DYNAMIC SIMULATION OF WATER MOVEMENT AND UPTAKE IN UNSATURATED SOIL ZONES

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Background

A plant lives in two realms, the soil and the atmosphere. Water movement from the soil, through a plant, and out into the surrounding atmosphere can be treated as a series of mutually related and dependent processes. Taken together, these processes define water movement through the soil-plant-atmosphere continuum (SPAC) (Philip, 1966). A schematic representation of SPAC interactions is shown in Figure 1.

Because the interrelationships are complex, especially under natural conditions, the SPAC is often studied using simulation models. Frequently such models divide the soil root zone into several layers and assume that the canopy-atmosphere interaction can be represented by an evapotranspiration equation combining energy balance and aerodynamic concepts (Federer, 1979).

Simulation models differ in their approaches to describing plant behavior and water uptake from the soil. The rate of plant transpiration is determined not only by plant characteristics, but also by the evaporative demand of the atmosphere and the soil's ability to provide water. Since climatic factors and soil physical properties vary continually and markedly in both time and space, the modeling of plant responses to its environment remains one of the most intriguing problems in irrigation management.

Considerable research work has been done on each of the separate components of the soil-plant-atmosphere system. For example, soil physicists and agricultural engineers have been among those studying such soil water processes as infiltration, redistribution, and evaporation. Plant physiologists, botanists, and others have studied plant water relations at both the cellular and whole plant levels. The physics of the evapotranspiration process have been analyzed by micrometeorologists and other agricultural scientists. The interdisciplinary nature of the problem is evident.

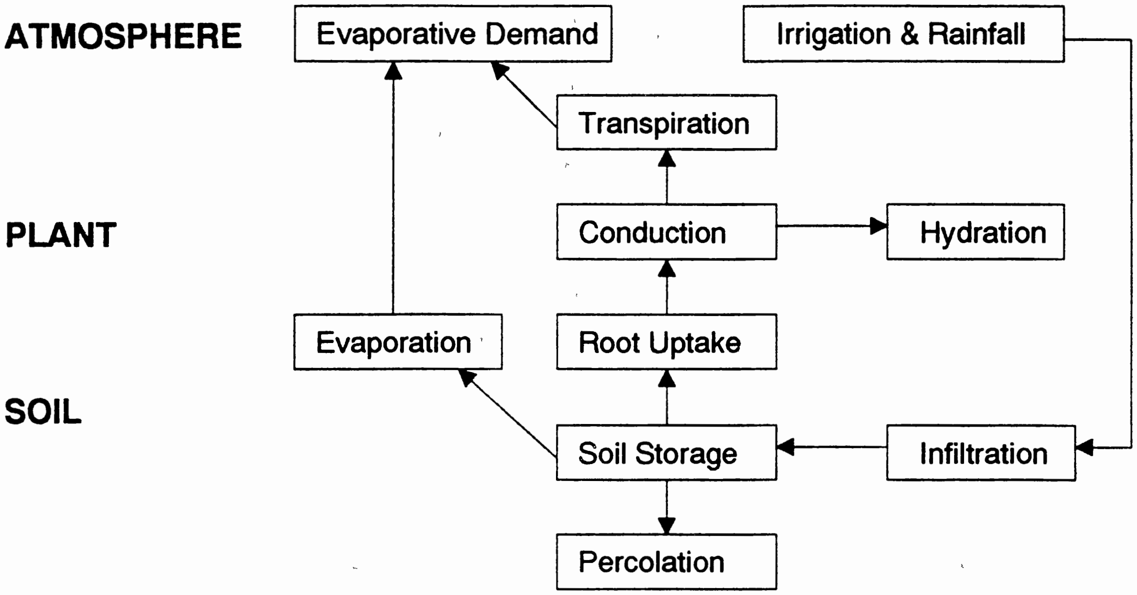


Figure 1. Water Movement in the Soil-Plant-Atmosphere Continuum

Understanding root growth and water uptake is perhaps the weakest link in modeling water movement through the SPAC. The roots of a plant are indeed an intricate system, with their main function being to absorb water and mineral nutrients from the soil. Plant roots comprise the interface between water activity in the soil and in the plant.

The growth and activity of plant roots and their interaction with soil environments are influenced by a number of factors. These may include soil moisture, mechanical resistance, temperature, chemical composition of the soil solution, and the genetic characteristics and current physiological status of the plant itself. Because of this complexity and the inherent difficulty in making root measurements, research on root growth and activity has been a challenge.

Early conceptual models of water uptake by plant roots were based on single roots assumed to be semi-infinite line sinks or "mathematical" roots (Philip, 1957; Gardner, 1960; Cowan, 1965). Later on, more complexity was introduced in root water uptake models (Molz and Remson, 1970; Feddes et al., 1974). A comprehensive review article (Molz, 1981) summarized root extraction functions which have appeared in the literature.

The approaches can be generally classified as one of two types. The first type builds on the concepts of van den Honert (1948), who stated that, under steady flow conditions, the rate of water flow through a plant part is directly proportional to the water potential difference across that part and inversely proportional to the water flow resistance (or directly proportional to the water flow conductivity). The application of this approach requires knowledge of such physical properties as water potentials in the soil and at the soil-root interface, and the soil and root conductivities.

In the second category of extraction functions, an estimated evapotranspiration (ET) rate per unit surface area is divided among soil layers.

Several methods of dividing the ET have been proposed (Molz and Remson, 1970; Raats, 1976; Feddes et al., 1976; Molz, 1981; Novak, 1987). A common approach is to use the product of unsaturated soil diffusivity (or conductivity) and root length density as a weighting factor to divide ET among soil layers. Under typical irrigated conditions, the potential root activity plays a more important role than do soil properties. To date, there are limited references to dynamic simulation of water movement in crop root zones with emphasis on root activity. This is especially true for two-dimensional simulations which can realistically describe row crop behavior in a field environment.

Objectives of Study

The overall objective of this study was to simulate water movement through the soil-plant-atmosphere continuum, with particular emphasis on plant water uptake by roots. The specific supporting objectives were to:

1. using peanut field data as a case study, develop schemes for empirically describing the spatial distribution of roots;
2. incorporate the functional "root sink" term into a dynamic simulation model of unsaturated flow in crop root zones;
3. test the model using field data from an irrigated peanut crop with differential water treatments.

CHAPTER II

LITERATURE REVIEW

Modeling Water Movement in the Soil-Plant-Atmosphere Continuum

General

In the last two decades, significant progress has been made in modeling water transport in the soil-plant-atmosphere continuum. Klepper et al. (1983) draw a helpful distinction between soil-centered models and plant-centered models. Soil-centered models are based on water balance concepts from a soil physics perspective and typically provide for a "root sink". The root sink term is an attempt to quantify the amount of water leaving the profile via root water uptake. The models of Nimah and Hanks (1973a,b) and Feddes et al. (1974) are two among many examples of soil-centered models.

Plant-centered models, on the other hand, are based on the concepts of the water balance and carbon balance from the view of soil physics and plant physiology. A plant-centered model has the potential to give an explicit expression of root water uptake as affected by the soil environment and meteorological factors during the plant growing season.

A good example of a plant-centered model was presented by Huck and Hillel (1983). Later on, this model was modified and tested by Hoogenboom et al. (1987a). They described a model of root growth and water uptake accounting for photosynthesis, respiration, transpiration, and soil hydraulics. They provided a conceptual framework for the formulation and testing of theories regarding plant adoption to variable environments. This approach could overcome the shortcomings of numerous models which have attempted to characterize separately the effects of either the soil conditions, plant attributes or the climate regime, while holding the other variables constant or assigning them arbitrary values. For example, some root activity and water uptake models consider the canopy to be constant, whereas other models portray canopy growth as if detached from the roots or as if linked to a static root system of fixed spatial distribution.

The main physical principles used to describe water movement through the soil-plant-atmosphere continuum are thermodynamics and hydrodynamics. The underlying theory for each of these will be briefly discussed in the following sections.

Thermodynamics

Thermodynamics is the science of energy transformation. According to the second law of thermodynamics, all kinds of energy in a system can be expressed as follows:

$$\begin{aligned} G &= E + P \times V - T \times S \\ &= H - T \times S \qquad (1) \end{aligned}$$

where G is the Gibbs free energy, E is the internal energy, P is the absolute pressure, V is volume, T is the absolute temperature, S is entropy, and H is enthalpy. The free energy per unit quantity of substance, specifically per gram molecular weight (i.e., the free energy/mol), is called the chemical potential (Salisbury and Ross, 1985).

In 1943, Edlefsen and Anderson published a valuable report entitled "Thermodynamics of Soil Moisture". It was the first systematic study of thermodynamics of water in soil, and it emphasized the importance of the use of chemical potential. The authors pointed out the advantages of using the chemical potential:

1. If a heterogeneous system arrives at equilibrium, the chemical potential of each substance involved in the system shows the same value through all phases. Therefore, the value of the chemical potential of water in soil under a certain water content can be obtained by allowing the soil to arrive at equilibrium with ice or water vapor whose chemical potential is already known.
2. If the chemical potential of any substance is greater in one part of the system than in another, that substance will move from the former to the latter place if an osmotic barrier is present, i.e., a gas phase or cell membrane. Therefore, the direction of water movement between two points in the soil or in a plant or between the soil and a plant can be estimated easily according to the potential values of the two points. This theory plays an important role in water uptake by roots.
3. It becomes possible to estimate the change of the state quantity of water in soil resulting from a temperature change.

The chemical potential of water is an extremely valuable concept in studies of the soil-plant-atmosphere system. Most plant physiologists and soil scientists now use the following definition of water potential. The water potential (ψ) is the chemical potential of water in a system or part of a system, expressed in units of pressure (energy per unit volume) and compared to the chemical potential (also in pressure units) of pure water at atmospheric pressure and at the same temperature. The chemical potential of pure water is arbitrarily set at zero.

A noteworthy analysis of unsaturated soil was done by Sposito and Chu (1981). They attempted to describe the state of an unsaturated soil with a set of independent variables: the masses of the three components of soil (solids, water, and air), together with the applied pressure and absolute temperature. Although, at the present stage, the analysis is not sufficiently complete to be used for practical purposes, such a thermodynamic study on a total soil system, including not only the water but the solids and air, will be important in future research on soil water.

In a series of papers published in 1958, Philip (1958a, b) developed the first detailed quantitative description of water transport in plant tissue. His approach resulted in a diffusion equation which could be written with water potential as the dependent variable. Philip's derivation assumed that water movement was primarily from vacuole to vacuole.

Hydrodynamics

Classical hydrodynamic equations which describe the flow of viscous fluids are derived from considerations of momentum balance, conservation of mass, and conservation of energy. For water flow through isotropic soil, combining Darcy's law with the equation of continuity, the Richards (1931) water flow equation can be written as (Hillel, 1980):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}(K(\theta)\frac{\partial \psi}{\partial x}) + \frac{\partial}{\partial y}(K(\theta)\frac{\partial \psi}{\partial y}) + \frac{\partial}{\partial z}(K(\theta)\frac{\partial \psi}{\partial z}) + \frac{\partial K(\theta)}{\partial z} \qquad (2)$$

where θ is the volumetric water content (L^3/L^3), K is the unsaturated soil conductivity (L/T), ψ is the soil water pressure potential (L), t is time (T), and x, y, z are geometric variables (L).

For water flow through the root zone, one or two dimensional equations are generally used. Combination of the two dimensional equation with a "root sink" yields the following equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}(K(\theta)\frac{\partial \psi}{\partial x}) + \frac{\partial}{\partial z}(K(\theta)\frac{\partial \psi}{\partial z}) + \frac{\partial K(\theta)}{\partial z} - S(x,z,t) \qquad (3)$$

where S(x,z,t) is the intensity of water uptake by roots $[(L^3/L^3)/T]$.

In 1952, Klute obtained a diffusion-type equation from the pressure potential equation (2). Combining the two dimensional equation with a "root sink" term, it can be expressed as

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}(D(\theta)\frac{\partial\theta}{\partial x}) + \frac{\partial}{\partial z}(D(\theta)\frac{\partial\theta}{\partial z}) + \frac{\partial K(\theta)}{\partial z} - S(x,z,t) \tag{4}$$

where $D(\theta)$ is soil diffusivity and defined as

$$D(\theta) = K(\theta)\ \frac{\partial\psi}{\partial\theta}$$

Equations (2), (3) and (4) are highly nonlinear due to the dependency of the hydraulic conductivity, soil diffusivity and water potential on water content, and they belong to the class of nonlinear, second order, partial differential equations. These have led to a host of analytical and numerical solutions (Klute, 1952; Philip, 1957; and Raats, 1976) describing water entry into soil and its movement under a variety of boundary conditions.

Modeling Water Uptake by Roots

Background

In the study of water movement through the SPAC, much attention has been paid to the intensity of the root sink term. A valuable review of papers on modeling water uptake by roots was provided by Molz (1981). The first notable root water uptake model was presented by Gardner (1960). Because of the complex structure and geometry of plant roots, the root was taken to be an infinitely long cylinder of uniform radius and water-absorbing properties, water was assumed to move only in the radial direction, and the gravitational potential was considered to be negligible. The governing Darcy flow equation can be written in radial coordinates as

$$\frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\ K(\psi)\frac{\partial \psi}{\partial r}\right) \tag{5}$$

Gardner (1960) suggested that transient drying of the soil conditions could be approximated as a series of steady states (i.e. $\partial\theta/\partial t = 0$), and obtained equation (6) as the steady-state solution of equation (5) under the assumption of constant K :

$$q = \frac{2\pi K(\psi_s - \psi_r)}{\ln(r_2/r_1)} \tag{6}$$

where q is the rate of water extraction per unit length of root, r_1 and r_2 are the root radius and half the average distance between roots, and ψ_s and ψ_r are the pressure potentials of soil and root. The use of the model can be limited when the root spatial arrangement is highly variable.

In many studies, the water uptake rate was assumed to decrease linearly or exponentially with the depth below the soil surface (Molz and Remson, 1970; Raats, 1976; Novak, 1987). A group of methods has been developed to determine the root sink from the distribution of the evapotranspiration rate (E_t) in the vertical direction of the root zone depending on the soil and root characteristics (Gardner, 1964; Molz and Remson, 1970). Other authors have assumed that the root sink is proportional to the soil water content or to soil water potential (Feddes, et al., 1974, 1976). In the upper soil layer, water uptake rate decreases as soil water potential decreases, whereas in the deeper layers, an increase in the water uptake rate may occur with decreasing soil water potential (Glinski and Lipiec, 1990).

During the 1970's, more and more experimental work was done in the field. Taylor and Klepper observed the water uptake by a corn root system in 1973, and examined the assumptions of the single root model for cotton in 1975. Molz (1976) and Hillel and Talpaz (1976) presented more complicated root sink models by assuming nonuniform root systems.

In recent years, a number of other researchers have studied water uptake and root distribution under different environments and management schemes. Jung (1980) did research on water uptake and transport of soybeans as a function of root distribution patterns; Hoogenboom et al. (1987b) studied the root growth rate of soybeans as affected by drought stress; Said (1980) examined the root growth of cowpeas in soils with layers compacted in a chamber at different bulk densities; Lascano (1982) studied cotton root water uptake as influenced by soil water distribution in the root zone; Aina and Fapohunda (1986) investigated the root distribution and water uptake patterns of maize under field conditions subjected to differential irrigation; Gajri and Prihar (1985) did research on wheat's rooting, water use and yield relations; Berliner and Oosterhuis (1987) studied the root and water distribution of spring wheat grown in lysimeters and in the field under water stress conditions; Grecu et al. (1988) did research on root growth and penetration resistance of alfalfa and fescue in a claypan with a maize or soybean rotation; and Dwyer et al. (1988) investigated the rooting characteristics of corn, soybeans and barley affected by water availability and soil physical properties.

Fourteen different water extraction functions were presented by Molz in 1981. Twenty-four different water extraction functions are reviewed herein. Generally speaking, they can be classified into two types, those using potential flow theory and those which apportion transpiration.

Potential Flow Approach

The first approach to modeling root water uptake follows the school of van den Honert (1948). He defined that under steady conditions the rate of water flow through a plant part is directly proportional to the water potential difference across that part and inversely proportional to the water flow resistance (or directly proportional to the water flow conductivity). For the case of plant roots, the equation was written as

$$Q_w = \frac{\phi_{rs} - \phi_{rx}}{R_r} \tag{7}$$

Where Q_w is the rate of water flow (cm³/sec), ϕ_{rs} is the water potential at the root surface (kPa), ϕ_{rx} is the water potential of the root xylem (kPa), and R_r is the resistance of the root system to water flow (kPa sec/cm³).

Sixteen water extraction functions which use this general approach are described herein. One important characteristic of the approach is that S is predicted by knowing the physical quantities related to water flow through the soil and the plant, such as resistance and water potential. The symbols used are those in the original references.

1. Gardner (1964):

$$S = B(\delta - \tau - z)kL \tag{8}$$

where B is a constant, δ is the water potential of plant roots, τ is the suction potential of soil, z is the depth below the soil surface, k is the unsaturated hydraulic conductivity, and L is the length of roots per unit soil volume.

2. Cowan (1965):

$$S = \frac{\psi_s - \psi_r}{[h\alpha/(DK)]} \tag{9}$$

where ψ_s is the soil water potential, ψ_r is the water potential at the root surface, h is a conversion factor from head of water to pressure, and equal to 9.807 kPa/m, D is the thickness of a single layer of soil, K is the soil hydraulic conductivity evaluated at the geometric mean potential $(\psi_s\psi_r)^{1/2}$, and α is Cowan's root parameter:

$$\alpha = \frac{1}{8\pi L} (\delta - 3 - 2\ln\frac{\delta}{1-\delta}) \tag{10}$$

where δ is the volume of root per unit volume of soil, and L is the length of root per unit volume of soil.

3. Whisler et al. (1968):

$$S = A(z)\ k\ (h_p - h_s) \tag{11}$$

where A(z) is a root density function, k is the unsaturated hydraulic conductivity, h_p is the water potential of roots, and h_s is the water potential of soil.

4. Nimah and Hanks (1973a):

$$S = \frac{[H_{root} + (PRES)(z) - H(z,t) - s(z,t)]RDF(z)K(\theta)}{\Delta x \Delta z} \tag{12}$$

where H_{root} is the internal root pressure head at the soil surface where z is considered zero, z is depth, PRES is the head loss coefficient for longitudinal water flow in the root xylem, H(z,t) is soil pressure head, s(z,t) is soil osmotic head, RDF(z) is the proportion of total active roots in depth increment Δz, $K(\theta)$ is soil hydraulic conductivity, and Δx is the distance between roots at depth z.

5. Feddes et al. (1974):

$$S = - K(\theta) \frac{h_r(z)-h(z)}{b(z)} \tag{13}$$

where $K(\theta)$ is soil hydraulic conductivity, $h_r(z)$ is the pressure head at the soil-root interface, h(z) is the pressure head in the soil, and b(z) is an empirical function representing the geometry of the flow.

6. van Bavel (1974):

$$S_j = \frac{(\phi_{s,j}-\phi_{l,j})RD_j}{SRPL} \tag{14}$$

where j is the root zone layer or compartment, S_j is the rate of water extraction from the jth compartment, $\phi_{s,j}$ is the soil water potential in that compartment, $\phi_{l,j}$ is the effective leaf water potential in that compartment, RD_j is the relative (fractional) root density in the compartment, and SRPL is the specific plant resistance.

7. Taylor and Klepper (1975):

$$q_r = \frac{-2\pi k_{sys}[\psi_{rootxylem}-\psi_s]}{\ln(r_{cyl}/r_{stele})} \tag{15}$$

where q_r is the water uptake rate per centimeter of root, k_{sys} is the hydraulic conductivity of the combined soil-root radial pathway, $\psi_{rootxylem}$ is a value obtained from shoot water potential measurements, ψ_s is the pressure potential of water at a distance $r_{cyl} = r_{bulksoil}$, r_{cyl} is the radius of the cylinder of soil through which water is moving, and r_{stele} is the radius of the root stele.

8. Hillel and Talpaz (1976):

$$S = \frac{\phi_{soil}-\phi_{plant}}{R_{soil}+R_{roots}} \tag{16}$$

where ϕ_{soil} is the total hydraulic head of the soil as a function of depth, ϕ_{plant} is the hydraulic head in the plant at the base of the stem, R_{soil} is the resistance to water flow in the soil, and equal to 1/(BKL), B is an empirical constant, K is the soil hydraulic conductivity, L is the length of active roots per unit soil volume, and R_{roots} is the hydraulic resistance of the roots taken to be the sum of a resistance of absorption and a resistance to conduction which depends on depth.

9. Herkelrath et al. (1977):

$$S = \frac{\theta}{\theta_{sat}} \rho \ell(\psi_s - \psi_r) \tag{17}$$

where θ is the volumetric soil water content, θ_{sat} is the saturation water content, ρ is the root permeability per unit length of root, ℓ is the length of roots per unit volume of soil, ψ_s is the soil water potential, and ψ_r is the water potential inside the root.

10. Rowse et al. (1978):

$$S = \frac{\Delta Z L(h_s - h_p)}{R_s + R_p} \tag{18}$$

where ΔZ is the thickness of the soil layer, L is the length of roots per unit soil volume, h_s is the bulk soil water potential, h_p is the plant water potential assumed constant throughout the root xylem, R_s is the soil resistance to root water uptake per unit length of root, and R_p is the plant resistance to water uptake per unit length of root.

11. Taylor and Klepper (1978):

$$U_i = V_i D_i K_i(\psi_{si} - \psi_p + \psi_{zi} + \sum_{j=1}^{i} \Delta\psi_{fj}) \tag{19}$$

where U_i is the rate of water uptake from soil unit i, V_i is the volume of soil in the unit, D_i is the root length density in the unit, K_i is the root-soil system permeability, ψ_{si} is the soil water potential in the unit, ψ_p is the xylem water potential at the land surface, ψ_{zi} is the loss in potential due to elevation, and $\Delta\psi_{fj}$ are the water potential losses between units due to friction in the moving water column.

12. Zur and Jones (1981):

$$q_{si} = \frac{\psi_{rooti} - \psi_{si}}{R_{si} + R_{ri}} \tag{20}$$

with

$$\psi_{rooti} = \psi_L - q_p R_x - i(\Delta z) \tag{21}$$

$$d\psi_{si} = (V_{si}/C_{si}) d\theta_{si} \tag{22}$$

$$R_{si} = \frac{\ln(r_{cyl}/r_{root})}{2\pi k_{si} \rho_{ri} V_{si}} \qquad \text{(Gardner, 1960)} \tag{23}$$

$$R_{ri} = \frac{1}{k_r \rho_{ri} V_{si}} \qquad \text{(Taylor and Klepper, 1975)} \tag{24}$$

where q_{si} is the total flux of water from a soil layer to the roots of one plant (cm^3/s), ψ_{rooti} is the water potential at the root surface (bars), ψ_{si} is the water potential of a soil layer (bars), R_{si} is the resistance to water flow from a soil layer to the roots (bar s/cm^3), R_{ri} is the resistance to radial water flow inside the roots (bar s/cm^3), ψ_L is the total water potential of leaves (bars), q_p is the total flux of water from the soil volume to the plant (cm^3/s), R_x is the resistance to water flow through the plant xylem system (bar s/cm^3), V_{si} is the volume of the soil layer per plant (cm^3), C_{si} is the slope of the soil water retention curve multiplied by the soil volume, r_{cyl} is the radius of the soil cylinder through which water is moving (cm), assumed to be one half the distance between adjacent roots, r_{root} is the radius of root stele (cm), ρ_{ri} is the density of roots in layer i (cm/cm^3), k_{si} is the soil hydraulic conductivity in layer i (cm/s), $1/k_r = (1/k_{sys}) - (1/k_s)$, where k_{sys} is the overall root-soil conductivity, and k_s and k_r are soil and root conductivity.

13. Rowse et al. (1983):

$$S = CD[h(\pi - 2A) - 2\psi_m \cos A]/\pi \tag{25}$$

with

$$C = \frac{1}{(R_S+R_P)} \tag{26}$$

$$A = \sin^{-1}(h/\psi_m) \tag{27}$$

where S is the daily uptake of water from a unit volume of soil, D is the duration of daylight (as a fraction of a whole day), h is the hydraulic head of bulk soil, ψ_m is the minimum (most negative) plant water potential (measured at the soil surface), and R_S and R_P are soil and root resistances per unit volume of soil. R_P was calculated as R_r/L_V, where R_r (day/cm) is the radial resistance per unit length of root, and L_V (cm^{-2}) is the length of root per unit volume of soil.

14. McCoy et al. (1984):

$$J(t) = 2\pi r_r D(\theta)\frac{\partial\theta}{\partial r} \qquad t>0,\ r=r_r \tag{28}$$

with

$$\theta(r,0) = \theta_0(r) \qquad t=0,\ r_r \leq r \leq R$$

$$\frac{\partial\theta}{\partial r} = 0, \qquad t>0,\ r=R$$

where J(t) is the transient flux at the root surface due to evaporation from the leaf (cm^3/cm^2 root surface per hour), r_r is the radius of the root (cm), R is the radius of the outer boundary of the soil cylinder (cm) located at the half-distance between adjacent roots, and $D(\theta)$ is the soil water diffusivity as a function of the water content.

15. Protopapas and Bras (1987)

$$U_j = (\psi_{sj} - \psi_p)\ \frac{ROOTY_j + pROOTO_j}{K_R}\ f_T\ f_{\psi_{sj}} \tag{29}$$

where U_j is the water uptake rate at the jth soil compartment (g/m^2sec), ψ_{sj} is the effective water potential in the soil (bars), ψ_p is the water potential in the roots, characterizing the water status of the plant (bars), $ROOTY_j$ is the weight of young roots at the jth compartment, $ROOTO_j$ is the weight of old roots at the jth compartment, K_R is the effective conductivity of the root system per unit weight of roots, f_T is the effect of soil temperature, $f_{\psi_{sj}}$ is the effect of soil potential, and p is the proportion of old roots still active in water uptake.

16. Marino and Tracy (1988):

$$q = \frac{\partial}{\partial z}\left[K_s\left(\frac{\partial \psi_s}{\partial z} + 1\right)\right] - \left(\beta S_s + S_y \frac{dS_l}{d\psi_s}\right)\frac{\partial \psi_s}{\partial t} \tag{30}$$

where q is the extraction of soil-water by a crop's root system, z is the vertical coordinate, K_s is the hydraulic conductivity of the soil, ψ_s is the soil-water pressure head, $\beta=0$ if $\psi_s \leq 0$ and $\beta=1$ if $\psi_s > 0$, S_y is the specific yield of the soil, S_l is the effective saturation in the soil, and S_s is the specific storage of the soil.

Apportioned Transpiration Approach

In the second approach to modeling root water uptake, a known transpiration rate per unit surface area is divided among soil layers, considering conditions in the soil profile. Eight such functions are described herein.

1. Molz and Remson (1970):

$$S = -\frac{1.6T}{v^2} z + \frac{1.8T}{v} \tag{31}$$

where S is the intensity of water uptake by roots, T is the transpiration rate per unit soil surface area, z is the depth below the soil surface, and v is the depth of the root zone. Integration of this equation yields the familiar root water uptake pattern where 40% of the uptake comes from the first quarter of the rooting depth, 30% from the second, 20% from the third and 10% from the fourth.

2. Molz and Remson (1970):

$$S = \frac{TL(z)D_s(\theta)}{\int_0^v L(z)D(\theta)dz} \tag{32}$$

where S is the intensity of water uptake by roots, T is the transpiration rate per unit soil surface area, L(z) is the length of roots per unit volume of soil, $D_s(\theta)$ is the soil water diffusivity, z is the depth below the soil surface, θ is the volumetric soil water content, and v is the depth of the root zone.

3. Raats (1976):

$$S = T\delta^{-1} \exp(-z/\delta) \tag{33}$$

where S is the intensity of water uptake by roots, T is the transpiration rate per unit soil surface area, δ is a parameter chosen so that the integral of S over the root zone is equal to T, and z is the depth.

4. Selim and Iskandar (1978):

$$S = \frac{TL(z)K_s(\psi)}{\int_0^v L(z)K_s(\psi)dz} \tag{34}$$

where S is the intensity of water uptake by roots, T is the transpiration rate per unit soil surface area, L(z) is the length of roots per unit soil volume, $K_s(\psi)$ is the unsaturated hydraulic conductivity of the soil, z is the depth below the soil surface, ψ is the soil water pressure potential, and v is the depth of the root zone.

5. Feddes et al. (1978):

$$
\begin{aligned}
S &= 0 && 0 \geq \psi > \psi_1 \\
S &= S_{max} && \psi_1 \geq \psi > \psi_2 \\
S &= S_{max}(\psi - \psi_3)/(\psi_2 - \psi_3) && \psi_2 \geq \psi > \psi_3 \\
S &= 0 && \psi_3 \geq \psi
\end{aligned}
\tag{35}
$$

with

$$S_{max} = T/z_r \tag{36}$$

where S is the intensity of water uptake by roots, S_{max} is the maximum rate of root water uptake, T is the potential transpiration rate, z_r is the root depth, ψ is the pressure head of soil moisture, ψ_1 is the maximum soil pressure head for which $S = S_{max}$, ψ_2 is the minimum soil pressure head for which $S = S_{max}$, and ψ_3 is the soil pressure head at the wilting point.

6. Molz (1981):

$$S = \frac{T(t)\theta(z,t)L(z.t)[\psi(z,t)-\phi_x(t)]}{\int_0^{v(t)} \theta(z,t)L(z,t)[\psi(z,t)-\phi_x(t)]dz} \qquad (37)$$

where S is the intensity of water uptake by roots, z is the depth below the soil surface, t is time, ψ is the soil water pressure potential, T is the transpiration rate per unit soil surface area, θ is the volumetric soil water content, L is the length of roots per unit soil volume, ϕ_x is the pressure potential of the root xylem, and v is the depth of the root zone.

7. Novak (1987):

$$S = S_0 \; P(\psi_s) \qquad (38)$$

with

$$S_0 = E_{tp} \frac{\delta \exp[-\delta(z/z_r)]}{z_r[1-\exp(-\delta)]}$$

where S is the intensity of water uptake by roots, $S_0(z)$ is the rate of water extraction by roots unlimited by the soil water potential, E_{tp} is the potential transpiration, δ is an empirical constant, z_r is the root depth, $P(\psi_s)$ is a function dependent on the soil water potential distribution, and

$$P(\psi_s) = 1 \qquad \text{if} \quad \psi_a > \psi_s \geq \psi_{k1};$$

or

$$P(\psi_s) = 0 \qquad \text{if} \quad \psi_s \leq \psi_{k2};$$

or

$$0 < P(\psi_s) < 1 \qquad \text{if} \quad \psi_{k2} < \psi_s < \psi_{k1}$$

where ψ_a is the anaerobiosis point, ψ_{k1} is dependent on the transpiration rate, the soil-water properties, the species, and the growth stage of the plant, and ψ_{k2} is near the permanent wilting point.

8. Perrochet (1987):

$$S = \alpha(\psi)g(z)T_p \tag{39}$$

where S is the intensity of water uptake by roots, $\alpha(\psi)$ is the reducing factor (dimensionless), g(z) is the root distribution function (m^{-1}), and T_p is the potential transpiration (m/s). The root distribution function $\alpha(\psi)$ was defined as a linear function of depth (Ritchie, 1984):

$$g(z) = \frac{c(2z-L)+L}{L^2} \qquad -1 \leq c \leq 1, \quad |z| \leq L$$

where c is a constant depending on the plant and its vegetative stage, L is the depth of the root zone, and z is the depth below the soil surface. Moreover, under optimal moisture conditions and for c = -0.8, this approach is the same as approach 1 by Molz and Remson (1970). The reducing factor $\alpha(\psi)$ was defined as:

$$\alpha(\psi) = \frac{K(\psi)(\psi_r - \psi)}{K(\psi_0)(\psi_r - \psi_0)} \qquad |\psi| > |\psi_0|$$

or under optimal water conditions:

$$\alpha(\psi) = 1 \qquad |\psi| \leq |\psi_0|$$

where $K(\psi)$ is the hydraulic conductivity of the soil containing roots at a given depth (m/s), ψ_r is the root suction generated by plants (m), ψ is the soil suction around the roots at the given depth (m), and ψ_0 is the soil suction around the roots at which the transpiration rate starts to diminish (m).

Peanut Root Activity

Peanut (Arachis hypogaea), also called groundnut, is grown worldwide in a variety of climates. Peanut plants grow in two main ways, either as a bunch plant or as a runner plant (Wynne and Coffelt, 1982). Bunch-type peanuts are either spanish or valencia types, have a fairly erect main stem and produce multi-seeded pods. The runner-type plants, with their vine-like stems, grow mostly prostrate along the ground and produce seeds that vary in size from the small spanish to the larger virginia types. Peanuts in the temperate zone of the U. S. mature in 120 to 140 days for spanish-types and 140 to 180 days for runner types.

Peanut roots form a deep foundation to hold the plant in place. The plant's taproot and secondary branch roots absorb nutrients and water from the soil for the above-ground portions of the plants. During early growth stages, the roots grow faster than the above ground stems and leaves. The basic root system has been formed when the plant starts to flower, about 30 days after planting. Peanut plants grow deep taproots. They can extend to depths of 120 cm by six weeks after planting. Each taproot can produce many lateral roots. The extent of the root system depends on the distribution of water in the soil. Normally, plants grow best when there is adequate (but not too much) water in the soil, and roots grow quickly to seek out moisture when water is somewhat limiting.

Although scientists have conducted a great deal of research on peanut growth and environmental effects on production, data on peanut root growth patterns are sparse. This is, of course, partly due to the difficulty in digging roots. Robertson et al. (1980) reported that roots penetrated deeper than 150 cm in the fine sands on which the experiments were conducted.

Peanut root elongation and distribution are significantly affected by soil moisture level. During drought stress periods, lower roots continue to grow down into deeper moist zones even though top growth may appear to stop (Allen et al., 1976). Rooting depth is frequently deeper for water stressed plants as compared to irrigated peanuts (Lin et al., 1963).

Genetic variability can have a large influence on root and shoot growth. Ketring et al. (1982) found significant differences in both root growth (length and numbers) and shoot growth (dry weight and leaf area) among the genotypes tested. A method to estimate root growth potential of peanut by measuring root volumes was developed and used to make comparisons among peanut genotypes (Ketring, 1984). In all of these studies there was a strong positive correlation between root and shoot growth.

Peanut growth models have been used to simulate peanut growth and production (e.g., Young et al., 1979; Boote et al., 1985). The earliest physiologically-based peanut growth model was developed by Young et al. (1979). Grosz et al.

(1988) calibrated this model to simulate the growth and yield of spanish peanuts under Oklahoma conditions. The model did not have a soil-water submodel nor a root growth submodel. Soil moisture content during the growing season is one of the inputs to their computer program.

Singh and Young (1988) presented a peanut root growth model for incorporation in Young's peanut growth model. In their soil-water submodel, the potential evapotranspiration was calculated using a modified Penman equation (1948). The actual transpiration rate and water uptake were simulated by combining Feddes' (1981) model with Nimah and Hanks model (1973a). Two basic assumptions were used: (1) the water uptake rate from a given soil layer decreases linearly between ψ_1 and ψ_2, where ψ_1 is the upper limit of the soil water potential above which water uptake rate is maximum, and ψ_2 is the lower limit of the soil water potential below which water uptake rate is zero; and (2) the water uptake rate for a given soil layer is proportional to the amount of roots in the layer. There were two basic features of their root submodel: (1) photosynthate was partitioned between roots and shoots, and (2) the distribution of the roots was used to apportion photosynthate among soil zones. Also, a moisture stress factor was included for the case when soil moisture is limiting.

In the soil-water submodel of Boote et al. (1985), the potential plant transpiration rate was determined by weather conditions and the LAI (leaf area index). The water-supplying capability of the soil-root system was calculated and compared with the potential plant transpiration. Actual plant transpiration and water uptake by roots was the minimum of the two rates.

In their root growth submodel, the rate of root-depth increase was 0.249 cm/^{0}C-day starting at an initial root depth at emergence and ending when the maximum root-depth was reached. The maximum depth was soil-and crop-limited (a value of

210 cm was used in their research). Total root length was estimated by the carbohydrate partitioned to roots and a weight-to-length parameter. The root length weighting function was developed based on the data of Robertson et al. (1980). The distribution of roots among soil layers was determined based on the root depth, the soil water condition in those layers, and an empirical weighting function that represented the probability distribution of roots growing in each layer later in the season if well-watered. The root growth in each layer was estimated by dividing the total growth according to the root distribution function and soil water condition in that layer.

CHAPTER III

MODEL DESCRIPTION

Because the relationships among the soil, the plant, and the atmosphere are complicated under natural conditions, the general physical processes are often described by simulation models. A "model" is another term for a group of equations that describe the functional relationships involved. A model can be either very simple or very complicated depending on the volume of input data and parameters needed.

There are two basic categories of soil water transport models used to describe water movement toward roots in unsaturated zones. One type is based on the soil potential energy concept which relates changes in root water uptake to changes in soil hydraulic conductivity. Another type is based on the diffusion equation which is related to the soil diffusivity. In this research, the potential energy equation was selected to describe water flow in plant root zones. The simulations were based on a well documented computer model (VS2D) developed by the United States Geological Survey (Lappala et al., 1987) for solving problems of variably saturated, single-phase flow in porous media. The flow equation is written with total water potential as the dependent variable. This allows straightforward treatment of both saturated and unsaturated conditions.

Description of the VS2D Model

Governing Equation

The equation that describes water movement under isothermal and isohaline conditions was developed by combining the equation for conservation of mass for water with auxiliary equations for flux and storage. The equation solved by VS2D is:

$$v\{\rho[c_m + sS_s]\}\frac{\partial H}{\partial t} - \rho \sum_{k=1}^{\hat{m}} A_k K_s K_r(h)\frac{\partial H}{\partial n_k} - \rho q v = 0 \tag{40}$$

where v is the volume of the porous medium (L^3); ρ is the liquid density (M/L^3); c_m is the specific moisture capacity, which is the slope of the moisture retention curve (1/L) or $c_m = \partial\theta/\partial h$; s is the liquid saturation (dimensionless); S_s is the specific storage (1/L); H is the total hydraulic head, expressed as the height of a column of the liquid (L); h is the pressure head (L); t is time (T); $\hat{m}$is the number of faces of a general curvilinear polygonal volume, v (dimensionless); A_k is the area of the kth face to which n_k is orthogonal (L^2); n is direction (L); K_s is the saturated hydraulic conductivity (L/T); K_r is the relative hydraulic conductivity (dimensionless); and q is the volumetric source-sink term accounting for liquid added to (+q) or taken away from (-q) the volume, v, per unit volume per unit time (1/T).

Initial Conditions

The initial conditions must specify values of the total potential, H, throughout the entire solution domain. The initial conditions usually represent some type of steady state or equilibrium. Since equation (40) is nonlinear, it is not appropriate to use the principle of superposition to subtract out the effects of transient initial conditions, as is often done in simulations of fully saturated groundwater flow, where the aquifer properties are not a function of total potential.

Boundary Conditions

The boundary conditions must specify either the water flux across each boundary and the total potential along those boundaries, or the combination of water flux and pressure potential. The general form of the flux boundary condition is:

$$\rho\overset{>}{u}_k = f_1(x,t,\partial H/u_k,h)_k \tag{41}$$

where $\overset{>}{u}_k$ is the water flux per unit area in the direction k, and f_1 is a general function of position, time, the gradient in total hydraulic potential across the face, and the pressure head at the face.

The general form of the boundary condition for total water potential is:

$$H_k = f_2(x,t,\partial H/u_k,h)_k \tag{42}$$

where f_2 is a general time-dependent function.

Four kinds of boundary conditions that can not be priori specified are included in the computer code for VS2D simulations. They are infiltration, evaporation, evapotranspiration, and discharge through seepage faces.

Infiltration and Ponding. Infiltration of water into a soil layer from rainfall or sprinkler irrigation is a two-stage process. During the first stage, water enters the system at the applied rate as long as the conductive and sorptive capacities of the medium are not exceeded. If these capacities are exceeded, water ponds on the surface and infiltration decreases exponentially to a rate equal to the saturated hydraulic conductivity of the soil. This process is illustrated in Figure 2.

Evaporation. Evaporation is also a two-stage process analogous to infiltration. During the first stage of evaporation, occurring when the soil surface is wet, the meteorological conditions limit the rate (energy input and transport are the limiting factors). The evaporation rate is equal to the evaporative demand of the atmosphere defined as the potential evaporation rate. This rate will be constant if the conditions are constant. During the second stage of evaporation, occurring when water is limiting, the soil hydraulic conductivity will be reduced. The dryer the soil, the lower its conductivity. This process is also illustrated in Figure 2.

In the VS2D model, evaporation is computed as the upward flux driven by the pressure-potential gradient between the soil and the atmosphere by the equation:

$$E = K\, S_r\, (H_a - h) \tag{43}$$

with

$$H_a = \frac{RT}{M_w g} \ln(h_u) \tag{44}$$

where E is evaporation from the bare soil (cm/day), K is the soil hydraulic conductivity (cm/day), S_r is the soil surface resistance (1/m), H_a is the pressure potential of the atmosphere (m), R is a constant and equal to 8.31 (kg m^2/sec^2 ^{0}K g-mol), M_w is equal to 0.018 (kg/g-mol), T is air temperature (^{0}K), h_u is the relative humidity of the atmosphere, g is a gravitational constant and equal to 9.81 (m/sec^2), and h is soil pressure potential at the soil surface (L).

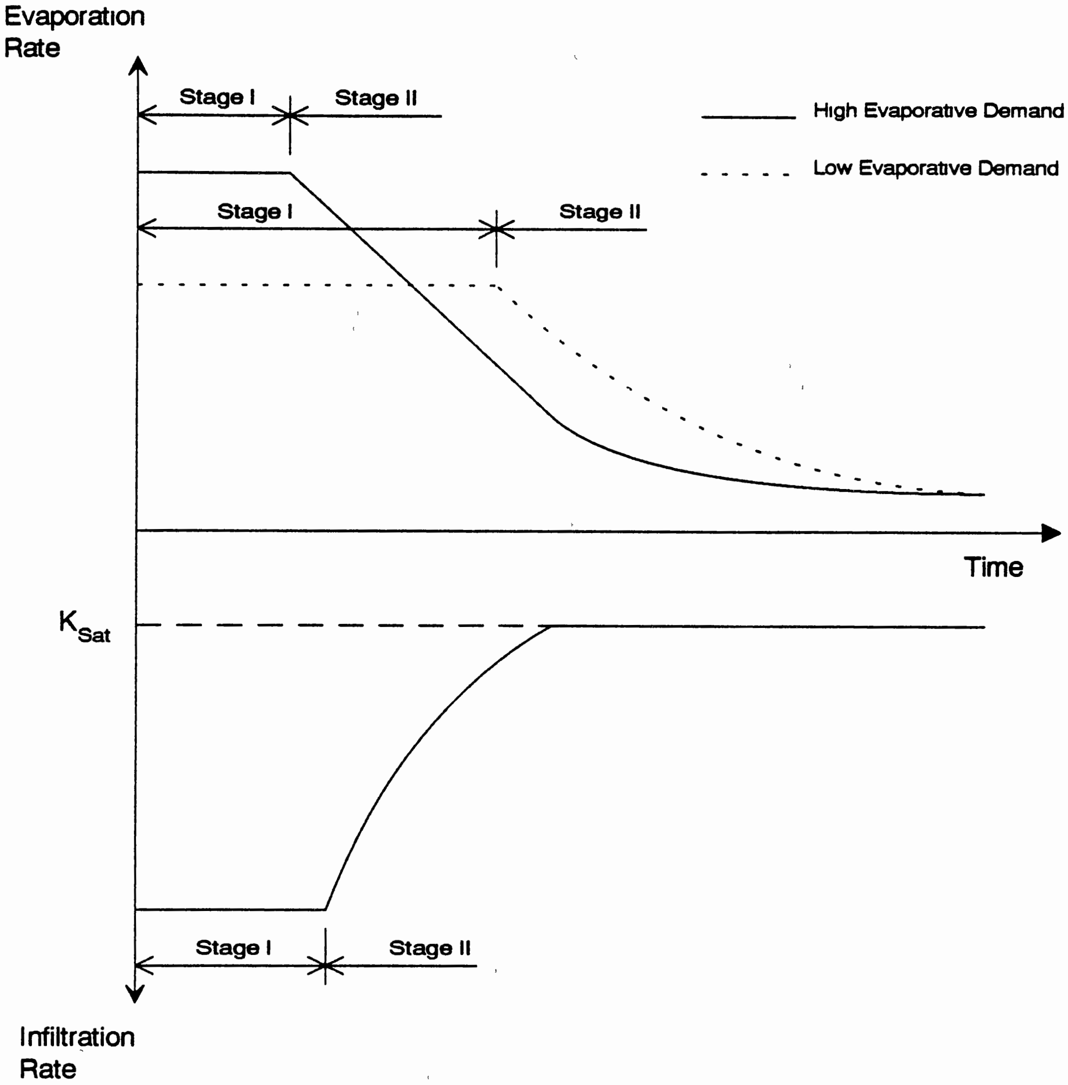


Figure 2. Schematic Representation of the Two-Stage Process of Evaporation and Infiltration

Evapotranspiration. When plants grow in the soil, evapotranspiration occurs by evaporation from the soil surface and transpiration through root water uptake from the rooting zones. The extraction rate from a soil layer is limited by the amount of available energy to the potential evapotranspiration rate, and by the soil supplying capability.

Using a development similar to that of Hillel and Talpaz (1976), plant root extraction is expressed as:

$$(\rho q v)_m = v \frac{\rho(h_m - h_{root})}{R_m + R_{root_m}}, \qquad \text{if } h_m > h_{root} \tag{45}$$

and

$$(\rho q v)_m = 0, \qquad \text{if } h_m \leq h_{root} \tag{46}$$

with

$$R_m + R_{root_m} = \frac{1}{K(h) r(z,t)} \tag{47}$$

where h_m is the soil pressure potential (L), h_{root} is the pressure potential in the plant roots (L), R_m is the resistance to flow in the soil (LT), R_{root_m} is the hydraulic resistance of the roots (LT), K is the unsaturated hydraulic conductivity (L/T), and r is the root activity function which is calculated by linearly interpolating the root length density at the top and base of a root zone ($1/L^2$).

Transpiration from the soil column, $\hat{Q}$ is the sum of the uptake rate computed by equation (45) over all cells containing roots in that column.

$$\hat{Q} = \rho \sum_{m=1}^{\bar{m}} (qv)_m \tag{48}$$

where $\bar{m}$ is the number of volume subdivisions in the column. If the transpiration from a unit of soil surface, $\hat{Q}/(\rho A)$, is greater than potential ET, q_m for each node is reduced uniformly so that the two terms are equal. If $\hat{Q}/(\rho A)$ is less than potential ET, q_m remains as originally computed. Finally, if h_m becomes less than h_{root}, q_m is equal to zero. In each case, q_m is a specified flux for that node. Because q_m is dependent on the pressure potential difference between soil and roots, unsaturated hydraulic conductivity, and root activity function, its value must be evaluated iteratively.

Potential evapotranspiration is treated simplistically in VS2D as an empirically determined value that can vary in time similar to evaporation.

Seepage Faces. Seepage faces are boundaries along which water leaves the system and along which the total potential is equal to the elevation potential, $H=h_z$. Examples of these boundaries are along the interfaces between the surface of the solution domain and the atmosphere, such as along stream banks and spring discharge zones. These boundaries are usually not linear.

Nonlinear Parameter Estimation

The coefficients in equation (40) are nonlinear functions of the pressure potential. Several functional relations for porous media have been developed (e.g., Gardner, 1958; Brooks and Corey, 1964; Haverkamp et al., 1977; van Genuchten, 1980). The functional relations used by VS2D are:

1. Soil moisture characteristics, which describe the volumetric water content as a function of pressure potential, $\theta(h)$, or the inverse function, $h(\theta)$.
2. Specific moisture capacity, which is the slope of the moisture retention curve, as a function of pressure potential, $c_m(h) = d\theta/dh$.
3. Relative hydraulic conductivity as a function of pressure potential, $K_r(h)$.

When experimental data cannot be fit well by functional relations, tabulations of parameters can be used in the VS2D program.

Because hysteresis exists in the relationship between volumetric water content and pressure potential, different functions should be used during drainage and wetting. This hysteretic relation is quite complicated and consists of the main wetting and drying curves and a family of scanning curves that represent the functional relation when a partially drained medium is rewetted, or when drainage follows incomplete wetting (Hillel, 1971; Kirkham and Powers, 1972). The VS2D program does not treat hysteresis among the head-related functional parameters.

Soil Moisture Characteristic Curve. Three different functional equations to represent the relations between volumetric water content and pressure head can be used in the VS2D program, including one by Brooks and Corey (1964), one by Gardner (1958), as used by Haverkamp et al. (1977), and one by van Genuchten (1980).

Brooks and Corey (1964) equation:

$$s_e = \frac{\theta-\theta_r}{\phi-\theta_r} = \left(\frac{h_b}{h}\right)^{\lambda} \qquad h<h_b \tag{49}$$

$$s_e = 1.0 \qquad h \geq h_b \tag{50}$$

where s_e is the effective saturation (dimensionless), θ is the volumetric moisture content (L^3/L^3), θ_r is the residual moisture content (L^3/L^3), ϕ is porosity (dimensionless), h_b is the bubbling or air-entry pressure potential, equal to the pressure potential required to desaturate the largest pores in the medium (L), h is pressure potential (L), and λ is a pore size distribution index based on soil texture (dimensionless).

Haverkamp et al. (1977) equation:

$$s_e = \frac{1}{1+(\frac{h}{\alpha})^{\beta}} \qquad (51)$$

where α is the pressure potential at which s_e=0.5, (L), and β is the slope of the log-log plot of $[(1/s_e)-1]$ versus h (dimensionless).

Van Genuchten (1980) equation:

$$s_e = [\frac{1}{1+(\frac{h}{\alpha'})^{\beta'}}]^{\gamma} \qquad (52)$$

where $\alpha' = \alpha/[(2^{1/\gamma} - 1)^{1-\gamma}]$, (L), β' is an exponent, and γ is an exponent equal to $1-(1/\beta')$.

The parameters required by the three types of equations are listed in the VS2D documentation for 11 soils. Comparisons of these equations with experimental data on moisture content and pressure head have shown the best fit for sand and light clay soils.

Specific Moisture Capacity. Specific moisture capacity is defined as the slope of the soil moisture characteristic curve. It can be expressed as:

$$c_m(h) = \frac{\partial\theta}{\partial h} \tag{53}$$

For the moisture-characteristic curves represented by the Brooks-Corey equation, specific moisture capacity is defined as:

$$c_m(h) = -(\phi - \theta_r)\frac{(\lambda/h_b)}{(h/h_b)^{\lambda+1}} \qquad h \leq h_b \tag{54}$$

and

$$c_m(h) = 0 \qquad h > h_b \tag{55}$$

where all terms are as defined previously.

If the moisture-characteristic curve is expressed by the Haverkamp equation, specific moisture capacity is defined as:

$$c_m(h) = -(\phi-\theta_r)\frac{(\beta/\alpha)(h/\alpha)^{1/\beta}}{[1+(h/\alpha)^{\beta}]^2} \qquad h<0 \tag{56}$$

and

$$c_m(h) = 0 \qquad h \geq 0 \tag{57}$$

If the moisture-characteristic curve is expressed by the van Genuchten equation, specific moisture capacity is defined as:

$$c_m(h) = -\frac{\gamma\beta'(\phi-\theta_r)(h/\alpha')^{\beta'-1}}{\alpha'[1+(h/\alpha')^{\beta'}]^{\gamma+1}} \qquad h<0 \tag{58}$$

and

$$c_m(h) = 0 \qquad h\geq 0 \tag{59}$$

When the soil moisture characteristic curve is represented in tabular form, specific moisture capacity can be estimated by taking the slope of the line segment between data points adjacent to the h value of interest.

Relative Hydraulic Conductivity. Relative hydraulic conductivity is defined as the ratio of unsaturated to saturated hydraulic conductivity. It decreases with the increase of the negative pressure potential. It may be obtained experimentally or may be estimated by the empirical formulas below.

Haverkamp approach:

$$K_r = \frac{1}{1+(\frac{h}{A'})^{B'}} \tag{60}$$

where A' is the pressure potential at which $K_r = 0.5$, (L), and B' is a constant, equal to the slope of the log-log plot of $[(1/K_r)-1)]$ versus the pressure potential.

Brooks-Corey approach:

$$K_r = (\frac{h}{h_b})^{-(2+3\lambda)} \qquad h<h_b \tag{61}$$

and

$$K_r = 1.0 \qquad\qquad h \geq h_b \qquad (62)$$

This equation fits the data for sandy soils very well, but poorly represents the data for clay soils.

van Genuchten approach:

$$K_r = \frac{\{1-(\frac{h}{\alpha'})^{\beta'-1}[1+(\frac{h}{\alpha'})^{\beta'}]^{-\gamma}\}^2}{[1+(\frac{h}{\alpha'})^{\beta'}]^{\gamma/2}} \qquad (63)$$

This equation also fits measured data for sandy soils better than for clay soils.

Numerical Solution Scheme

VS2D is a finite difference model which approximates spatial derivatives by central differences written about grid-block boundaries, and time derivatives by a fully implicit backward scheme. The saturated hydraulic conductivity is computed using a distance-weighted harmonic mean of the adjacent cells to represent the intercell hydraulic conductivity. The relative hydraulic conductivity is calculated using either a geometric mean or a weighted arithmetic mean. Geometric mean averages provide the most accurate simulation, and they are recommended for use whenever possible. These approximations result in a set of nonlinear algebraic equations (or matrix) that must be first linearized, and then solved. Implicit linearization is used to estimate nonlinear parameters of hydraulic conductivity, source-sink terms, and those which may occur in boundary condition equations. These terms are evaluated at the current time step. The matrix can be solved by iterative techniques.

The VS2D program is written in FORTRAN language with extensive use of subprograms, thereby simplifying the process of program modification.

Data Input

Input data for running VS2D include the following five types:

1. Executive control file. This file includes data of solution domain dimensions, simulation periods of infiltration and evapotranspiration, time and space steps, program options, and output location and times for monitoring files.
2. Initial data and boundary conditions. This file includes: (a) initial values of total hydraulic potential or soil moisture in the whole solution domain, and the initial water table depth, and (b) parameters for calculating surface evaporation such as H_a and S_r.
3. Weather data. This file includes data on irrigation and rainfall, and data describing the variation of potential ET and potential evaporation with time.
4. Soil texture and characteristics. These data include the parameters for calculating the relationships between water potential and soil moisture, relative hydraulic conductivity, and specific moisture capacity, such as saturated hydraulic conductivity, K_s, soil porosity ϕ, and some exponents (e.g., λ, α, and β). Tabulations of the above relationships can be used when experimental data can not be fit well by functional relations.
5. Crop root water uptake. These data include the pressure potential in the soil and in the root, the root activity function (i.e., the root length density at the top and base of a root zone), and root depth.

Data Output

Several output files are provided by the VS2D model:

1. Pressure head, moisture content, and saturation at the selected points and at the end of each time step.
2. Head changes for each iteration in every time step.
3. Pressure head and moisture content at selected times.
4. One-line mass balance summary for each time step and at ends of recharge periods.

Model Modifications for this Study

Evapotranspiration

Various versions of the Penman combination equation have been widely used to calculate the potential evapotranspiration (ET) of a reference crop such as grass or alfalfa under well watered conditions. Crop ET can then be estimated by multiplying the potential ET by an appropriate crop coefficient.

Reference crop ET was computed from the modified Penman equation (Burman et al., 1980):

$$ET_r = \frac{\Delta}{\Delta+\gamma}(R_n + G) + \frac{\gamma}{\Delta+\gamma}\, 15.36 W_f(e_a - e_d) \tag{64}$$

where ET_r is alfalfa reference crop ET [cal/(cm²day)], Δ is the slope of the vapor pressure-temperature curve [mbar/°C], γ is the psychrometric constant [mbar/°C], R_n is net radiation [cal/(cm²day)], G is soil heat flux to the surface [cal/(cm²day)], W_f is the dimensionless wind function, $(e_a - e_d)$ is the mean daily vapor pressure deficit [mbar], and 15.36 is a constant of proportionality [cal/(cm²day mbar)]. W_f is expressed as:

$$W_f = a + bU \tag{65}$$

where U is the daily wind speed (km/day) at a height of 2 m, and a and b are regression coefficients. Elliott et al. (1988) calibrated equation (65) for Oklahoma conditions and arrived at values of -0.3405 and 0.0108 for a and b, respectively.

Crop coefficients for peanuts were determined by dividing the measured ET of well watered peanuts by reference crop ET (Elliott et al., 1988). The third-order polynomial which best fitted the data was:

$$K_c = - 1.644 + 12.05F - 17.155F^2 + 7.499F^3 \tag{66}$$

where K_c is the crop coefficient for peanuts, and F is the fraction of the growing season (ratio of days since planting to days between planting and harvesting). This is a time dependent function. Thus the potential crop ET, ET_c, was obtained as the product of the potential reference crop ET, ET_r, and the crop coefficient, K_c. ET_c is also equal to actual crop ET when soil moisture is not limiting.

Root Water Uptake

Recall the root sink models reviewed in Chapter II. The sinks can be depth and time dependent variables. The root extraction submodel in VS2D follows the potential flow approach and requires information on soil and root pressure potentials and resistances. For the apportioned transpiration approach, most uptake models were developed by considering both the root activity and one or more parameters relating to the soil moisture conditions. A general mathematical expression can be written as

$$S = T\ f_w(K,D,\psi,r) \tag{67}$$

where S is the root water uptake rate at depth z (1/T), T is the transpiration rate per unit soil surface for a one-dimensional approach (L/T) or the transpiration rate per unit length in the third dimension (parallel to the crop row) for a two-dimensional approach (L^2/T), f_w is a weighting function, r is a root activity function, and K, D, and ψ are the soil water conductivity, diffusivity, and potential, respectively.

It would seem that root activity plays a more important role than soil properties do in some situations, especially when the crop is irrigated. Thus, a modified water uptake model is proposed for inclusion in the VS2D program.

There are three main aspects of the model. First, the root activity function is defined based on experimental data. Second, crop transpiration is apportioned among soil layers according to the root activity function. Third, water uptake in each layer is reduced if soil moisture is limiting.

1. Root Activity Function. A two dimensional root activity function, r(x,z,t), will be estimated based on the experimental data. It is a depth- and lateral direction-dependent variable for a specific growth stage, defined as a normalized root length density, L/L^3. For one-dimensional modeling, r is a function of depth and time.

2. Apportioning Transpiration. The potential amount of total soil water extracted by crop roots is set equal to T_c as determined by the type of crop, stage of growth, and climatic parameters, and can be estimated by subtracting soil evaporation from crop ET. Then this potential amount is apportioned in either one or two dimensions according to the root activity function. Thus for the one-dimensional approach:

$$S_p(z) = T_c \ r(z) \tag{68}$$

with

$$r(z) = \frac{RLD(z)}{\int_0^{z_r} RLD(z)dz} \tag{69}$$

where $S_p(z)$ is the potential rate of extraction of soil water by roots at depth z [1/T], T_c is the potential crop transpiration per unit soil surface area [L/T], r(z) is a root activity function (1/L), RLD(z) is the root length density (length of roots per unit soil volume) at depth z [L/L^3], and z_r is the depth of the root zone [L].

For the two dimensional approach:

$$S_p(x,z) = T_c\ r(x,z) \tag{70}$$

with

$$r(x,z) = \frac{RLD(x,z)}{\int_A RLD(x,z)dxdz} \tag{71}$$

where $S_p(x,z)$ is the potential rate of extraction of soil water by roots at depth z and lateral distance x (1/T), T_c is the potential rate of crop transpiration per unit length in the third dimension (L^2/T), r(x,z) is a two dimensional root activity function (1/L^2), and A is equal to the product of the root depth, z_r, and row spacing (L^2).

3. Reductions due to Soil Moisture. The potential water uptake rate by roots at location (x,z) is reduced if soil moisture is limiting:

$$S(z) = S_p(z)\ f(\psi) \tag{72}$$

or

$$S(x,z) = S_p(x,z)\ f(\psi) \tag{73}$$

where S is the actual rate of extraction of soil water by roots at location (x,z) $[T^{-1}]$, and $f(\psi)$ is a function which varies between 0 and 1 and depends on the soil water potential. Following Feddes et al. (1978), a linear function can be used to estimate $f(\psi)$:

$$\begin{aligned}
f(\psi) &= 0 & 0 &\geq \psi > \psi_1 \\
f(\psi) &= 1 & \psi_1 &\geq \psi > \psi_2 \\
f(\psi) &= (\psi - \psi_3)/(\psi_2 - \psi_3) & \psi_2 &\geq \psi > \psi_3 \\
f(\psi) &= 0 & \psi_3 &\geq \psi
\end{aligned} \tag{74}$$

where ψ is soil moisture potential [L], ψ_1 is maximum soil moisture potential for which $f(\psi) = 1$ (near the anaerobiosis point), ψ_2 is minimum soil moisture potential for which $f(\psi) = 1$ (near the limiting point), and ψ_3 is soil moisture potential at wilting.

CHAPTER IV

PROCEDURE

Field Measurements

Layout

Field research was conducted during the 1988 and 1989 peanut growing seasons at the Agronomy Research Station near Perkins, Oklahoma. Two different sites for the study were designated as site 1 for the year of 1988 and site 2 for the year of 1989. The two sites had a very similar layout in terms of field size and orientation, crop arrangement, water supply system, and the location of the weather station. Site 2 was immediately adjacent to site 1, and to the south of it. A schematic diagram of the field arrangement for site 2 is given in Figure 3.

The soil type was a Teller sandy loam (fine, mixed, thermic, udic, Argiustoll). Three water treatments (full, intermediate, minimum) were established by means of a line-source sprinkler irrigation system (Hanks et al., 1976). Within each treatment, there were six blocks, with plots of two different peanut genotypes in each block. The genotypes were Okrun and Florunner. Two-row plots (0.91 m row spacing x 6.1 m long) were planted with a two-row cone planter on 6 June 1988 or calendar day (CD) 158 and 16 June 1989 or CD 167. One hundred seeds were planted each 6.1 m of row length. Rows were planted parallel to the line-source gradient irrigation system.

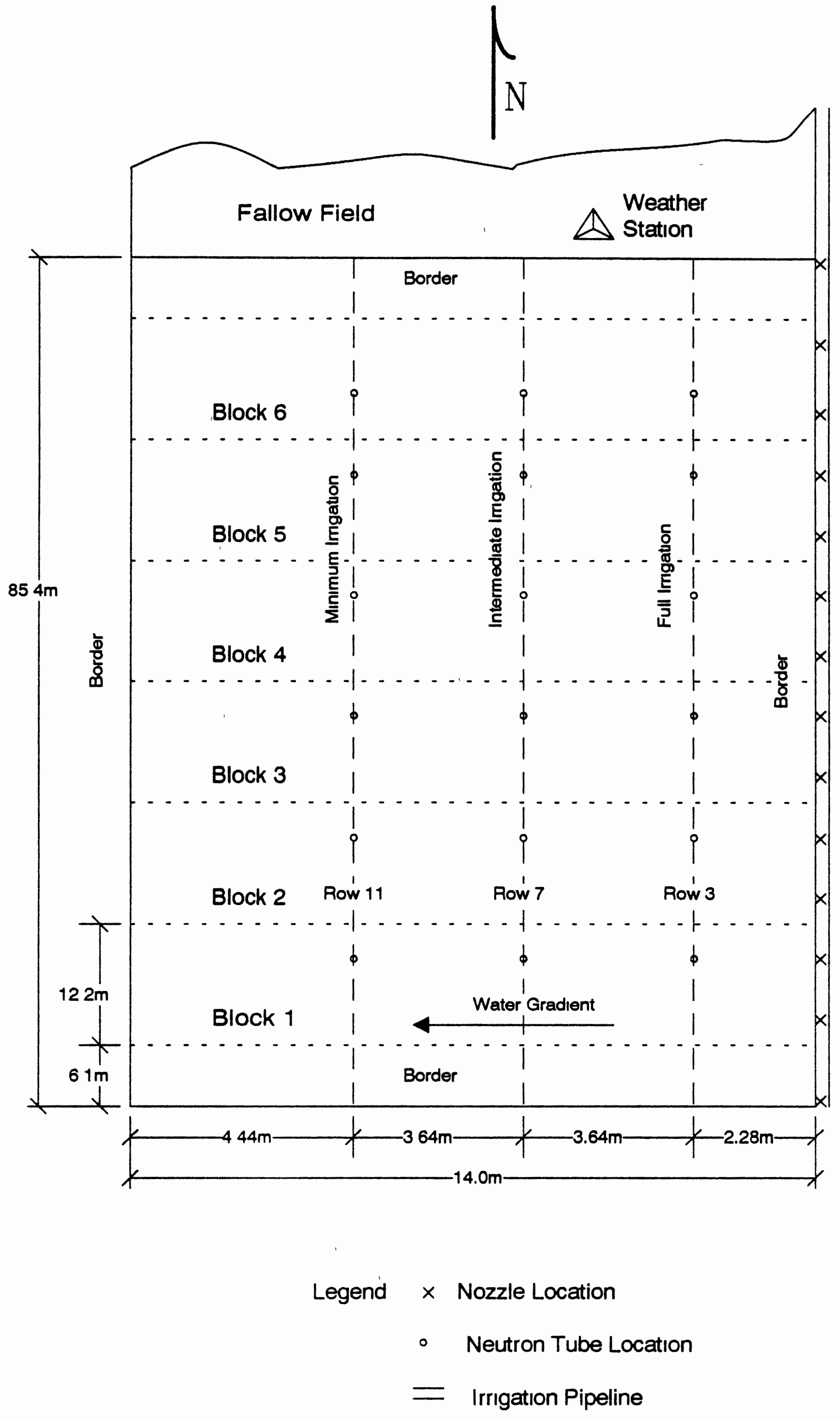


Figure 3. Field Layout of Site 2

Neutron Scattering Measurements of Soil Water

A field calibrated neutron moisture gauge (Troxler Electronic Laboratories, Model 3333) was used to measure volumetric soil water content at eighteen different locations within the plots. One additional sampling site (number 19) was in an area adjacent to the plots but void of plants. The access tubes were made of 3.81 cm diameter electro-mechanical tubing and were installed in the crop row soon after the peanuts emerged. In 1988, there were nine tubes located in Okrun plots (three tubes for each treatment), and another nine tubes located in Florunner plots. These eighteen tubes were located in blocks 1 through 6. In 1989, there were fifteen tubes located in Okrun plots of blocks 1 through 5 (three tubes for each treatment). Soil water content was measured every 15 cm to a depth of 120 cm. Measurements were made about two times per week throughout the growing season. When an irrigation occurred, measurements were made just before and two days after the irrigation event.

Soil Core Samples

In order to determine root length densities, soil cores were taken five times during the 1988 growing season and four times during the 1989 growing season using a hydraulic soil coring machine (The Gidding Machine Co., Model GSR-T-S). During 1988, the cores were 4.13 cm in diameter for the first three sampling times and 3.81 cm for the last two sampling times and taken to a depth of 120 cm. A smaller core diameter was used later in the season in 1988 due to hardness of the soil and inability of the larger core size to penetrate the soil. At the first sampling time, eighteen cores were taken (three cores for each genotype within each treatment) from the crop row. At the second and the third times, twelve cores were taken from the crop row for only two treatments (no samples were taken from the minimum water treatment because of excessive soil resistance). At the fourth sampling time, only the full water treatment could be sampled. Most of the cores were taken from the crop row, but later in the season some additional lateral sampling was done between crop rows. At times, the penetration resistance of clay layers precluded coring to the full 120 cm depth.

During 1989, the cores were 3.81 cm in diameter and taken to a depth of 120 cm every time. At each sampling time, eighteen cores were taken (two cores for each treatment at each of three locations relative to the crop row). The three locations were in the crop row, 15 cm away from the row, and 46 cm away from the row (in the center between adjacent rows). All of the root samples were taken from the Okrun genotype plots in 1989. Tables 1 and 2 show the scheduling for taking soil cores during these two years.

The cores were cut in the field at intervals of 15 cm for root analysis. The root samples were bagged and then frozen for later analysis at the USDA-ARS Plant Science Research Laboratory, Stillwater, OK. Each 0.15 m sample was washed free of soil using a Gillison hydropneumatic root washer and manually picked free of other debris. Root lengths were determined with a Comair rootlength scanner.

A soil moisture core was taken within a few cm of each root core. These cores were cut in the field at intervals of 7.5 cm and stored in cans for the measurement of gravimetric water content (grams of water per gram of oven-dry soil) in the ground water laboratory of the Agricultural Engineering Department, OSU. The wet weight of each sample was measured on the sampling day using a computer controlled balance. Water was removed from the soil by oven-drying at 105°C to a constant weight. The dry weight of each sample was obtained and then the gravimetric water content determined.

TABLE 1

SCHEDULING FOR TAKING SOIL CORES DURING 1988

Date	Days After Planting	Treat-ment	Maximum Coring Depth (cm)	Lateral Distance from Crop Row (cm)
July 21	45	Full	120	0
		Inter.	120	0
		Min.	120	0
Aug. 11	66	Full	120	0
		Inter.	120	0
		Min	-	-
Aug. 25	80	Full	120	0
		Inter.	120	0
		Min	-	-
Sept. 8	94	Full	120	0
			30	10
			60	20
			105	30
			120	40
		Inter.	-	-
		Min	-	-
Oct. 4	120	Full	120	0
		Inter.	45	0
		Min	60	0

TABLE 2

SCHEDULING FOR TAKING SOIL CORES DURING 1989

Date	Days After Planting	Maximum Coring Depth (cm)	Lateral Distance from Crop Row (cm)
July 26	40	120	0 15 46
Aug. 17	62	120	0 15 46
Sept. 7	83	120	0 15 46
Sept. 28	104	120	0 15 46

Weather Data

A microprocessor-based weather station (Campbell Scientific, Inc.) was set up immediately adjacent to the field plots. The weather station's datalogger computed hourly and daily summaries of wet and dry bulb temperature, solar radiation, and wind speed. The data were stored and read once per week.

Rainfall and irrigation data were collected using multiple rain gauges mounted just above the crop canopy. The gauges were checked soon after rainfall or irrigation events. Except when significant rainfall amounts were received, the plots were irrigated approximately once per week, with application amounts of about 30, 20, and 10 mm for the full, intermediate, and minimum irrigation treatments, respectively.

Laboratory Measurements

Soil properties were measured in the ground water laboratory of the Agricultural Engineering Department using samples from undisturbed soil cores. Soil water characteristic data (water potential, ψ, versus water content, θ) were determined using a 15 bar pressure plate apparatus (Klute, 1982).

Soil water diffusivity was measured using the Bruce-Klute method (1956) and a Mariotte flask arrangement permitted the supply of water at constant head. All flow columns were packed using plastic films. During the filling process the flow column was placed on a wooden horizontal stand. Soil hydraulic conductivity was calculated from the diffusivity and water characteristic data under wetting conditions.

Field capacity, saturated water content, anaerobiosis point, and wilting point were obtained from soil water characteristic data.

CHAPTER V

FIELD AND LABORATORY DATA ANALYSIS

Neutron Scattering Data

The neutron scattering measurements of soil water were taken every 15 cm to a depth of 120 cm. The readings were in the form of a count ratio relating a measured count to a reference count. These data were transformed into volumetric soil moisture content data using linear equations calibrated by the OSU Agronomy Department:

1. For the year of 1988:

$$\theta = 0.0098 + 0.5855 \text{ R} \qquad \text{for depth} = 15 \text{ cm}$$

$$\theta = - 0.0161 + 0.5678 \text{ R} \qquad \text{for depths} > 15 \text{ cm}$$

2. For the year of 1989:

$$\theta = 0.0099 + 0.582 \text{ R} \qquad \text{for depth} = 15 \text{ cm}$$

$$\theta = - 0.0161 + 0.5643 \text{ R} \qquad \text{for depths} > 15 \text{ cm}$$

where θ is the volumetric water content (cm^3/cm^3) and R is the count ratio. The first reading represents the count ratio to a depth of 22.5 cm, and the last reading represents the count ratio at a depth of 112.5-120 cm. Appendix I shows the total water content throughout the 120 cm depth during the peanut growing season in 1988 and 1989.

Statistical analysis was conducted to check the existence of differences among the three water treatments. The data in Appendix I were used in the following calculations. For the data of 1988, the number of observations for each genotype under the same water treatment was 93. There were 186 observations in each treatment. There were 558 total observations used for statistical analysis. The means and standard deviations for the three water treatments are shown in Table 3. The analysis of variance is given in Table 4. There was significant difference among the three water treatments at the 5% level.

For the data of 1989, only the fifteen tubes located in Okrun plots were considered (Table 5). There were 125 observations in each treatment, and a total of 375 observations were used in the ANOVA calculations. Table 6 shows no significant difference among at least two water treatments at the 5% level. Table 7 shows that significant differences existed between the full and minimum water treatments.

Weather conditions were drier and hotter in 1988 than in 1989. Periodic rains in 1989 precluded establishment of a complete water gradient.

Gravimetric Water Content

The gravimetric water content was measured at each time when soil cores were taken. In order to compare the gravimetric data with the neutron probe data, soil bulk densities were obtained by dividing soil dry weight by soil volume. If the soil samples are "good", the soil volume should be the product of the sample length (7.5 cm) and the cross-sectional area (11.4 cm^2 for the 3.81 cm diameter soil cores or 13.4 cm^2 for the 4.13 cm diameter soil cores). Figures 4 and 5 show the scatter plots of the data. Bulk density values less than 1.5 g/cm^3 or greater than 1.8 g/cm^3 were assumed to be clearly unrepresentative (either incomplete or overly compacted soil samples). Good samples were not obtained for the last depth increments at the

TABLE 3

STATISTICAL ANALYSIS OF NEUTRON PROBE READINGS OF TOTAL WATER (cm) IN 120 cm DEPTH DURING 1988

Treatment	Item	Florun	Okrun	Average
Full	Mean	24.959	25.347	25.153
	SD	3.337	3.423	3.377
Intermediate	Mean	24.434	23.245	23.839
	SD	3.392	3.638	3.558
Minimum	Mean	22.947	22.698	22.822
	SD	3.452	3.616	3.528

TABLE 4

ANOVA FOR NEUTRON PROBE READINGS OF 1988

Source	Sum of Squares	DF	MS	F-Ratio	Prob.
Treatment	507.894	2	253.947	20.903	0.000 **
Genotype	17.078	1	17.078	1.406	0.236
Replication	30.267	2	15.133	1.246	0.288
Error	6706.144	552	12.149		

** - Significant difference among water treatments at the 5% level of probability.

TABLE 5

STATISTICAL ANALYSIS OF NEUTRON PROBE READINGS OF TOTAL WATER (cm) IN 120 cm DEPTH DURING 1989

Treatment	Item	Okrun
Full	Mean	27.906
	SD	2.169
Intermediate	Mean	27.586
	SD	2.534
Minimum	Mean	27.273
	SD	2.857

TABLE 6

ANOVA FOR NEUTRON PROBE READINGS OF FIFTEEN TUBES LOCATED IN OKRUN PLOTS IN 1989

Source	Sum of Squares	DF	Mean-Square	F-Ratio	Prob.
Treatment	25.066	2	12.533	1.955	0.143
Replication	32.946	4	8.237	1.285	0.275
Error	2359.165	368	6.411		

TABLE 7

t-TEST BETWEEN TREATMENTS

Between Treatments	t Statistic	Prob.
Full & Intermediate	1.426	0.155
Full & Minimum	2.255	0.025 **
Intermediate & Minimum	0.865	0.388

** - Significant difference between the full and minimum water treatments at the 5% level of probability.

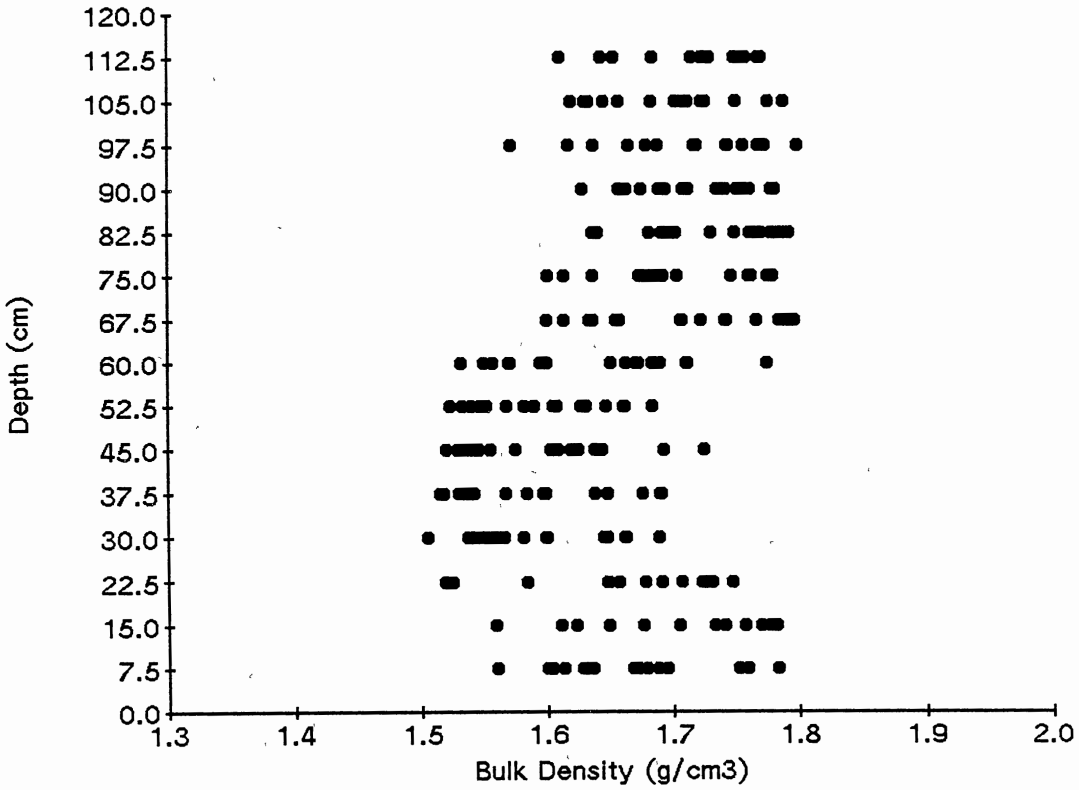


Figure 4. Bulk Density Distribution at Site 1 (1988)

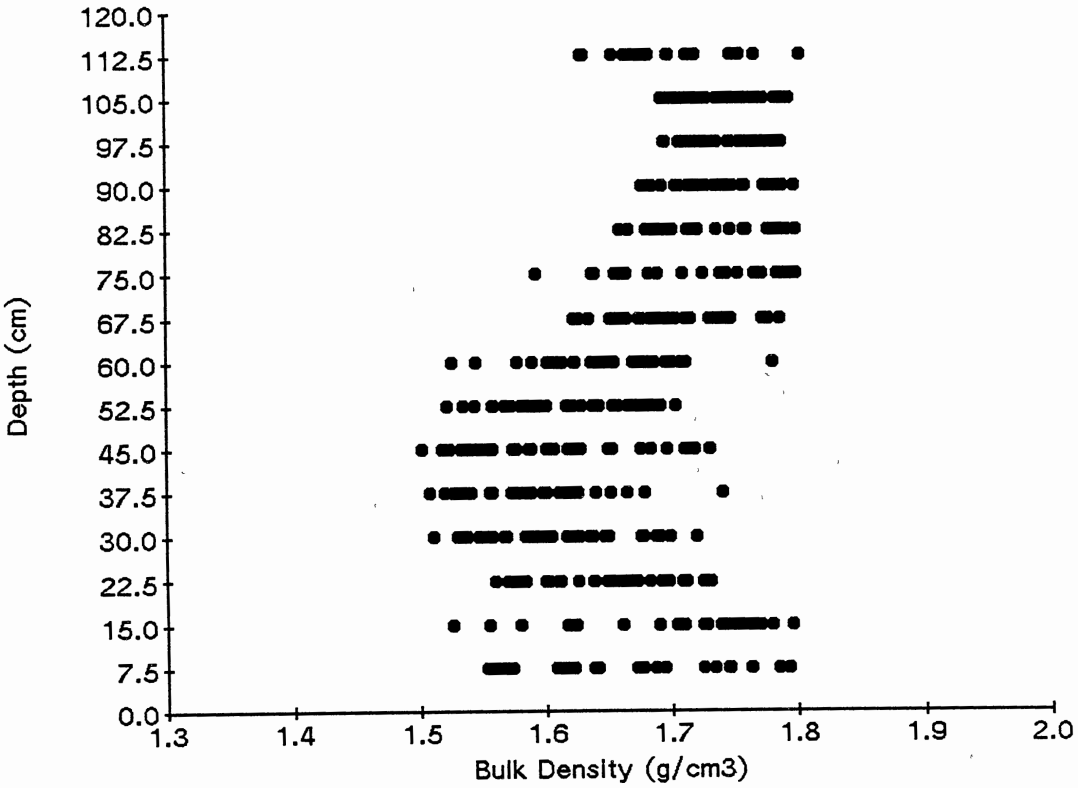


Figure 5. Bulk Density Distribution at Site 2 (1989)

bottom of the soil cores. Table 8 shows the results for bulk density at the different depths at site 1 and site 2.

The gravimetric data were averaged over depths at which neutron data were measured. These data and the corresponding neutron probe data (measured in the same plot, at the same depth, and at the same time) are plotted and shown in Appendix II. These figures indicate that the measurements by the two methods were in reasonably good agreement, particularly considering the inherent spatial variability in soil moisture.

Weather Data

Appendix III shows the summary of the weather data through the 1988 and 1989 peanut growing seasons. The daily alfalfa reference crop evapotranspiration was estimated using these weather data. Peanut ET was estimated using the method discussed in Chapter III. The daily reference crop ET, peanut ET and crop coefficients are listed in Appendix IV.

Rainfall and irrigation data are shown in Appendix V. During the 1988 peanut growing season, the total rainfall was 331 mm. Irrigation occurred 11 times with total amounts of 317 mm, 198 mm, and 117 mm for the full, intermediate, and minimum water treatments. The corresponding average amounts per irrigation were 29 mm, 18 mm, and 11 mm, respectively. During the 1989 peanut growing season, the total rainfall was 349 mm. Irrigation occurred 7 times with total amounts of 208 mm, 133 mm, and 61 mm for the three water treatments. The corresponding average amounts were 30 mm, 19 mm, and 9 mm, respectively.

Soil Water Balance Simulation

In order to compare the weather-based ET estimates to field observations, it is necessary to conduct a water balance simulation to predict the daily total water in a

TABLE 8

RESULTS FOR BULK DENSITY AT SITE 1 AND SITE 2

Site	Depth (cm)	No. of Cases	Mean (g/cm^3)	Std. Dev. (g/cm^3)
1	0 - 22.5	44	1.673	0.069
	22.5 - 60	88	1.601	0.060
	60 - 120	112	1.705	0.081
2	0 - 22.5	84	1.667	0.071
	22.5 - 60	167	1.615	0.058
	60 - 120	196	1.727	0.045

crop root zone of 120 cm. In the water balance, irrigation or rainfall amounts are added and ET, runoff, and deep percolation amounts are subtracted. Model inputs included irrigation and rainfall data, weather data necessary for computing reference crop ET, values of the crop coefficient, and the soil's field capacity to be used as the starting point for the simulations. Appendix VI shows the daily water balance results. There are two assumptions in the simulations:

1. The first 6 mm of irrigation or rainfall were not added to the root zone (Elliott et al., 1988).
2. Because of the difficulty in estimating runoff, a significant portion of the rainfall was not added to the root zone when the daily rainfall was greater than 50 mm. This assumption was used twice during the 1988 growing season. In addition, whenever the simulation showed that field capacity had been reached, any excess water was assigned to runoff.

Figures 6 and 7 show the model estimates and the neutron measurements of total water in a soil zone of 120 cm under full irrigation. Because the total rainfall was 140 mm between calendar days 257 and 262 in 1988, this period is omitted in Figure 6. The calculations were restarted on calendar day 263. During 1989, a rainfall of 80 mm occurred on calendar day 255. The water balance simulations were restarted one week after this large rainfall event. These figures indicate that the overall predictive ability of the simulation model was good and that the weather-based estimates of peanut ET can be applied to root water uptake modeling.

Laboratory Data

Soil parameters were measured for the soil at site 2 in 1989. The undisturbed soil cores were used in the measurement of soil water characteristic data (water potential, ψ, versus water content, θ) as shown in Table 9. There were 16 samples, and each represented a length of 7.5 cm. The three depth increments were defined

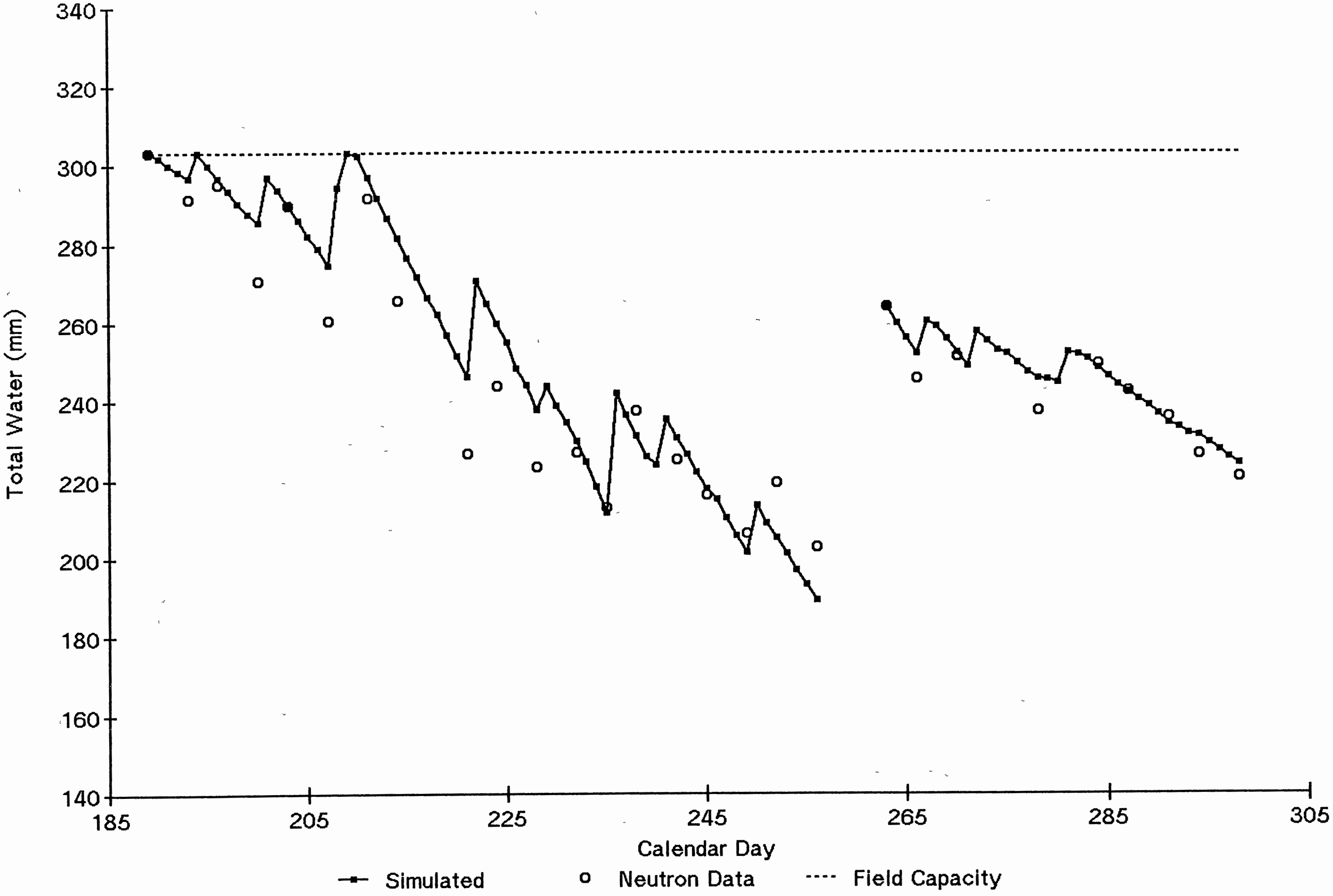


Figure 6. Simulated and Measured Soil Water in 120 cm Depth for the 1988 Peanut Growing Season

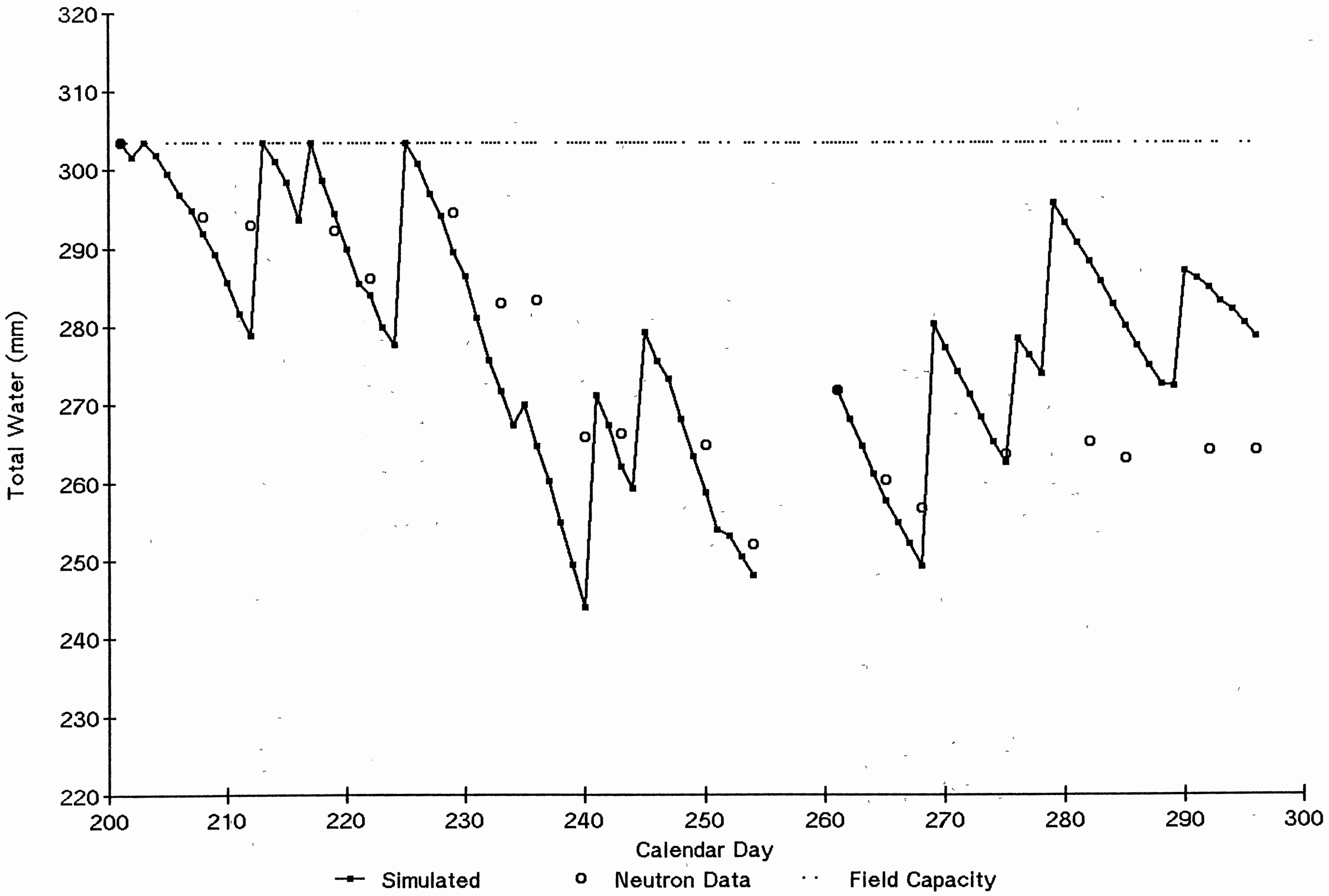


Figure 7. Simulated and Measured Soil Water in 120 cm Depth for the 1989 Peanut Growing Season

TABLE 9

RELATIONSHIP BETWEEN SOIL WATER POTENTIAL AND SOIL WATER CONTENT AT SITE 2 (1989)

$-\psi$ (kPa)	Depth (cm)					
	0-37.5		37.5-90		90-120	
	θ_d	θ_w	θ_d	θ_w	θ_d	θ_w
0	0.351	0.351	0.354	0.354	0.339	0.339
2	0.338	0.309	0.342	0.295	0.322	0.267
10	0.279	0.251	0.301	0.265	0.261	0.236
20	0.263	0.241	0.285	0.254	0.235	0.207
33	0.255	0.222	0.274	0.242	0.212	0.184
50	0.222	0.203	0.259	0.226	0.195	0.168
100	0.209	0.194	0.238	0.195	0.179	0.150
300	0.170	0.162	0.200	0.174	0.156	0.125
500	0.145	0.141	0.175	0.169	0.138	0.124
1500	0.120	0.120	0.141	0.141	0.120	0.120

Notation:

θ_d -- Soil water content (cm^3/cm^3) under drying conditions;

θ_w -- Soil water content (cm^3/cm^3) under wetting conditions.

based on the laboratory results. Soil diffusivity data are shown in Table 10. After plotting these data as shown in Figures 8 through 11, the best fit equations are in the following forms:

$$\ln(-\psi) = a_1 + b_1\theta \tag{75}$$

$$\ln(D) = a_2 + b_2\theta \tag{76}$$

where θ is soil water content (cm^3/cm^3), ψ is soil water potential (kPa), D is soil diffusivity (cm^2/sec), and a's and b's are empirical constants.

The soil hydraulic conductivity can be estimated by the following equation:

$$K = - D \left(\frac{\partial\theta}{\partial\psi}\right) \tag{77}$$

where K is the soil hydraulic conductivity (cm/sec). From Equations (75) (76), and (77), the relationship of θ and K can also be written in the logarithmic form:

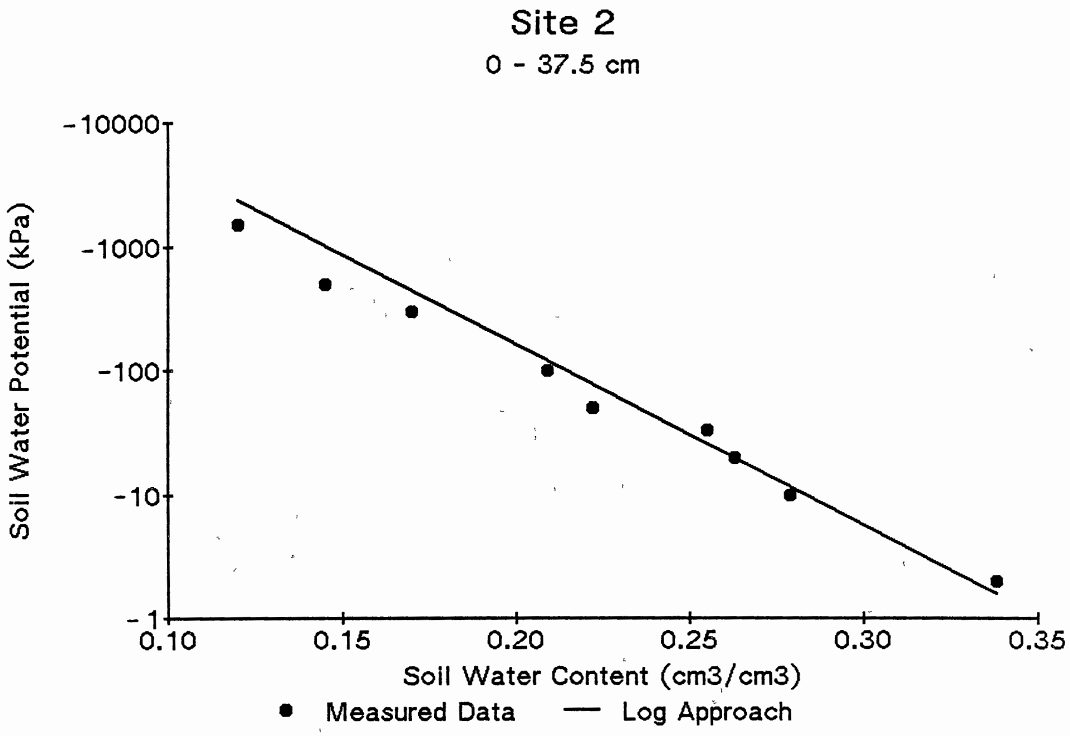
$$\ln(K) = a_3 + b_3\theta \tag{78}$$

with

$$a_3 = a_2 - a_1 - \ln(-b_1) \tag{79}$$

$$b_3 = b_2 - b_1 \tag{80}$$

Table 11 shows the soil parameters calculated by the logarithmic approach Since the VS2D model can accommodate tabular data, the values in Table 9 were used as model inputs for $\psi(\theta)$. Because the model does not treat hysteresis among the water potential related functional parameters, the data for the drying condition were used in the calculations. The $K(\theta)$ relationship was derived from $\psi(\theta)$ and



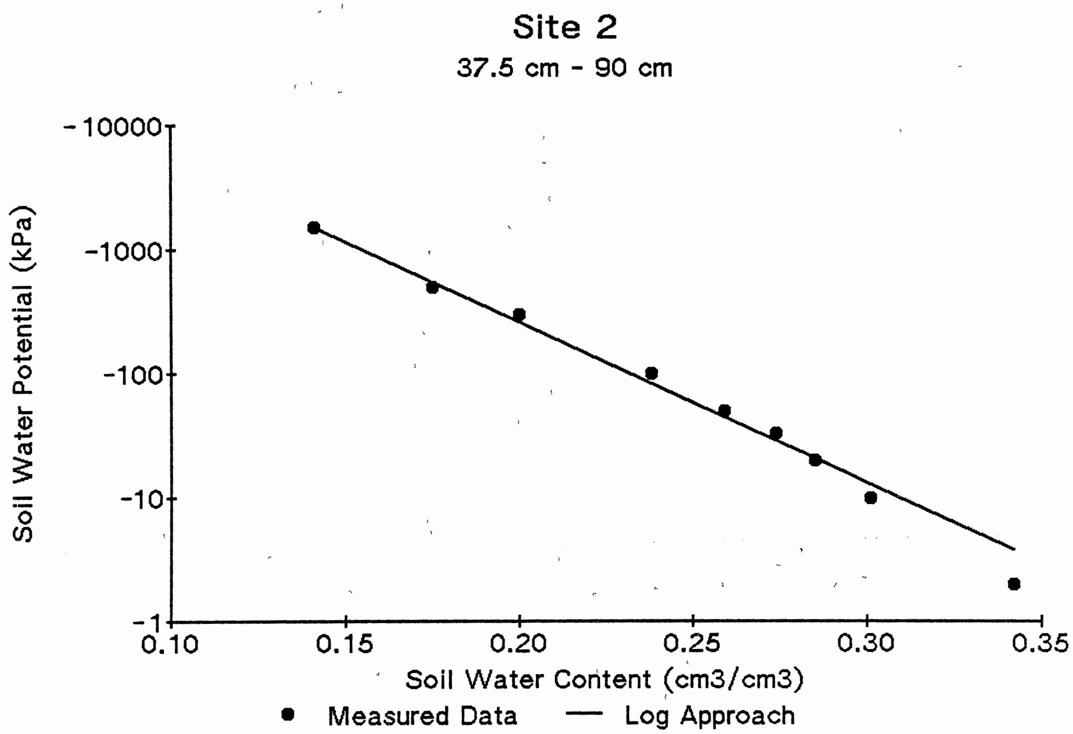


Figure 8. Measured Soil Water Contents and Soil Water Potentials for Depths 0-37.5 cm and 37.5-90 cm at Site 2 under Drying Conditions.

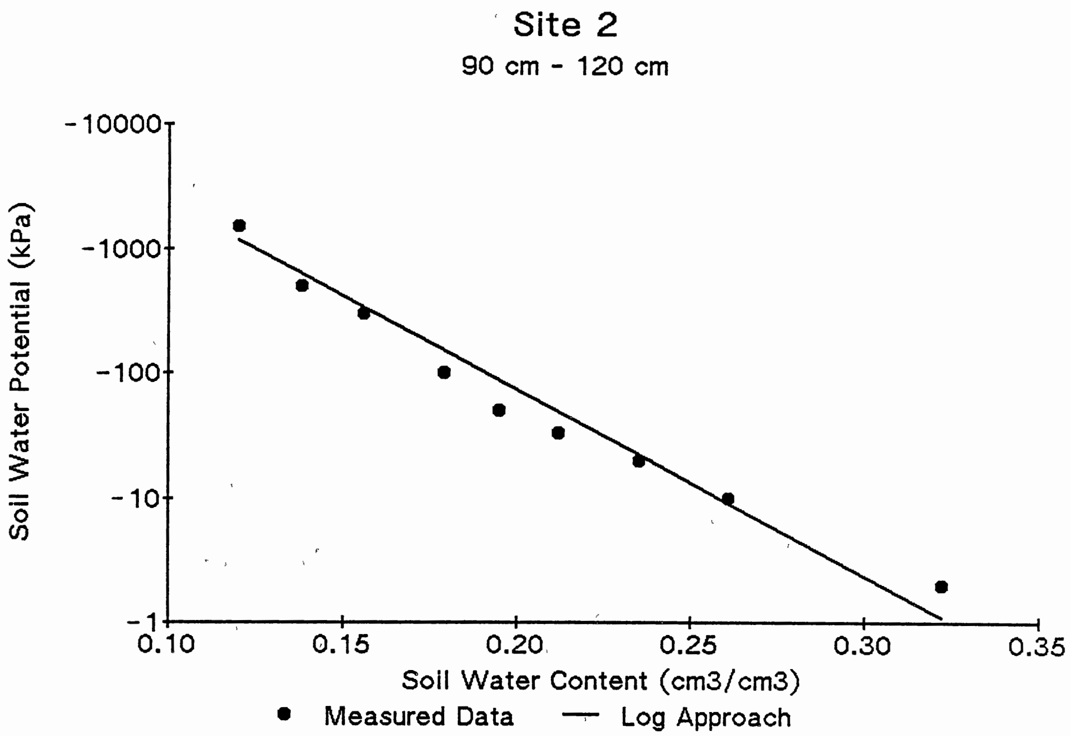


Figure 9. Measured Soil Water Contents and Soil Water Potentials for Depths 90-120 cm at Site 2 under Drying Conditions.

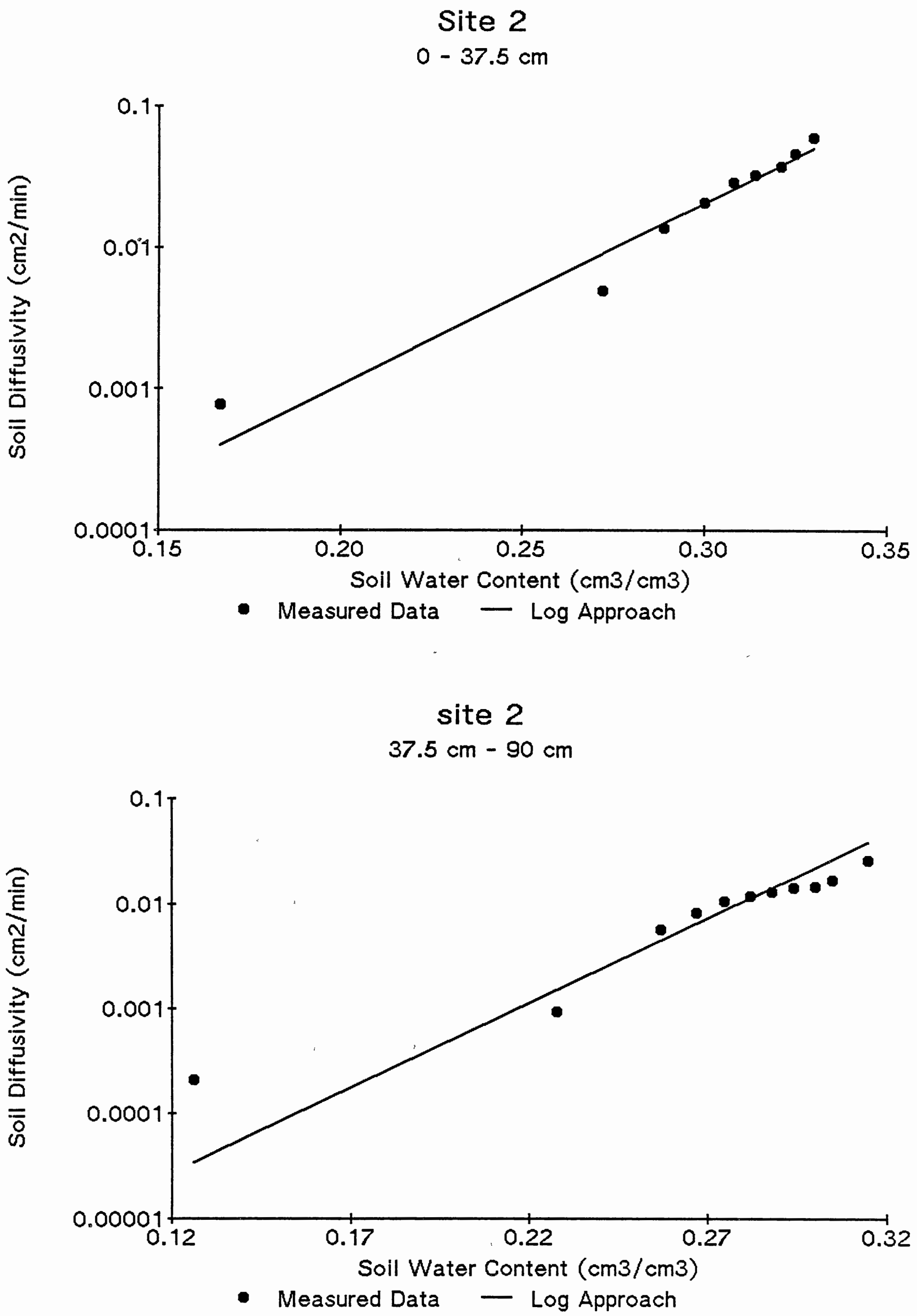


Figure 10. Measured Soil Water Contents and Soil Water Diffusivities for Depths 0-37.5 cm and 37.5-90 cm at Site 2 under Drying Conditions

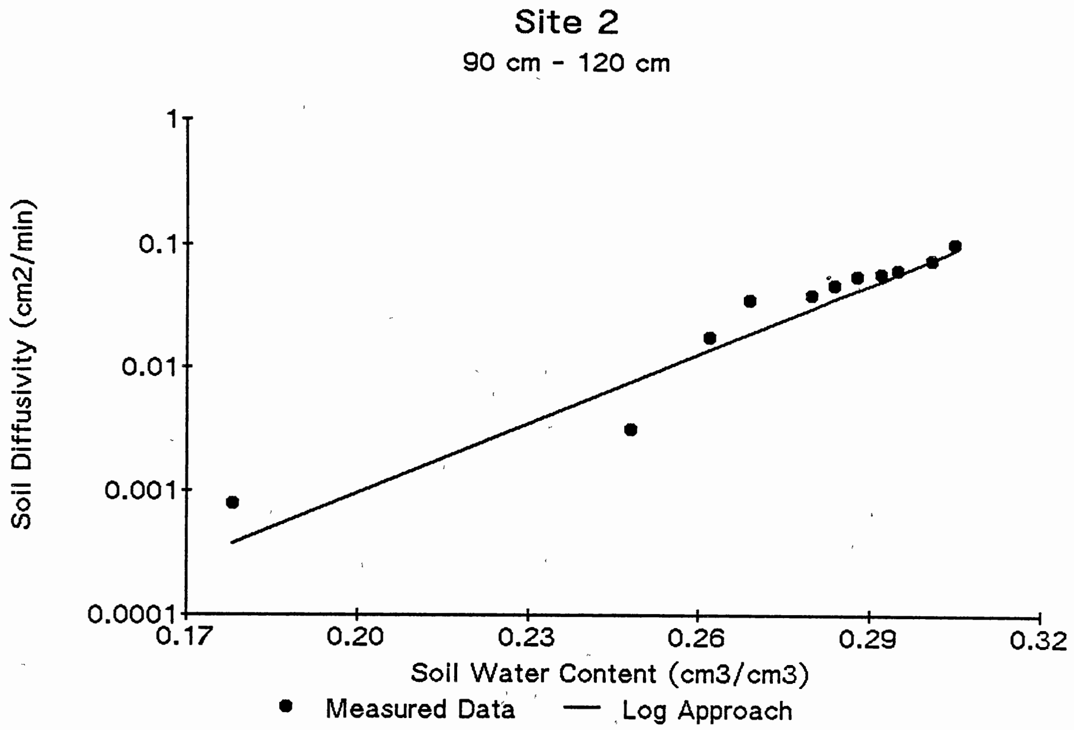


Figure 11. Measured Soil Water Contents and Soil Water Diffusivities for Depths 90-120 cm at Site 2 under Drying Conditions

TABLE 10

RELATIONSHIP BETWEEN SOIL DIFFUSIVITY AND SOIL WATER CONTENT AT SITE 2 (1989)

Depth (cm)					
0 - 37.5		37.5 - 90		90 - 120	
θ cm^3/cm^3	$D(\theta)$ cm^2/sec	θ cm^3/cm^3	$D(\theta)$ cm^2/sec	θ cm^3/cm^3	$D(\theta)$ cm^2/sec
0.044	1.1E-06	0.059	4.3E-06	0.051	6.2E-06
0.167	0.00078	0.126	0.00021	0.178	0.00078
		0.228	0.00095	0.248	0.00317
		0.257	0.00567	0.262	0.01755
0.272	0.00494	0.267	0.00828	0.269	0.03487
0.289	0.01362	0.275	0.01057	0.280	0.03851
0.300	0.02075	0.282	0.01206	0.284	0.04690
0.308	0.02874	0.288	0.01328	0.288	0.05467
0.314	0.03261	0.294	0.01437	0.292	0.05726
0.321	0.03751	0.300	0.01490	0.295	0.06105
0.325	0.04609	0.305	0.01685	0.301	0.07386
0.330	0.05953	0.315	0.02648	0.305	0.09880

TABLE 11

ESTIMATED SOIL PARAMETERS FOR THE LOGARITHMIC APPROACH

Soil Parameter	Depth (cm)	a	b
$-\psi(\theta)$	0 - 37.5	11.80	-33.55
	37.5 - 90	11.50	-29.27
	90 - 120	11.19	-34.45
$D(\theta)$	0 - 37.5	-12.77	29.61
	37.5 - 90	-14.96	37.20
	90 - 120	-15.56	43.04
$K(\theta)$	0 - 37.5	-28.08	63.16
	37.5 - 90	-29.84	66.47
	90 - 120	-30.29	77.49

D(θ), so the regression equations from table 11 were used as model inputs for K(θ).

Field capacity, saturated water content, and wilting point were estimated from the soil water characteristic data and field observations. The soil water potentials and the corresponding soil water contents in the 120 cm root zone are listed in Table 12.

Root Data and Analysis

Root length measurements were made using a Comair rootlength scanner. The root length density (RLD) was calculated in two steps (Commonwealth Aircraft Corporation Ltd.):

$$RLD = L_a \, (100/\ V) \tag{81}$$

with

$$L_a = -\ 0.2246 + 0.9655\ L_e + 0.00123\ L_e^2 \tag{82}$$

where RLD is the root length density (cm root length per cm³ soil volume), L_e is the estimated root length (m), L_a is the actual root length (m), V is the soil volume (cm³) and equal to 171 cm³ if the diameter of the soil cores is 3.81 cm or 201 cm³ if the diameter of the soil cores is 4.13 cm. The distributions of root length density for 1989 are shown in Appendix VII. The values represent the average of two replications for each row location.

Using 17 August 1989 data, Figures 12 and 13 contrast the full and minimum water treatments for each of three locations relative to the crop row. Presenting the same data in a different way, Figure 14 highlights the effect of the sampling location relative to the crop row under full and minimum water treatments.

Several trends are apparent in these data. In almost all cases, the RLD values

TABLE 12

ESTIMATED SOIL WATER CONTENTS (cm) AT SATURATION, FIELD CAPACITY, AND WILTING POINT FOR A 120 cm ROOT ZONE

	Pressure (kPa)	Depth (cm)			
		0-37.5	37.5-90	90-120	Total
Saturation	0	13.2	18.6	10.2	42.0
Field Capacity	33	9.6	14.4	6.4	30.4
Wilting Point	1500	4.5	7.4	3.6	15.5

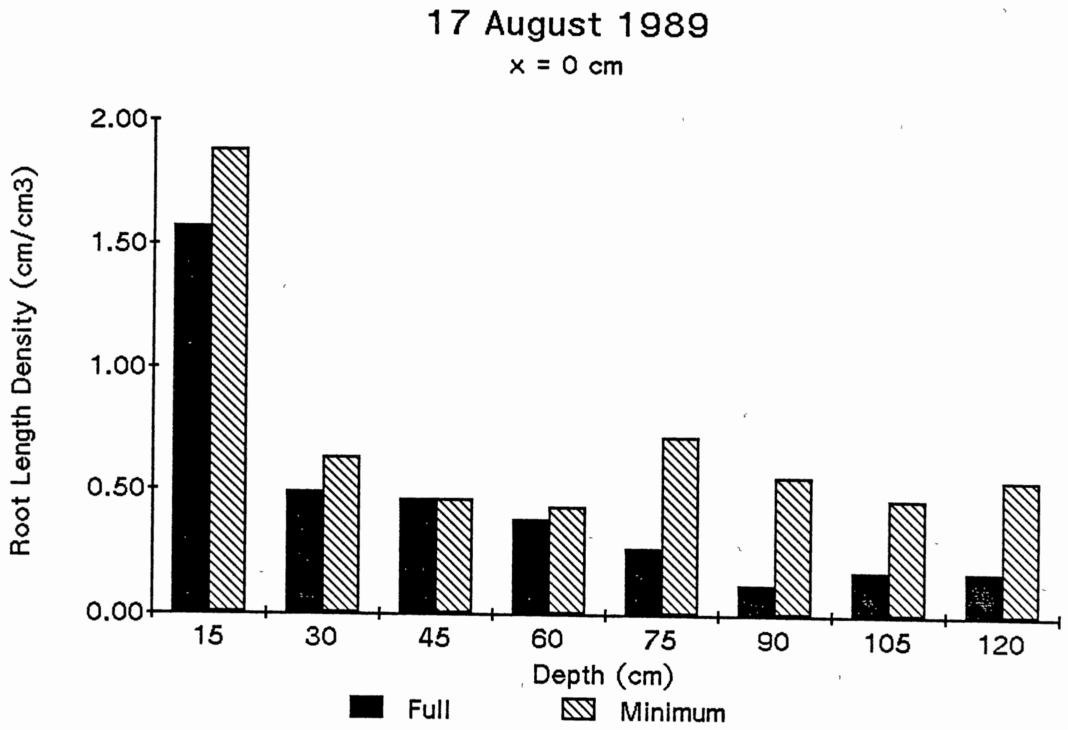


Figure 12. Observed Peanut Root Length Densities under Full and Minimum Water Treatments. Soil Cores were Taken in the Crop Row (x=0) on 17 August 1989.

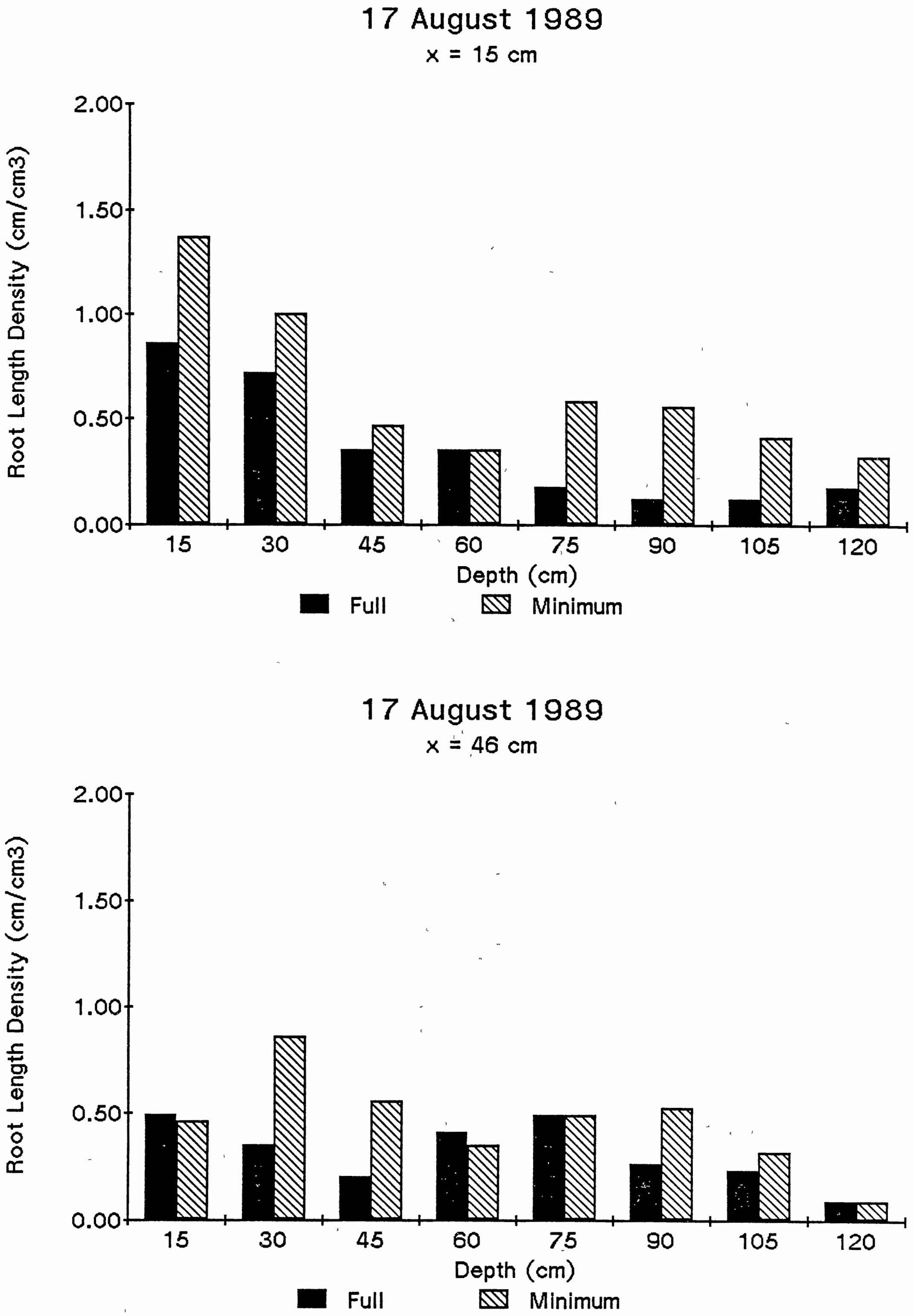


Figure 13. Observed Peanut Root Length Densities under Full and Minimum Water Treatments. Soil Cores were Taken 15 cm and 46 cm from the Crop Row on 17 August 1989.

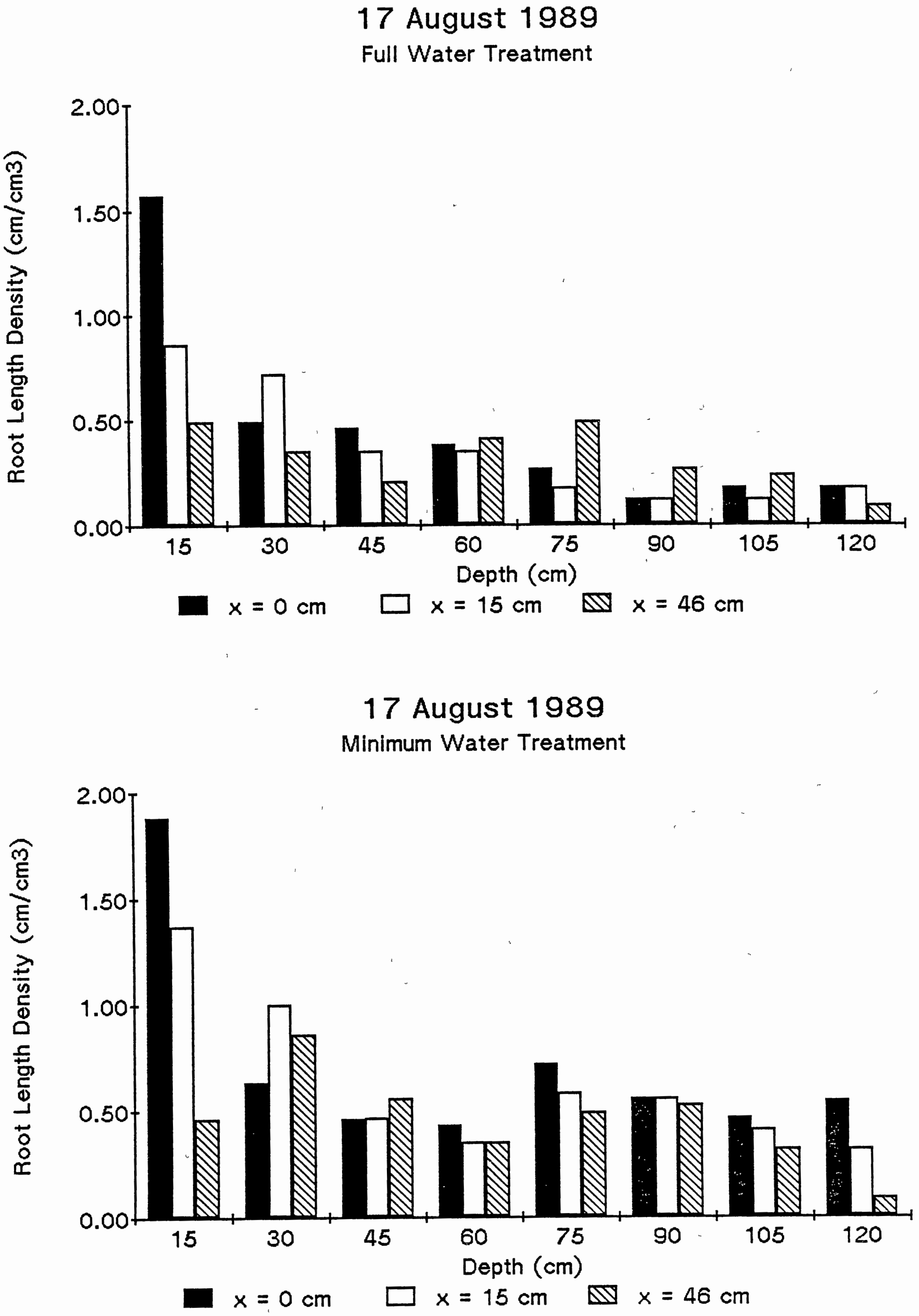


Figure 14. Observed Peanut Root Length Densities under Full and Minimum Water Treatments. Soil Cores were Taken at Three Locations Relative to the Crop Row on 17 August 1989.

are greater in the minimum water treatment, reflecting one response of the peanut plant to increased water stress. In the crop row, the RLD in the top 15 cm of soil is substantially higher than at greater depths. As the sampling location moves away from the crop row, the RLD tends (with some exceptions) to decrease in magnitude and become more uniform.

Using only one sampling location (in the crop row), Figure 15 compares RLD data for two successive sampling dates (17 August 1989 and 7 September 1989) under full and minimum water treatments. Except at the deeper depths in the minimum water treatment, the RLD tends to increase during the three week period between sampling dates. This increase is particularly evident in the top 30 cm of soil.

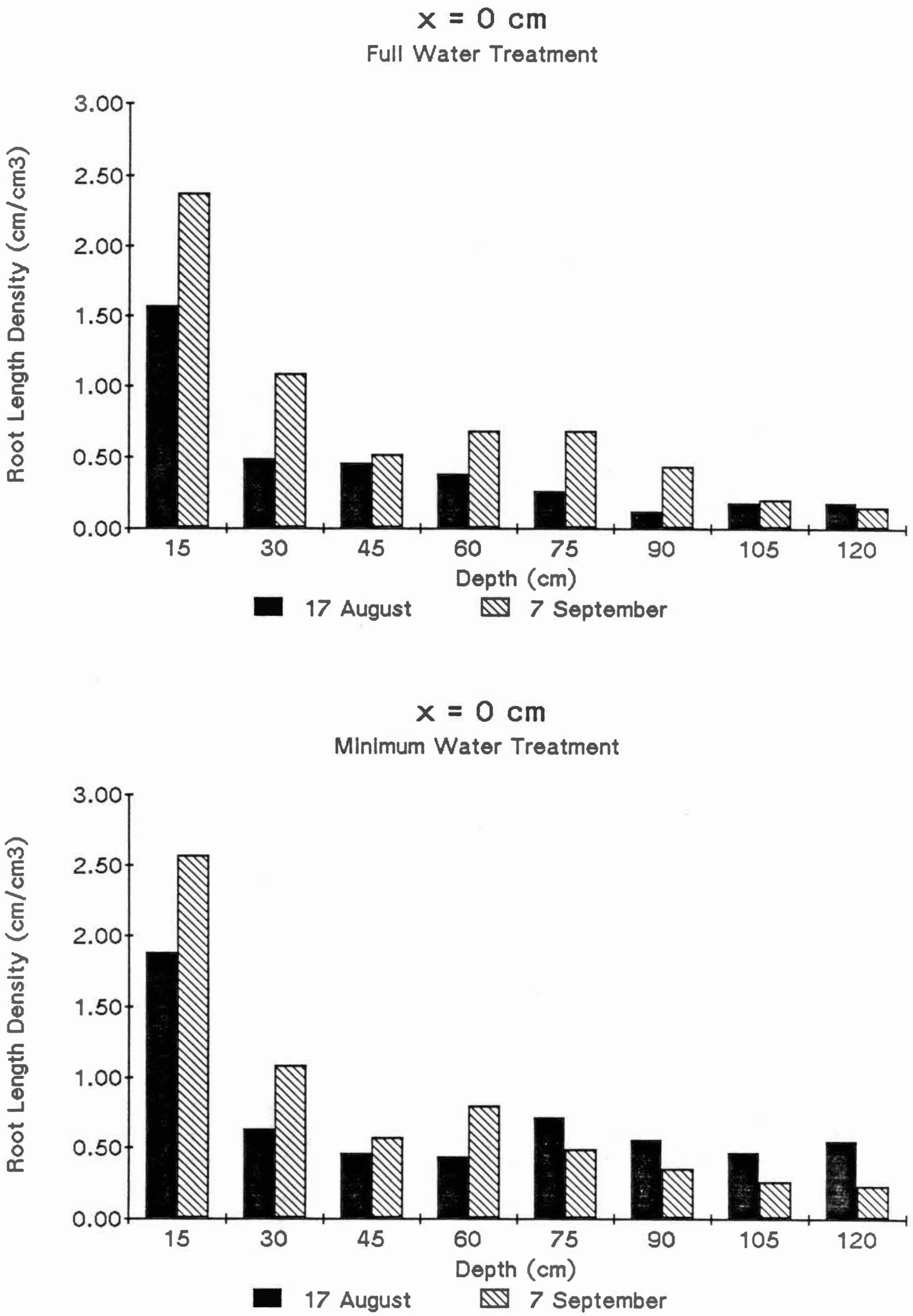


Figure 15. Observed Peanut Root Length Densities under Full and Minimum Water Treatments. Soil Cores were Taken in the Crop Row (x=0) on 17 August and 7 September 1989.

CHAPTER VI

MODELING RESULTS AND DISCUSSION

Root Activity Functions

Recall the models of root water uptake in Chapter III. The root activity function is an important part of those models which apportion transpiration. The two dimensional root activity function can be expressed as:

$$r(x,z) = \frac{RLD(x,z)}{\int_A RLD(x,z)dxdz} \tag{83}$$

where r is a two dimensional root activity function $[1/L^2]$, RLD is the root length density $[L/L^3]$, and A is the area of the solution domain and equal to the product of the root depth and the plant row spacing $[L^2]$.

In order to estimate the root activity function, the distribution of root length density data (Appendix VII) should be analyzed. There are perhaps several ways of empirically representing root length density as a function of depth and the lateral direction. Two approaches are presented here.

1. Linear Approach

Suppose the root length density is a linear function of depth, z, and lateral direction, x. The general expression could be written as:

$$RLD = \beta_0 - \beta_1 z - \beta_2 x \tag{84}$$

where RLD is the root length density, and β_0, β_1, and β_2 are empirical constants.

According to Equations (83) and (84), r(x,z) can be expressed as:

$$r(x,z) = \frac{c_1(2z-z_r)+c_2(2x-x_r)+z_r}{x_r z_r^2} \tag{85}$$

with

$$c_1 = -\frac{\beta_1 z_r}{2\beta_0-\beta_1 z_r-\beta_2 x_r} \tag{86}$$

$$c_2 = -\frac{\beta_2 z_r}{2\beta_0-\beta_1 z_r-\beta_2 x_r} \tag{87}$$

where all terms are as previously defined.

For the one dimensional problem with $\beta_2 = 0$, r(z) can be expressed as:

$$r(z) = \frac{c(2z-z_r)+z_r}{z_r^2} \tag{88}$$

with

$$c = -\frac{\beta_1 z_r}{2\beta_0-\beta_1 z_r} \tag{89}$$

Equation (88) is in the same form obtained by Ritchie in 1984. The range of c is between -1 and 1. Figure 16 illustrates the effect of c on the root distribution pattern. As the c value decreases, proportionally more roots are present in the upper layers.

2. Exponential Approach

Suppose the root length density is an exponential function of depth, z, and lateral direction, x. The general expression of root length density could be written as:

$$RLD = \beta_0 \exp(-\beta_1 z) \exp(-\beta_2 x) \tag{90}$$

where all terms are as defined previously.

According to Equations (83) and (90), r(x,z) can be expressed as:

$$r(x,z) = \alpha \exp(-\beta_1 z) \exp(-\beta_2 x) \tag{91}$$

with

$$\alpha = \frac{\beta_1 \beta_2}{[1-\exp(-\beta_1 z_r)][1-\exp(-\beta_2 x_r)]} \tag{92}$$

For the one dimensional problem with $\beta_2 = 0$, r(z) can be derived as:

$$r(z) = \alpha \exp(-\beta_1 z) \tag{93}$$

with

$$\alpha = \frac{\beta_1}{1-\exp(-\beta_1 z_r)} \tag{94}$$

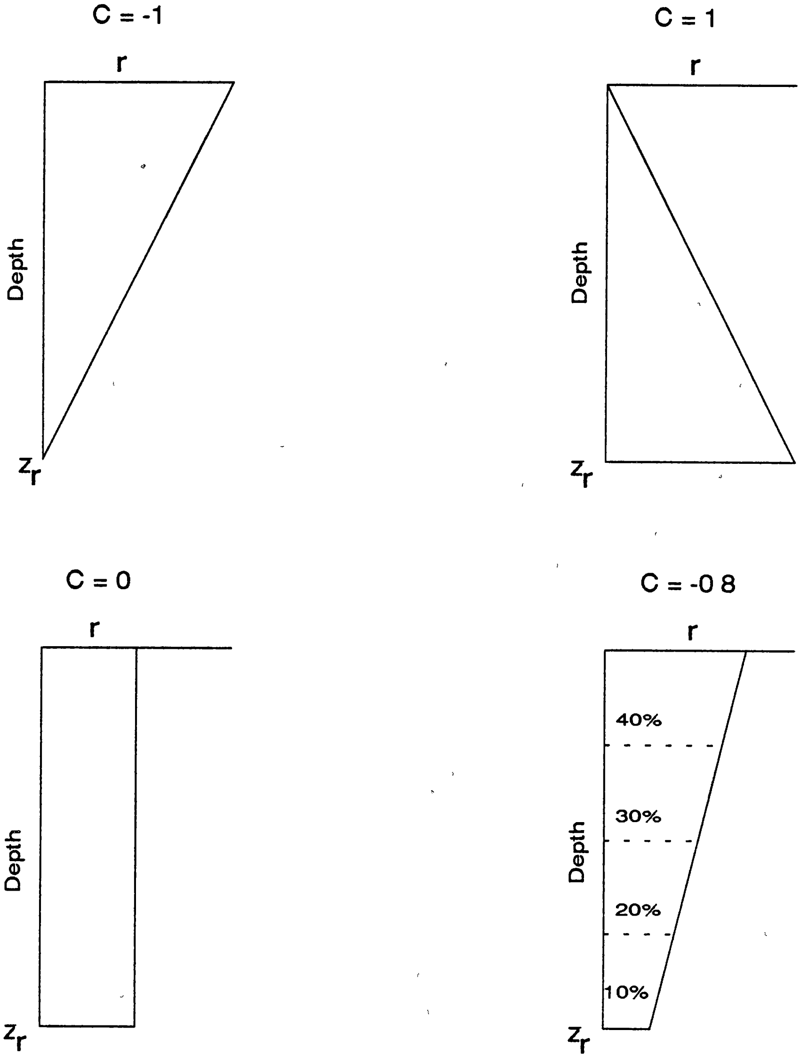


Figure 16. Sketches of the Root Activity Function (r) for the One-dimensional Linear Approach, Showing the Effect of the Parameter c on the Resulting Root Distribution.

3. Parameters Estimated from Field Data

Prior to 12 September 1989 (when a large rainfall event occurred), the total rainfall was 239 mm, and irrigation occurred four times with a total of 122 mm, 80 mm, and 32 mm for the full, intermediate, and minimum water treatments, respectively. Compared with the amount of water received (both irrigation and rainfall) by the full irrigation plots, there was 12% less under intermediate irrigation, and 25% less under minimum irrigation. From the statistical analysis in Chapter V, the significant difference exists between the full and minimum water treatments. The following calculations are conducted using the data from only the full and minimum water treatments. These treatments can be considered to represent well irrigated and limited irrigated conditions, respectively.

By linear and exponential regression analysis using a software package called SYSTAT (SYSTAT, Inc., 1985), the parameters for estimating root length density and the root activity function were obtained. The rooting depth was assumed to be 120 cm and the root activity and water uptake below 120 cm were assumed to be not significant, although it would be possible to model below that depth. Tables 13 and 14 show the estimated parameters and the standard errors. Table 15 gives the error sum of squares for the estimated root length densities. From the values listed in Table 15, the exponential regression seems to be the better approach for describing the distribution of root length density.

According to the one dimensional exponential regression for the root data of 26 July 1989 for the full water treatment, the coefficient β_1 is equal to 0.0273. By substituting this regression coefficient and a rooting depth of 120 cm into equation (94), we get $\alpha = 0.0284$. By integrating the calculated root activity function over four equal depth increments, the corresponding root water uptake pattern is that

TABLE 13

THE ESTIMATED PARAMETERS AND THE CORRESPONDING STANDARD ERRORS FOR THE ROOT DATA ON 26 JULY AND 17 AUGUST 1989

Date & Method	Treatment	Parameter		
		β_0	β_1	β_2
July 26				
Linear	Full & 1D	0.570	0.00469	
	STD Error	0.110	0.00159	
	Full & 2D	0.729	0.00532	0.00282
	STD Error	0.103	0.00132	0.00236
	Minimum & 1D	0.521	0.00362	
	STD Error	0.053	0.00077	
	Minimum & 2D	0.547	0.00362	0.00126
	STD Error	0.060	0.00077	0.00138
Exponential	Full & 1D	0.836	0.02730	
	STD Error	0.208	0.00999	
	Full & 2D	1.739	0.04117	0.05576
	STD Error	0.135	0.00335	0.00781
	Minimum & 1D	0.584	0.01236	
	STD Error	0.073	0.00281	
	Minimum & 2D	0.700	0.01317	0.00817
	STD Error	0.098	0.00274	0.00445
August 17				
Linear	Full & 1D	0.808	0.00640	
	STD Error	0.104	0.00137	
	Full & 2D	0.865	0.00640	0.00280
	STD Error	0.115	0.00137	0.00245
	Minimum & 1D	1.039	0.00650	
	STD Error	0.135	0.00178	
	Minimum & 2D	1.152	0.00650	0.00556
	STD Error	0.142	0.00170	0.00304
Exponential	Full & 1D	1.211	0.02156	
	STD Error	0.218	0.00499	
	Full & 2D	1.789	0.02522	0.01638
	STD Error	0.298	0.00458	0.00511
	Minimum & 1D	1.299	0.01308	
	STD Error	0.222	0.00357	
	Minimum & 2D	1.639	0.01387	0.01089
	STD Error	0.280	0.00334	0.00474

TABLE 14

THE ESTIMATED PARAMETERS AND THE CORRESPONDING STANDARD ERRORS FOR THE ROOT DATA ON 7 SEPTEMBER AND 28 SEPTEMBER 1989

Date & Method	Treatment	Parameter		
		β_0	β_1	β_2
September 7				
Linear	Full & 1D	1.315	0.00971	
	STD Error	0.147	0.00195	
	Full & 2D	1.384	0.00971	0.00340
	STD Error	0.164	0.00195	0.00350
	Minimum & 1D	1.373	0.00992	
	STD Error	0.156	0.00206	
	Minimum & 2D	1.419	0.00992	0.00225
	STD Error	0.176	0.00209	0.00375
Exponential	Full & 1D	1.848	0.01851	
	STD Error	0.277	0.00379	
	Full & 2D	2.371	0.02004	0.01090
	STD Error	0.358	0.00352	0.00430
	Minimum & 1D	1.827	0.01672	
	STD Error	0.277	0.00357	
	Minimum & 2D	2.357	0.01864	0.01026
	STD Error	0.392	0.00357	0.00471
September 28				
Linear	Full & 1D	1.117	0.00937	
	STD Error	0.147	0.00188	
	Full & 2D	1.117	0.00937	0.00000
	STD Error	0.147	0.00188	0.00000
	Minimum & 1D	1.201	0.01068	
	STD Error	0.135	0.00195	
	Minimum & 2D	1.316	0.01068	0.00580
	STD Error	0.146	0.00187	0.00335
Exponential	Full & 1D	1.849	0.02849	
	STD Error	0.198	0.00466	
	Full & 2D	1.869	0.02862	0.00044
	STD Error	0.264	0.00489	0.00351
	Minimum & 1D	1.747	0.02572	
	STD Error	0.214	0.00471	
	Minimum & 2D	2.320	0.02716	0.01440
	STD Error	0.231	0.00357	0.00361

TABLE 15

THE ERROR SUM OF SQUARES FOR THE ESTIMATED ROOT LENGTH DENSITIES

Date	Treatment	Error Sum of Squares	
		Linear	Exponential
July 26	Full & 1D	1.568	1.392
	Full & 2D	1.030	0.160
	Minimum & 1D	0.368	0.356
	Minimum & 2D	0.354	0.302
August 17	Full & 1D	1.179	0.936
	Full & 2D	1.109	0.568
	Minimum & 1D	1.982	1.769
	Minimum & 2D	1.710	1.369
September 7	Full & 1D	2.364	1.835
	Full & 2D	2.262	1.348
	Minimum & 1D	2.642	2.215
	Minimum & 2D	2.598	1.752
September 28	Full & 1D	2.107	1.049
	Full & 2D	2.107	1.048
	Minimum & 1D	2.370	1.515
	Minimum & 2D	2.074	0.775

58% of the uptake comes from the first quarter of the rooting depth, 26% from the second, 11% from the third and 5% from the fourth.

By regressing the data of 26 July 1989 under the minimum irrigation condition, we get $\beta_1 = 0.0124$ and $\alpha = 0.0160$. The corresponding water uptake pattern is that 40% of the uptake comes from the first quarter of the rooting depth, 28% from the second, 19% from the third and 13% from the fourth. This means that more roots are distributed at the deeper layers when soil moisture is limiting.

Table 16 shows the percentages obtained by using a root zone depth of 120 cm and integrating the root activity functions for both linear and exponential approaches over four equal depth increments. As a check on the ability of the functions to reproduce the observed root data, the percentages calculated directly from field data (incorporating all these sampling locations) are also included in Table 16. Although the model percentages deviate somewhat from the observed percentages, the trends in spatial root distributions are clearly preserved. Overall the exponential model seems to better represent the observed data.

Overall Root Growth

Figure 17 shows the average root length densities over the eight depths and three lateral locations through the 1989 growing season. It seems that the growth rate under the minimum water treatment is slightly higher than that under the full water treatment. This is consistent with what was reported in Chapter V. At 41 days after planting, there was only a slight difference in root growth between the full and minimum water treatments. This may be due to the fact that significant rainfall (a total of 106 mm) occurred during this period along with only one irrigation event. Between 41 and 62 days after planting, root growth was especially rapid under the minimum water treatment. For both treatments, there was a decline in average RLD between 83 and 104 days after planting, perhaps indicating

TABLE 16

RELATIVE ROOT DISTRIBUTIONS OVER FOUR EQUAL DEPTH INCREMENTS FOR OBSERVED DATA AND THE ONE-DIMENSIONAL EMPIRICAL FUNCTIONS

Date & Treatment	Method	Percentage Root Distributions			
		0-30	30-60	60-90	90-120
July 26					
Full	Observed	54	21	14	11
	Linear	52	33	15	0
	Exponential	58	26	11	5
Minimum	Observed	39	29	19	13
	Linear	52	34	14	0
	Exponential	40	28	19	13
August 17					
Full	Observed	50	24	16	10
	Linear	42	31	19	8
	Exponential	52	27	14	7
Minimum	Observed	43	18	24	15
	Linear	36	29	21	14
	Exponential	41	28	19	12
September 7					
Full	Observed	47	21	21	11
	Linear	37	29	21	13
	Exponential	48	27	16	9
Minimum	Observed	46	22	19	13
	Linear	36	29	21	14
	Exponential	46	28	17	10
September 28					
Full	Observed	55	19	15	11
	Linear	39	30	20	11
	Exponential	59	25	11	5
Minimum	Observed	56	20	14	10
	Linear	40	30	20	10
	Exponential	56	26	12	16

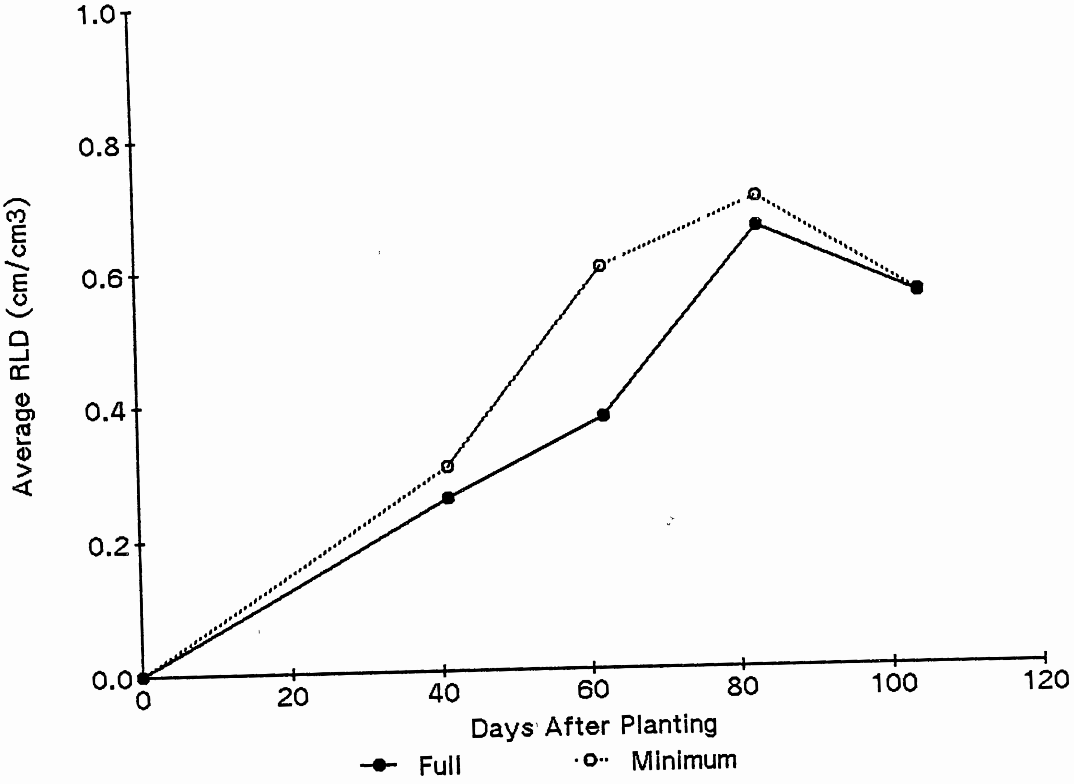


Figure 17. Root Growth over Time in 1989

root senescence. Table 17 shows the data used in Figure 17.

VS2D Simulations

Bare Soil

The mathematical model was first used to simulate water movement in a bare-soil (no root water uptake). Neutron moisture data were used to compare to the simulation results. The starting time for the model simulation was 17 August 1989. The ending time was 31 August 1989, two days before 30 mm of rainfall. This two-week period represented a drying cycle uninterrupted by rainfall. The bare-soil neutron tube was shaded with a plexiglass cover to prevent direct sunlight on the soil surface and reduce evaporation. The evaporation flux computed by VS2D varied between 1.1 and 1.6 mm/d. For the lower boundary condition, a constant water content of 0.212 cm^3/cm^3, which was the average of the observed field data at a depth of 120 cm, was assumed throughout the simulation period. Figure 18 shows that the simulated water contents agreed well with the measured water contents.

Peanut Root Zone

VS2D was then used to model water movement in the root zone of a peanut crop. Using the functional relationships for root length density, the root activity function can be obtained mathematically. The sink term in Richards flow equation can then be quantified by using the root activity function and the crop transpiration. The crop transpiration is determined by the type of crop, stage of growth, and climatic parameters, and can be estimated by subtracting soil evaporation from crop ET. The estimates of crop ET by Elliott et al. (1988) were previously tested using soil water balance simulations as shown in Figure 7. The

TABLE 17

AVERAGE ROOT LENGTH DENSITIES OVER EIGHT DEPTHS AND THREE LATERAL LOCATIONS

Days After Planting	Root Length Density (cm/cm^3)	
	Full Treatment	Minimum Treatment
0	0	0
41	0.257	0.305
62	0.376	0.600
83	0.659	0.703
104	0.556	0.558

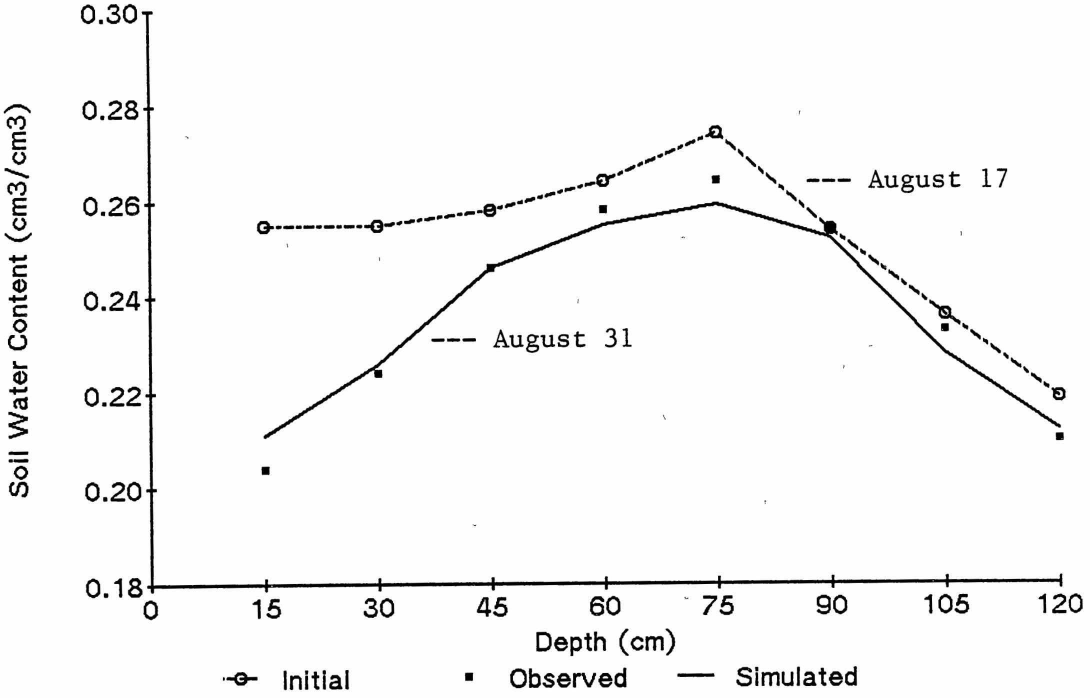


Figure 18. Observed and Simulated Soil Water Contents over a Period of 14 Days for Bare Soil Conditions

difficulty in estimating runoff was noted in Chapter V, and the same infiltrated amounts used in the water balance simulations were also used in the VS2D simulations. The simulations discussed in this section are based on the two dimensional root activity functions for the data of the 1989 peanut growing season.

The soil zone simulated was 2 m deep by 0.46 m wide (half the distance between crop rows). The upper boundary conditions varied in time according to the evaporation demand and the soil water availability at the soil surface. The rooting depth was assumed to be 1.2 m for all simulation periods. For the lower boundary condition, the water content was assumed to be constant and equal to 0.212 cm^3/cm^3 which is about the field capacity at depth 1.2 m. Because measurements of soil parameters and water contents at depths below 1.2 m were lacking, the soil texture at depths of 1.2 to 2 m was assumed to be the same as that at a depth of 1.2 m.

The starting time for the simulations was 20 July 1989, about one week before the first root data were taken. The ending time was 2 October 1989, four days after the last root core sampling data were taken. Because of a very large rainfall event on September 12, and the difficulty in estimating the infiltrated amount, the simulation period was interrupted and restarted on September 18.

The neutron probe access tubes were located in the crop row. The radius of measurement changes with the soil moisture conditions. In VS2D, the output grid spacing in the lateral direction is 4.5 cm. For comparison to the field neutron data, three grid points (0, 4.5, and 9 cm) were averaged when the soil moisture was greater than or equal to 0.2 cm^3/cm^3, and four grid points (0, 4.5, 9, 13.5 cm) were averaged when the soil moisture was less than 0.2 cm^3/cm^3. The assumption of three or four grid points has a small effect on the computed average soil moisture content.

Figures 19 through 22 show, for selected times, the measured data and simulated results under a full water treatment. Both linear and exponential

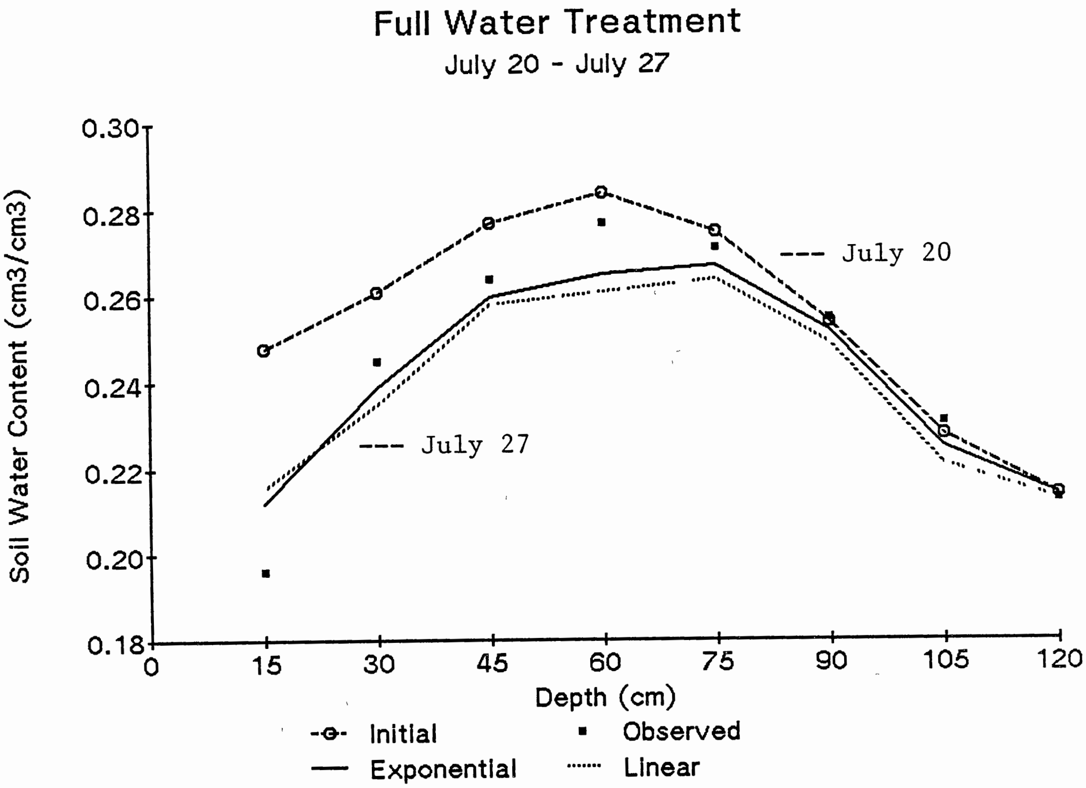
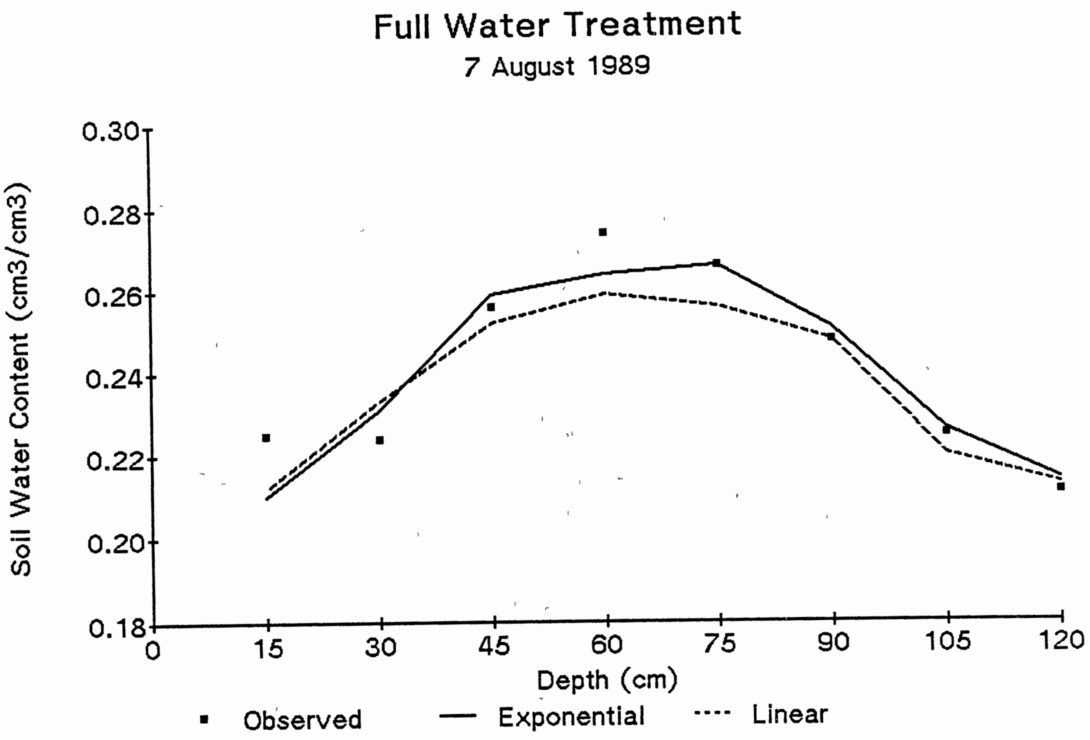


Figure 19. Observed and Simulated Soil Water Contents under a Full Water Treatment on 27 July 1989. The Starting Time is 20 July 1989.



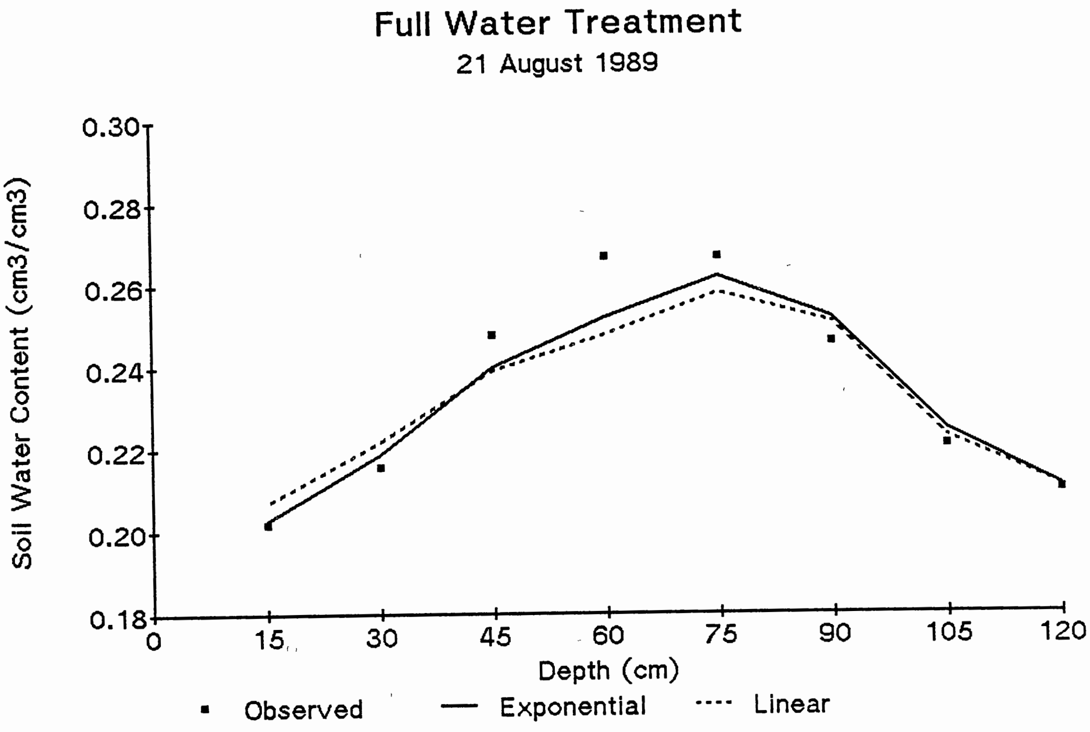


Figure 20. Observed and Simulated Soil Water Contents under a Full Water Treatment on 7 August 1989 and 21 August 1989.

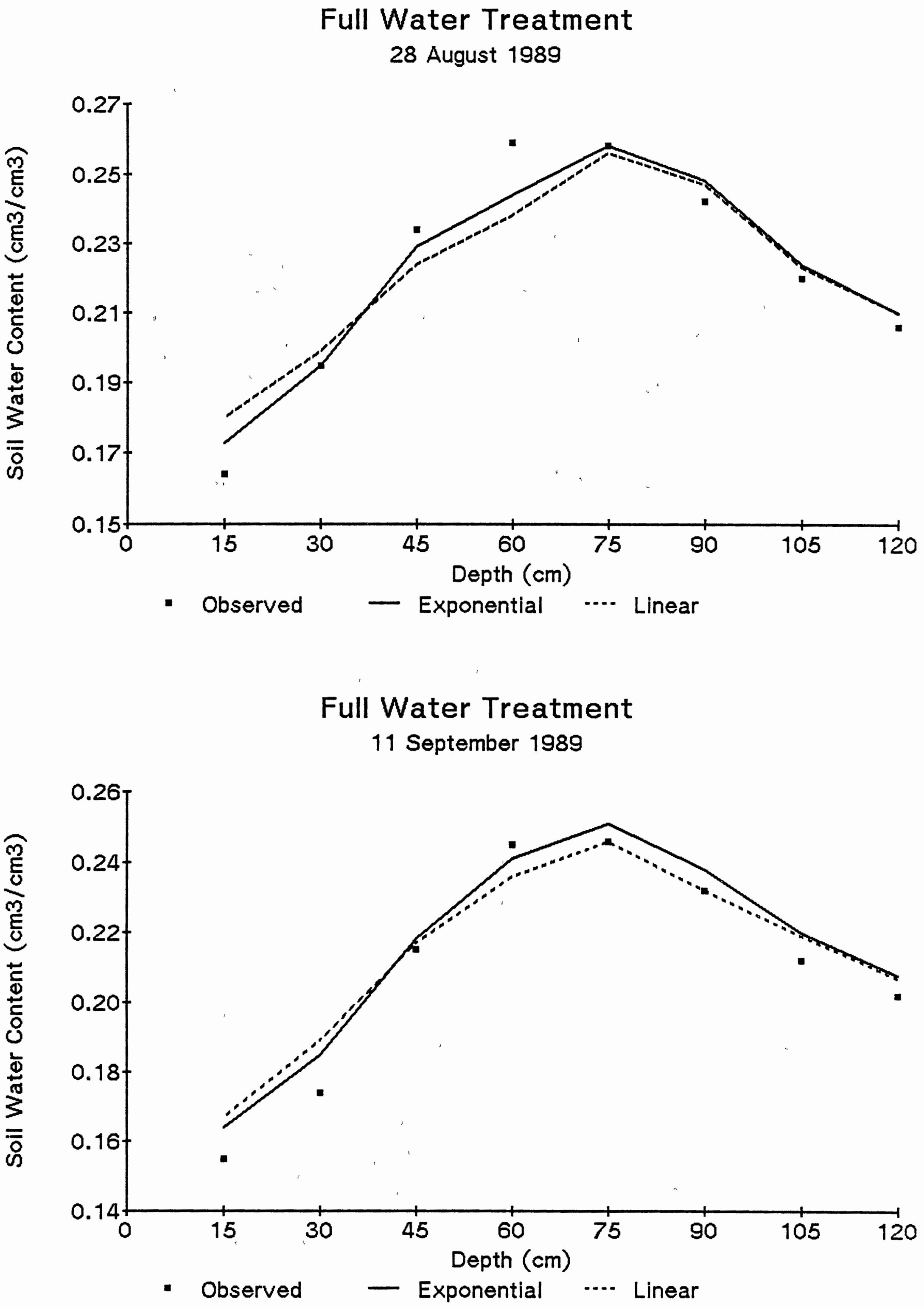
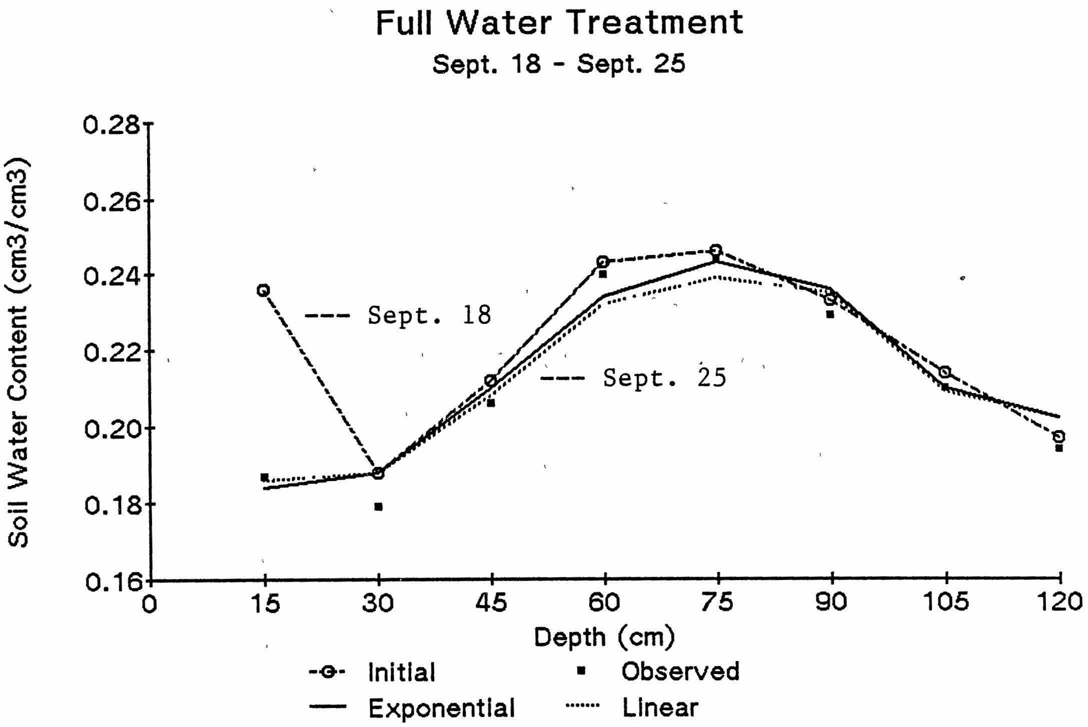
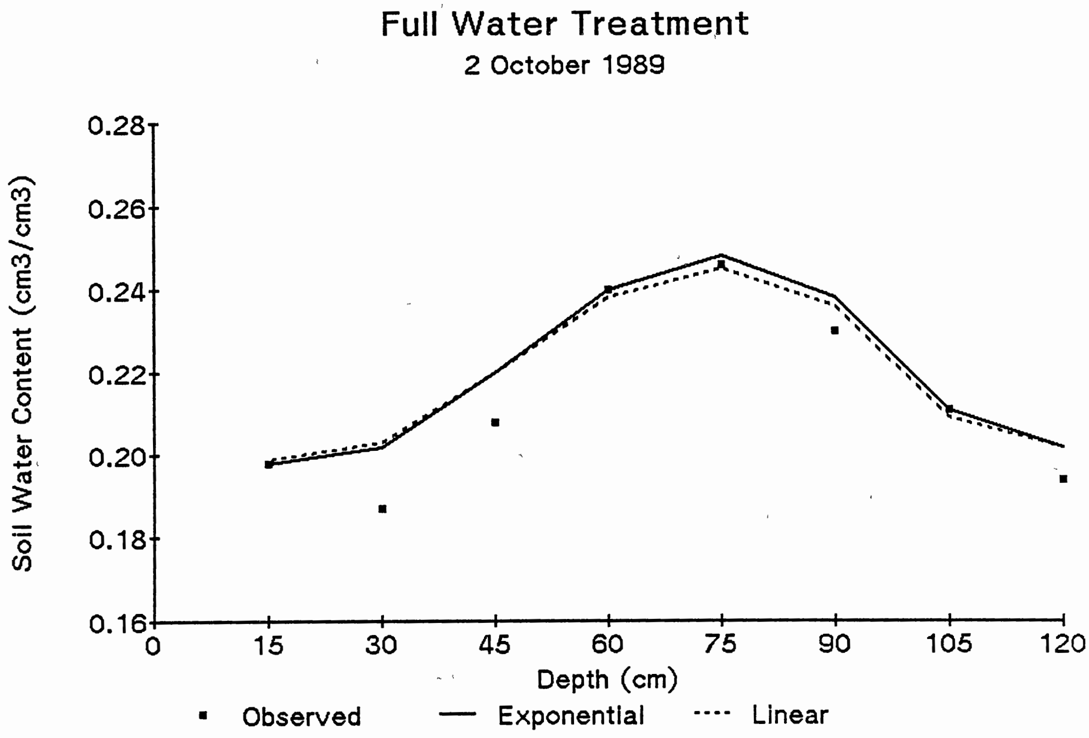


Figure 21. Observed and Simulated Soil Water Contents under a Full Water Treatment on 28 August 1989 and 11 September 1989.



Full Water Treatment

Sept. 18 - Sept. 25



Full Water Treatment

2 October 1989

Figure 22. Observed and Simulated Soil Water Contents under a Full Water Treatment on 25 September 1989 and 2 October 1989. The Starting Time is September 18, One Week after a Large Rainfall Occurred.

approaches were used in modeling root distributions. Figures 23 through 26 show the measured data and simulated results under the minimum water treatment.

Figures 27 through 34 provide an alternative way of looking at the dynamic simulation results. These are plots of soil water content throughout the simulation period for a particular treatment and depth.

Figures 19 through 26 show that the model generally did a good job of simulating the distribution of soil water with depth. In Figures 19 through 22, for the full water treatment, the exponential approach to root distribution seemed to fit the field data slightly better than did the linear approach. According to the root data plotted in Chapter V, the root length density in the top 15 cm of soil was substantially higher than at greater depths, especially under the full water treatment. The exponential function can better match the high root densities observed near the soil surface.

Figures 23 through 26 indicate that, for the minimum water treatment, differences in simulation results for the linear and exponential approaches are insignificant. According to the root data plotted in Chapter V, the root length densities were greater in the minimum water treatment and more roots grew at deeper layers. In this situation, both functional approaches were able to estimate root distributions well, leading to quite similar simulations of water uptake and movement.

Figures 27 through 34 show that the simulation results fit with the field data at most of the depths except at a depth of 60 cm under the full water treatment and at a depth of 90 cm under the minimum water treatment. Inaccurate characterization of soil parameters would be one possible explanation for these deviations.

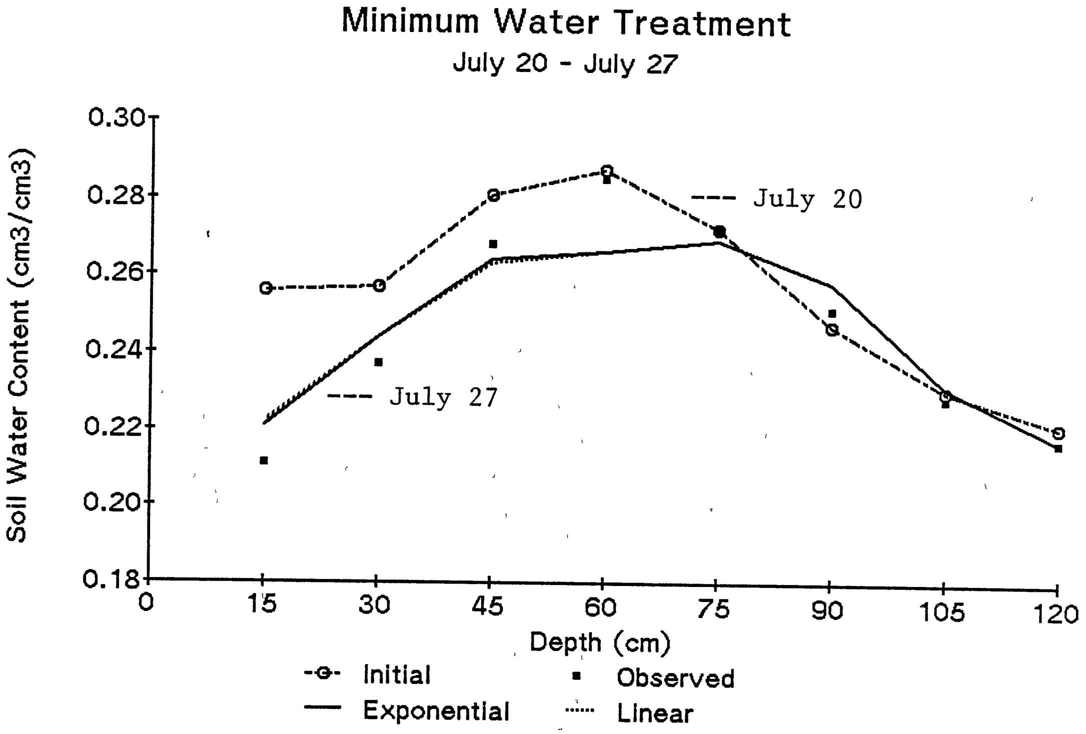
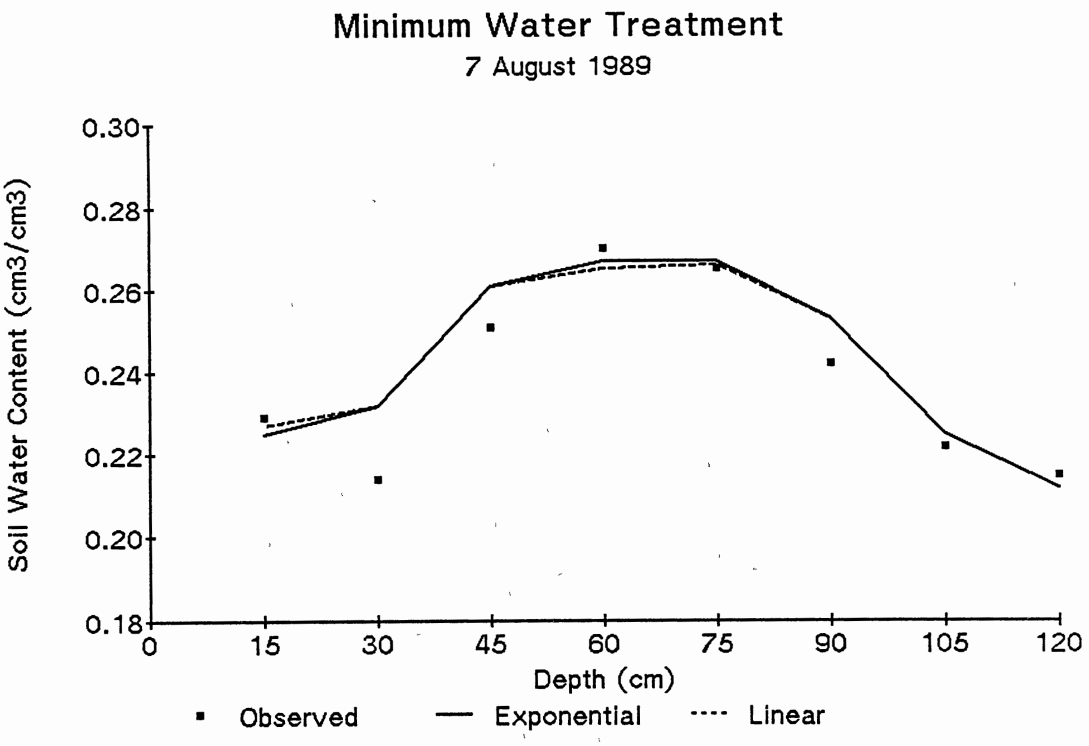


Figure 23. Observed and Simulated Soil Water Contents under a Minimum Water Treatment on 27 July 1989. The Starting Time is 20 July 1989.



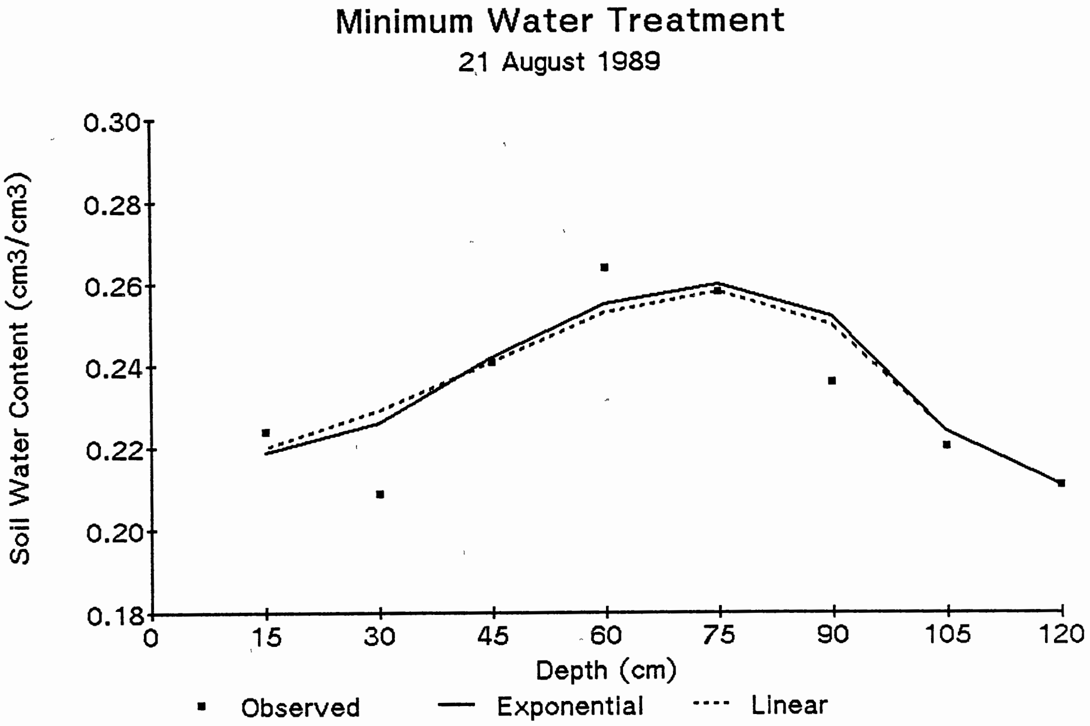
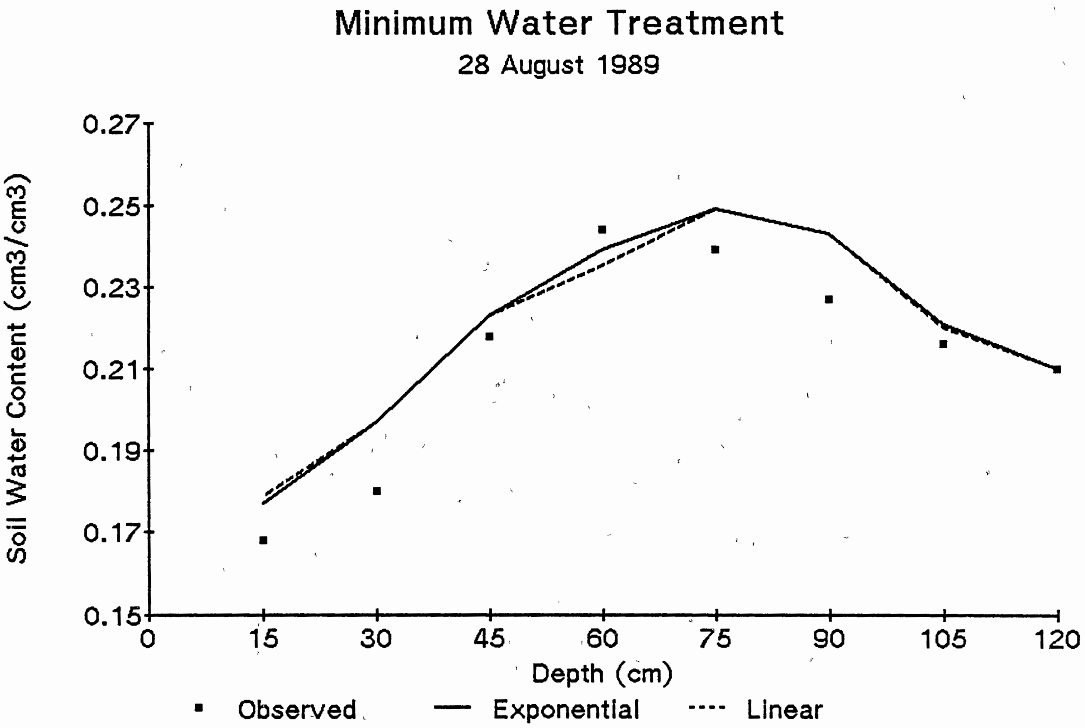


Figure 24. Observed and Simulated Soil Water Contents under a Minimum Water Treatment on 7 August 1989 and 21 August 1989.



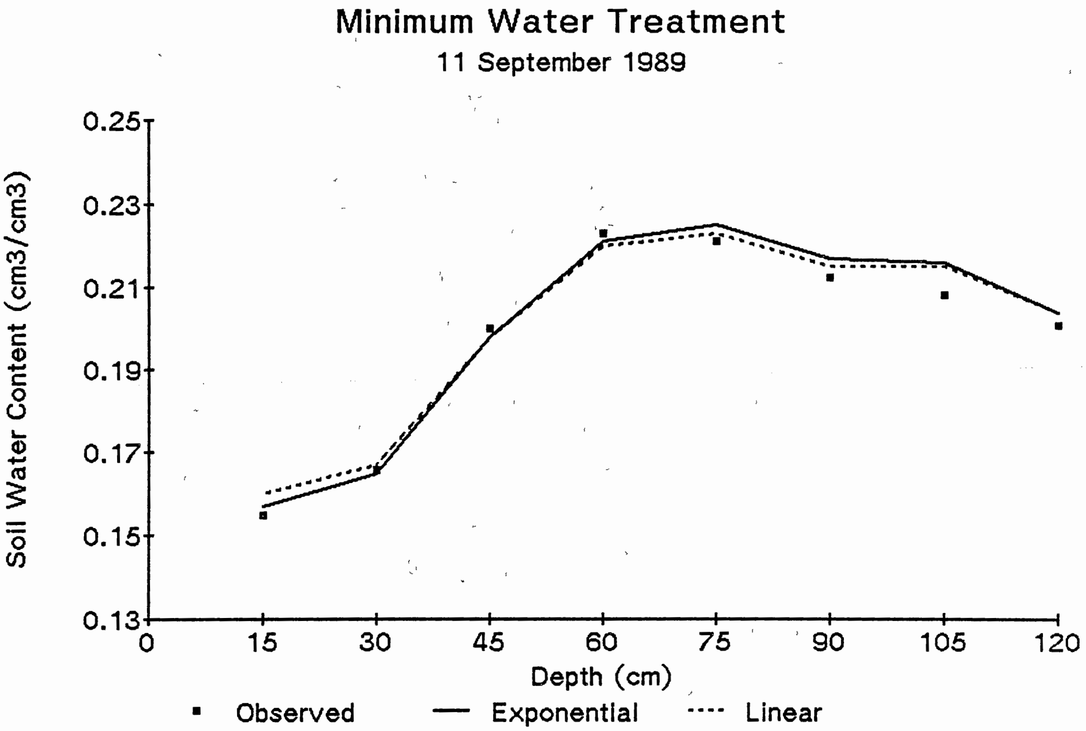
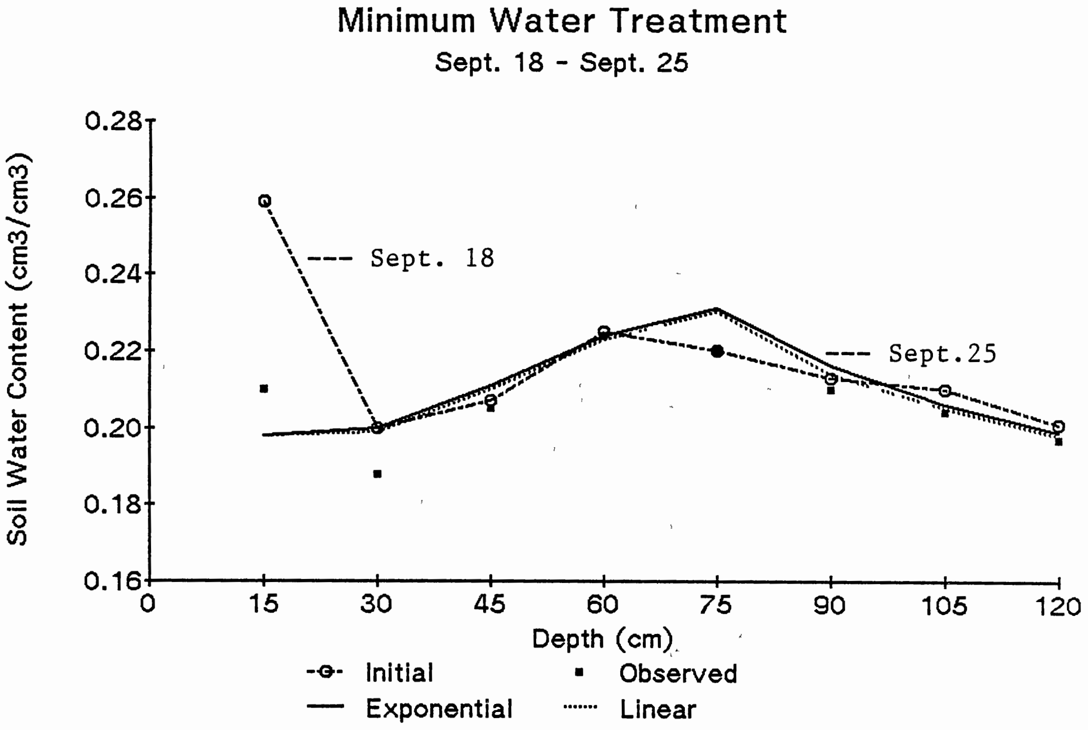


Figure 25. Observed and Simulated Soil Water Contents under a Minimum Water Treatment on 28 August 1989 and 11 September 1989.



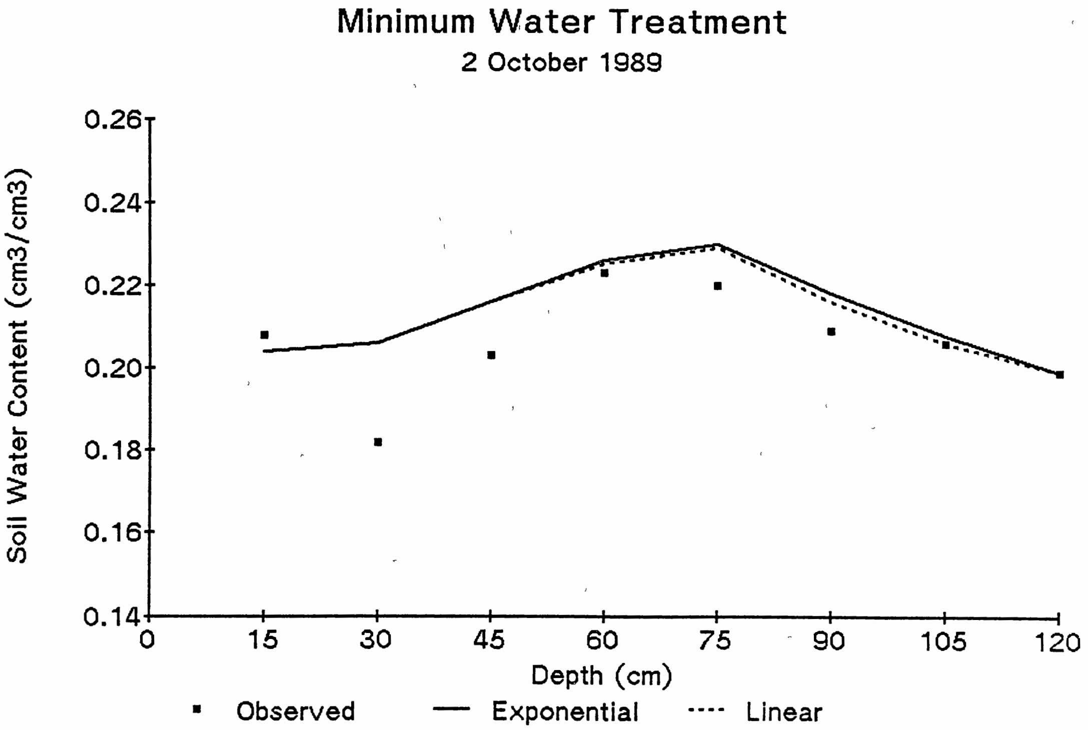
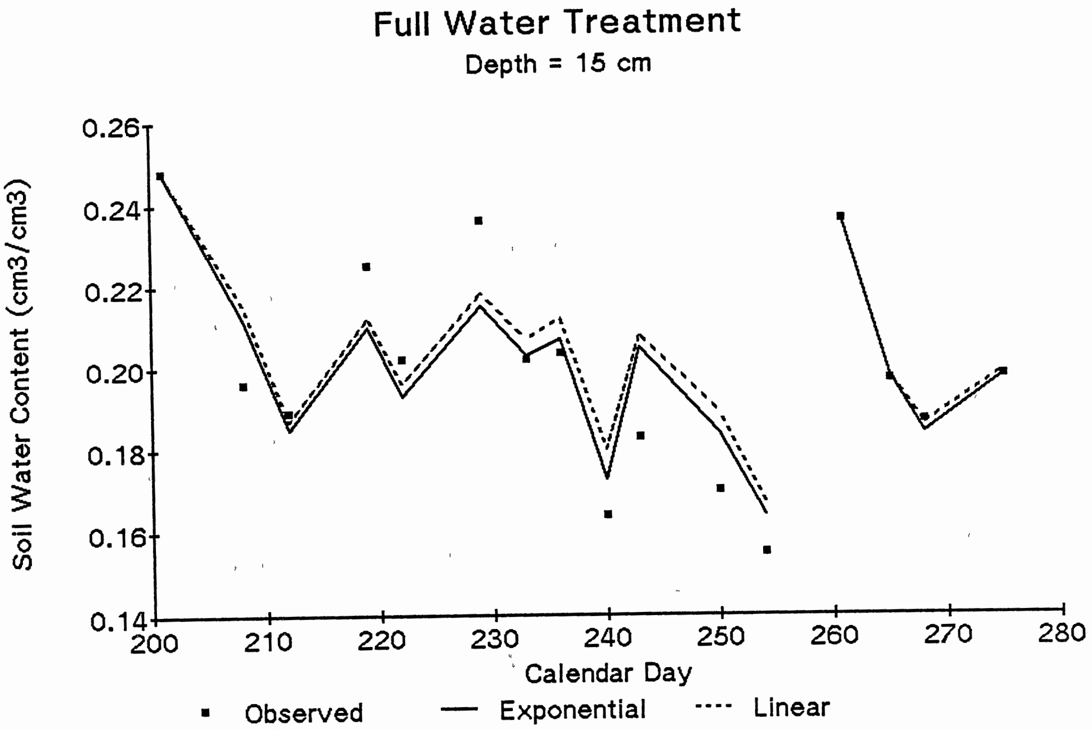


Figure 26. Observed and Simulated Soil Water Contents under a Minimum Water Treatment on 25 September 1989 and 2 October 1989. The Starting Time is September 18, One Week after a Large Rainfall Occurred.



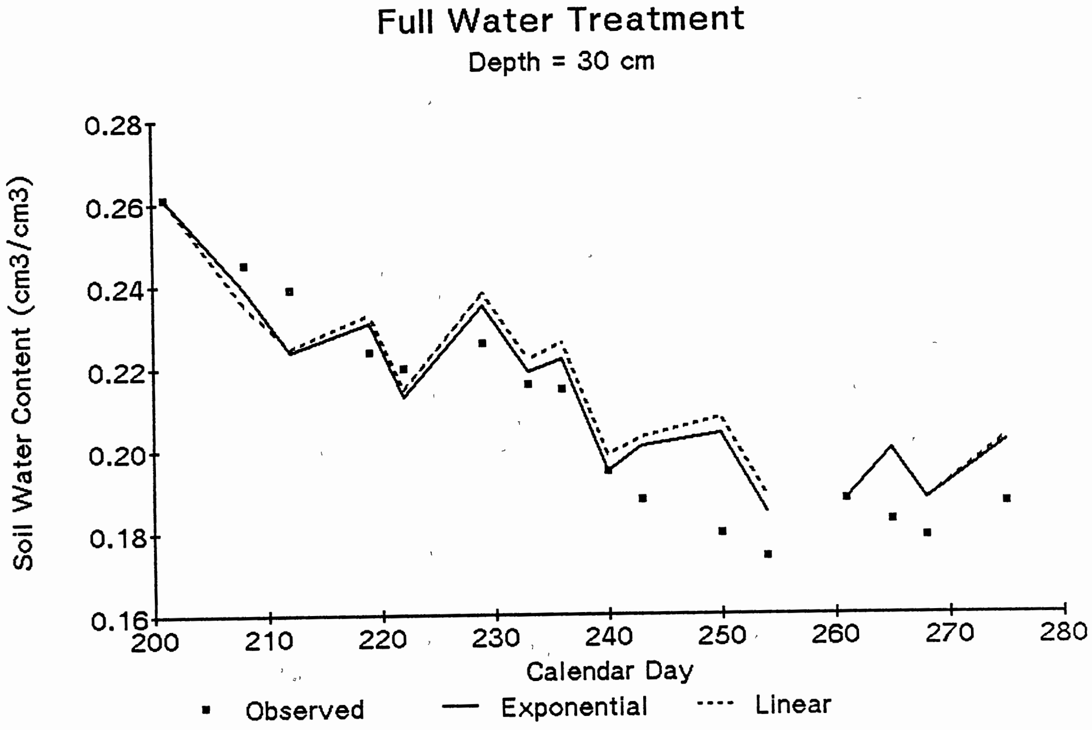


Figure 27. Observed and Simulated Soil Water Contents at Depths of 15 cm and 30 cm under a Full Water Treatment during 1989 Peanut Growing Season.

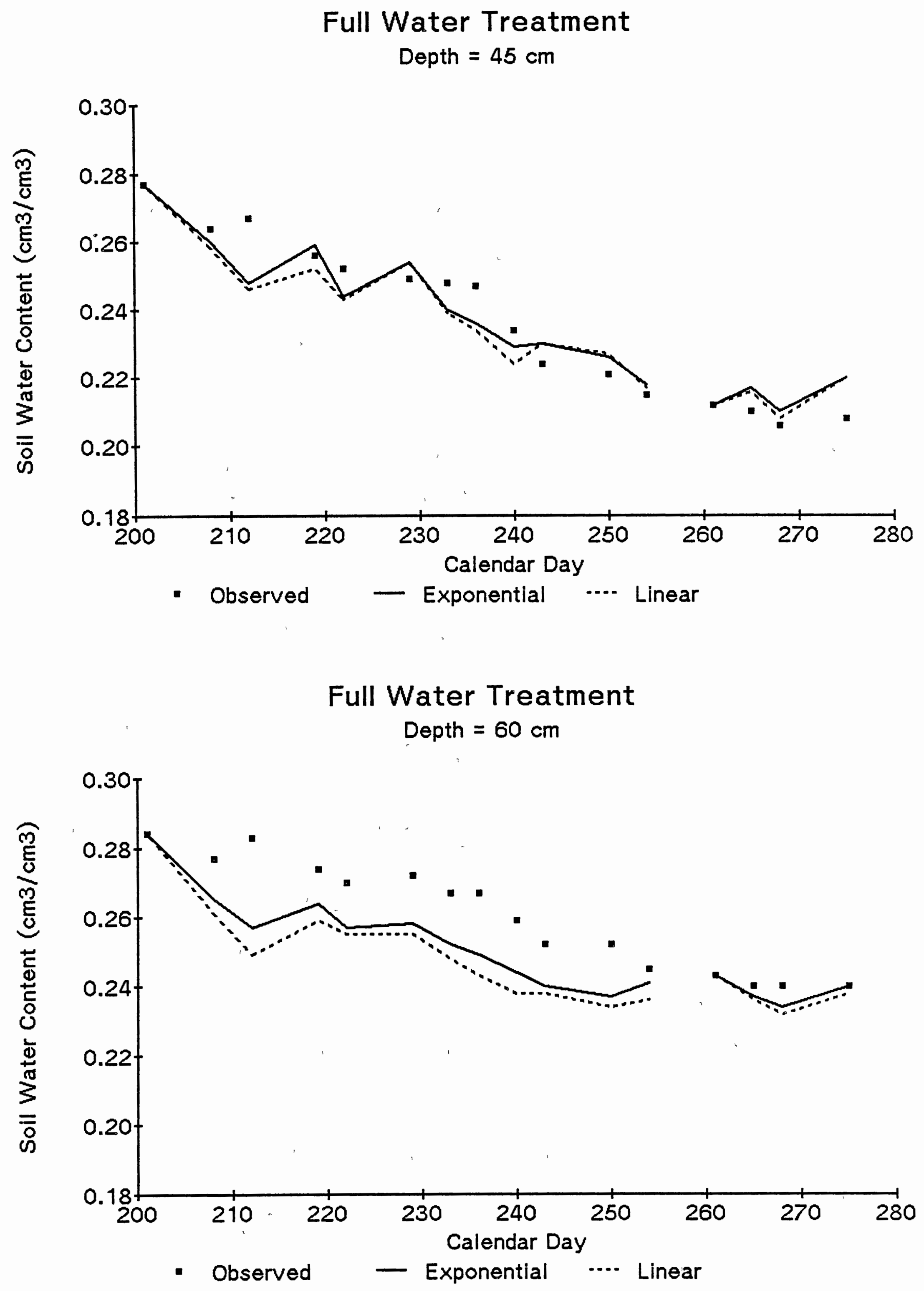
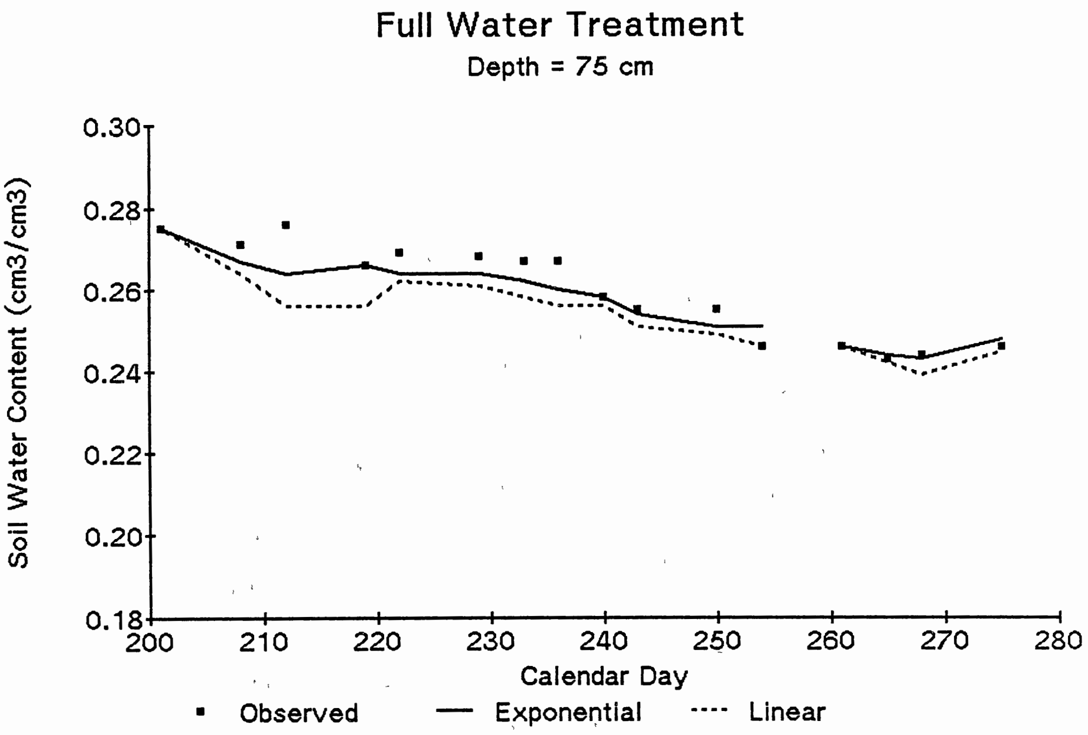


Figure 28. Observed and Simulated Soil Water Contents at Depths of 45 cm and 60 cm under a Full Water Treatment during 1989 Peanut Growing Season.



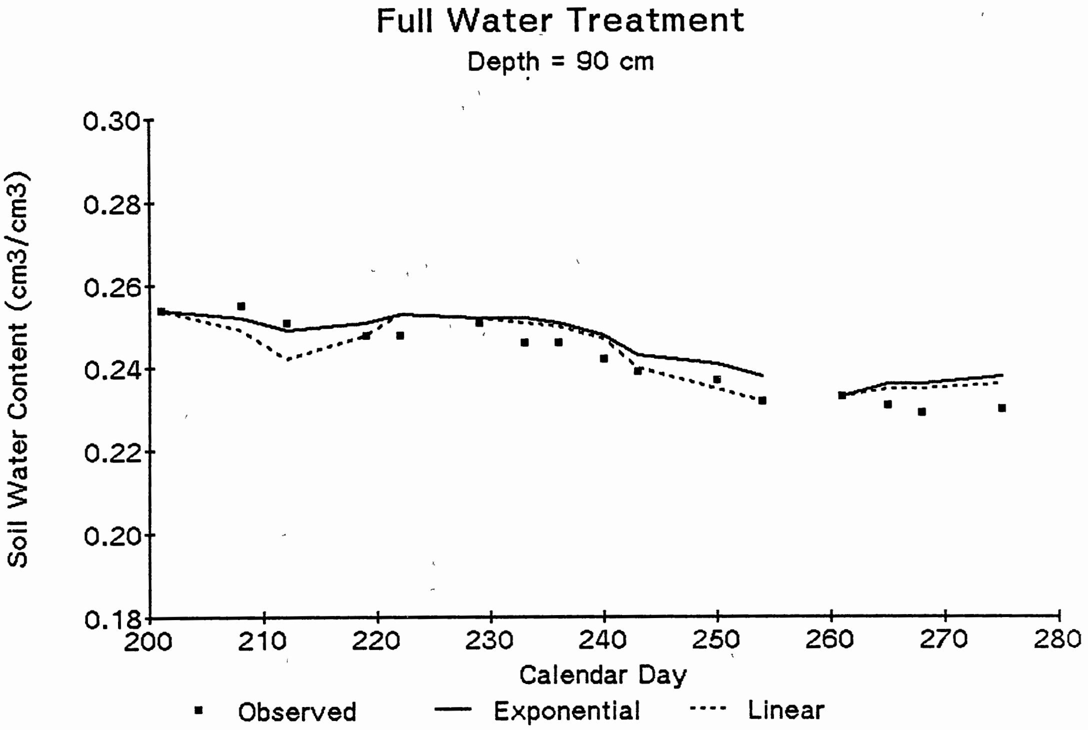
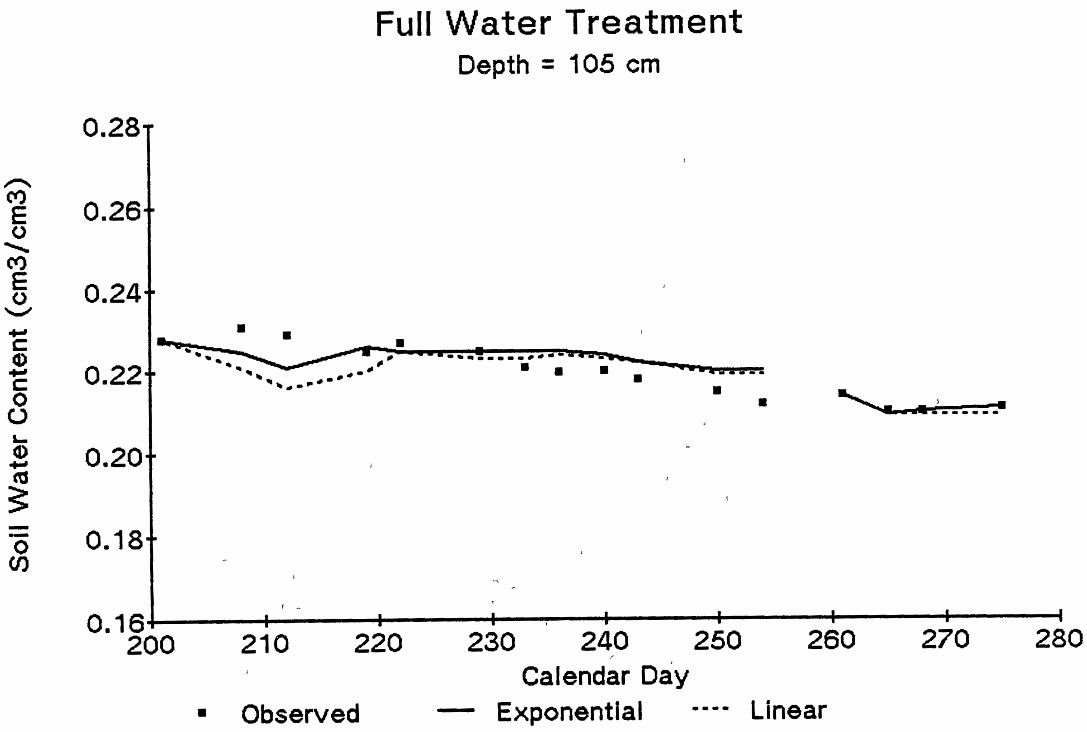


Figure 29. Observed and Simulated Soil Water Contents at Depths of 75 cm and 90 cm under a Full Water Treatment during 1989 Peanut Growing Season.



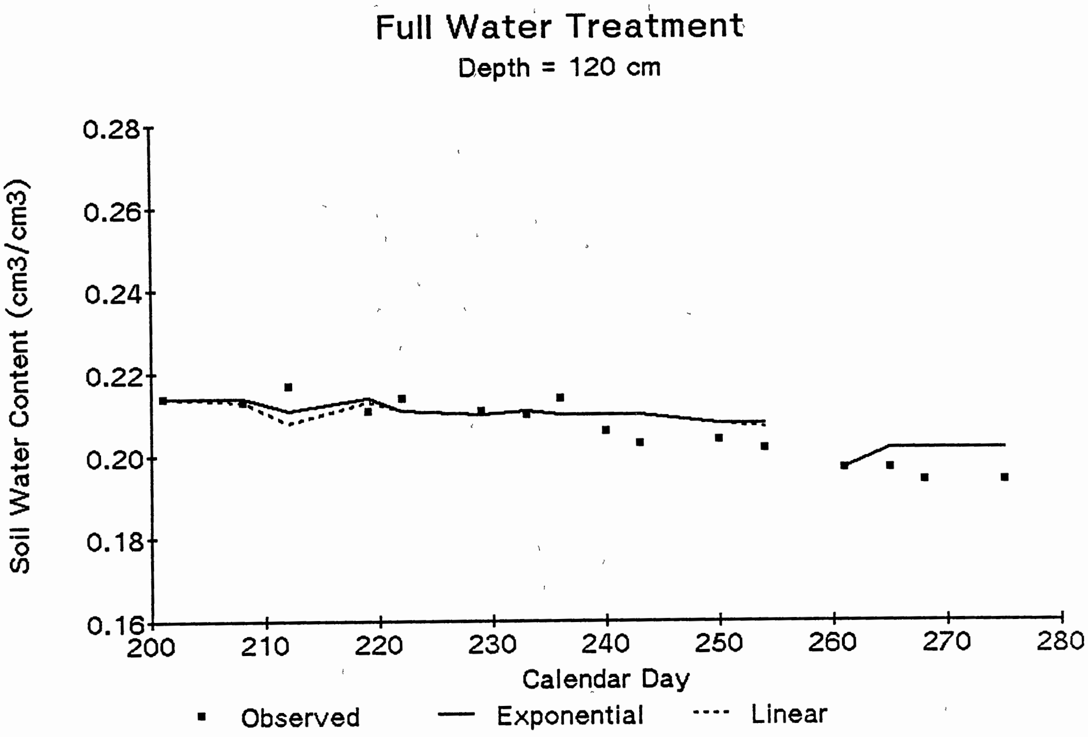
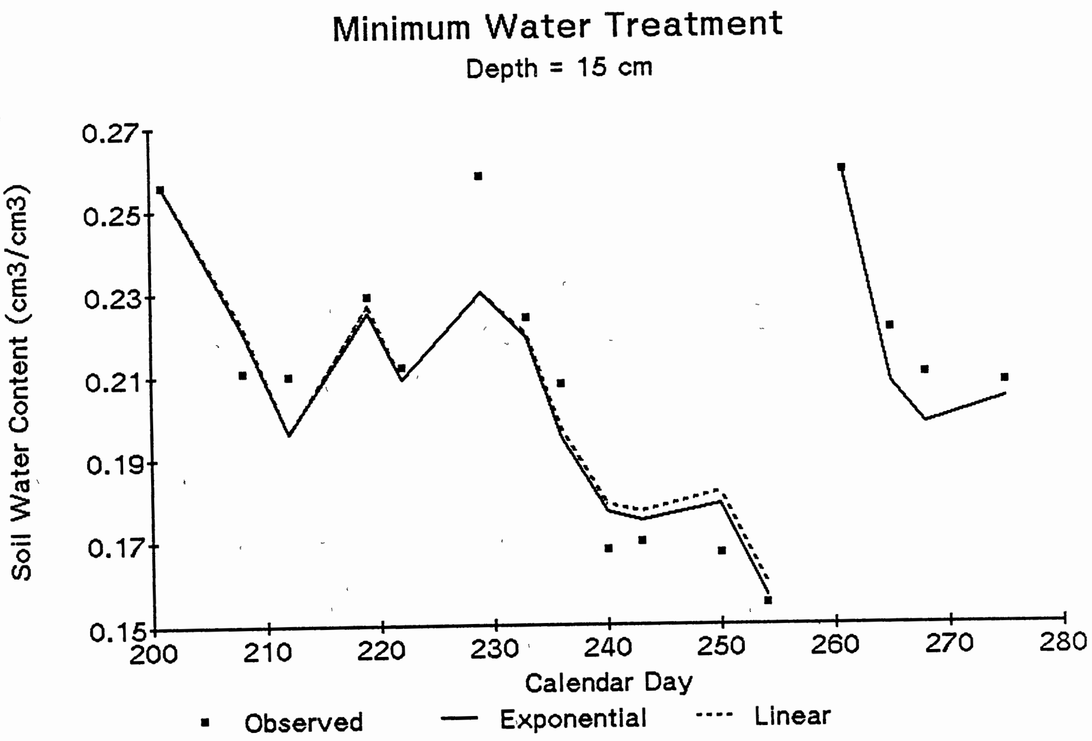


Figure 30. Observed and Simulated Soil Water Contents at Depths of 105 cm and 120 cm under a Full Water Treatment during 1989 Peanut Growing Season.



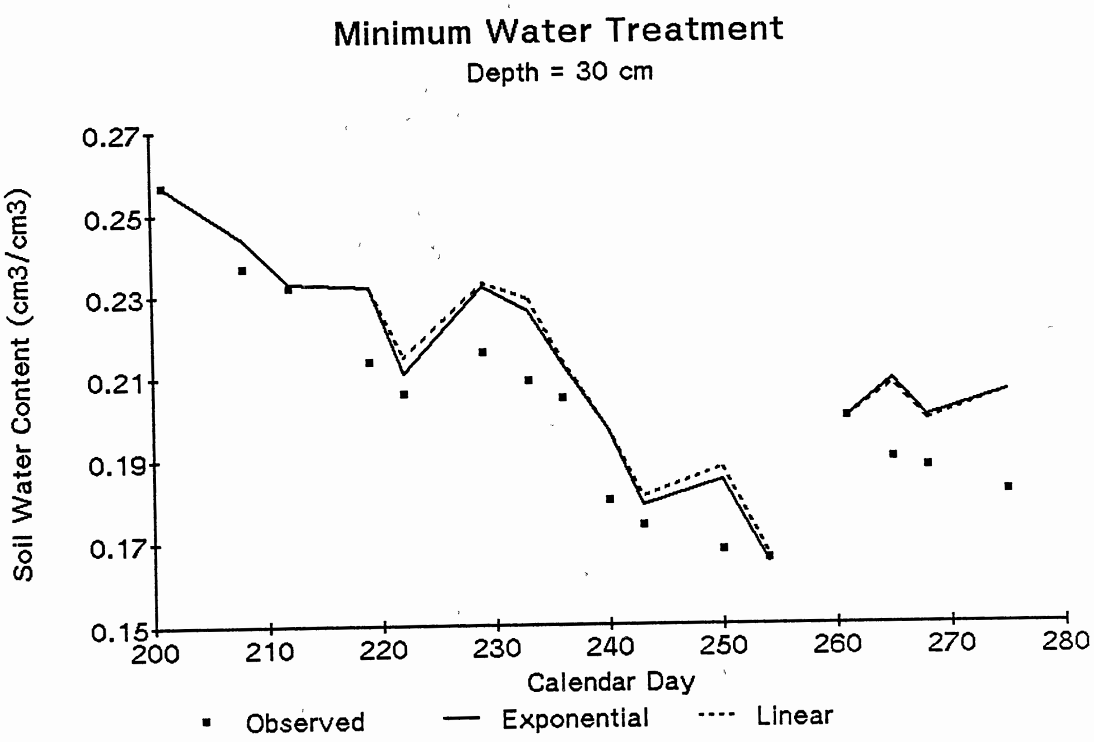


Figure 31. Observed and Simulated Soil Water Contents at Depths of 15 cm and 30 cm under a Minimum Water Treatment during 1989 Peanut Growing Season.

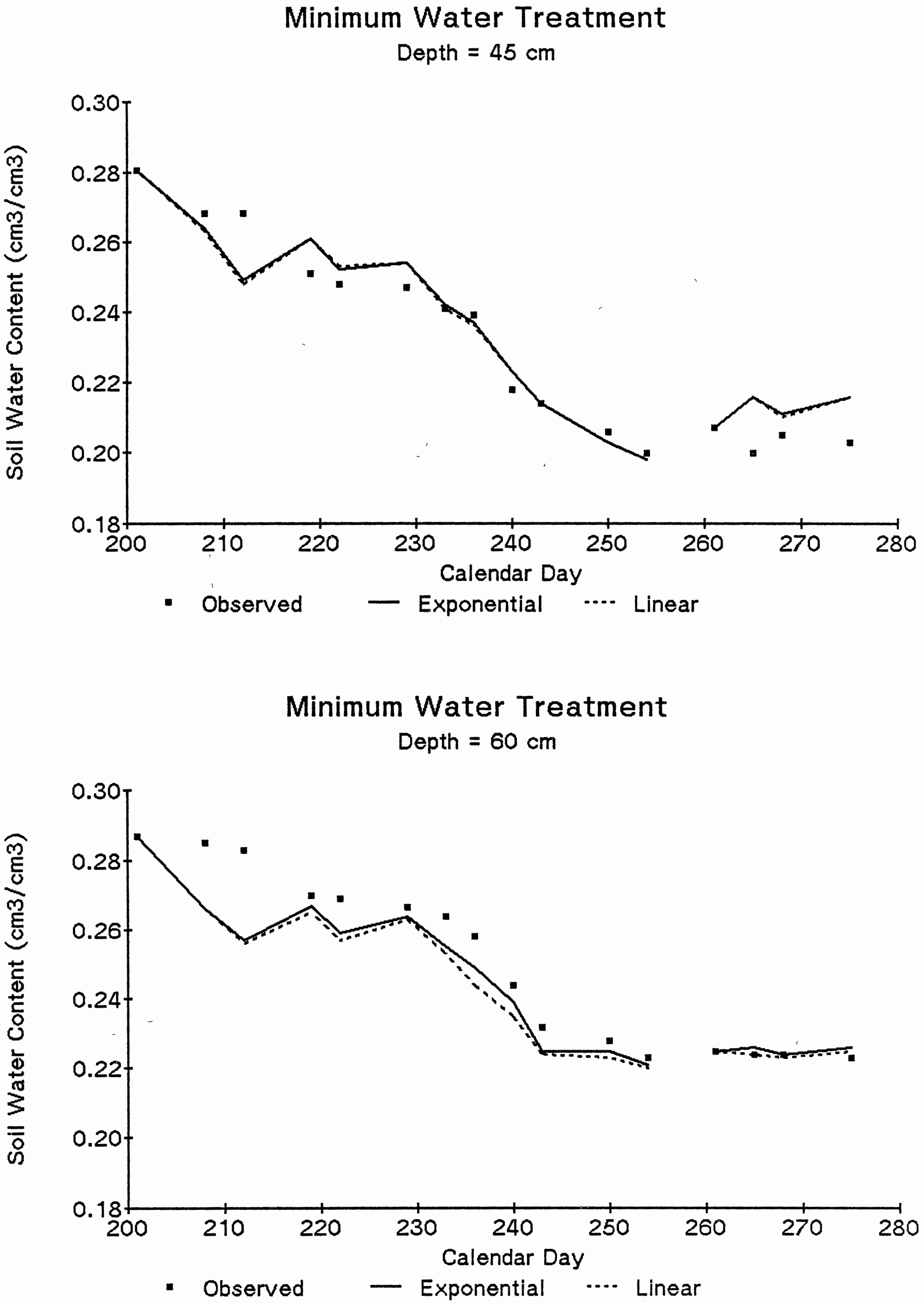
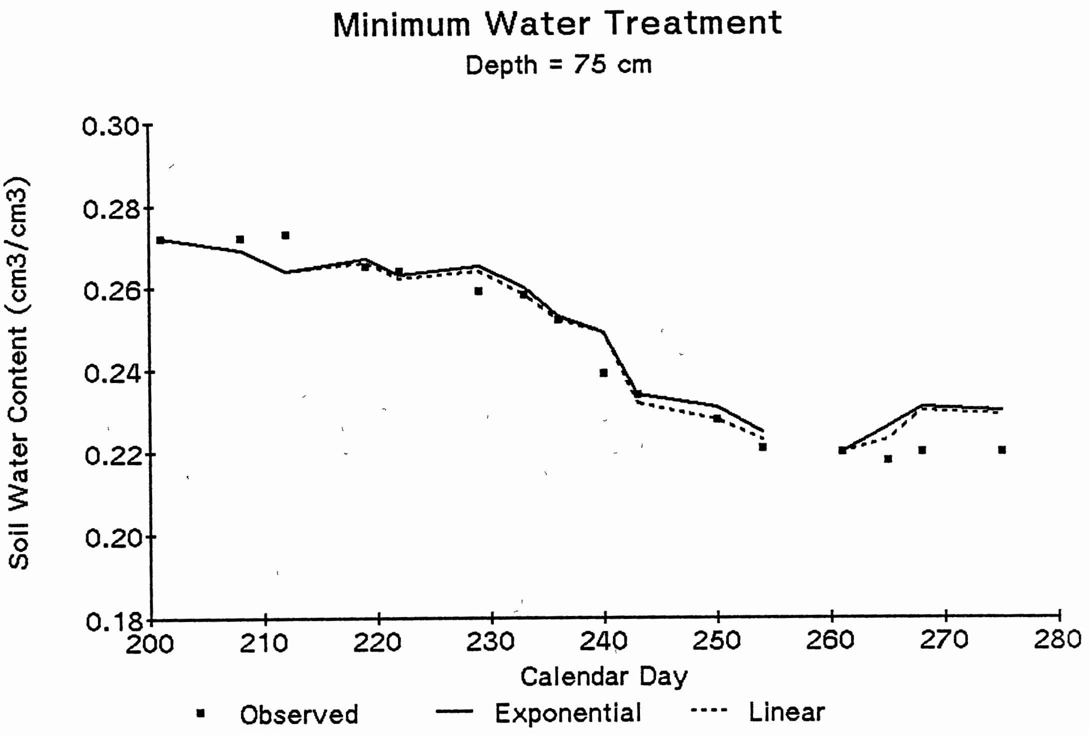


Figure 32. Observed and Simulated Soil Water Contents at Depths of 45 cm and 60 under a Minimum Water Treatment during 1989 Peanut Growing Season.



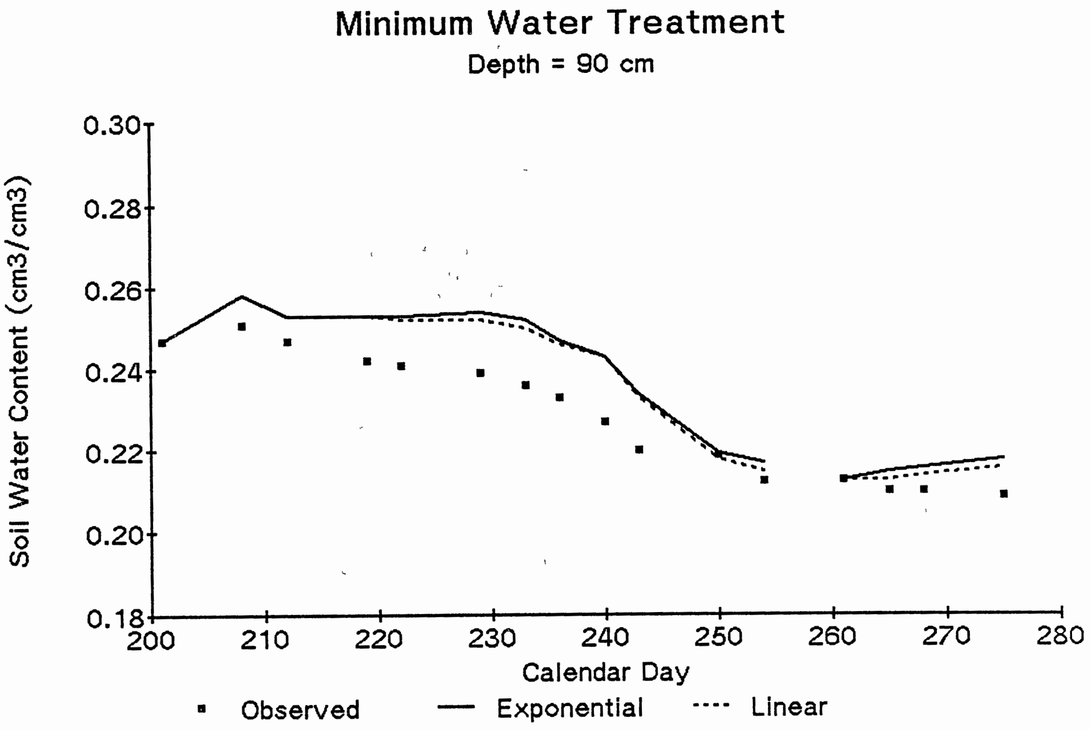
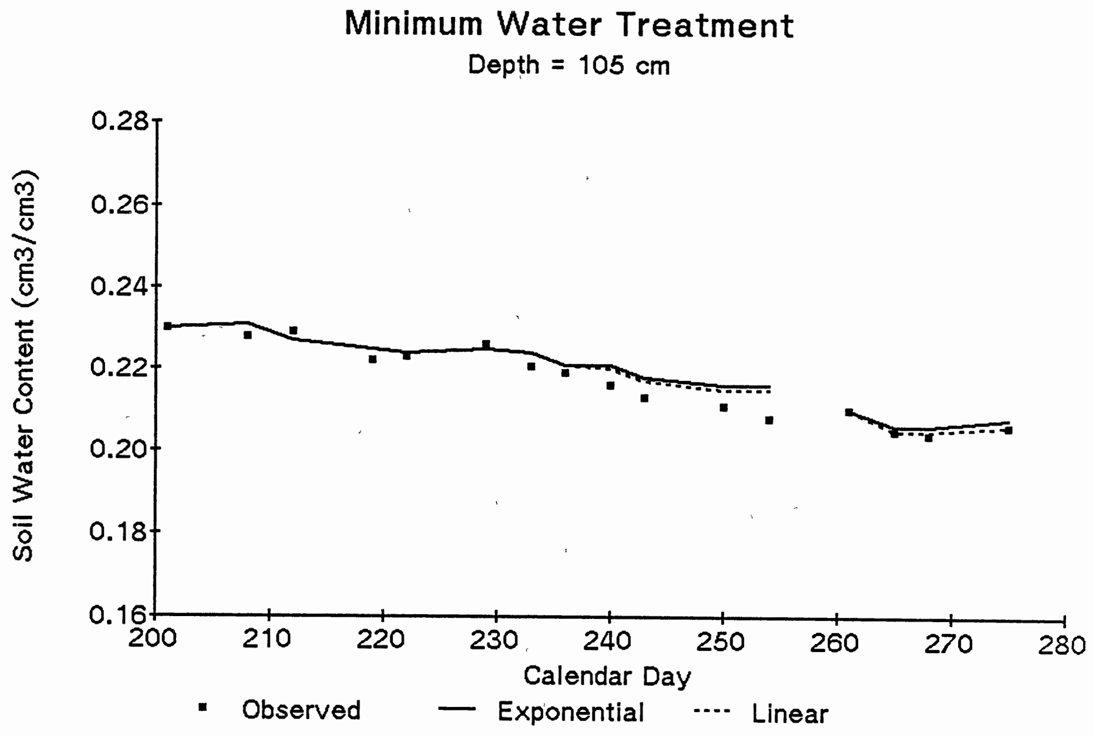


Figure 33. Observed and Simulated Soil Water Contents at Depths of 75 cm and 90 cm under a Minimum Water Treatment during 1989 Peanut Growing Season.



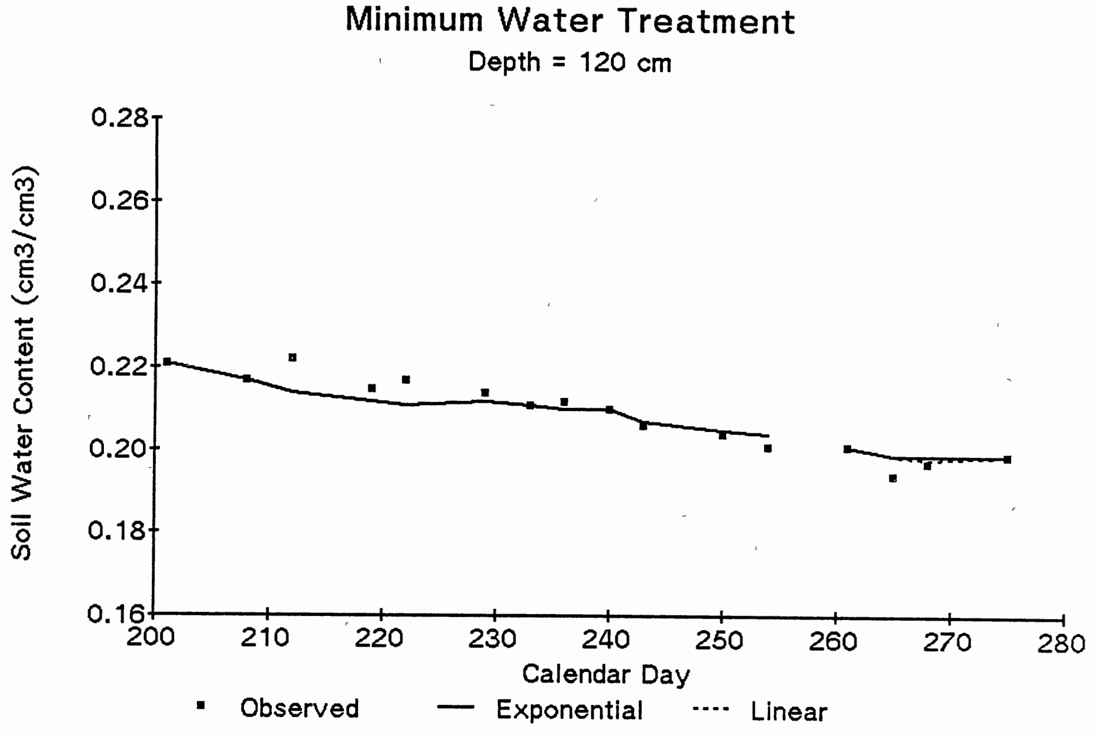


Figure 34. Observed and Simulated Soil Water Contents at Depths of 105 cm and 120 cm under a Minimum Water Treatment during 1989 Peanut Growing Season.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Summary

Improved understanding of root water uptake is an important element in advancing the state-of-the-art in modeling water movement through the soil-plant-atmosphere continuum. Researchers have traditionally placed far less attention on roots than on the above-ground portions of the plant. Even in an applied field such as irrigation management, there is opportunity for a more rigorous treatment of root growth and activity, particularly with regard to spatial and temporal patterns of root development and water uptake.

The modeling of water transport and uptake in root zones has been addressed in many different ways. Some models tend to concentrate on the soil and greatly simplify the process of water extraction by roots, while others place greater emphasis on physiological processes. Some models use a simple mass balance to describe water movement in the soil, while others use fundamental flow theory and numerical solution schemes. Two general types of root water uptake models are present in the literature. The models in one category are based on potential flow theory and require estimates of resistances and potentials. Models in the other category apportion plant transpiration based on the density of roots and the soil water condition.

A dynamic simulation model named VS2D was used for solving the two-dimensional equation of fluid flow in variably saturated porous media. The flow equation is written with total water potential as the dependent variable and is solved using finite difference techniques. The VS2D program was written in FORTRAN language with extensive use of subprograms, thereby simplifying the process of program modification. The subprogram for estimating crop evapotranspiration was changed by incorporating the Penman combination equation and appropriate crop coefficients. The root water uptake submodel was converted from a potential flow approach to an apportioned transpiration approach.

Field data were collected during the 1989 peanut growing season. Different water treatments were established by means of a line-source sprinkler irrigation system. Neutron measurements of soil water were taken twice a week throughout the season. Root data and gravimetric soil water data were collected four times between 26 July and 28 September. Irrigation and weather data were also collected. Laboratory measurements were made for estimating soil parameters needed in the VS2D model.

Statistical analysis was conducted to check the existence of differences among the water treatments. Two water treatments (full and minimum) were significantly different. A comparison of gravimetric water contents and neutron measurements indicated that the two methods were in reasonably good agreement. In order to compare the weather-based ET estimates to field observations, a water balance simulation was conducted to predict the daily total water in a crop root zone of 120 cm. Results showed that the overall predictive ability of the simulation model was good and that the weather-based estimates of peanut ET could be used in root water uptake modeling.

Root length measurements were made and root length densities were calculated. Results showed that the root length density values tended to be greater in the minimum water treatment. In the crop row, the root length density in the top 15 cm of soil was much higher than at greater depths. As the sampling location moved away from the crop row, the root length density tended to decrease in magnitude and become more uniform with depth.

Linear and exponential approaches were presented for describing the root distributions in either one or two dimensions. A root activity function was defined which is essentially a normalized root length density. This function can be obtained mathematically from the linear and exponential regression fits to root data, and can be used to calculate relative root distributions.

Results obtained by VS2D simulations of the full and minimum water treatments were in good agreement with field data. Both linear and exponential approaches were used in modeling the two-dimensional root distributions. The model is general in the sense that it has the potential to be easily applied to other crops.

Conclusions

Two dimensional root distribution functions were developed and incorporated into a dynamic simulation model of water uptake and movement. The results led to the following conclusions:

1. The weather-based estimates of peanut ET can be applied to root water uptake modeling.

2. The values of root length density were generally greater in the minimum water treatment than in the full water treatment. In the crop row, the root length density in the top 15 cm of soil was much higher than at greater depths. As the sampling location moved away from the crop row, the root length density tended to decrease in magnitude and become more uniform with depth.

3. The linear and exponential root distribution functions can be used to represent peanut root distributions in either one or two dimensions. The exponential model seemed to agree better with the observed data. Functional

relationships have the advantages of being concise representations, and mathematically continuous rather than discrete.

4. In the VS2D simulations, the sink term was successfully modified from a potential flow approach to an apportioned transpiration approach.

5. The simulated distributions of soil water with depth were in good agreement with the field data. For the full water treatment, the exponential approach to root distribution seemed to fit the field data slightly better than did the linear approach. For the minimum water treatment, both linear and exponential approaches were able to estimate root distributions well, leading to quite similar simulations of water uptake and movement.

Recommendations

The research in this dissertation presents a preliminary study of two dimensional simulation of water movement and uptake in crop root zones with specific application to peanuts. The possible directions for future research may be described as follows:

1. Modeling approaches may be developed for describing spatial and temporal patterns in root growth.

2. Research may be done under no irrigation (rain-fed) conditions. The effects of water stress on root distribution and water uptake should be more obvious.

3. Other approaches to the root distribution in addition to linear and exponential functions may be investigated.

4. The model has the potential to be applied to other crops, and to be incorporated into dynamic crop growth models.

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APPENDICES

APPENDIX A

NEUTRON PROBE MEASUREMENTS OF TOTAL WATER (cm) IN 120 cm SOIL ZONE

NEUTRON PROBE MEASUREMENTS OF TOTAL WATER (cm) IN 120 cm SOIL ZONE IN 1988
(Full Irrigation)

Calendar Day	Florunner			Okrun		
	Tube 1	Tube 3	Tube 5	Tube 2	Tube 4	Tube 6
179	30.29	30.76	30.11	30.10	29.64	30.09
182	31.04	31.19	30.39	30.71	31.23	31.15
186	30.38	30.54	29.76	30.12	29.21	29.80
189	30.28	30.64	29.85	30.60	30.39	30.19
193	29.92	29.30	28.59	29.91	27.94	29.32
196	29.54	29.79	28.86	30.14	29.36	29.58
200	26.52	26.76	26.44	26.72	28.85	27.26
203	29.37	29.11	27.75	30.04	28.64	29.11
207	25.78	26.56	25.45	26.62	25.05	26.96
211	29.28	29.00	28.91	30.36	28.17	29.42
214	26.19	26.58	26.47	27.26	25.38	27.57
221	22.85	23.00	22.78	22.74	21.08	23.71
224	23.65	24.51	23.55	26.99	23.11	24.56
228	21.94	22.58	22.36	23.23	20.93	22.97
232	21.92	22.57	22.06	24.38	20.86	24.41
235	20.59	21.60	21.05	22.01	19.62	23.00
238	22.67	23.76	22.44	25.44	22.00	26.29
242	21.50	22.79	21.79	24.05	20.51	24.56
245	20.73	21.80	21.20	22.67	19.56	23.71
249	20.22	20.74	20.45	21.06	18.90	22.53
252	21.43	22.37	21.67	22.48	19.98	23.67
256	19.72	20.75	20.27	20.64	18.37	22.03
263	25.95	25.64	27.47	25.17	24.42	29.84
266	24.27	23.74	25.35	24.02	22.96	27.29
270	24.42	24.60	25.78	24.71	23.51	27.86
278	22.89	23.47	24.05	23.43	22.31	26.39
284	24.16	24.88	25.45	24.60	23.52	27.15
287	23.58	24.33	24.34	24.01	22.78	26.57
291	22.63	23.21	24.14	23.09	22.32	26.26
294	21.71	22.07	23.26	22.33	21.35	25.17
298	20.87	21.44	22.76	21.90	20.66	24.74

NEUTRON PROBE MEASUREMENTS OF TOTAL WATER (cm)
IN 120 cm SOIL ZONE IN 1988
(Intermediate Irrigation)

Calendar Day	Florunner			Okrun		
	Tube 8	Tube 10	Tube 12	Tube 7	Tube 9	Tube 11
179	29.22	31.04	29.49	29.69	29.45	29.27
182	29.76	31.07	29.93	30.07	30.57	29.32
186	29.05	30.78	29.55	29.32	29.19	29.03
189	29.24	30.83	29.54	29.43	29.69	28.77
193	28.86	30.33	28.61	27.61	27.90	26.90
196	28.51	29.72	28.09	27.26	27.89	26.69
200	26.54	27.62	26.52	25.32	25.26	24.51
203	27.57	28.56	27.75	26.33	26.49	25.42
207	25.79	26.94	25.55	24.24	24.33	23.51
211	28.28	27.29	27.58	28.21	26.69	26.42
214	26.59	26.54	26.00	25.86	24.58	24.88
221	22.73	23.82	22.77	21.79	20.74	21.86
224	22.66	23.95	22.75	21.85	21.25	21.86
228	21.66	22.93	22.15	21.12	20.03	21.09
232	21.21	22.32	21.59	20.17	19.97	19.83
235	20.49	21.74	21.23	19.64	19.28	19.43
238	20.66	21.92	21.11	19.98	19.42	19.14
242	20.32	21.65	20.88	19.79	19.28	18.72
245	19.84	21.13	20.27	19.56	18.87	18.32
249	19.18	20.64	20.29	18.78	18.23	17.75
252	19.30	20.49	20.05	18.84	18.29	17.69
256	18.73	19.70	19.34	17.78	18.03	16.83
263	25.13	23.89	24.90	25.75	23.77	22.58
266	23.57	22.99	23.69	24.01	22.44	21.74
270	24.40	23.54	24.44	24.90	23.47	22.59
278	23.07	22.95	23.56	23.05	22.34	22.04
284	24.06	23.97	24.57	24.57	23.54	22.82
287	23.56	23.50	23.85	24.11	23.24	22.78
291	23.39	23.22	23.66	22.99	22.70	22.33
294	22.60	22.18	23.09	22.32	21.74	21.52
298	22.10	21.50	22.77	21.17	21.12	20.81

NEUTRON PROBE MEASUREMENTS OF TOTAL WATER (cm) IN 120 cm SOIL ZONE IN 1988 (Minimum Irrigation)

Calendar Day	Florunner			Okrun			
	Tube 13	15	17	14	16	18	19
179	29.43	29.73	29.02	28.24	28.91	29.26	28.05
182	28.78	29.01	28.57	28.04	28.23	28.81	27.63
186	29.02	28.85	28.17	27.62	27.63	28.08	27.97
189	28.12	28.24	27.55	26.94	26.98	27.91	27.86
193	27.75	27.30	26.26	25.98	26.01	27.13	27.61
196	27.23	26.94	26.08	25.52	26.01	26.63	27.32
200	25.57	24.85	24.46	23.96	23.93	25.23	27.18
203	26.21	25.16	24.71	25.15	24.69	25.74	27.78
207	24.57	23.59	23.18	23.09	22.72	24.43	27.05
211	25.75	24.75	24.64	26.36	23.36	25.56	28.71
214	24.40	23.31	23.42	23.88	22.12	24.28	28.14
221	21.88	20.88	20.54	20.75	19.16	21.76	27.48
224	21.46	20.97	20.33	20.42	19.17	21.16	27.59
228	20.89	19.81	19.59	19.97	18.20	20.26	27.17
232	19.77	19.28	18.60	19.19	17.66	19.60	26.74
235	19.52	19.02	18.21	18.75	17.17	18.87	26.69
238	19.51	19.33	19.00	19.22	17.74	19.10	26.43
242	19.24	19.42	18.65	19.20	17.99	19.12	27.46
245	19.23	18.84	18.34	18.52	17.33	18.43	26.90
249	18.75	18.30	18.03	18.16	17.13	18.18	26.36
252	18.60	18.44	17.70	18.19	17.17	18.27	25.94
256	17.99	17.43	17.17	17.76	16.55	17.50	25.54
263	24.93	24.64	25.90	28.38	22.81	25.14	27.82
266	23.20	23.15	24.34	25.88	21.63	23.23	27.36
270	24.15	24.65	24.94	26.97	22.62	24.36	27.87
278	22.68	22.99	23.21	25.86	21.61	22.69	27.92
284	23.69	23.79	24.01	26.88	22.30	23.91	28.79
287	23.14	23.33	23.33	26.14	21.86	23.02	28.24
291	22.37	22.44	22.68	25.33	21.21	22.60	28.35
294	21.32	21.34	21.93	24.51	20.26	21.36	28.44
298	20.65	20.93	20.97	23.71	19.68	20.90	27.76

NEUTRON PROBE MEASUREMENTS OF TOTAL WATER (cm) IN 120 cm SOIL ZONE IN 1989 (Full Irrigation)

Calendar	Florunner	Okrun				
Day	Tube 1	Tube 2	Tube 3	Tube 4	Tube 5	Tube 6
187	30.17	32.10	31.64	32.06	31.48	30.73
191	31.62	31.27	31.32	29.60	30.91	30.65
198	30.44	32.13	31.91	31.68	32.01	31.37
201	29.12	31.96	31.07	31.32	31.17	30.54
208	27.87	29.80	29.48	29.49	29.41	28.86
212	27.86	29.90	29.41	28.97	29.55	28.69
219	27.95	29.83	29.23	29.18	29.36	28.55
222	27.54	29.13	28.52	28.37	28.67	28.39
229	28.24	30.24	29.34	29.30	29.62	28.78
233	27.07	29.60	27.99	27.88	28.51	27.51
236	27.00	29.24	27.96	27.91	28.88	27.73
240	25.00	28.43	25.97	25.45	27.28	25.84
243	24.58	28.30	26.02	25.66	27.57	25.58
250	24.02	27.85	25.71	25.54	27.61	25.75
254	22.98	26.83	24.55	24.14	26.01	24.50
257	25.66	28.85	27.20	26.63	28.30	26.84
261	24.97	28.86	26.81	26.21	27.84	26.25
265	23.78	27.78	25.62	24.50	27.18	25.12
268	23.34	27.41	25.52	24.17	26.68	24.57
275	23.45	28.07	25.82	24.77	27.20	25.99
282	23.89	27.85	26.25	24.82	27.84	25.89
285	23.45	27.94	26.27	24.53	27.56	25.30
292	23.85	28.61	26.54	24.26	27.57	25.11
296	23.61	28.15	26.95	24.14	27.72	25.16
299	23.57	27.70	26.68	24.01	27.68	24.74

NEUTRON PROBE MEASUREMENTS OF TOTAL WATER (cm) IN 120 cm SOIL ZONE IN 1989
(Intermediate Irrigation)

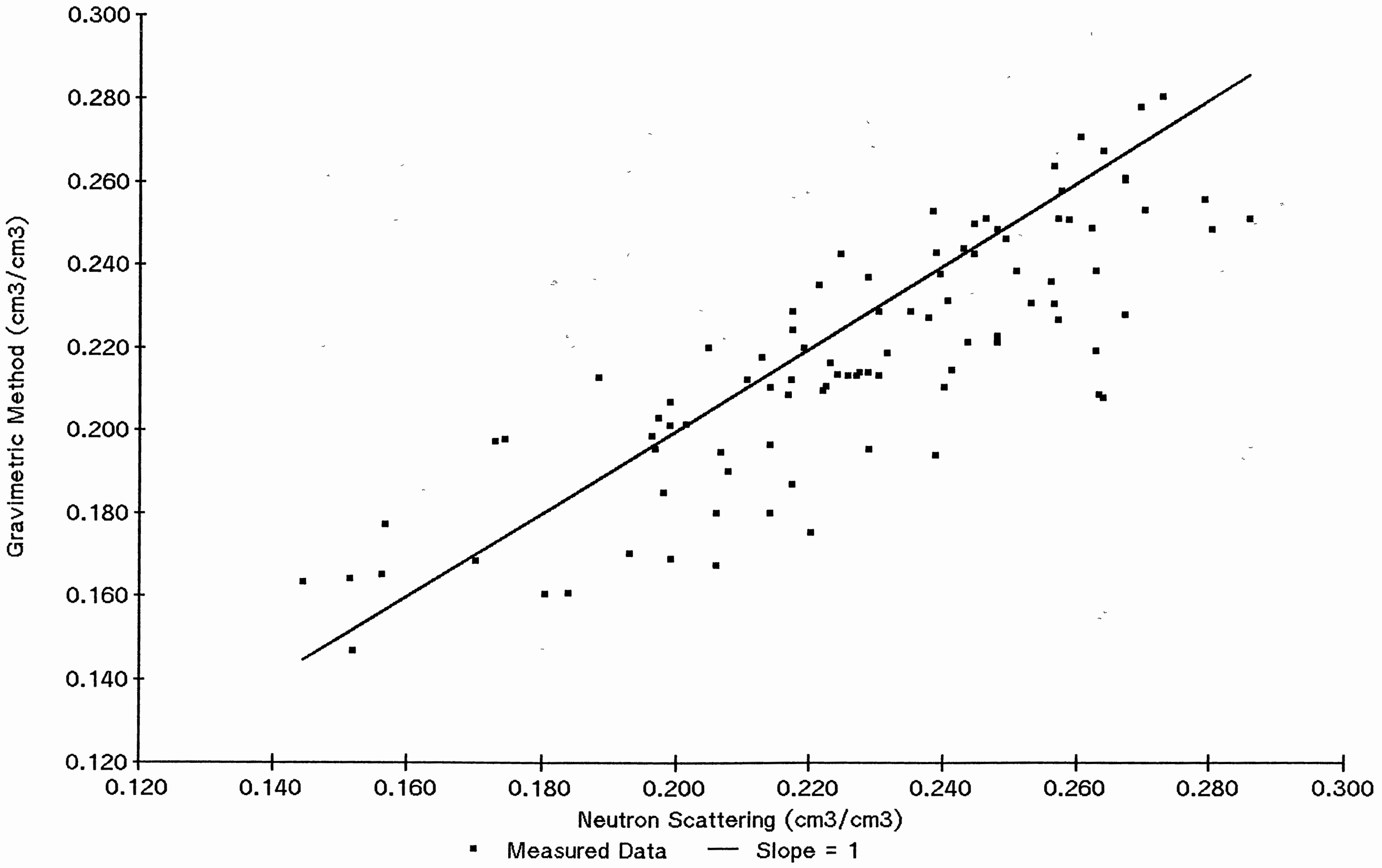
Calendar	Florunner	Okrun				
Day	Tube 12	Tube 7	Tube 8	Tube 9	Tube 10	Tube 11
187	32.12	31.53	31.99	32.51	32.54	32.61
191	31.53	31.22	31.07	31.23	31.76	32.00
198	32.49	31.49	31.35	31.93	32.46	32.92
201	31.70	30.78	30.97	31.33	31.52	31.87
208	29.81	29.20	29.31	29.33	29.99	30.13
212	30.22	29.41	28.95	29.55	30.09	29.85
219	30.18	29.06	29.03	28.82	29.76	30.40
222	29.92	28.51	28.52	28.59	29.27	29.66
229	30.30	29.02	30.01	29.60	29.90	30.58
233	29.38	27.74	28.46	28.26	28.79	29.30
236	29.27	27.94	27.96	27.46	28.69	29.44
240	27.46	24.44	26.07	26.03	26.82	26.61
243	27.31	25.55	25.18	25.67	26.52	26.64
250	26.82	25.11	24.97	25.00	26.07	26.37
254	26.10	23.88	24.06	23.84	24.88	25.39
257	28.07	26.42	26.70	27.03	27.21	28.25
261	27.94	25.76	26.36	26.53	26.84	27.82
265	26.96	24.49	25.24	25.10	25.68	26.31
268	26.73	24.24	24.97	25.00	25.48	25.81
275	26.83	24.48	25.20	24.78	25.36	26.32
282	27.27	24.94	25.89	25.44	25.77	26.46
285	27.11	24.61	25.77	25.11	25.32	26.80
292	27.19	24.53	25.71	24.66	25.41	26.70
296	26.98	24.21	25.66	24.50	25.20	26.70
299	26.83	24.35	25.88	24.48	25.52	26.54

NEUTRON PROBE MEASUREMENTS OF TOTAL WATER (cm)
IN 120 cm SOIL ZONE IN 1989
(Minimum Irrigation)

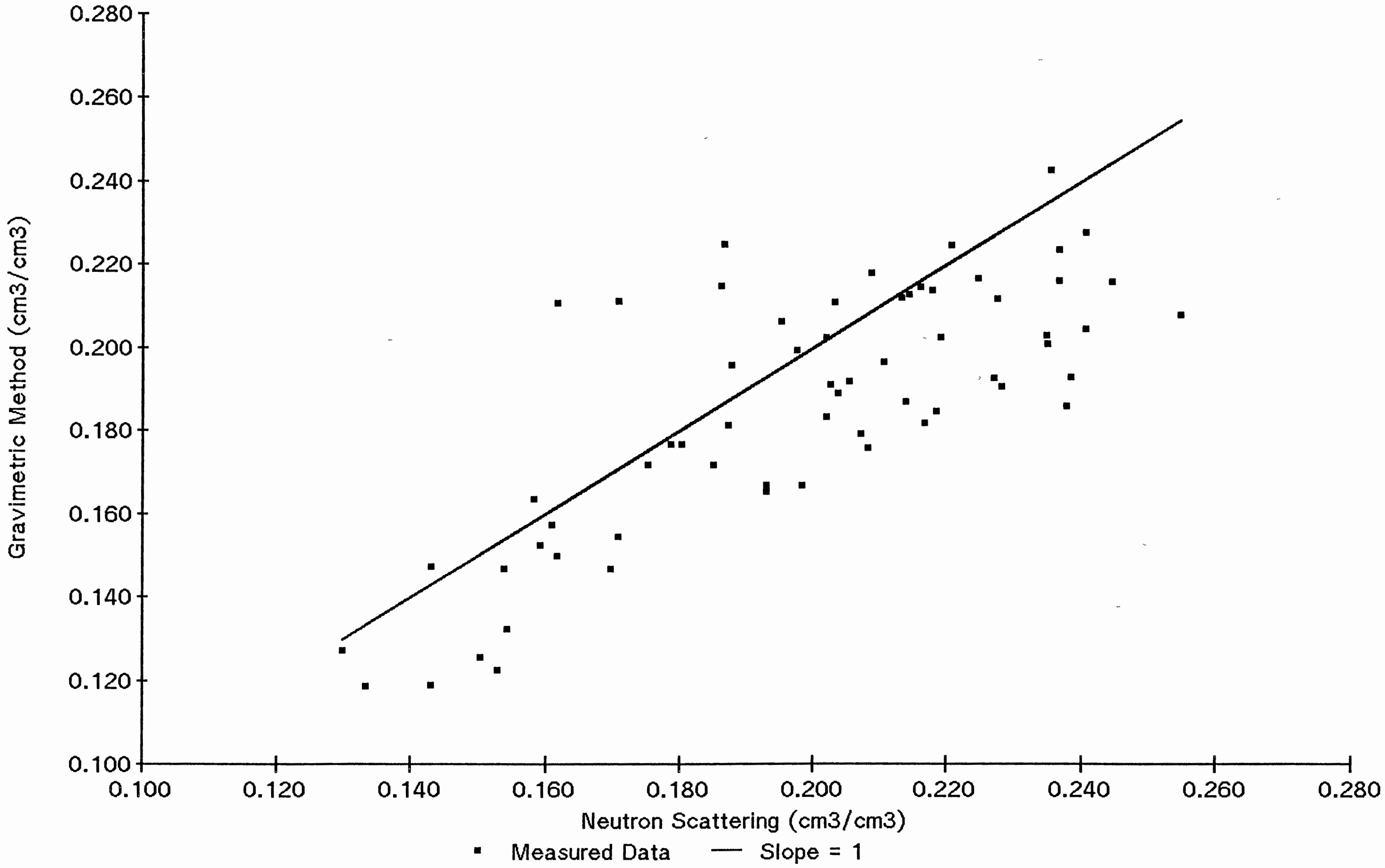
Calendar	Florunner	Okrun					
Day	Tube 13	14	15	16	17	18	Tube 19
187	31.92	32.58	33.38	32.42	32.51	32.59	31.17
191	31.14	32.36	32.90	31.66	31.97	31.96	30.55
198	30.54	32.00	32.31	31.34	31.44	31.46	30.48
201	29.93	31.63	31.72	31.02	30.91	30.95	30.40
208	28.29	30.05	30.53	29.57	29.12	29.33	29.10
212	27.80	30.05	30.94	29.35	29.04	29.12	30.34
219	27.06	30.09	30.04	28.55	28.61	28.05	29.94
222	26.33	29.61	29.41	28.12	28.04	27.55	30.14
229	27.96	30.11	30.27	29.64	28.70	28.59	30.34
233	27.12	28.79	28.98	28.51	27.34	27.63	30.17
236	26.71	28.47	28.46	27.70	26.35	27.05	29.65
240	23.97	26.77	26.29	25.29	23.99	24.93	28.94
243	23.87	26.34	25.36	24.79	23.60	24.19	28.34
250	23.46	26.07	25.18	24.76	23.55	24.42	27.84
254	22.19	24.60	24.21	23.70	22.44	23.54	27.86
257	26.68	27.29	27.78	27.77	26.19	26.13	30.23
261	25.76	27.09	27.11	27.42	25.86	25.40	29.74
265	24.46	26.01	26.08	25.68	24.11	24.51	29.15
268	24.20	25.77	25.87	25.65	23.98	24.33	29.01
275	24.10	25.75	25.62	25.32	24.10	24.43	28.70
282	24.99	26.10	25.99	25.35	23.99	24.72	28.95
285	24.61	26.36	26.14	25.23	24.44	24.78	28.48
292	23.53	25.58	25.42	24.39	23.59	24.45	28.19
296	23.90	25.62	25.13	23.23	23.96	24.07	27.93
299	23.69	25.47	25.48	24.51	23.80	23.89	27.72

APPENDIX B

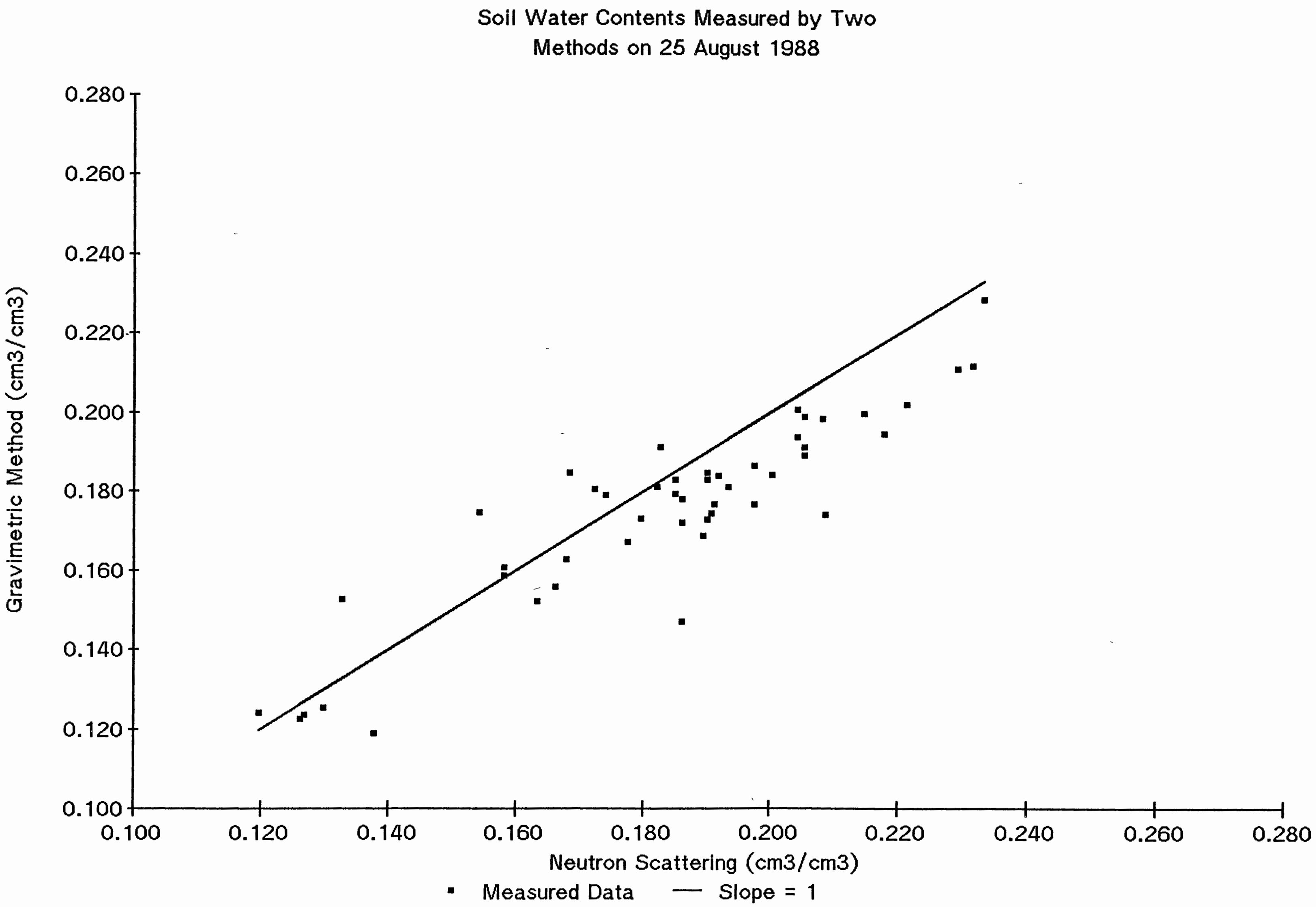
GRAVIMETRIC WATER CONTENTS AND THE CORRESPONDING NEUTRON READINGS IN 1988 AND 1989



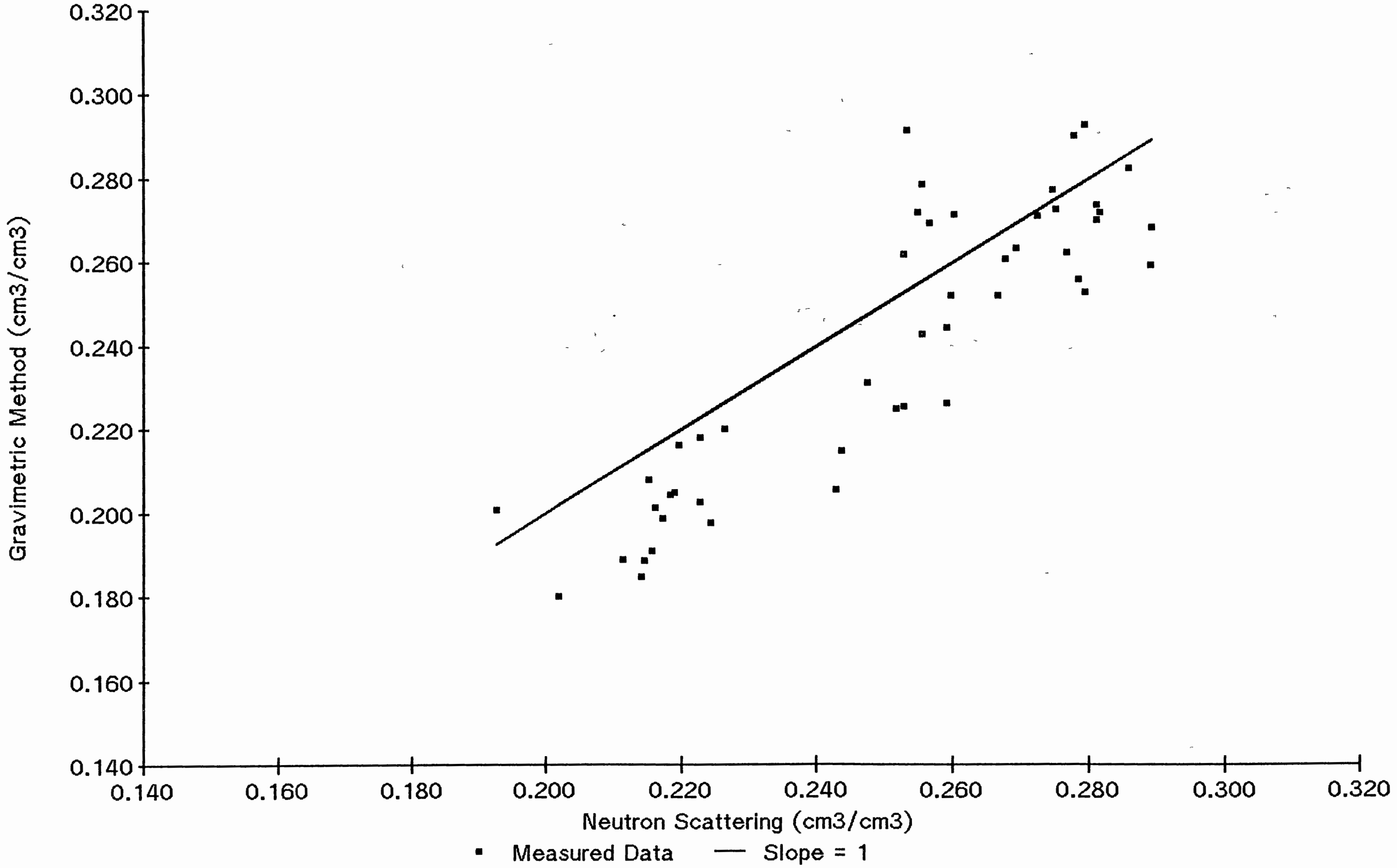
Soil Water Contents Measured by Two Methods on 21 July 1988



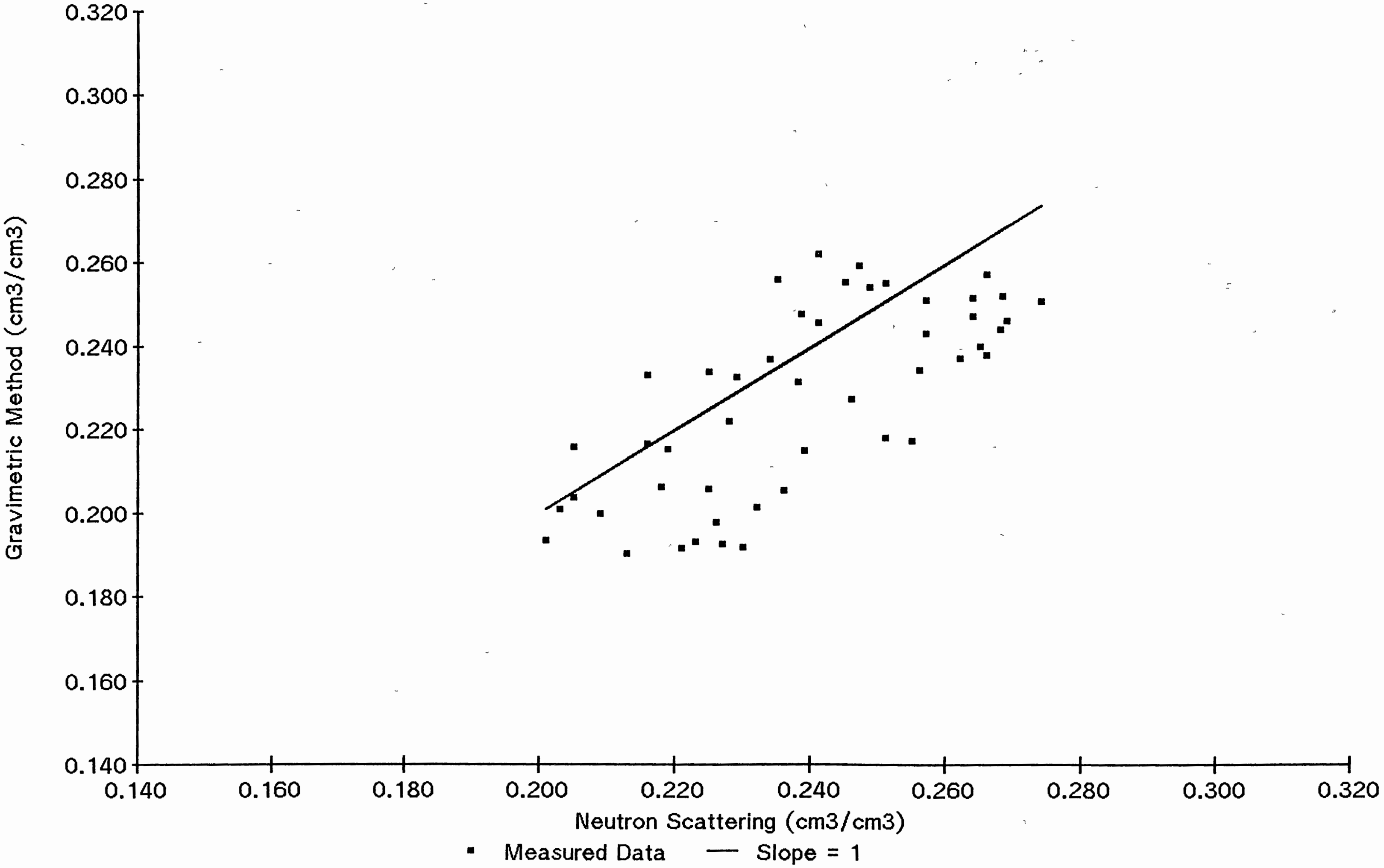
Soil Water Contents Measured by Two Methods on 11 August 1988


Soil Water Contents Measured by Two Methods on 25 August 1988
Gravimetric Method (cm3/cm3)
0.280
0.260
0.240
0.220
0.200
0.180
0.160
0.140
0.120
0.100
0.100
0.120
0.140
0.160
0.180
0.200
0.220
0.240
0.260
0.280
Neutron Scattering (cm3/cm3)
■ Measured Data
— Slope = 1

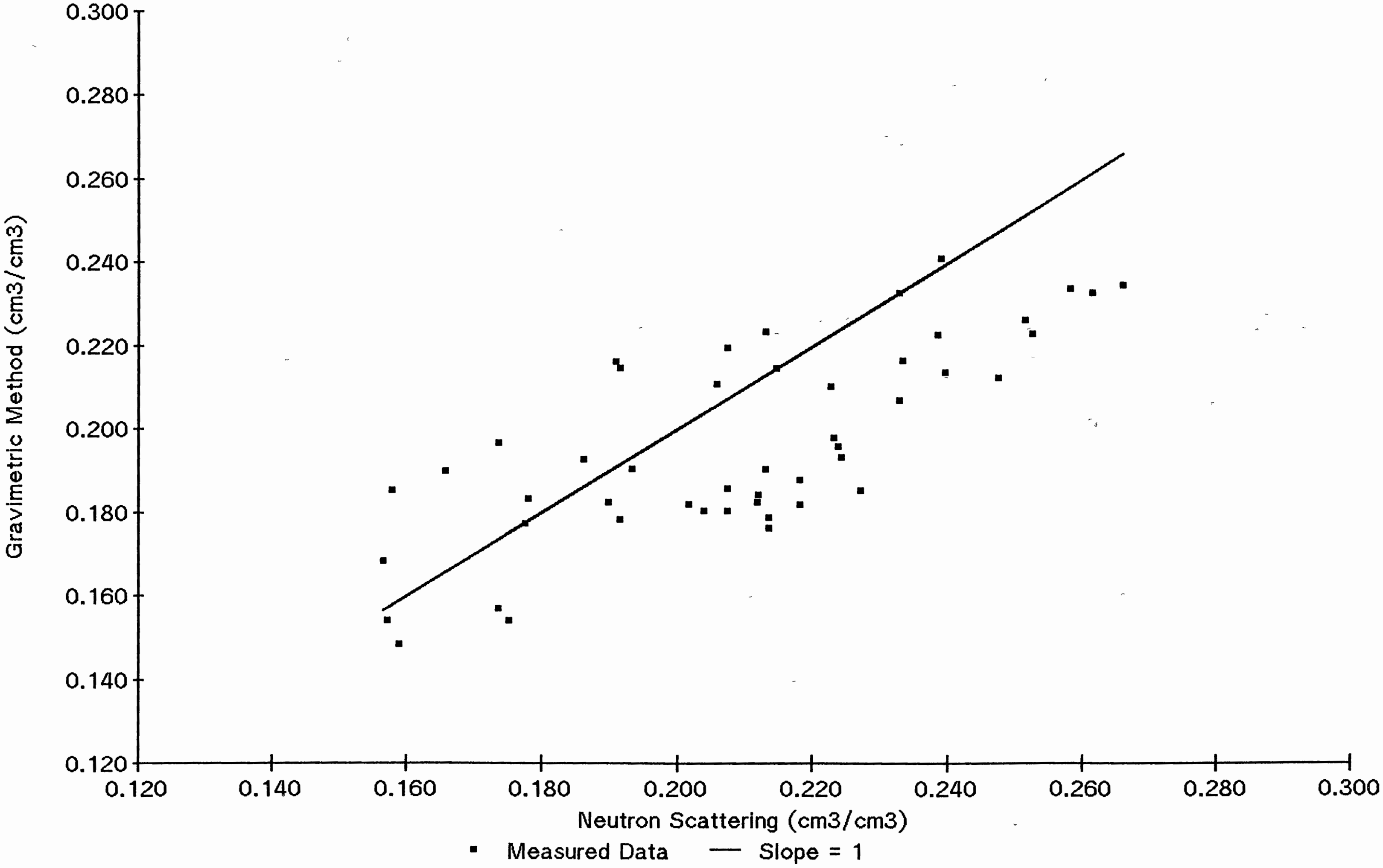
Soil Water Contents Measured by Two Methods on 26 July 1989



Soil Water Contents Measured by Two
Methods on 17 August 1989



Soil Water Contents Measured by Two Methods on 7 September 1989



APPENDIX C

WEATHER DATA FOR REFERENCE CROP ET CALCULATIONS

WEATHER DATA OF 1988

Calendar Day	Net Radiation (cal/cm^2.day)	Wind Run (km/day)	Mean Temperature (^{0}C)	Mean VPD (mbar)
161	385.3	16.87	25.59	14.59
162	387.3	9.17	21.84	14.82
163	403.9	11.02	22.13	17.15
164	398.0	14.04	25.39	19.46
165	381.8	12.92	25.89	17.97
166	381.0	12.33	26.50	17.57
167	316.7	8.26	26.45	14.23
168	284.6	8.16	24.95	9.15
169	366.2	7.37	27.17	16.75
170	381.6	11.99	28.84	19.75
171	391.5	14.39	29.76	22.25
172	391.5	14.25	30.04	24.10
173	393.9	12.64	30.00	22.41
174	401.7	11.43	29.85	23.18
175	430.6	6.49	29.40	21.83
176	376.5	6.00	30.76	24.62
177	282.4	8.69	28.82	16.39
178	218.0	7.42	27.78	13.57
179	331.0	5.99	27.79	17.16
180	414.6	10.10	28.12	19.21
181	438.4	12.20	29.23	22.62
182	397.7	15.92	32.11	24.48
183	257.1	13.17	25.74	12.83
184	230.1	10.03	22.55	13.51
185	385.8	6.29	26.71	21.89
186	399.7	9.70	30.11	21.22
187	461.4	10.12	29.77	19.47
188	356.4	10.10	29.32	21.46
189	354.6	9.77	27.67	14.43
190	296.5	7.55	26.05	11.88
191	316.2	9.59	26.57	17.92
192	267.0	6.32	27.53	15.28
193	261.8	9.28	26.97	10.62
194	361.2	5.97	28.65	18.07
195	419.2	10.60	31.15	20.15
196	372.0	14.62	31.71	16.54
197	395.5	16.43	31.71	14.96
198	334.4	12.29	31.62	13.47
199	279.4	10.80	31.97	13.03
200	232.7	7.59	30.15	10.75
201	245.1	9.32	25.75	7.68
202	342.8	15.49	23.92	6.40
203	408.9	5.85	25.51	7.29
204	365.8	9.60	26.70	5.60
205	373.7	14.39	28.88	5.18
206	288.5	10.99	30.15	4.37
207	391.6	8.83	30.14	4.09
208	376.4	8.20	29.53	4.04
209	264.6	9.04	24.72	6.26
210	183.5	10.95	24.04	6.74

WEATHER DATA OF 1988 (CONTINUED)

Calendar Day	Net Radiation (cal/cm^2.day)	Wind Run (km/day)	Mean Temperature (^0C)	Mean VPD (mbar)
211	442.4	10.84	29.50	5.32
212	420.0	8.46	30.67	3.98
213	402.4	8.87	30.04	3.74
214	400.9	11.40	30.15	2.78
215	374.4	11.67	30.14	2.53
216	383.9	10.68	29.54	2.52
217	387.6	10.05	29.96	3.27
218	321.9	7.15	29.35	1.63
219	387.6	6.89	30.93	3.83
220	386.4	10.34	33.10	1.61
221	377.4	9.56	33.87	1.04
222	267.9	7.13	28.76	1.85
223	406.6	6.21	29.09	4.34
224	384.1	8.15	28.75	1.50
225	310.6	9.29	28.29	13.36
226	385.5	14.98	31.30	21.50
227	254.5	11.04	31.33	20.20
228	358.4	9.36	31.96	22.66
229	392.0	7.38	31.28	14.11
230	311.2	7.13	29.69	12.81
231	282.0	5.20	28.01	13.26
232	279.7	5.95	28.06	15.21
233	319.4	6.29	29.29	18.04
234	372.4	9.78	31.67	23.89
235	368.8	14.27	32.35	24.88
236	185.7	9.89	28.83	16.50
237	345.6	5.11	28.37	17.56
238	325.7	9.37	30.44	17.62
239	338.8	9.87	28.33	13.88
240	115.3	11.99	27.09	9.87
241	94.5	9.51	18.92	5.28
242	370.9	8.98	19.25	5.67
243	320.0	7.28	20.66	5.59
244	324.8	8.28	22.58	6.19
245	309.7	6.58	23.77	6.17
246	200.0	5.43	23.97	3.98
247	335.8	11.37	24.72	5.78
248	351.6	13.80	21.97	4.45
249	336.8	8.80	22.39	4.83
250	374.7	8.80	22.60	7.16
251	346.8	15.42	23.41	5.78
252	271.2	13.05	24.71	4.64
253	302.7	6.54	25.83	5.35
254	307.4	6.87	25.70	5.08
255	297.1	6.80	25.37	4.43
256	287.1	9.08	27.39	5.70
257	318.1	7.44	25.87	4.84
258	171.8	6.32	24.07	2.63
259	190.8	6.30	23.38	2.92
260	233.2	9.50	24.27	2.63

WEATHER DATA OF 1988 (CONTINUED)

Calendar Day	Net Radiation (cal/cm^2.day)	Wind Run (km/day)	Mean Temperature (^{0}C)	Mean VPD (mbar)
261	148.9	9.19	24.41	2.89
262	187.6	10.62	23.42	2.63
263	370.2	13.50	21.75	3.33
264	360.5	5.72	20.66	3.70
265	321.0	11.59	26.16	4.11
266	319.4	14.19	26.65	3.63
267	69.7	9.61	19.76	1.54
268	133.9	9.34	15.54	2.62
269	306.1	4.60	18.34	3.24
270	316.7	8.10	21.42	3.98
271	296.8	9.60	23.58	4.17
272	230.5	14.29	22.87	3.15
273	228.6	8.41	17.13	2.59
274	256.5	5.48	16.43	2.44
275	73.9	7.94	15.39	2.17
276	272.4	9.24	17.11	2.92
277	247.0	4.40	16.69	2.86
278	157.7	7.03	15.00	2.09
279	48.4	12.15	8.61	0.87
280	97.0	9.90	10.36	1.40
281	35.0	7.14	10.43	1.17
282	66.5	4.76	12.50	1.99
283	138.6	4.44	12.49	2.30
284	254.2	7.36	15.10	2.96
285	245.1	10.11	14.46	2.56
286	242.3	5.27	13.11	2.51
287	232.8	11.92	16.30	2.75
288	195.3	17.79	19.73	2.47
289	152.3	14.82	20.69	2.24
290	223.7	6.61	22.45	4.44
291	217.2	14.45	24.74	4.40
292	142.2	14.44	14.49	1.59
293	202.6	7.77	13.65	2.25
294	115.9	6.04	15.48	2.50
295	216.8	3.71	16.39	3.49
296	206.6	12.15	17.59	3.27
297	192.5	13.92	17.54	2.94
298	192.9	6.68	15.08	2.65

WEATHER DATA OF 1989

Calendar Day	Net Radiation (cal/cm^2.day)	Wind Run (km/day)	Mean Temperature (^{0}C)	Mean VPD (mbar)
172	392.8	14.35	29.10	19.11
173	274.2	13.92	24.21	10.27
174	336.8	9.17	23.11	10.84
175	396.2	8.21	28.04	18.68
176	361.8	4.75	28.97	25.27
177	380.3	7.40	28.44	20.41
178	411.3	11.95	24.59	12.72
179	369.3	7.73	26.22	15.12
180	338.4	8.31	26.67	16.13
181	303.1	6.51	27.61	19.78
182	304.8	7.50	26.92	17.70
183	138.5	8.41	27.07	17.29
184	428.1	8.41	27.07	17.29
185	344.3	5.12	28.09	20.50
186	340.0	4.61	28.36	21.42
187	314.9	4.76	28.43	22.28
188	304.6	5.01	27.94	16.02
189	325.5	5.18	28.26	11.57
190	353.0	11.13	29.17	11.84
191	391.0	14.83	30.34	15.16
192	379.5	13.66	28.16	8.16
193	296.5	10.44	29.21	8.88
194	307.7	8.84	27.77	7.66
195	114.7	5.74	24.58	5.91
196	345.6	5.78	26.79	11.83
197	409.6	8.50	26.92	8.16
198	328.0	13.52	25.51	4.89
199	267.8	8.40	27.51	6.07
200	358.9	13.92	26.45	11.34
201	338.4	11.85	24.69	10.48
202	298.6	7.58	23.81	9.64
203	239.8	4.69	24.45	8.49
204	227.3	7.03	22.41	8.49
205	332.8	6.22	24.31	4.44
206	343.6	5.00	26.29	6.66
207	234.3	5.75	26.64	5.97
208	333.8	6.51	27.10	7.31
209	296.3	5.97	27.19	7.17
210	352.4	9.85	30.14	10.75
211	369.1	10.39	31.50	13.02
212	270.1	9.38	29.09	5.66
213	365.1	6.44	27.52	7.09
214	221.8	10.50	26.56	5.58
215	239.7	15.22	27.47	8.80
216	394.7	17.32	30.33	14.53
217	371.3	12.96	30.68	15.97
218	391.2	8.55	26.14	10.10
219	384.9	12.79	22.06	6.52
220	364.1	4.34	22.03	8.92

WEATHER DATA OF 1989 (CONTINUED)

Calendar Day	Net Radiation (cal/cm^2.day)	Wind Run (km/day)	Mean Temperature (^{0}C)	Mean VPD (mbar)
221	355.9	5.46	22.83	9.37
222	120.7	7.64	19.79	2.78
223	317.7	6.51	23.11	7.78
224	177.6	4.87	23.04	4.65
225	32.6	5.49	20.86	9.37
226	161.7	9.98	20.41	16.35
227	290.9	4.06	23.70	6.81
228	217.6	6.45	22.66	2.10
229	339.2	6.42	25.02	5.74
230	226.2	6.67	25.25	3.31
231	369.9	13.52	28.50	8.84
232	365.4	13.87	27.52	9.87
233	278.5	10.55	27.83	6.08
234	293.8	9.20	29.20	9.68
235	366.7	5.58	30.56	11.36
236	342.9	5.83	30.80	12.06
237	287.4	8.42	29.29	8.31
238	343.9	10.62	30.98	12.80
239	339.6	8.68	30.45	11.82
240	342.1	9.21	30.67	12.77
241	301.8	10.60	27.18	8.32
242	260.9	6.54	27.31	5.58
243	341.7	14.14	30.47	10.97
244	167.3	11.10	28.14	9.57
245	235.4	4.26	25.98	13.24
246	260.3	7.89	26.45	4.57
247	144.7	8.69	24.40	9.32
248	320.9	10.97	28.37	6.08
249	333.6	11.74	28.25	6.58
250	307.2	11.14	28.56	6.97
251	323.2	13.55	29.24	9.29
252	58.8	12.41	21.59	1.33
253	215.6	7.76	20.79	2.09
254	191.4	10.89	20.93	1.96
255	35.7	10.60	16.21	6.19
256	44.1	13.88	11.27	7.58
257	74.0	10.95	12.93	3.16
258	195.4	4.37	16.29	1.57
259	338.4	5.95	19.13	4.23
260	336.5	7.00	22.51	5.67
261	322.3	8.40	21.89	3.98
262	304.5	5.68	21.14	4.37
263	285.1	5.26	20.90	4.66
264	279.0	4.26	22.07	5.43
265	290.2	16.57	20.22	4.12
266	287.5	18.84	12.05	1.65
267	277.9	5.49	11.79	2.86
268	270.8	4.76	13.77	4.04
269	292.0	6.26	15.79	4.74
270	274.8	6.05	16.84	3.96

WEATHER DATA OF 1989 (CONTINUED)

Calendar Day	Net Radiation (cal/cm^2.day)	Wind Run (km/day)	Mean Temperature (^{0}C)	Mean VPD (mbar)
271	270.4	3.31	16.80	5.79
272	257.0	3.24	18.13	6.58
273	251.4	3.40	19.30	6.62
274	266.0	8.47	20.86	7.60
275	248.5	5.46	12.38	3.42
276	250.6	10.00	16.91	2.64
277	214.5	8.79	18.75	2.27
278	214.6	12.84	23.44	3.85
279	245.5	13.54	18.30	6.77
280	263.3	6.92	14.70	2.71
281	262.7	4.33	15.59	3.70
282	238.5	5.62	18.14	3.74
283	247.4	4.71	19.56	5.77
284	245.4	12.51	23.30	11.59
285	233.3	7.52	23.87	9.88
286	230.2	9.58	22.82	8.60
287	228.6	10.98	23.41	8.07
288	223.8	14.26	23.61	6.79
289	30.4	14.82	14.02	0.28
290	80.2	15.18	9.36	0.01
291	145.0	13.27	6.33	0.00
292	197.5	10.00	4.40	0.33
293	221.3	6.61	8.64	2.85
294	115.6	7.97	15.57	3.07
295	176.4	7.20	18.49	3.86

APPENDIX D

REFERENCE CROP ET, PEANUT ET AND CROP COEFFICIENTS

PEANUT ET IN 1988

Date	Calendar Day	Alfalfa ET (mm)	K_c	Peanut ET (mm)
June 9	161	5.8	0.2	1.2
June 10	162	5.6	0.2	1.1
June 11	163	6.3	0.2	1.3
June 12	164	6.2	0.2	1.2
June 13	165	5.9	0.2	1.2
June 14	166	5.9	0.2	1.2
June 15	167	4.9	0.2	1.0
June 16	168	4.1	0.2	0.8
June 17	169	5.7	0.2	1.1
June 18	170	6.1	0.2	1.2
June 19	171	6.4	0.2	1.3
June 20	172	6.5	0.2	1.3
June 21	173	6.4	0.2	1.3
June 22	174	6.6	0.2	1.3
June 23	175	6.9	0.2	1.4
June 24	176	6.3	0.2	1.3
June 25	177	4.5	0.2	0.9
June 26	178	3.5	0.2	0.7
June 27	179	5.3	0.2	1.1
June 28	180	6.4	0.2	1.3
June 29	181	7.0	0.2	1.4
June 30	182	6.6	0.2	1.3
July 1	183	3.9	0.2	0.8
July 2	184	3.5	0.2	0.7
July 3	185	6.2	0.2	1.2
July 4	186	6.5	0.2	1.3
July 5	187	7.2	0.2	1.4
July 6	188	5.9	0.22	1.3
July 7	189	5.4	0.27	1.4
July 8	190	4.4	0.30	1.3
July 9	191	5.1	0.34	1.7
July 10	192	4.3	0.38	1.6
July 11	193	4.0	0.41	1.6
July 12	194	5.8	0.45	2.6
July 13	195	6.7	0.48	3.2
July 14	196	5.9	0.51	3.0
July 15	197	6.2	0.54	3.3
July 16	198	5.2	0.57	3.0
July 17	199	4.4	0.60	2.7
July 18	200	3.6	0.63	2.3
July 19	201	3.5	0.66	2.3
July 20	202	4.6	0.68	3.1
July 21	203	5.6	0.71	4.0
July 22	204	5.1	0.73	3.7
July 23	205	5.3	0.75	4.0
July 24	206	4.1	0.77	3.2
July 25	207	5.5	0.79	4.4
July 26	208	5.3	0.81	4.3
July 27	209	3.6	0.83	3.0
July 28	210	2.6	0.85	2.2

PEANUT ET IN 1988 (CONTINUED)

Date	Calendar Day	Alfalfa ET (mm)	K_c	Peanut ET (mm)
July 29	211	6.2	0.87	5.4
July 30	212	6.0	0.88	5.2
July 31	213	5.7	0.90	5.1
Aug. 1	214	5.6	0.91	5.1
Aug. 2	215	5.2	0.92	4.8
Aug. 3	216	5.3	0.94	5.0
Aug. 4	217	5.4	0.95	5.1
Aug. 5	218	4.4	0.96	4.2
Aug. 6	219	5.5	0.97	5.3
Aug. 7	220	5.5	0.98	5.4
Aug. 8	221	5.4	0.99	5.3
Aug. 9	222	3.7	1.00	3.6
Aug. 10	223	5.7	1.00	5.7
Aug. 11	224	5.2	1.20	5.2
Aug. 12	225	4.7	1.26	4.8
Aug. 13	226	6.3	1.02	6.4
Aug. 14	227	4.3	1.03	4.4
Aug. 15	228	6.0	1.03	6.2
Aug. 16	229	6.0	1.03	6.2
Aug. 17	230	4.8	1.04	5.0
Aug. 18	231	4.3	1.04	4.5
Aug. 19	232	4.4	1.04	4.6
Aug. 20	233	5.1	1.04	5.3
Aug. 21	234	6.2	1.04	6.5
Aug. 22	235	6.2	1.04	6.4
Aug. 23	236	3.1	1.04	3.2
Aug. 24	237	5.3	1.04	5.6
Aug. 25	238	5.2	1.04	5.4
Aug. 26	239	5.1	1.04	5.3
Aug. 27	240	1.9	1.04	2.0
Aug. 28	241	1.3	1.03	1.3
Aug. 29	242	4.6	1.03	4.8
Aug. 30	243	4.1	1.03	4.2
Aug. 31	244	4.3	1.02	4.4
Sept. 1	245	4.2	1.29	4.3
Sept. 2	246	2.7	1.25	2.8
Sept. 3	247	4.5	1.20	4.6
Sept. 4	248	4.5	1.01	4.6
Sept. 5	249	4.4	1.00	4.4
Sept. 6	250	5.3	0.99	5.0
Sept. 7	251	4.6	0.99	4.6
Sept. 8	252	3.7	0.98	3.6
Sept. 9	253	4.2	0.98	4.1
Sept.10	254	4.2	0.97	4.1
Sept.11	255	4.2	0.96	3.9
Sept.12	256	4.0	0.96	3.9
Sept.13	257	4.3	0.95	4.1
Sept.14	258	2.3	0.94	2.2
Sept.15	259	2.5	0.94	2.3
Sept.16	260	3.0	0.93	2.8

PEANUT ET IN 1988 (CONTINUED)

Date	Calendar Day	Alfalfa ET (mm)	K_c	Peanut ET (mm)
Sept.17	261	2.2	0.92	1.9
Sept.18	262	2.4	0.92	2.2
Sept.19	263	4.7	0.91	4.2
Sept.20	264	4.5	0.90	4.0
Sept.21	265	4.4	0.89	3.9
Sept.22	266	4.3	0.89	3.8
Sept.23	267	0.9	0.88	0.7
Sept.24	268	1.6	0.87	1.4
Sept.25	269	3.7	0.86	3.2
Sept.26	270	4.1	0.86	3.5
Sept.27	271	3.9	0.85	3.3
Sept.28	272	3.0	0.84	2.5
Sept.29	273	2.7	0.84	2.3
Sept.30	274	3.0	0.83	2.5
Oct. 1	275	0.9	0.82	0.7
Oct. 2	276	3.2	0.82	2.6
Oct. 3	277	2.9	0.81	2.4
Oct. 4	278	1.8	0.80	1.4
Oct. 5	279	0.5	0.80	0.4
Oct. 6	280	1.0	0.79	0.8
Oct. 7	281	0.3	0.79	0.3
Oct. 8	282	0.7	0.78	0.5
Oct. 9	283	1.5	0.78	1.2
Oct. 10	284	2.9	0.77	2.3
Oct. 11	285	2.8	0.77	2.1
Oct. 12	286	2.7	0.76	2.0
Oct. 13	287	2.7	0.76	2.1
Oct. 14	288	2.4	0.76	1.8
Oct. 15	289	1.9	0.76	1.5
Oct. 16	290	3.0	0.75	2.2
Oct. 17	291	3.0	0.75	2.2
Oct. 18	292	1.6	0.75	1.2
Oct. 19	293	2.2	0.75	1.7
Oct. 20	294	1.4	0.75	1.0
Oct. 21	295	2.6	0.75	1.9
Oct. 22	296	2.5	0.75	1.9
Oct. 23	297	2.3	0.75	1.8
Oct. 24	298	2.2	0.75	1.7

PEANUT ET IN 1989

Date	Calendar Day	Alfalfa ET (mm)	K_c	Peanut ET (mm)
June 21	172	6.2	0.20	1.2
June 22	173	4.0	0.20	0.8
June 23	174	4.8	0.20	1.0
June 24	175	6.2	0.20	1.2
June 25	176	6.1	0.20	1.2
June 26	177	6.1	0.20	1.2
June 27	178	5.9	0.20	1.2
June 28	179	5.6	0.20	1.1
June 29	180	5.3	0.20	1.1
June 30	181	5.1	0.20	1.0
July 1	182	4.9	0.20	1.0
July 2	183	2.3	0.20	0.5
July 3	184	6.5	0.20	1.3
July 4	185	5.6	0.20	1.1
July 5	186	5.6	0.20	1.1
July 6	187	5.3	0.20	1.1
July 7	188	4.9	0.20	1.0
July 8	189	4.9	0.20	1.0
July 9	190	5.3	0.20	1.1
July 10	191	6.1	0.20	1.2
July 11	192	5.5	0.20	1.1
July 12	193	4.4	0.20	0.9
July 13	194	4.4	0.20	0.9
July 14	195	1.7	0.20	0.3
July 15	196	5.1	0.20	1.0
July 16	197	5.8	0.23	1.3
July 17	198	4.4	0.27	1.2
July 18	199	3.9	0.31	1.2
July 19	200	5.3	0.35	1.8
July 20	201	4.9	0.39	1.9
July 21	202	4.3	0.42	1.8
July 22	203	3.5	0.46	1.6
July 23	204	3.3	0.49	1.6
July 24	205	4.5	0.52	2.3
July 25	206	4.8	0.56	2.7
July 26	207	3.3	0.59	2.0
July 27	208	4.8	0.62	2.9
July 28	209	4.2	0.64	2.7
July 29	210	5.3	0.67	3.6
July 30	211	5.7	0.70	4.0
July 31	212	3.9	0.72	2.8
Aug. 1	213	5.2	0.74	3.8
Aug. 2	214	3.2	0.77	2.4
Aug. 3	215	3.5	0.79	2.8
Aug. 4	216	6.0	0.81	4.9
Aug. 5	217	5.8	0.83	4.8
Aug. 6	218	5.6	0.85	4.7
Aug. 8	220	5.0	0.88	4.4
Aug. 9	221	5.0	0.90	4.5

PEANUT ET IN 1989 (CONTINUED)

Date	Calendar Day	Alfalfa ET (mm)	K_c	Peanut ET (mm)
Aug. 10	222	1.6	0.91	1.4
Aug. 11	223	4.4	0.93	4.1
Aug. 12	224	2.5	0.94	2.3
Aug. 13	225	0.4	0.95	0.4
Aug. 14	226	2.8	0.96	2.7
Aug. 15	227	4.0	0.97	3.9
Aug. 16	228	2.8	0.98	2.7
Aug. 17	229	4.6	0.99	4.6
Aug. 18	230	3.1	1.00	3.1
Aug. 19	231	5.4	1.01	5.4
Aug. 20	232	5.3	1.22	5.4
Aug. 21	233	4.0	1.11	4.0
Aug. 22	234	4.3	1.02	4.4
Aug. 23	235	5.6	1.03	5.7
Aug. 24	236	5.3	1.03	5.4
Aug. 25	237	4.2	1.04	4.4
Aug. 26	238	5.2	1.04	5.4
Aug. 27	239	5.2	1.04	5.4
Aug. 28	240	5.2	1.04	5.4
Aug. 29	241	4.4	1.04	4.5
Aug. 30	242	3.7	1.04	3.8
Aug. 31	243	5.2	1.04	5.4
Sept. 1	244	2.6	1.04	2.7
Sept. 2	245	3.6	1.04	3.7
Sept. 3	246	3.6	1.04	3.7
Sept. 4	247	2.1	1.04	2.2
Sept. 5	248	5.0	1.03	5.2
Sept. 6	249	4.8	1.03	4.9
Sept. 7	250	4.4	1.03	4.5
Sept. 8	251	4.8	1.02	4.9
Sept. 9	252	0.7	1.29	0.7
Sept.10	253	2.7	1.24	2.7
Sept.11	254	2.4	1.01	2.4
Sept.12	255	0.4	1.00	0.4
Sept.13	256	0.4	1.00	0.4
Sept.14	257	0.9	0.99	0.9
Sept.15	258	2.3	0.99	2.2
Sept.16	259	4.2	0.98	4.1
Sept.17	260	4.5	0.97	4.4
Sept.18	261	4.1	0.97	4.0
Sept.19	262	3.9	0.96	3.7
Sept.20	263	3.7	0.95	3.5
Sept.21	264	3.7	0.95	3.5
Sept.22	265	3.7	0.94	3.4
Sept.23	266	3.0	0.93	2.8
Sept.24	267	3.0	0.92	2.7
Sept.25	268	3.1	0.92	2.9
Sept.26	269	3.5	0.91	3.2
Sept.27	270	3.3	0.90	3.0
Sept.28	271	3.4	0.89	3.0

PEANUT ET IN 1989 (CONTINUED)

Date	Calendar Day	Alfalfa ET (mm)	K_c	Peanut ET (mm)
Sept.29	272	3.3	0.89	3.0
Sept.30	273	3.3	0.88	2.9
Oct. 1	274	3.6	0.87	3.2
Oct. 2	275	3.1	0.86	2.7
Oct. 3	276	2.9	0.86	2.5
Oct. 4	277	2.6	0.85	2.2
Oct. 5	278	2.9	0.84	2.4
Oct. 6	279	3.2	0.84	2.7
Oct. 7	280	3.0	0.83	2.5
Oct. 8	281	3.1	0.82	2.5
Oct. 9	282	2.9	0.81	2.4
Oct. 10	283	3.2	0.81	2.6
Oct. 11	284	3.6	0.80	2.9
Oct. 12	285	3.4	0.80	2.7
Oct. 13	286	3.3	0.79	2.6
Oct. 14	287	3.2	0.78	2.5
Oct. 15	288	3.1	0.78	2.4
Oct. 16	289	0.3	0.78	0.2
Oct. 17	290	0.7	0.77	0.5
Oct. 18	291	1.2	0.77	0.9
Oct. 19	292	1.6	0.76	1.2
Oct. 20	293	2.3	0.76	1.7
Oct. 21	294	1.5	0.76	1.1
Oct. 22	295	2.3	0.75	1.7

APPENDIX E

IRRIGATION AND RAINFALL DATA

IRRIGATION AND RAINFALL DATA OF 1988

Date	Calendar Day	Rain (mm)	FI (mm)	II (mm)	MI (mm)
Planted					
June 6	158				
June 15	167	0	23	11	4
June 23	175	0	29	19	10
June 26	178	2			
June 28	180	4	30	24	7
July 1	183	7			
July 5	187	0	27	23	9
July 12	194	0	26	17	11
July 19	201	13	39	26	19
July 26	208	0	30	18	10
July 27	209	22			
July 28	210	7			
Aug. 9	222	5	29	20	7
Aug. 16	229	18			
Aug. 23	236	1	38	21	20
Aug. 28	241	19			
Sept. 2	246	3			
Sept. 6	250	0	23	7	9
Sept. 13	257	0	23	12	11
Sept. 15	259	17			
Sept. 16	260	44			
Sept. 17	261	1			
Sept. 18	262	56			
Sept. 19	263	4			
Sept. 23	267	57			
Sept. 28	272	17			
Oct. 1	275	3			
Oct. 5	279	4			
Oct. 6	280	4			
Oct. 7	281	14			
Oct. 15	289	2			
Oct. 20	294	7			
Oct. 24	298				
Total		331	317	198	117
Rain+Irrigation			648	529	448

Notation:

FI -- Full Irrigation
II -- Intermediate Irrigation
MI -- Minimum Irrigation

IRRIGATION AND RAINFALL DATA OF 1989

Date	Calendar Day	Rain (mm)	FI (mm)	II (mm)	MI (mm)
Planted					
June 16	167				
June 27	178	20			
July 2	183	13			
July 11	192	0	30	20	0
July 13	194	9			
July 14	195	49			
July 22	203	15			
Aug. 1	213	0	39	25	16
Aug. 3	215	6			
Aug. 5	217	56			
Aug. 13	225	35			
Aug. 20	232	5			
Aug. 21	233	1			
Aug. 23	235	0	15	13	2
Aug. 29	241	0	38	22	14
Sept. 2	245	30			
Sept. 12	255	80			
Sept. 26	269	0	40	22	21
Oct. 3	276	0	25	15	8
Oct. 6	279	30			
Oct. 17	290	0	21	16	0
Total		349	208	133	61
Rain+Irrigation			557	482	410

Notation:

FI -- Full Irrigation
II -- Intermediate Irrigation
MI -- Minimum Irrigation

APPENDIX F

RESULTS OF WATER BALANCE SIMULATIONS AND THE CORRESPONDING NEUTRON MEASUREMENTS

WATER BALANCE SIMULATION FOR THE 1988 PEANUT GROWING SEASON (Full Irrigation)

Calendar Day	Irrigation & Rainfall (mm)	Runoff (Assumed) (mm)	Estimated ET (mm)	Simulated Soil Water (mm)	Measured Soil Water (mm)
189				**303**	**303**
190			1	302	
191			2	300	
192			2	298	
193			2	297	292
194	26	17	3	**303**	
195			3	300	
196			3	297	295
197			3	294	
198			3	291	
199			3	288	
200			2	286	271
201	53	39	2	297	
202			3	294	
203			4	290	290
204			4	286	
205			4	282	
206			3	279	
207			4	275	261
208	30		4	294	
209	22	11	3	**303**	
210	7		2	302	
211			5	297	292
212			5	292	
213			5	287	
214			5	282	266
215			5	277	
216			5	272	
217			5	267	
218			4	262	
219			5	257	
220			5	252	
221			5	246	227
222	34		4	271	
223			6	265	
224			5	260	244
225			5	255	
226			6	249	
227			4	244	
228			6	238	223
229	18		6	244	
230			5	239	
231			4	235	
232			5	230	227
233			5	225	
234			7	218	
235			6	212	213

WATER BALANCE SIMULATION FOR THE 1988 PEANUT GROWING SEASON
(Full Irrigation)

Calendar Day	Irrigation & Rainfall (mm)	Runoff (Assumed) (mm)	Estimated ET (mm)	Simulated Soil Water (mm)	Measured Soil Water (mm)
236	40		3	242	
237			6	237	
238			5	231	238
239			5	226	
240			2	224	
241	19		1	235	
242			5	231	225
243			4	227	
244			4	222	
245			4	218	216
246			3	215	
247			5	210	
248			5	206	
249			4	201	207
250	23		5	213	
251			5	209	
252			4	205	219
253			4	201	
254			4	197	
255			4	193	
256			4	189	203
257	23		4		
258			2		
259	17		2		
260	44		3		
261			2		
262	56		2		
263	4		4	264	264
264			4	260	
265			4	256	
266			4	252	246
267	57	48	1	260	
268			1	259	
269			3	256	
270			3	252	252
271			3	249	
272	17		3	258	
273			2	256	
274			2	253	
275			1	252	
276			3	250	
277			2	247	
278			1	246	238
279			0	246	
280			1	245	
281	14		0	253	
282			1	252	

WATER BALANCE SIMULATION FOR THE 1988 PEANUT GROWING SEASON (Full Irrigation)

Calendar Day	Irrigation & Rainfall (mm)	Runoff (Assumed) (mm)	Estimated ET (mm)	Simulated Soil Water (mm)	Measured Soil Water (mm)
283			1	251	
284			2	249	250
285			2	246	
286			2	244	
287			2	242	243
288			2	241	
289			1	239	
290			2	237	
291			2	235	236
292			1	233	
293			2	232	
294	7		1	231	227
295			2	229	
296			2	227	
297			2	226	
298			2	224	221

WATER BALANCE SIMULATION FOR THE 1989 PEANUT GROWING SEASON
(Full Irrigation)

Calendar Day	Irrigation & Rainfall (mm)	Runoff (Assumed) (mm)	Estimated ET (mm)	Simulated Soil Water (mm)	Measured Soil Water (mm)
201				**304**	**304**
202			2	302	
203	15	11	2	**304**	
204			2	302	
205			2	300	
206			3	297	
207			2	295	
208			3	292	294
209			3	289	
210			4	286	
211			4	282	
212			3	279	293
213	39	11	4	**304**	
214			2	301	
215	6		3	298	
216			5	294	
217	56	41	5	**304**	
218			5	299	
219			4	294	292
220			4	290	
221			4	286	
222			1	284	286
223			4	280	
224			2	278	
225	35	8	0	**304**	
226			3	301	
227			4	297	
228			3	294	
229			5	290	295
230			3	287	
231			5	281	
232			5	276	
233			4	272	283
234			4	267	
235	15		6	270	
236			5	265	283
237			4	260	
238			5	255	
239			5	250	
240			5	244	266
241	38		5	271	
242			4	267	
243			5	262	266
244			3	259	
245	30		4	279	
246			4	276	
247			2	273	

WATER BALANCE SIMULATION FOR THE 1989 PEANUT GROWING SEASON (Full Irrigation)

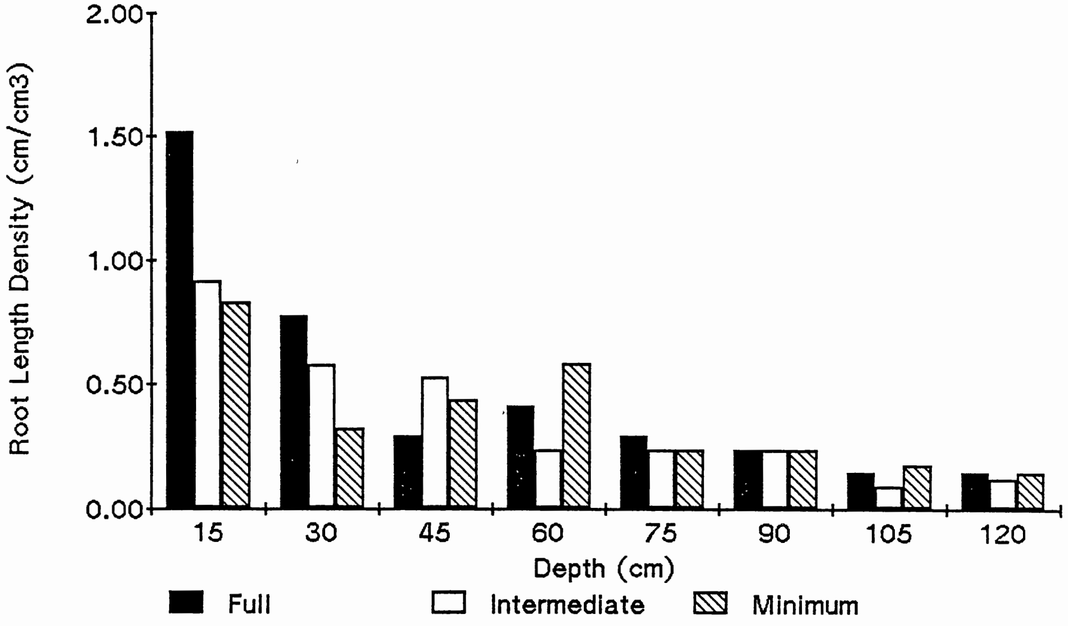
Calendar Day	Irrigation & Rainfall (mm)	Runoff (Assumed) (mm)	Estimated ET (mm)	Simulated Soil Water (mm)	Measured Soil Water (mm)
248			5	268	
249			5	263	
250			5	259	265
251			5	254	
252			1	253	
253			3	251	
254			2	248	252
255	294		0		
256			0		
257			1		
258			2		
259			4		
260			4		
261			4	272	272
262			4	268	
263			3	265	
264			3	261	
265			3	258	260
266			3	255	
267			3	252	
268			3	249	257
269	40		3	280	
270			3	277	
271			3	274	
272			3	271	
273			3	268	
274			3	265	
275			3	263	264
276	25		3	279	
277			2	276	
278			2	274	
279	30		3	296	
280			2	293	
281			3	291	
282			2	288	265
283			3	286	
284			3	283	
285			3	280	263
286			3	278	
287			3	275	
288			2	273	
289			0	272	
290	21		1	287	
291			1	286	
292			1	285	264
293			2	283	
294			1	282	

WATER BALANCE SIMULATION FOR THE 1989 PEANUT GROWING SEASON (Full Irrigation)

Calendar Day	Irrigation & Rainfall (mm)	Runoff (Assumed) (mm)	Estimated ET (mm)	Simulated Soil Water (mm)	Measured Soil Water (mm)
295			2	281	
296			2	279	264
297			1	278	
298			1	277	
299			1	276	262

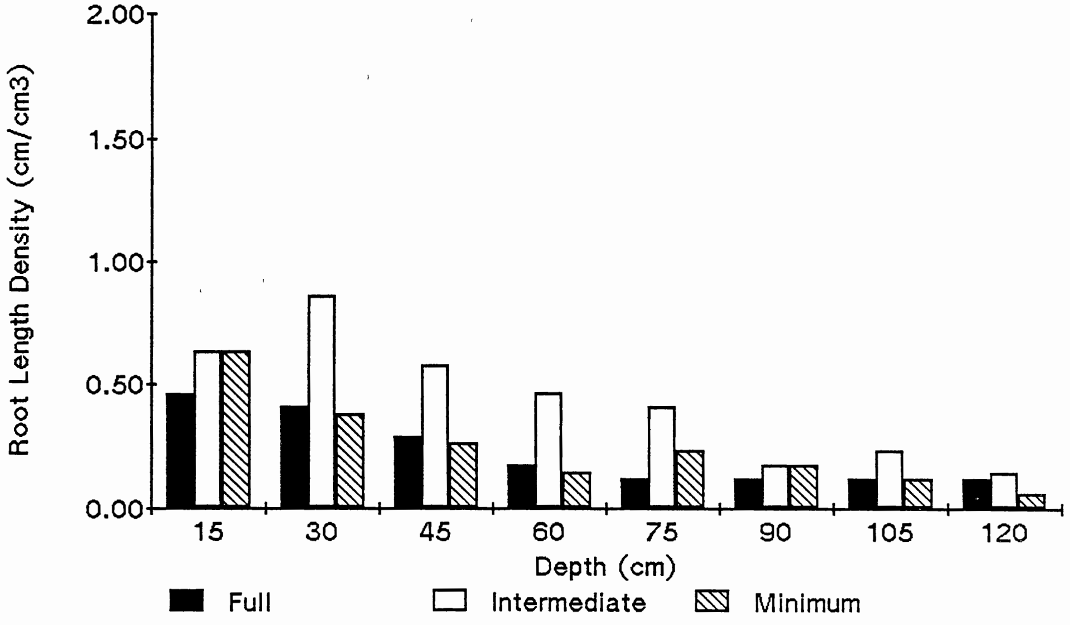
APPENDIX G

DISTRIBUTION OF ROOT LENGTH DENSITY



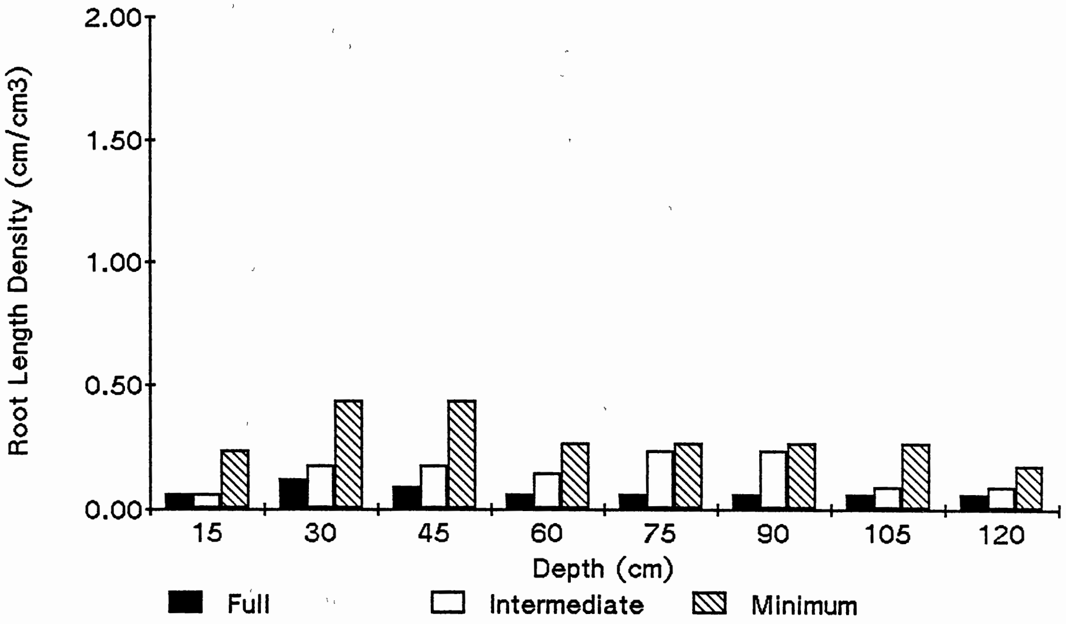
26 July 1989

x = 0 cm

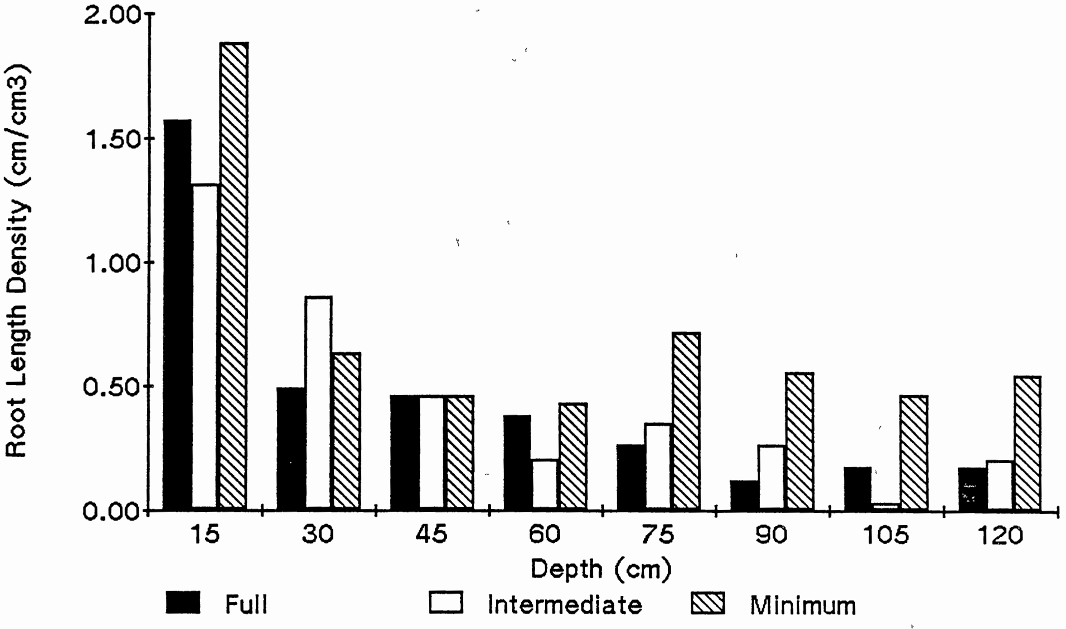


26 July 1989

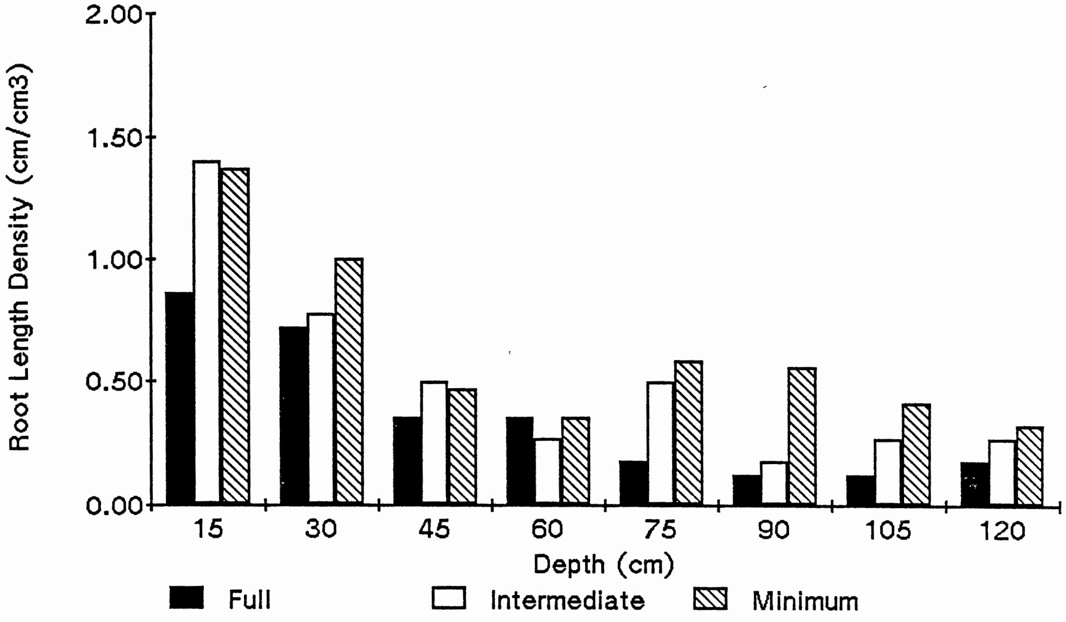
x = 15 cm


26 July 1989

x = 46 cm

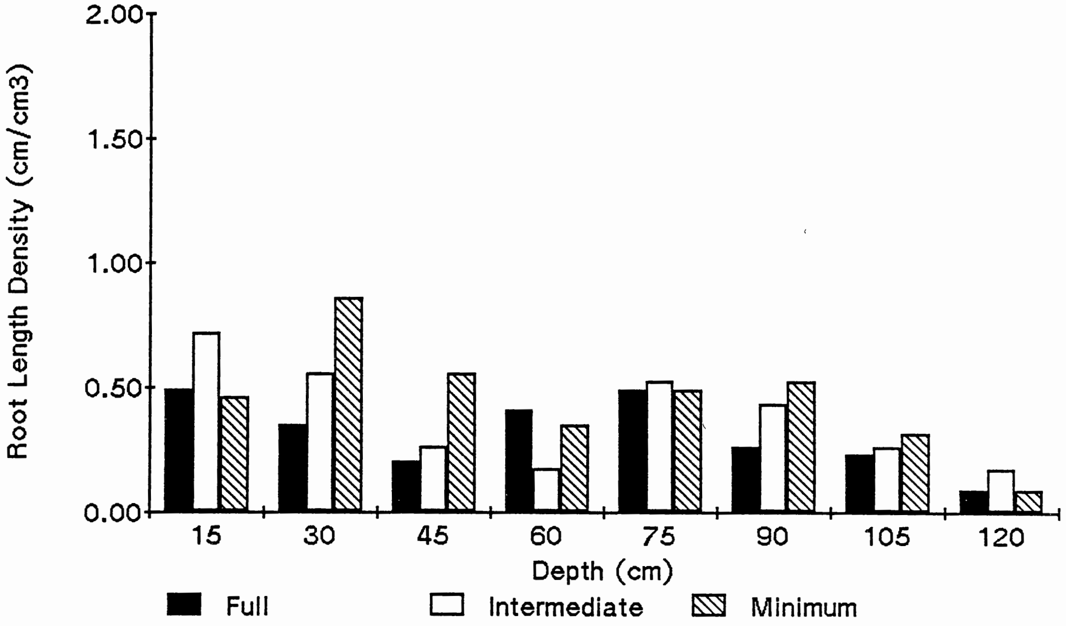

17 August 1989

x = 0 cm



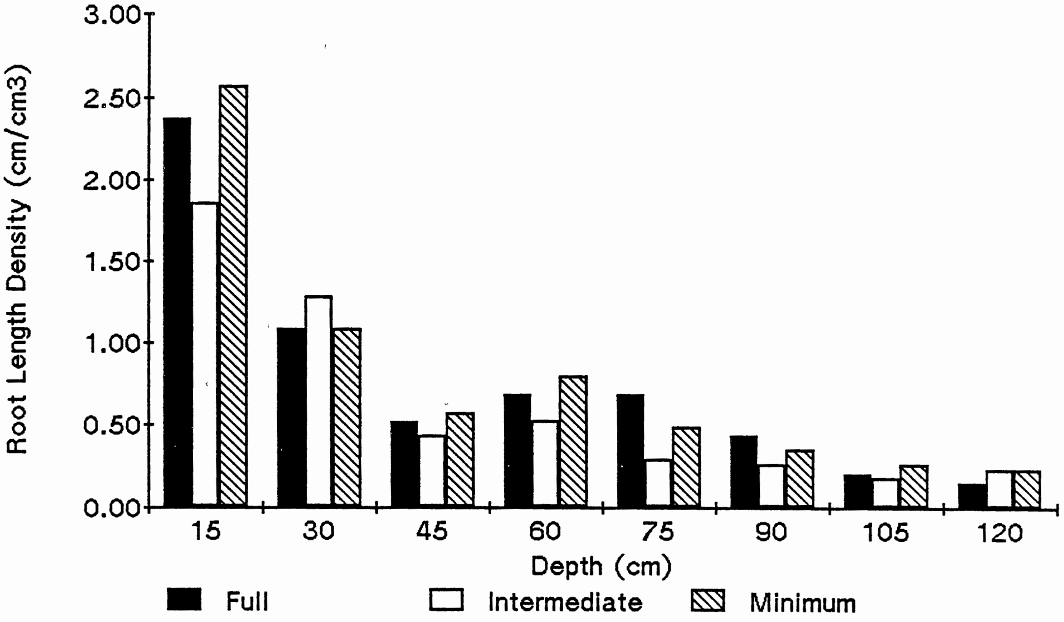
17 August 1989

x = 15 cm



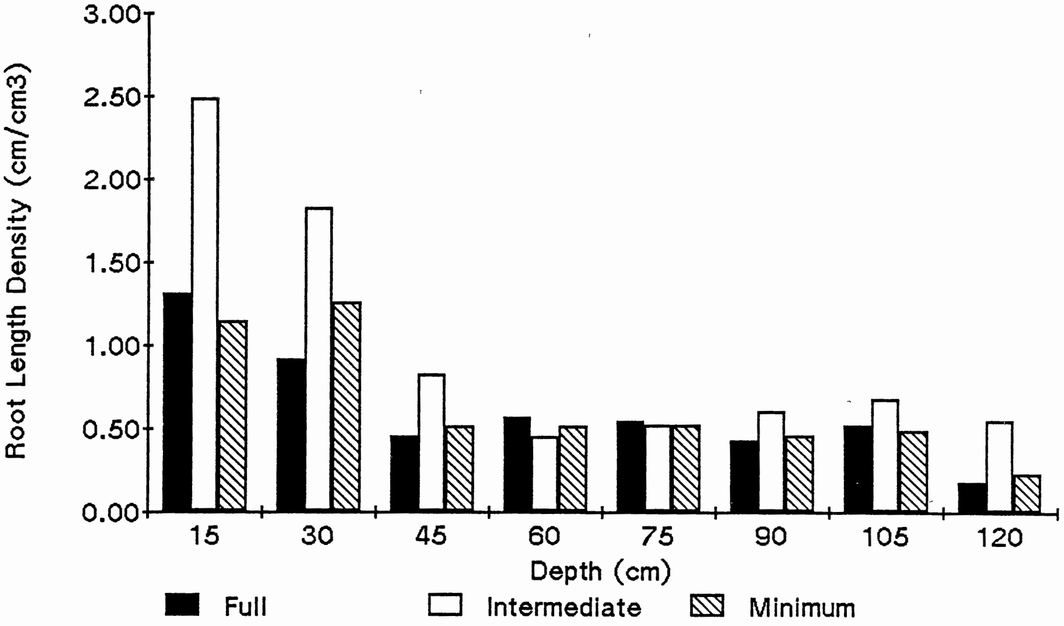
17 August 1989

x = 46 cm



7 September 1989

x = 0 cm

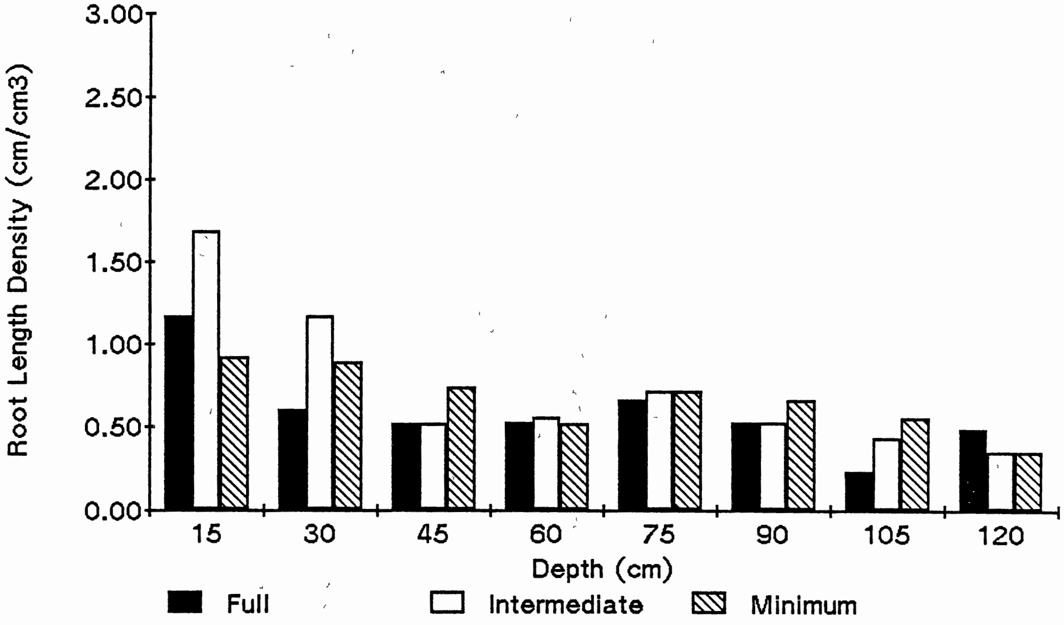


7 September 1989

x = 15 cm

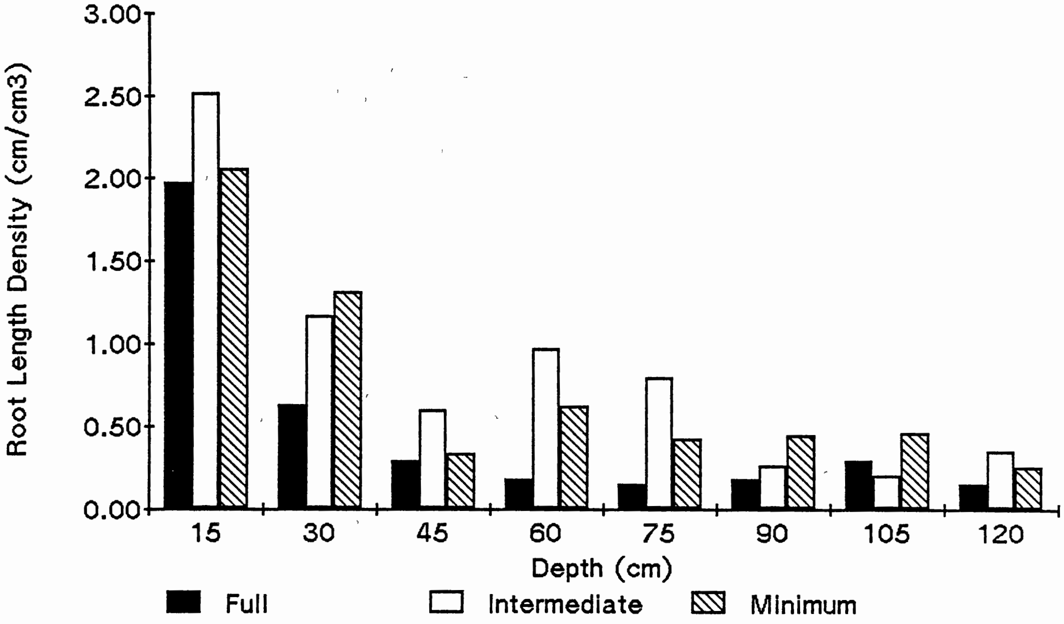
7 September 1989

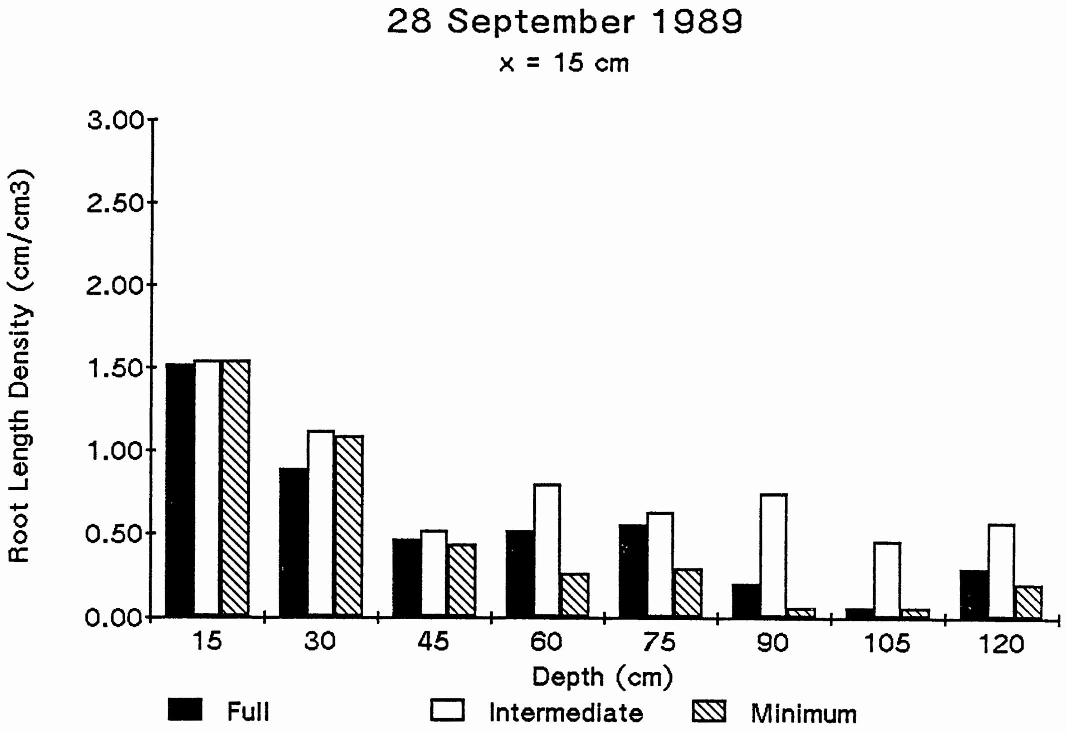
x = 46 cm

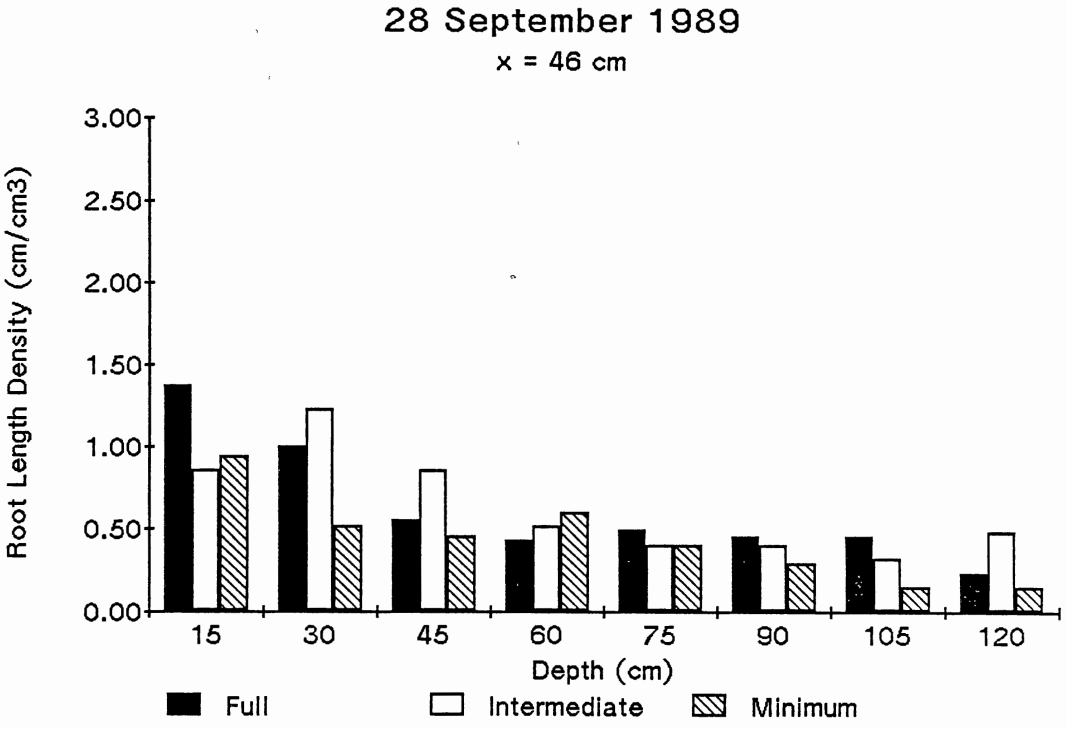


28 September 1989

x = 0 cm




28 September 1989
x = 15 cm
Root Length Density (cm/cm3)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
15
30
45
60
75
90
105
120
Depth (cm)
Full
Intermediate
Minimum


28 September 1989
x = 46 cm
Root Length Density (cm/cm3)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
15
30
45
60
75
90
105
120
Depth (cm)
Full
Intermediate
Minimum

2

VITA

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Doctor of Philosophy

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