	8.87
June 4, 1971	.42	.26	.07	108.5	17.79	11.24	10.00	20.37	16.57	.56	9.43
June 5, 1971	.43	.26	.08	94.5	16.66	10.97	10.50	18.97	15.67	.49	9.92
June 6, 1971	.48	.30	.08	79.4	14.72	10.28	10.00	16.74	14.16	.53	10.45
June 7, 1971	.48	.30	.08	79.4	14.72	10.28	10.00	16.74	14.16	.53	10.98
June 8, 1971	.44	.28	.07	45.0	19.00	11.67	10.50	21.99	17.73	.54	11.52
June 9, 1971	.42	.27	.07	62.0	20.80	13.00	10.75	24.40	20.00	.55	12.07
June 10, 1971	.28	.15	.07	60.0	19.00	13.20	11.50	21.20	18.20	.31	12.38

Table 14. Continued

Date	Radiation Total ly/min	Radiation Net ly/min	Radiation Long ly/min	Wind miles/day	Temperature Dry Bulb °C	Temperature Wet Bulb °C	Temperature Soil °C	Vapour Pressure Saturated MB	Vapour Pressure Actual MB	ET-Pen cm/day	ET-cum. cm
June 11, 1971	.28	.15	.07	60.0	19.00	13.20	11.50	21.20	18.20	.31	12.69
June 12, 1971	.46	.30	.08	60.0	16.90	11.11	12.00	19.30	15.92	.57	13.26
June 13, 1971	.50	.32	.08	47.1	17.17	11.30	11.80	19.50	16.10	.56	13.82
June 14, 1971	.43	.27	.07	60.0	20.00	13.82	10.12	23.82	19.88	.53	14.35
June 15, 1971	.43	.27	.06	54.5	21.88	14.28	9.67	26.21	21.78	.56	14.91
June 16, 1971	.41	.27	.07	60.9	21.50	14.52	9.70	25.62	21.58	.52	15.43
June 17, 1971	.43	.27	.08	61.6	18.61	12.78	12.50	21.44	18.06	.50	15.93
June 18, 1971	.38	.24	.06	72.4	24.52	15.56	12.30	30.60	25.45	.52	16.45
June 19, 1971	.34	.22	.05	62.8	26.00	16.20	12.58	33.48	27.76	.54	16.99
June 20, 1971	.48	.33	.06	52.4	23.06	15.56	12.25	28.13	23.75	.60	17.59
June 21, 1971	.48	.33	.06	52.4	23.06	15.56	12.25	28.13	23.75	.60	18.19
June 22, 1971	.43	.29	.05	56.6	24.86	15.90	9.06	31.28	26.07	.61	18.80
June 23, 1971	.39	.27	.04	123.0	26.75	15.00	13.00	37.90	30.43	.58	19.38
June 24, 1971	.41	.28	.05	82.9	26.70	14.75	13.00	34.85	27.87	.66	20.04
June 25, 1971	.46	.32	.05	83.1	26.05	14.50	13.70	33.55	26.84	.70	20.74
June 26, 1971	.51	.36	.05	83.3	25.40	14.25	14.75	32.25	25.81	.73	21.47
June 27, 1971	.32	.20	.05	100.6	25.56	14.17	13.50	32.58	25.95	.47	21.94
June 28, 1971	.53	.34	.08	128.8	18.89	11.67	14.25	21.82	17.62	.67	22.61
June 29, 1971	.42	.28	.06	126.4	23.72	14.44	15.60	29.26	23.86	.62	23.23
June 30, 1971	.38	.23	.07	65.7	19.44	12.50	16.00	22.58	18.54	.45	23.68
July 1, 1971	.43	.29	.06	65.0	22.43	12.12	15.75	27.18	21.19	.64	24.32
July 2, 1971	.45	.29	.07	78.0	20.00	14.44	16.00	23.37	20.13	.56	24.88
July 3, 1971	.45	.29	.07	78.6	19.44	14.72	15.50	22.58	19.83	.54	25.42
July 4, 1971	.45	.29	.07	89.7	19.17	13.06	15.75	22.20	18.64	.56	25.98
July 5, 1971	.45	.29	.07	93.0	19.44	13.33	16.00	22.58	19.03	.55	26.53
July 6, 1971	.43	.27	.07	63.3	20.00	13.39	16.25	23.37	19.81	.53	27.06
July 7, 1971	.42	.27	.07	94.6	20.28	14.72	16.00	23.77	20.54	.53	27.59
July 8, 1971	.47	.30	.07	93.0	20.28	15.28	16.75	23.77	20.86	.58	28.17

Table 14. Continued

Date	Radiation			Wind	Temperature			Vapour Pressure		ET-Pen	ET-cum.
	Total ly/min	Net ly/min	Long ly/min	miles/day	Dry Bulb °C	Wet Bulb °C	Soil °C	Saturated MB	Actual MB	cm/day	cm
July 9, 1971	.43	.27	.07	62.1	19.17	13.89	16.50	22.20	19.12	.51	28.68
July 10, 1971	.50	.32	.08	52.2	18.06	12.50	16.50	20.71	17.48	.59	29.27
July 11, 1971	.51	.33	.08	52.2	18.89	13.06	16.50	21.81	18.42	.61	29.88
July 12, 1971	.54	.36	.07	52.2	20.00	13.61	16.50	23.37	19.65	.68	30.56
July 13, 1971	.53	.36	.07	71.4	20.58	15.00	16.50	24.18	20.94	.67	31.23
July 14, 1971	.42	.28	.06	72.2	21.11	18.33	16.25	25.02	23.39	.52	31.75
July 15, 1971	.44	.30	.06	68.4	21.39	18.89	16.25	25.44	23.98	.55	32.30
July 16, 1971	.50	.33	.07	36.3	20.83	16.39	16.50	24.60	22.00	.62	32.92
July 17, 1971	.49	.34	.05	43.7	25.00	18.06	16.25	31.55	27.48	.68	33.60
July 18, 1971	.37	.26	.04	46.0	27.78	20.28	16.25	37.00	32.61	.53	34.13
July 19, 1971	.29	.17	.06	52.4	22.78	18/06	16.50	27.66	24.90	.34	34.47
July 20, 1971	.20	.09	.07	34.6	16.94	14.72	16.50	19.30	18.01	.16	34.63
July 21, 1971	.31	.16	.08	15.0	15.00	13.75	16.50	17.05	16.32	.27	34.90
July 22, 1971	.37	.22	.08	53.9	16.39	14.58	16.25	18.64	17.58	.37	35.27
July 23, 1971	.31	.17	.07	67.2	17.78	15.00	16.50	20.35	18.73	.32	35.59
July 24, 1971	.48	.31	.07	42.9	18.60	15.00	16.50	21.44	19.33	.56	36.15
July 25, 1971	.48	.32	.07	42.9	19.17	15.00	16.25	22.20	19.77	.58	36.73
July 26, 1971	.45	.29	.07	42.9	19.44	15.00	16.25	22.58	19.99	.53	36.26
July 27, 1971	.45	.29	.07	45.0	20.00	15.56	16.25	23.37	20.78	.54	37.80
July 28, 1971	.45	.29	.07	38.1	18.61	16.11	16.00	21.44	19.98	.52	38.32
July 29, 1971	.48	.32	.07	35.6	18.06	17.78	16.00	20.71	20.55	.55	38.87
July 30, 1971	.46	.30	.07	34.4	18.08	17.34	15.75	21.01	20.46	.53	39.40
July 31, 1971	.44	.28	.07	33.2	18.10	16.90	15.75	21.31	20.37	.51	39.91
Aug. 1, 1971	.42	.26	.07	32.0	18.12	16.46	15.75	21.61	20.28	.49	40.40
Aug. 2, 1971	.40	.25	.07	30.8	18.14	16.02	15.75	21.91	20.19	.47	40.87
Aug. 3, 1971	.38	.23	.07	29.8	19.17	15.56	15.75	22.20	20.09	.43	41.30
Aug. 4, 1971	.42	.25	.08	48.4	15.56	13.33	15.50	17.67	16.38	.43	41.73
Aug. 5, 1971	.28	.15	.08	50.7	17.22	13.61	15.50	19.65	17.55	.28	42.01
Aug. 6, 1971	.37	.24	.06	43.9	23.89	16.67	15.50	29.55	25.34	.48	42.49

Table 14. Continued

Date	Radiation			Wind	Temperature			Vapour Pressure		ET-Pen	ET-cum.
	Total ly/min	Net ly/min	Long ly/min	miles/day	Dry Bulb °C	Wet Bulb °C	Soil °C	Saturated MB	Actual MB	cm/day	cm
Aug. 7, 1971	.36	.25	.04	60.9	28.89	18.33	15.75	39.39	33.21	.55	43.04
Aug. 8, 1971	.24	.15	.04	63.6	27.78	17.78	16.00	37.00	31.16	.35	43.39
Aug. 9, 1971	.24	.15	.04	63.6	27.78	17.78	16.00	37.00	31.16	.35	43.74
Aug. 10, 1971	.36	.23	.06	56.7	22.22	15.00	16.50	26.76	22.55	.46	44.20
Aug. 11, 1971	.47	.31	.07	47.6	21.67	13.61	16.50	25.87	21.19	.60	44.80
Aug. 12, 1971	.39	.24	.07	69.7	22.22	13.89	17.25	26.76	21.91	.50	45.30
Aug. 13, 1971	.43	.27	.07	57.9	20.83	14.17	17.75	24.59	20.71	.54	45.84
Aug. 14, 1971	.43	.27	.07	60.7	20.28	13.89	17.75	23.77	20.05	.52	46.36
Aug. 15, 1971	.41	.27	.06	46.9	23.06	14.72	17.75	28.13	23.27	.54	46.90
Aug. 16, 1971	.43	.29	.05	41.0	26.11	16.39	18.00	33.65	27.97	.60	47.50
Aug. 17, 1971	.48	.34	.05	26.9	26.11	16.39	18.25	33.65	27.97	.69	48.19
Aug. 18, 1971	.34	.20	.07	8.7	20.56	14.31	17.75	24.18	20.54	.39	48.58
Aug. 19, 1971	.35	.19	.09	82.7	15.00	12.08	18.50	17/05	15.35	.34	48.92
Aug. 20, 1971	.29	.15	.08	41.8	15.83	12.78	18.75	17.99	16.21	.27	49.19
Aug. 21, 1971	.37	.22	.07	49.6	18.06	14.72	18.50	20.71	18.67	.40	49.59
Aug. 22, 1971	.42	.27	.06	37.3	21.11	15.83	18.25	25.02	21.94	.51	50.10
Aug. 23, 1971	.44	.28	.07	58.3	20.56	15.83	18.00	24.18	21.43	.54	50.64
Aug. 24, 1971	.37	.22	.07	48.1	18.89	14.44	18.00	21.82	19.23	.41	51.05
Aug. 25, 1971	.45	.29	.07	32.3	19.17	14.44	17.75	22.20	19.45	.53	51.58
Aug. 26, 1971	.19	.08	.07	21.5	18.33	15.56	18.00	21.07	19.45	.15	51.73
Aug. 27, 1971	.30	.17	.07	39.4	18.61	16.11	18.25	21.44	19.98	.30	52.03
Aug. 28, 1971	.30	.18	.06	40.7	21.39	17.50	18.00	25.44	23.17	.34	52.37
Aug. 29, 1971	.38	.24	.06	40.8	22.22	18.33	17.50	26.76	24.48	.47	52.84
Aug. 30, 1971	.40	.25	.06	75.0	20.28	16.67	17.50	23.77	21.66	.48	53.32
Sept. 1, 1971	.45	.30	.06	62.5	22.50	17.22	17.50	27.20	24.12	.59	54.18
Sept. 2, 1971	.43	.27	.07	60.0	19.44	15.00	17.00	22.58	19.99	.51	54.69
Sept. 3, 1971	.41	.24	.09	100.8	12.50	9.72	17.00	14.49	12.88	.40	55.09
Sept. 4, 1971	.28	.13	.09	53.3	10.83	8.06	16.50	12.97	11.37	.23	55.32
Sept. 5, 1971	.45	.30	.07	50.3	18.06	11.11	16.50	20.70	16.68	.55	55.87

Table 14. Continued

Date	Radiation			Wind	Temperature			Vapour Pressure		ET-Pen	ET-cum.
	Total ly/min	Net ly/min	Long ly/min	miles/day	Dry Bulb °C	Wet Bulb °C	Soil °C	Saturated MB	Actual MB	cm/day	cm
Sept. 6, 1971	.45	.29	.07	43.7	18.89	12.22	16.00	21.82	17.94	.55	56.42
Sept. 7, 1971	.40	.25	.08	74.3	16.39	12.50	15.75	18.64	16.38	.44	56.86
Sept. 8, 1971	.38	.22	.08	45.5	14.44	11.94	15.50	16.45	15.00	.38	57.24
Sept. 9, 1971	.38	.22	.08	44.0	11.67	10.67	15.50	13.71	13/07	.35	57.59
Sept. 10, 1971	.38	.23	.08	42.3	13.89	11.39	15.25	15.86	14.41	.38	57.97
Sept. 11, 1971	.36	.21	.07	35.4	17.22	13.06	15.25	19.65	17.23	.38	58.35

VITA

Musa N. Nimah

Candidate for the Degree of

Doctor of Philosophy

Dissertation: Model for Estimating Soil Water Flow, Water Content, Evapotranspiration and Root Extraction

Major Field: Soil Physics

Minor Field: Irrigation

BIOGRAPHICAL INFORMATION

Musa N. Nimah

Personal Data:

Name:	Musa Najib Nimah
Born:	Kulhat, Lebanon, April 26, 1942
Age:	29 years
Health:	Excellent
Family Status:	Married, one child

Education:

High School

Nader's College, Lebanon, 1954-1959 (Bac. 1st part)
International College, Beirut, Lebanon, 1959-1960 (Bac. 2nd part, Freshman Diploma).

College

American University of Beirut, Lebanon, 1960-1965, and 1968

Bachelor of Science: Agricultural Engineering 1963
Major area: Soils and Water. Received USAID scholarship 1960-1963.

Master of Science: Irrigation Science and Soils, 1968.

Utah State University, Logan, Utah, 1969 to present.

Ph.D. Soil Physics; Minor, Irrigation Science, 1972.

Language:

French:	One year - Utah State University
Arabic:	All my life
English:	All high school and college years

Experience:

Research:

May 1970 to September 1971, field reasearch was conducted at U.S.U. Vernal farm. The field research involved collection of data on moisture content profiles, weather data, and actual evapotranspiration from lysimeters. At Utah State University these data were analyzed and compared to computed data by mathematical model developed by me. It is hoped that this study will aid in determining the salt and water content within a

soil and in the drainage water as a function of time and depth for saturated and unsaturated soil water flow.

September 1969 to May 1970, field research data analysis at Utah State University. The analysis was made to compare evapotranspiration of oats as estimated by different methods to the actual evapotranspiration as measured by the lysimeters.

October 1963 to February 1965, and June to October 1968, field research was conducted at the American University of Beirut research station (AREC) to determine water use efficiency by different crops under different irrigation intervals, using a neutron source.

Employment:

Agricultural Engineer: Agriculture Economic Council, Beirut, Lebanon, June 1963-October 1963. The job was to study sugar and sugar beet production in Lebanon.

Teaching and Research Assistant: Soils and Irrigation Department, School of Agriculture, American University of Beirut, Beirut, Lebanon, October 1963-February 1965. The job entailed laboratory experiment set up, teaching lab and irrigation courses. Also, a field research experiment on water use efficiency of crops.

District Engineer: Green Project, Ministry of Agriculture, Beirut, Lebanon, February 1965-March 1967. The job was to develop new agricultural land, and selection of crops suitable for it.

Agronomist, Regional Technical Advisor and Irrigation Specialist: ESSO Chemical Company, Beirut, Lebanon, March 1967-December 1968. The job was to help farmers in the design of their irrigation systems, and the use and application of fertilizer.

Research Assistant: Utah State University, Logan, Utah, October 1969 to present. Received a $3600 per year research grant to develop a mathematical model to estimate evapotranspiration, drainage and runoff in the field.

Scientific Publications:

Nimah, M. 1968. Water use efficiency of corn, potato and sugar beet, as measured by the neutron probe. M.Sc. thesis, American University of Beirut.

Hanks, R. J., H. S. Jacobs, H. E. Schimmelpfennig, and M. Nimah. 1971. Evapotranspiration of oats, as estimated by the energy budget, aerodynamic and combination methods. Utah Agr. Exp. Sta. Utah Resources Series 53.

Hanks, R. J., H. S. Jacobs, H. E. Schimmelpfennig, and M. Nimah. 1971. Evaluation of several methods for estimating evapotranspiration. Proceedings of Symposium on Soil Water Physics and Technology, September 4, 1971 (In press).

Nimah, M., and R. J. Hanks. 1971. Model for estimating transpiration, root extraction, drainage, and evaporation from a crop. Presented at Western Society of Soil Science Meeting, June 16-18, 1971 at University of Wyoming, Laramie.

King, L. G., R. J. Hanks, M. N. Nimah, S. C. Gupta, R. B. Backus. 1972. Modeling subsurface return flows in Ashley Valley. For inclusion in the Proceedings of the National Conference on Managing Irrigated Agriculture to Improve Water Quality, Grand Junction, Colorado. May 16-18, 1972.