Natural Resources Conservation Service
Wetland Science Institute

DRAINMOD REFERENCE REPORT

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United States
Department of
Agriculture

**Soil
Conservation
Service**

South
National
Technical
Center

Fort Worth,
Texas

Drainmod

Reference Report

Methods for Design and Evaluation of Drainage-Water Management Systems for Soils with High Water Tables.

This report was prepared for the U. S. Department of Agriculture, Soil Conservation Service, by Dr. R. W. Skaggs, Professor, North Carolina State University, Raleigh, North Carolina.

PREFACE

This report was prepared for the Soil Conservation Service, United States Department of Agriculture. The purpose is to provide a guide for developing a computer simulation model for drainage - water management systems on high water table soils. The model and related methodologies presented herein were developed to facilitate the design and analysis for these systems. The methods can be used to evaluate the long-term performance of systems for surface and subsurface drainage, subirrigation, controlled drainage, and waste water application to artificially drained soils.

The materials presented in this report are based primarily on research conducted in the Biological and Agricultural Engineering Department at North Carolina State University to develop and test a water management simulation model. The methods draw heavily on the drainage and hydrology literature, and results of recent and ongoing research from several locations are utilized in the material presented. In many cases, approximate methods were favored over the so-called exact approach in the model development because of large differences in computational and input data requirements. The philosophy of the model development was to assemble the linkage between various components of the system, allowing the specifics to be incorporated as subroutines so that they can readily be modified as better methods are developed.

The report contains a detailed description of each component of the model. When possible, alternative methods for treating individual components are presented. Input data requirements are discussed and sources for the data identified. Numerous examples are given to demonstrate the application of the model and associated methodologies for design and evaluation of water management systems. The report also contains the results of sensitivity tests to determine the effect of errors in the input data on predicted design parameters. The subjects of subirrigation and seepage losses are considered in separate chapters in the report. Results of recent research to test the validity of the model were reviewed in detail and are presented as an appendix to this report. Model predictions were compared with field measurements from past drainage studies conducted in three states in addition to the specific work in North Carolina for testing the model. In general, predicted results were in good agreement with field observations and the model is judged to be suitable for application to field scale problems.

The model was developed and tested for use in humid regions. Although research to test, and, if necessary, modify the model for irrigated agriculture in semi-arid climates is currently being conducted, its application should be confined to humid regions at the present time. The methods presented herein were developed for field-sized units with parallel subsurface drains (relief drains). Lateral seepage due to a sloping landscape is not considered as an integral part of the model. This limits application of DRAINMOD to fields with slopes of less than about 5 percent. Freezing conditions are not considered in the model so its application at the present time is confined to periods when the soil is not frozen.

A concentrated effort was made to include all materials needed for development and utilization of a computer simulation model for water management systems on high water table soils. Although the resulting report is somewhat lengthy, I believe that it can be used to accomplish the stated objective.

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METHODS FOR DESIGN AND EVALUATION OF DRAINAGE-WATER MANAGEMENT SYSTEMS FOR SOILS WITH HIGH WATER TABLES

CHAPTER 1

INTRODUCTION

The design of efficient agricultural water management systems is becoming more and more critical as competitive uses for our water resources increase, and as installation and operational costs climb. In humid regions, artificial drainage is necessary to permit farming of some of the nation's most productive soils. Drainage is needed to provide trafficable conditions for seedbed preparation and planting in the spring and to insure a suitable environment for plant growth during the growing season. At the same time, excessive drainage is undesirable as it reduces soil water available to growing plants and leaches fertilizer nutrients, carrying them to receiving streams where they act as pollutants. In some cases, water table control or subirrigation can be used to maintain a relatively high water table during the growing season thereby supplying irrigation water for crop growth, as well as preventing excessive drainage. This type of irrigation has many advantages over other methods for certain conditions and has been practiced in scattered locations for many years (Clinton, 1948, Renfro, 1955). However, these lands constitute only a small percentage of the total land area suitable for subirrigation. This practice has not been rapidly accepted because of the lack of established design criteria and information characterizing the operation of systems in the field.

The design and operation of each component of a water management system should be dependent on soil properties, topography, climate, crops grown and trafficability requirements. Further, the design of one component should depend on the other components. For example, a field with good surface drainage will require less intensive subsurface drainage than it would if surface drainage is poor. This has been clearly demonstrated in both field studies of crop response (Schwab, et al, 1974) and by theoretical methods (Skaggs, 1974). The relative importance of water management components varies with climate, so, in humid regions, a well-designed drainage system may be critical in some years yet provide essentially no benefits in others. Thus, methods for designing and evaluating multicomponent water management systems should be capable of identifying sequences of weather conditions that are critical to crop production and of describing the performance of the system during those periods.

The purpose of this report is to describe methods for the design and evaluation of water management systems for soils with natural or induced high water tables. The basic tool that will be used for design and evaluation is a computer simulation model called DRAINMOD which was developed at North Carolina State University (Skaggs, 1978b). The simulation program characterizes the response of the soil water regime to various combinations of surface and subsurface water management. It can be used to predict the response of the water table and the soil water above the water table to rainfall, evapotranspiration (ET), given degrees of surface and subsurface drainage, and the use of water table control or subirrigation practices. Surface irrigation can also be considered and the model has been used to analyze sites for land disposal of waste water. Climatological data are used in the model to simulate the day to day performance of a given water management system over several years of record. In this way, an optimum water management system can be designed on a probabilistic basis as initially proposed for subsurface drainage by van Schilfgaarde (1965) and subsequently used by Young and Ligon (1972) and Wiser, et al, (1974).

The model establishes a link between the water management system and the water table and soil water conditions. Results of investigations of the effect of soil water stresses (due to both excessively dry and wet conditions) on crop yield responses will allow the model to be used to relate the water management system design to crop yields. Approximate methods for accomplishing this task are now being developed and will be available in the near future. More sophisticated methods are on the horizon. Ongoing research toward developing crop models will provide much more accurate approximations of water management system effects on yields and will increase the value of simulation models of the type discussed here.

This report begins with a description of each of the components now used in DRAINMOD. In some cases, a number of methods could be employed to quantify a single hydrologic component. Therefore, whenever possible, the discussion of each component, such as infiltration or subsurface drainage, includes alternative methods that could be used and which may be advantageous for some applications. Water management model objective functions are discussed in Chapter 3 and the procedures for simulating the performance of a water management system are discussed in Chapter 4. Input data requirements for DRAINMOD, sources of available data and methods for measuring the needed inputs are discussed in Chapter 5. Several examples showing the use of the model for design and analysis of water management systems are given in Chapter 6. Sensitivity analyses which examine the effect of errors in the various input data on the model predictions are given in Chapter 7. While the emphasis in this report is on the simulation model, design and evaluation of subirrigation or water table control systems also requires analysis of short-term effects such as the time required to raise the water level at the beginning of an irrigation cycle, etc. Methods for making these analyses are given in Chapter 8 and the subject of seepage losses during subirrigation is treated in Chapter 9. Finally, field tests of the validity of the simulation model based on data obtained in North Carolina, Ohio, Florida, and California are presented in a separate Appendix.

The methods presented herein for the design and evaluation of water management systems are not exact. Approximations are involved in almost every component of the model as more exact treatments were bypassed in favor of methods that have feasible computational requirements and for which necessary input data can be obtained. Nevertheless, field tests of the model have shown it to be reliable for a wide range of soils and climatological conditions. Although research efforts to improve this and related models will continue, the most efficient means of improving the methodology lies in its application. Application of DRAINMOD to real world situations which are frequently complicated by a lack of input data have already resulted in modifications. It is anticipated that modifications will continue to be made as the model is applied to an ever widening range of conditions.

Limitations of the Model

The model, as developed and presented herein, can be used to analyze a broad range of drainage, subirrigation, and waste water application problems. However, DRAINMOD should not be applied to situations which are widely different than conditions for which it was developed, without further testing. DRAINMOD was developed and tested for use in humid regions. Although research to test and, if necessary, modify the model for irrigated agriculture in semi-arid climates is ongoing, its application should be confined to humid regions at the the present time. The methods were developed for field-sized units with parallel subsurface drains. Lateral seepage due to a sloping landscape is not considered in the present methodology. This limits application of the model to fields with slopes of less than about 5 percent, although the exact slope limitation is dependent on drain spacing, hydraulic conductivity, and other factors. Lateral seepage losses from a water table control system are considered in Chapter 9. Freezing conditions are not considered in the model so its application at the present time is confined to periods when the soil is not frozen.

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CHAPTER 2

THE MODEL

Background

A schematic of the type of water management system considered is given in Figure 2-1. The soil is nearly flat and has an impermeable layer at a relatively shallow depth. Subsurface drainage is provided by drain tubes or parallel ditches at a distance d, above the impermeable layer and spaced a distance, L, apart. When rainfall occurs, water infiltrates at the surface and percolates through the profile raising the water table and increasing the subsurface drainage rate. If the rainfall rate is greater than the capacity of the soil to infiltrate, water begins to collect on the surface. When good surface drainage is provided so that the surface is smooth and on grade, and outlets are available, most of the surface water will be available for runoff. However, if surface drainage is poor, a certain amount of water must be stored in depressions before runoff can begin. After rainfall ceases, infiltration continues until the water stored in surface depressions is infiltrated into the soil. Thus, poor surface drainage effectively lengthens the infiltration event for a given storm permitting more water to infiltrate and a larger rise in the water table than would occur if depression storage did not exist.

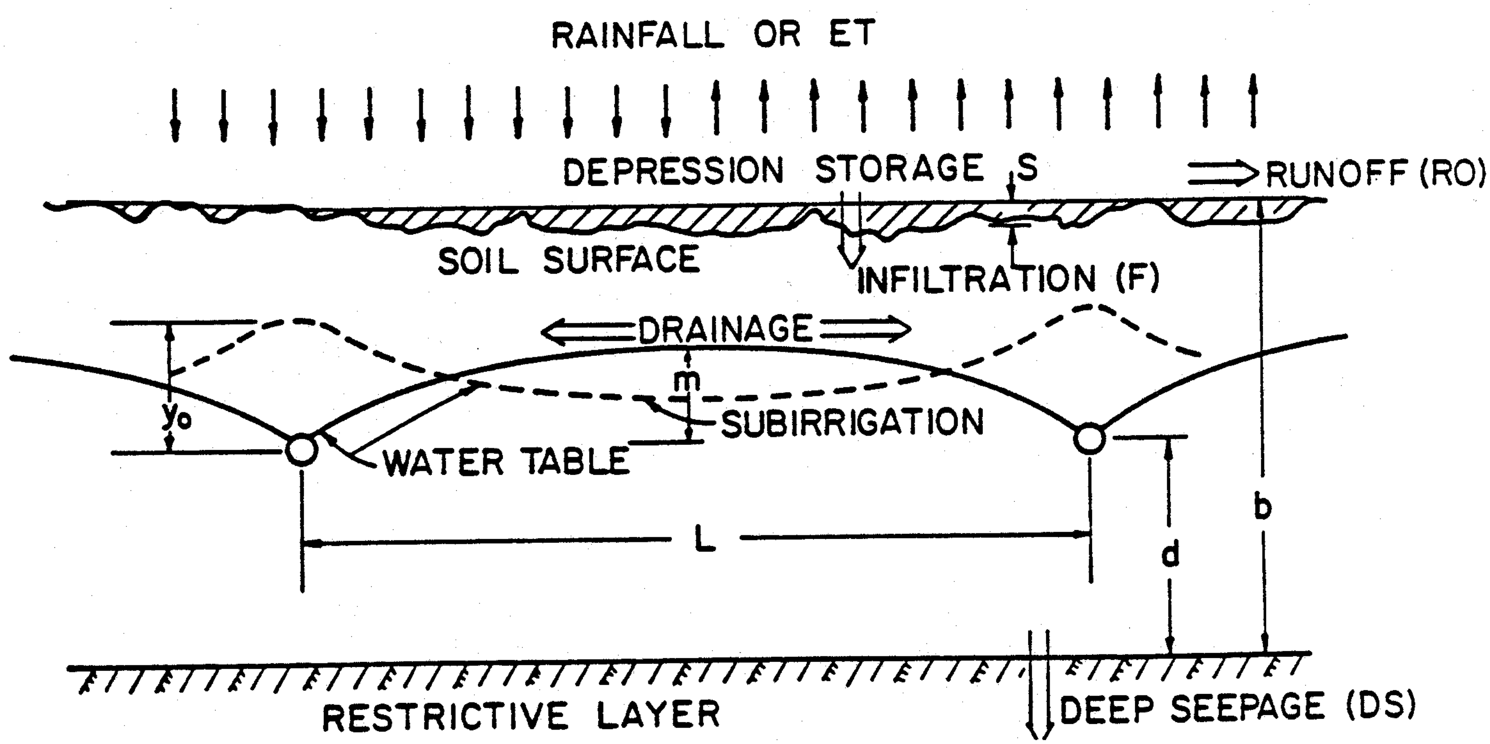

Figure 2-1. Schematic of water management system with subsurface drains that may be used for drainage or subirrigation.

The rate water is drained from the profile depends on the hydraulic conductivity of the soil, the derain depth and spacing, the effective profile depth, and the depth of water in the drains. When the water level is raised in the drains for purposes of supplying water to the root zone of the crop, the drainage rate will be reduced and water may move from the drains into the soil profile giving the shape shown by the broken curve in Figure 2-1. Studies by Skaggs (1974) showed that a high water table reduces the amount of storage available for infiltrating rainfall and may result in frequent conditions of excessive soil water if the system is not properly designed and managed. Water may also be removed from the profile by evapotranspiration (ET) and by deep seepage, both of which must be considered in the calculations if the soil water regime is to be modeled successfully.

Model Development

Two important criteria were adopted in the development of the computer model. First, the model must be capable of characterizing all aspects of water movement and storage in the profile so as to predict, as accurately as possible, the soil water regime and drainage rates with time. And second, the model must be developed such that the computer time necessary to simulate long-term events is not prohibitive. The movement of water in soil is a complex process; it would be an easy matter to become so involved with getting exact solutions to every possible situation that the final answer

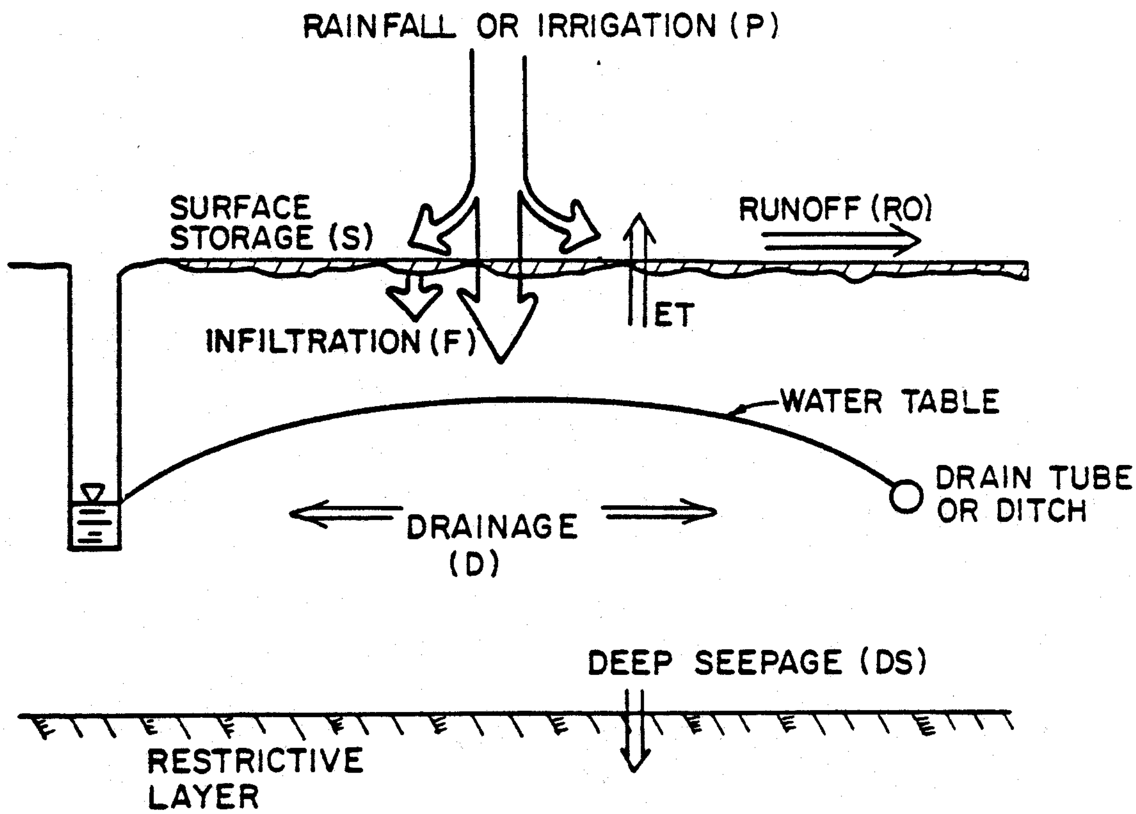

Figure 2-2. Schematic of water management system with drainage to ditches or drain tubes. Components considered in the water balance are shown on the diagram.

would never be obtained. The guiding principle in the model development was therefore to assemble the linkage between various components of the system, allowing the specifics to be incorporated as subroutines, so that they can readily be modified when better methods are developed.

The basis for the computer model is a water balance for the soil profile (Figure 2-2). The rates of infiltration, drainage, and evapotranspiration, and the distribution of soil water in the profile can be computed by obtaining numerical solutions to nonlinear differential equations (e.g., Freeze, 1971). However, these methods are impractical for our purposes because they require prohibitive amounts of computer time for long-term simulations. Instead, approximate methods were used to characterize the water movement processes. In order to insure that the approximate methods provided reliable estimates, they were compared to exact methods for a range of soils and boundary conditions. Further, the reliability of the total model was tested using field experiments.

The basic relationship in the model is a water balance for a thin section of soil of unit surface area which extends from the impermeable layer to the surface and is located midway between adjacent drains. The water balance for a time increment of Δt may be expressed as,

$$\Delta V_a = D + ET + DS - F \qquad (2\text{-}1)$$

Where ΔV_a is the change in the air volume (cm), D is lateral drainage (cm) from (or subirrigation into) the section, ET is evapotranspiration (cm), DS is deep seepage (cm), and F is infiltration (cm) entering the section in Δt.

The terms on the right-hand side of Equation 2-1 are computed in terms of the water table elevation, soil water content, soil properties, site and drainage system parameters, crop and stage of growth, and atmospheric conditions. The amount of runoff and storage on the surface is computed from a water balance at the soil surface for each time increment which may be written as,

$$P = F + \Delta S + RO \qquad (2\text{-}2)$$

Where P is the precipitation (cm), F is infiltration (cm), ΔS is the change in volume of water stored on the surface (cm), and RO is runoff (cm) during time Δt. The basic time increment used in Equations 2-1 and 2-2 is 1 hour. However, when rainfall does not occur and drainage and ET rates are slow such that the water table position moves slowly with time, Equation 2-1 is based on Δt of 1 day. When drainage is rapid but no rainfall occurs, $\Delta t = 2$ hours is used. Conversely, time increments of 0.05 hours or less are used to compute F when rainfall rates exceed the infiltration capacity. A general Flow Chart for DRAINMOD is given in Figure 2-3. Methods used to evaluate the terms in Equations 2-1 and 2-2 and other model components are discussed in the following sections.

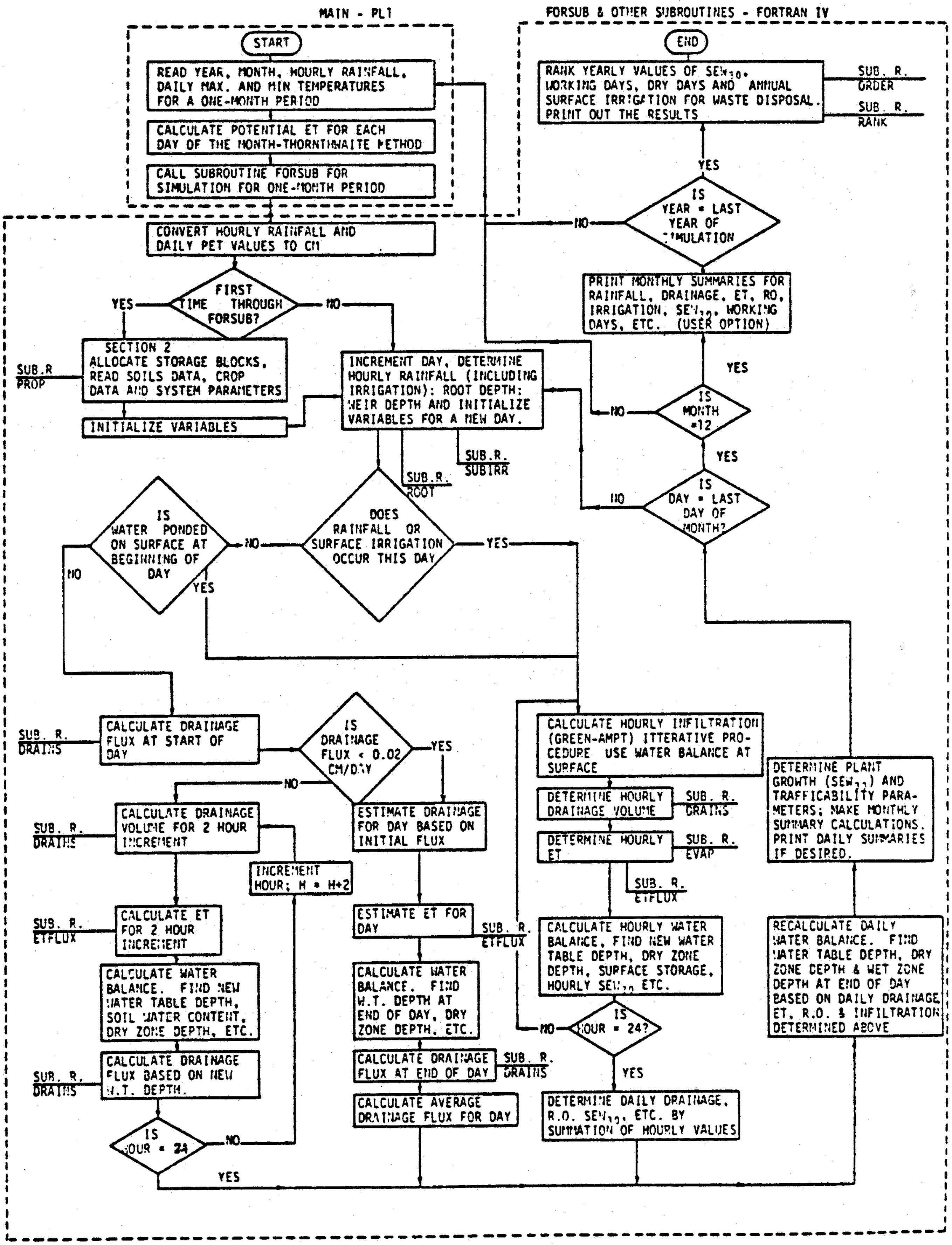

Figure 2-3. An abbreviated general flow chart for DRAINMOD.

Model Components

Precipitation

Precipitation records are one of the major inputs of DRAINMOD. The accuracy of the model prediction for infiltration, runoff, and surface storage is dependent on the complete description of rainfall. Therefore, a short time increment for rainfall input data will allow better estimates for these model components than with less frequent data. A basic time increment of one hour was selected for use in the model because of the availability of hourly rainfall data. While data for shorter time increments are available for a few locations, hourly rainfall data are readily available for many locations in the United States.

Hourly rainfall records are stored in the computer based HISARS (Wiser, 1972, 1975) for several locations in North Carolina and these records are automatically accessed as inputs to the model. A data set for selected locations (at least 2 per state where possible) in the eastern USA is now being developed at North Carolina State University. These hourly rainfall and daily maximum and minimum temperature data will be available to the SCS and to other public and private agencies and will permit the use of DRAINMOD for a wide variety of climatic and geographic conditions. Hourly data for other locations in the USA can be obtained from the National Weather Service at Asheville, North Carolina.

Infiltration

Infiltration of water at the soil surface is a complex process which has been studied intensively during the past two decades. A recent review of infiltration and methods for quantifying infiltration rates was presented by Skaggs, et al, (1979), Philip (1969), Hilel (1971), Morel-Seytoux (1973), and Hadas, et al, (1973) have also presented reviews of the infiltration processes. Infiltration is affected by soil factors such as hydraulic conductivity, initial water content, surface compaction, depth of profile, and water table depth; plant factors such as extent of cover and depth of root zone; and climatic factors such as intensity, duration, and time distribution of rainfall, temperature, and whether or not the soil is frozen.

Methods for characterizing the infiltration process have concentrated on the effects of soil factors and generally assume the soil system to be a fixed or undeformable matrix with well-defined hydraulic conductivity and soil water characteristic functions. Under these assumptions and the additional assumption that there is negligible resistance to the movement of displaced air, the Richards equation may be taken as the governing relationship for the process. For vertical water movement, the Richards equation may be written as,

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] - \frac{\partial K(h)}{\partial z} \qquad (2\text{-}3)$$

Where h is the soil water pressure head, z is the distance below the soil surface, t is time, K(h) is the hydraulic conductivity function, and C(h) is the water capacity function which is obtained from the soil water characteristic. The effects of rainfall rate and time distribution, initial soil water conditions, and water table depth are incorporated as boundary and initial conditions in the solution of Equation 2-3.

Although the Richards equation provides a rather comprehensive method of determining the effects of many interactive factors on infiltration; input and computational requirements prohibits its use in DRAINMOD. The hydraulic conductivity function required in the Richards equation is difficult to measure and is available in the literature for only a few soils. Furthermore, Equation 2-3 is nonlinear and for the general case, must be solved by numerical methods requiring time increments in the order of a few seconds. The computer time required by such solutions would clearly be prohibitive for long-term simulations covering several years of record. Nevertheless, these solutions can be used to evaluate approximate methods and, in some cases, to determine parameter values required in these methods.

Approximate equations for predicting infiltration rates have been proposed by Green and Ampt (1911), Horton (1939), Philip (1957), and Holton, et al, (1967), among others. Of these, the Green-Ampt equation appears to be the most flexible and is used to characterize the infiltration component in DRAINMOD. The Green-Ampt equation was originally derived for deep homogeneous profiles with a uniform initial water content. Water is assumed to enter the soil as slug flow resulting in a sharply defined wetting front which separates a zone that has been wetted from a totally uninfiltrated zone (Figure 2-4). Direct application of Darcy's law yields,

$$f = -K_s \frac{H_2 - H_1}{L_f} \qquad (2\text{-}4)$$

Where f is the infiltration rate which is equal to the downward flux (cm/hr), L_f is the length of the wetted zone, K_s is the hydraulic conductivity of the wetted or transmission zone, H_1 is the hydraulic head at the soil surface and H_2 is the hydraulic head at the wetting front. Taking the soil surface as the datum, $H_1 = H_o$, the ponded water depth and $H_2 = h_f - L_f$ where h_f is the soil water pressure head at the wetting front. Then, Equation 2-4 may be written as,

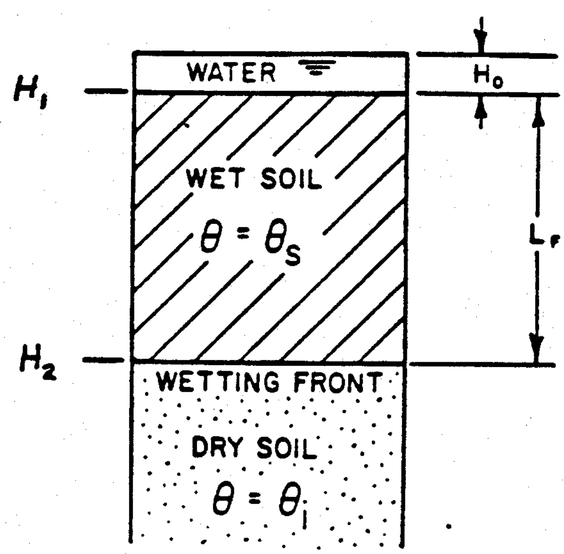

Figure 2-4. Definition sketch for derivation of the Green-Ampt equation.

$$f = -K_s\ (h_f - L_f - H_o)/L_f \qquad (2\text{-}5)$$

Note that h_f is a negative quantity. Substituting a positive quantity, S_{av}, the effective suction at the wetting front for h_f, i.e. $h_f = -S_{av}$ gives,

$$f = K_s\ (S_{av} + H_o + L_f)/L_f \qquad (2\text{-}6)$$

At any time the cumulative infiltration, F, may be expressed as, $F = (\theta_s - \theta_i)\ L_f = M\ L_f$, where θ_s is the volumetric water content in the wet zone, θ_i is the initial water content and M is the initial soil water deficit (or fillable porosity). Assuming H_o is negligible compared to $S_{av} + L_f$, and substituting $L_f = F/M$ into Equation 2-6 gives the Green-Ampt equation:

$$f = K_s + K_s\ M\ S_{av}/F \qquad (2\text{-}7)$$

Although the original derivation by Green and Ampt assumed total saturation behind the wetting front, this requirement was in effect relaxed by Philip (1954). He assumed the water content θ_s, was constant, but not necessarily equal to the total porosity. Likewise, K_s is expected to be less than the saturated hydraulic conductivity. For a given soil with a given initial water content, Equation 2-7 may be written as,

$$f = A/F + B \qquad (2\text{-}8)$$

Where A and B are parameters that depend on the soil properties, initial water content and distribution, and surface conditions such as cover, crusting, etc. Note that the derivation of Equation 2-7 assumes a ponded surface so that infiltration rate is equal to infiltration capacity at all times. This is not the case for rainfall infiltration where there may be long periods of infiltration at less than the maximum rate. In this case, the infiltration rate is assumed equal to the rainfall rate until it exceeds the capacity as predicted by Equation 2-7.

In addition to uniform profiles for which it was originally derived, the Green-Ampt equation has been used with good results for profiles that become denser with depth (Childs and Bybordi, 1969) and for soils with partially sealed surfaces (Hillel and Gardner, 1970). Bouwer (1969) showed that it may also be used for nonuniform initial water contents.

Mein and Larson (1973) used the Green-Ampt equation to predict infiltration from steady rainfall. Their results were in good agreement with rates obtained from solutions to the Richards equation for a wide variety of soil types and application rates. Mein and Larson's results imply that, for uniform deep soils with constant initial water contents, the infiltration rate may be expressed in terms of cumulative infiltration, F, alone, regardless of the application rate. This was first recognized by Smith (1972) and is implicitly assumed in the use of the Green-Ampt equation to predict rainfall infiltration. Reeves and Miller (1975) extended this assumption to the case of erratic rainfall where the unsteady application rate dropped below infiltration capacity for a period of time followed by a high intensity application. Their investigations showed that the infiltration capacity could be approximated as a simple function of F regardless of the application rate versus time history. These results are extremely important for modeling efforts of the type discussed herein. If the infiltration relationship is independent of application rate, the only input parameters required are those pertaining to the necessary range of initial conditions. On the other hand, a set of parameters covering the possible range in application rates would be required for each initial condition if the infiltration relationship depends on application rate.

A frequent initial condition for shallow water table soils is an unsaturated profile in equilibrium with the water table. Solutions for the infiltration rate - time relationship for a profile initially in equilibrium with a water table 100 cm deep are given in Figure 2-5 for a sandy loam soil. The solutions were obtained by solving the Richards equation for rainfall rates varying from 2 to 10 cm/hr and for a shallow ponded surface. Note that infiltration rate is dependent on both time and the application rate (Figure 2-5). However, when infiltration rate is plotted versus cumulative infiltration, $F = \int_o^t f\,dt$, the relationship is nearly independent of the application rate (Figure 2-6). This is consistent with Mein and Larson's (1973) results discussed above for deep soils with uniform initial water contents.

It should be noted that resistance to air movement was neglected in predicting the infiltration relationships given in Figures 2-5 and 2-6. Such effects can be quite significant for shallow water tables where air may be entrapped between the water table and the advancing wetting front (McWhorter, 1971, 1976). Morel-Seytoux and Khanji (1974) showed that the Green-Ampt equation retained its original form when the effects of air movement were considered for deep soils with uniform initial water contents. The equation parameters were simply modified to include the effects of air movement.

Infiltration relationships for a range of water table depths are plotted in Figure 2-7 for the sandy loam considered above. Although these curves were determined from solutions to the Richards equation, similar relationships could have been measured experimentally. The parameters A and B in Equation 2-8 may be determined by using regression methods to fit the equation to observed infiltration data. The resultant parameter values will reflect the effects of air movement, as well as other factors which would have otherwise been neglected. Infiltration predictions based on such measurements will usually be more reliable than if the predictions are obtained from basic soil property measurements. Methods for determining parameters A and B from infiltration measurements and from basic soil properties are discussed in detail in Chapter 5.

The model requires inputs for infiltration in the form of a table of A and B versus water table depth. When rainfall occurs, A and B values are interpolated from the table for the appropriate water table depth at the beginning of the rainfall event. An iteration procedure is used with Equation 2-8 to determine the cumulative infiltration at the end of hourly time intervals.

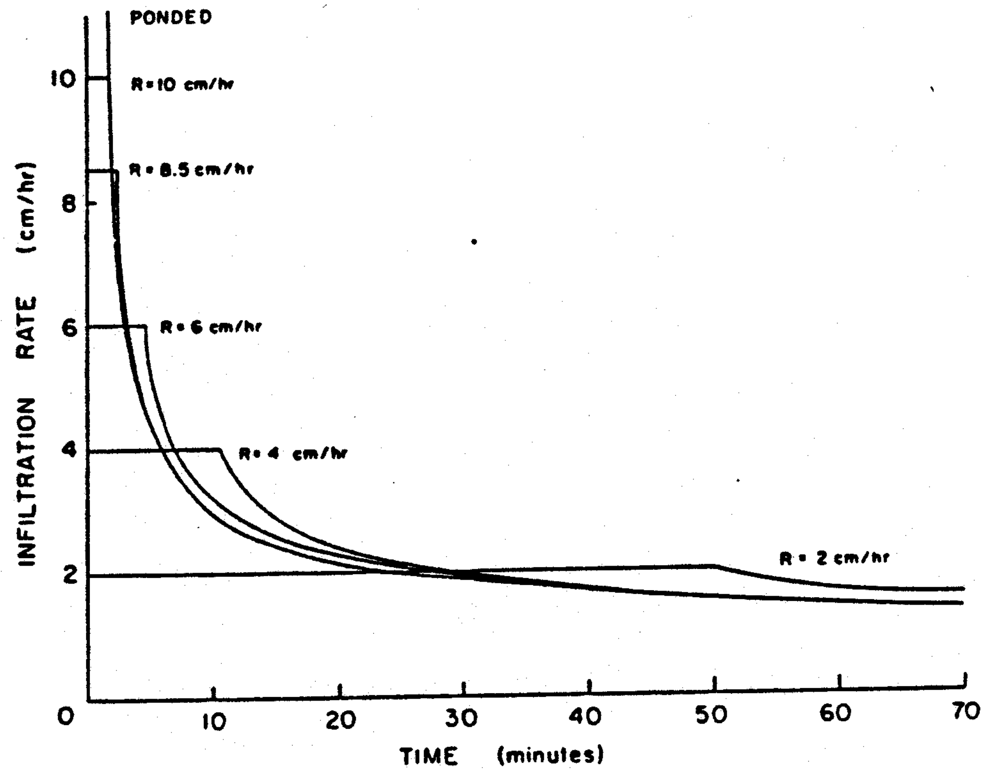

Figure 2-5. Infiltration rate versus time for a sandy loam soil initially drained to equilibrium to a water table 1.0 m deep. Note that the infiltration-time relationships are dependent on the rainfall rate.

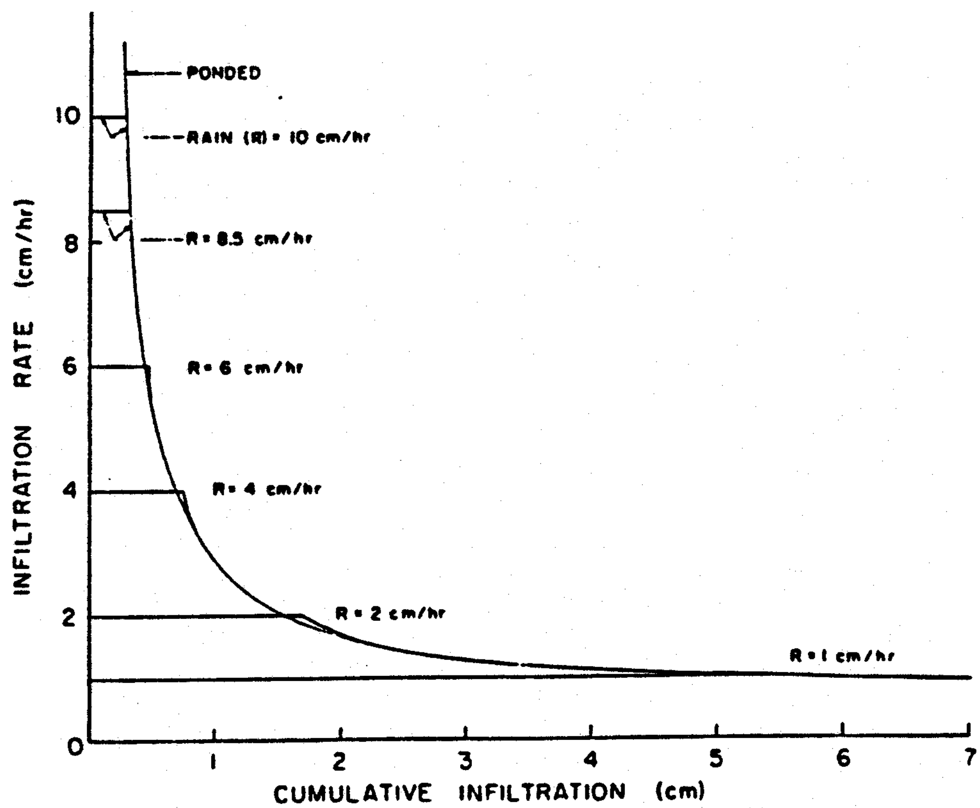

Figure 2-6. Infiltration rate - cumulative infiltration relationships as affected by rainfall rate for the same conditions as Figure 2-5.

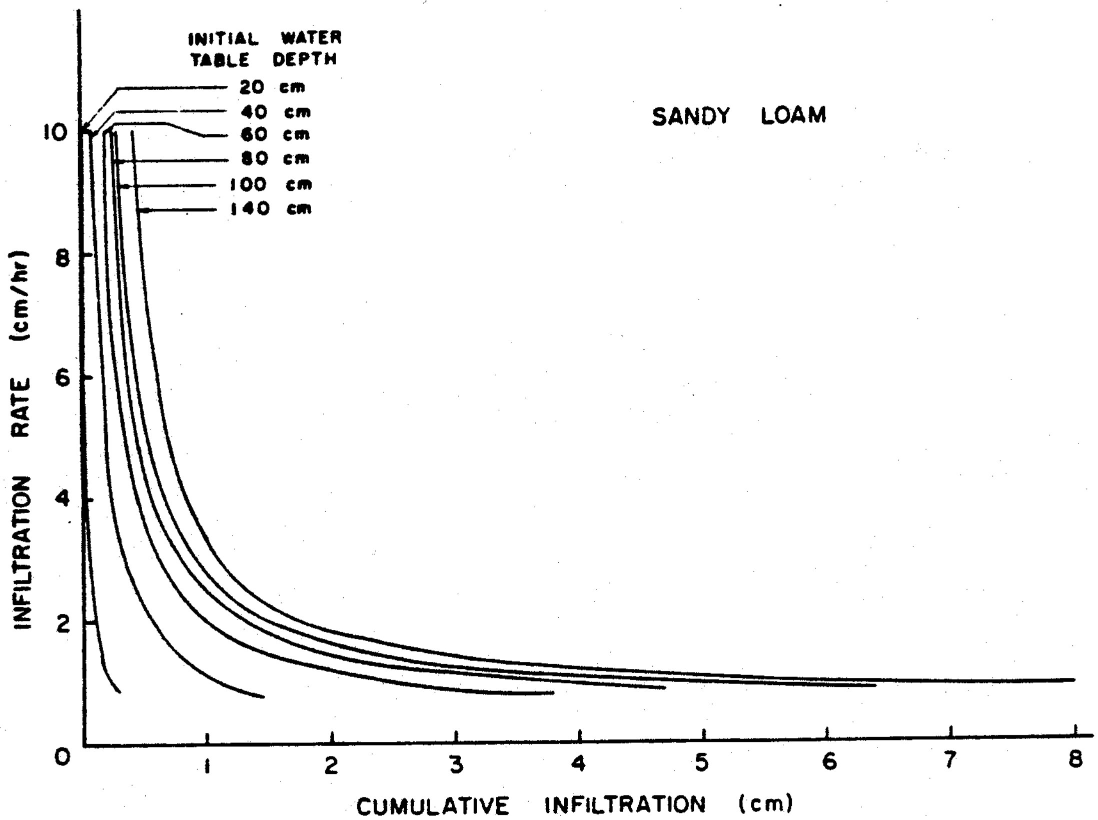

Figure 2-7. Infiltration relationships for the sandy loam soil of Figure 2-5 initially drained to equilibrium at various water table depths.

When the rainfall rate exceeds the infiltration capacity as given by Equation 2-8, Equation 2-2 is applied to conduct a water balance at the surface for Δt increments of 3 minutes (0.05 hour). Rainfall in excess of infiltration is accumulated as surface storage. When the surface storage depth exceeds the maximum storage depth for a given field, the additional excess is allotted to surface runoff. These values are accumulated so that, at the end of the hour, infiltration and runoff, as well as the present depth of surface storage are predicted. Hourly rainfall data are used in the program so the same procedure is repeated for the next hour using the recorded rainfall for that period. Infiltration is accumulated from hour to hour and used in Equation 2-8 until rainfall terminates and all water stored on the surface has infiltrated. Likewise, the same A and B values are used for as long as the rainfall event continues. An exception is when the water table rises to the surface, at which point A is set to A = 0 and B is set equal to the sum of the drainage, ET, and deep seepage rates. An infiltration event is assumed to terminate and new A and B values obtained for succeeding events when no rainfall or surface water has been available for infiltration for a period of at least 2 hours. This time increment was selected arbitrarily and can be easily changed in the program.

Although it is assumed in the present version of the model that the A and B matrix is constant, it is possible to allow it to vary with time or to be dependent on events that affect surface cover, compaction, etc.

Surface Drainage

Surface drainage is characterized by the average depth of depression storage that must be satisfied before runoff can begin. In most cases, it is assumed that depression storage is evenly distributed over the field. Depression storage may be further broken down into a micro component representing storage in small depressions due to surface structure and cover, and a macro component, which is due to larger surface depressions and which may be altered by land forming, grading, etc. A field study conducted by Gayle and Skaggs (1978) showed that the micro-storage component varies from about 0.1 cm for soil surfaces that have been smoothed by weathering (impacting rainfall and wind) to several centimeters for rough plowed land. Macro-storage values for eastern North Carolina fields varied from nearly 0 for fields that have been land formed and smoothed or that are naturally on grade to >3 cm for fields with numerous pot holes and depressions or which have inadequate surface outlets. Surface storage could be considered as a time dependent function or to be dependent on other events such as rainfall and the time sequence of tillage operations. Therefore, the variation in the micro-storage component during the year can be simulated. However, it is assumed to be constant in the present version of the model.

A second storage component that must be considered is the "film" or depth of surface water that is accumulated, in addition to the depression storage, before runoff from the surface begins and which remains during the runoff process. This volume is referred to as surface detention storage and depends on the rate of runoff, slope, and hydraulic roughness of the surface. It is neglected in the present version of the model which assumes that runoff moves immediately from the surface to the outlet. Actually, water that eventually runs off from one section of the field is temporarily stored as surface detention and may be infiltrated or stored at a location downslope as it moves from the field. However, the flow paths are relatively short and this volume is assumed to be small for the field size units normally considered in this model.

Subsurface Drainage

The rate of subsurface water movement into drain tubes or ditches depends on the hydraulic conductivity of the soil, drain spacing and depth, profile depth, and water table elevation. Water moves toward drains in both the saturated and unsaturated zones and can best be quantified by solving the Richards equation for two-dimensional flow. Solutions have been obtained for drainage ditches (Skaggs and Tang, 1976), drainage in layered soils (Tang and Skaggs, 1978), and for drain tubes of various sizes (Skaggs and Tang, 1978). Input and computational requirements prohibit the use of these numerical methods in DRAINMOD, as was the case for infiltration discussed previously. However, numerical solutions provide a very useful means of evaluating approximate methods of computing drainage flux.

The method used in DRAINMOD to calculate drainage rates is based on the assumption that lateral water movement occurs mainly in the saturated region. The effective horizontal saturated hydraulic conductivity is used and the flux is evaluated in terms of the water table elevation midway between the drains and the water level or hydraulic head in the drains. Several methods are available for estimating the drain flux, including the use of numerical solutions to the Boussinesq equation. However, Hooghoudt's steady state equation, as used by Bouwer and van Schilfgaarde (1963), was selected for use in DRAINMOD. Because this equation is used for both drainage and subirrigation flux, a brief derivation is given below.

Consider steady drainage due to constant rainfall at rate, R, as shown schematically in Figure 2-8. Making the Dupuit-Forchheimer (D-F) assumptions and considering flow in the saturated zone only, the flux per unit width can be expressed as:

$$Q = - K h\frac{dh}{dx} \tag{2-9}$$

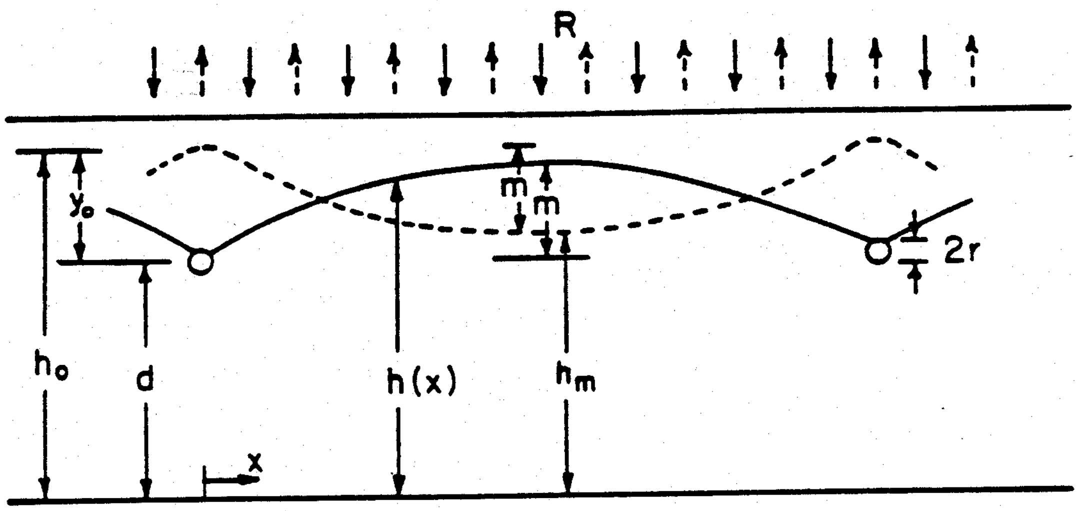

Figure 2-8. Schematic of water table drawdown to and subirrigation from parallel drain tubes.

Where K is the horizontal or lateral saturated hydraulic conductivity and h is the height of the water table above the restrictive layer. From conservation of mass we know that the flux at any point x is equal to the total rainfall between x and the midpoint, x = L/2.

$$-kh \frac{dh}{dx} = - R (L/2 - x) \tag{2-10}$$

Where the negative sign on the right-hand side of Equation 2-10 is due to the fact that flow to the drain at x = 0 is in the -x direction. Separating variables and integrating Equation 2-10 subject to the boundary conditions h = d at x = 0 and h = d + m at x = L/2 yields an expression for R in terms of the water table elevation at the midpoint as,

$$R = \frac{4K (2 md + m^2)}{L^2} \tag{2-11}$$

Although drainage is not a steady state process in most cases, a good approximation of the drainage flux can be obtained from Equation 2-11. That is, the flux resulting from a midpoint water table elevation of m may be approximated as equal to the steady rainfall rate which would cause the same equilibrium m value. Then, the equation for drainage flux may be written as,

$$q = \frac{8\,K\,d_e m + 4\,K\,m^2}{C\,L^2} \qquad (2\text{-}12)$$

Where q is the flux in cm/hr, m is the midpoint water table height above the drain, K is the effective lateral hydraulic conductivity and L is the distance between drains. Bouwer and van Schilfgaarde (1963) considered C to be equal to the ratio of the average flux between the drains to the flux midway between the drains. While it is possible to vary C depending on the water table elevation, it is assumed to be unity in the present version of the model. By solving Equation 2-12 for L with C = 1, we obtain the ellipse equation, which is often used to determine drain spacings. The ellipse equation is discussed in detail in the SCS-NEH (Section 16, Equation 4-8, and pages 4-57 to 4-69).

The equivalent depth, d_e, was substituted for d in Equation 2-11 in order to correct for convergence near the drains. The D-F assumptions used in deriving Equation 2-12 imply that equipotential lines are vertical and streamlines horizontal within the saturated zone. Numerical solutions for the hydraulic head (potential) distribution and water table position are plotted in Figure 2-9 for four different drains: a conventional 114 mm O.D. drain tube, a 114 mm tube with open side walls, an open ditch, and a drain tube surrounded by a square envelope, 0.5 m x 0.5 m in cross-section. The solutions were obtained by solving the two-dimensional Richards equation which requires no simplifying assumptions. These solutions show that, except for the region close to the drain, the equipotential lines in the saturated zone are nearly vertical. Thus, the D-F assumptions would appear reasonable for this case, providing convergence near the drain can be accounted for.

Hooghoudt (van Schilfgaarde, 1974) characterized flow to cylindrical drains by considering radial flow in the region near the drains and applying the D-F assumptions to the region away from the drains. The Hooghoudt analysis has been widely used to determine an equivalent depth, d_e, which, when substituted for d in Figure 2-8 will tend to correct drainage fluxes predicted by Equation 2-12 for convergence near the drain. Moody (1967) examined Hooghoudt's solutions and presented the following equations from which d_e can be obtained.

For $0 < d/L < 0.3$

$$d_e = \frac{d}{1 + \frac{d}{L}\left\{\frac{8}{\pi}\ln\left(\frac{d}{r}\right) - \alpha\right\}} \qquad (2\text{-}13)$$

In which

$$\alpha = 3.55 - \frac{1.6d}{L} + 2\left(\frac{2}{L}\right)^2 \qquad (2\text{-}14)$$

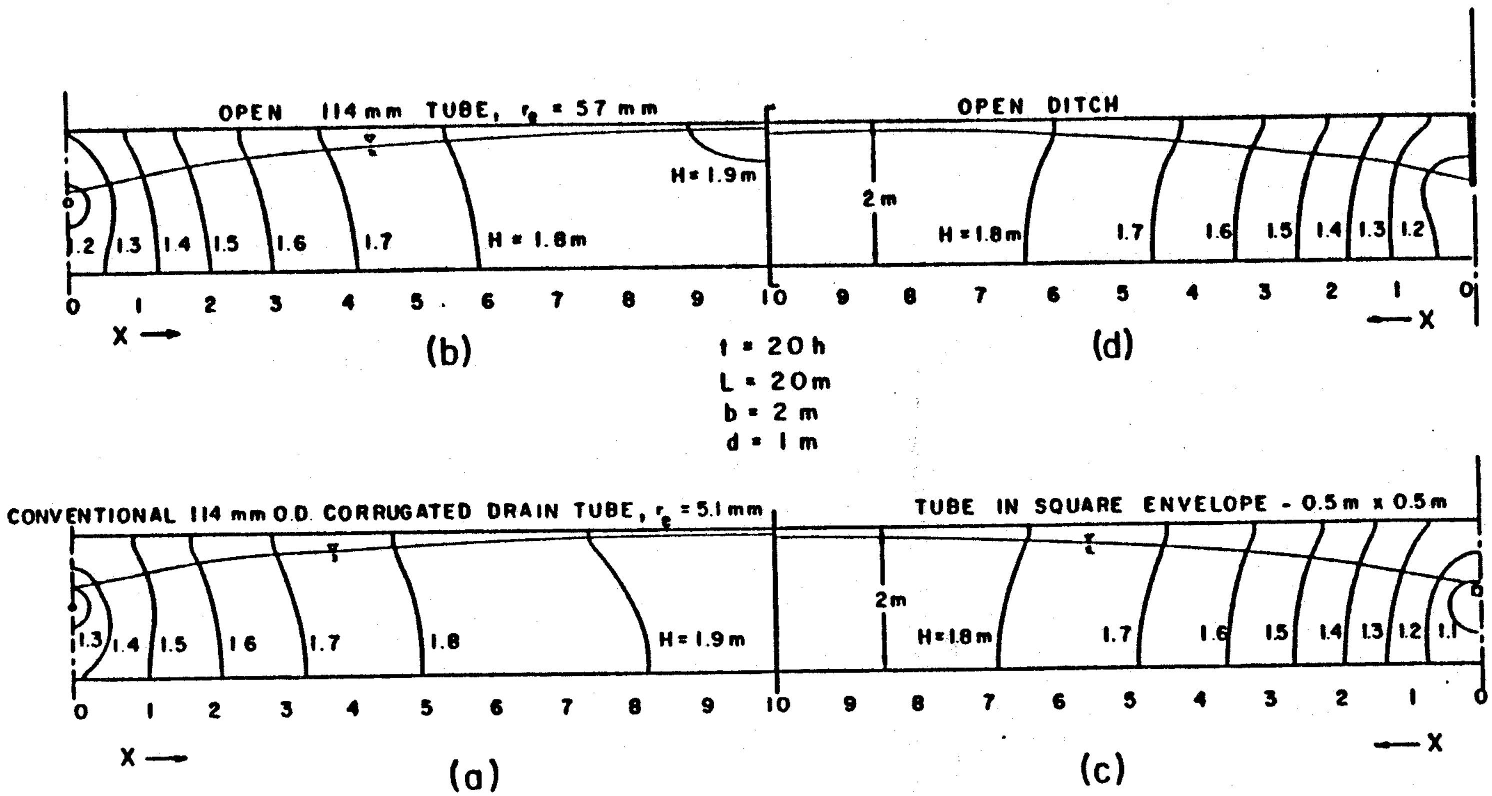

Figure 2-9. Water table position and hydraulic head, H, distribution in a Panoche soil after 20 hours of drainage to (a) conventional 114 mm (4-inch) drain tubes; (b) wide open (no walls) 114 mm diameter drain tubes; (c) a drain tube in a square envelope 0.5 m x 0.5 m; and (d) an open ditch 0.5 m wide. The drain spacings in all cases were 20 m. (After Skaggs and Tang, 1978).

And for d/L > 0.3

$$d_e = \frac{L\pi}{8\{\ln(\frac{L}{r}) - 1.15\}} \quad (2\text{-}15)$$

In which r = drain tube radius. Usually α can be approximated as α = 3.4 with negligible error for design purposes.

For real, rather than completely open drain tubes, there is an additional loss of hydraulic head due to convergence as water approaches the finite number of openings in the tube. The effect of various opening sizes and configurations can be approximated by defining an effective drain tube radius, r_e, such that a completely open drain tube with radius r_e will offer the same resistance to inflow as a real tube with radius r. Dennis and Trafford (1975) used Kirkham's (1949) equation for drainage from a ponded surface and measured drain discharge rates in a laboratory soil tank to define effective drain tube radii. Bravo and Schwab (1977) used an electric analog model to determine the effect of openings on radial flow to corrugated drain tubes. There data were used by the author (Skaggs, 1978b) to determine r_e = 0.51 cm for 11.4 cm (4.5-in.) O.D. tubing. Standard 4-in. (100-cm) corrugated tubing has an outside diameter of approximately 4.5 in. The same methods are used to determine r_e and then d_e which is an input to the model. More discussion of entrance resistance into drain is given in the FAO Irrigation and Drainage Paper No. 9 (FAO, 1972).

The above discussion treats the soil as a homogeneous media with saturated conductivity K. Most soils are actually layered with each layer having a different K value. Since subsurface water movement to drain is primarily in the lateral direction, the effective hydraulic conductivity in the lateral direction is used in Equation 2-12. Referring to Figure 2-10, the equivalent conductivity is calculated using the equation,

$$K_e = \frac{K_1 d_1 + K_2 D_2 + K_3 D_3 + K_4 D_4}{d_1 + D_2 + D_3 + D_4} \quad (2\text{-}16)$$

Because the thickness of the saturated zone in the upper layer is dependent on the water table position, K_e is determined prior to every flux calculation using the value of d_1 which depends on the water table position. If the water table is below layer 1, d_1 = 0 and a similarly defined d_2 is substituted for D_2 in Equation 2-16.

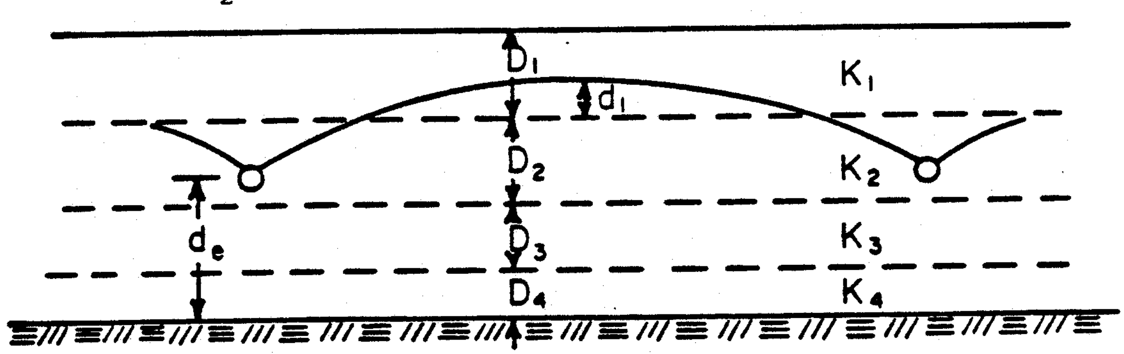

Figure 2-10. Equivalent lateral hydraulic conductivity is determined for soil profiles with up to 5 layers.

The use of the approach discussed above, employing Equations 2-12 through 2-16, will give satisfactory results as long as there are not major differences in the conductivities of the individual layers. When major differences occur, the thicknesses and conductivities of the layers should be considered in defining the equivalent depth, d_e. Van Beers (1976) summarized methods for predicting drain flux which consider convergence to the drains and layered profiles. These steady state methods included that developed by Ernst, which divides the loss in hydraulic head (m in Figure 2-8) into three components: $m = h_v + h_h + h_r$ where h_v = head loss due to vertical flow, h_h = head loss due to horizontal flow and h_r = head loss due to radial flow near the drain. This approach was combined with that of Hooghoudt to give the Hooghoudt-Ernst equation, which does not require a separate calculation for d_e. However, it is necessary to determine a geometric factor from a nomograph for some layered systems. The modified Hooghoudt-Ernest equation is also discussed by van Beers (1976) and could be easily employed in DRAINMOD.

The discussed methods above for predicting drainage flux assumed a curved (elliptical) water table completely below the soil surface, except at the midpoint where it may be coincident with the surface. However, in some cases, the water table may rise to completely inundate the surface with ponded water remaining there for relatively long periods of time. Then, the D-F assumptions will not hold as the streamlines will be concentrated near the drains with most of the water entering the soil surface in that vicinity. Kirkham (1957) showed that in one case, more than 95 percent of the flow entered the surface in a region bounded by ± one-quarter of the drain spacing. The shape of the streamlines for drainage from a ponded surface as compared to that for water table drawdown is shown in Figure 2-11. Drainage flux for a ponded surface can be quantified using an equation derived by Kirkham (1957):

$$q = \frac{4\pi k\ (t + b - r)}{gL} \qquad (2\text{-}17)$$

Where

$$g = 2\ \ln \left[\frac{\tan(\pi(2d-r)/4h)}{\tan \pi r/4h}\right] + 2 \sum_{m=1}^{\infty} \ln \left[\frac{\cosh\ (\pi m\ L/2h) + \cos\ (\pi r/2h)}{\cosh\ (\pi m\ L/2h) - \cos\ (\pi r/2h)} \cdot \frac{\cosh\ (\pi m\ L/2h) - \cos\ (\pi(2d - r)/2h)}{\cosh\ (\pi m\ L/2h) + \cos\ (\pi(2d - r)/2h)}\right] \qquad (2\text{-}18)$$

Where h is the depth of the profile (Figure 2-12) - actual depth not equivalent depth.

Equation 2-17 can be used after the water table rises to the surface for as long as surface water can move freely toward the drains. Recall that water is stored on the surface in depressions, so movement overland toward the drains may be restricted by surface roughness as shown schematically in Figure 2-12. When rows are oriented perpendicular to the drain tube direction, water may move along the furrows to the region above the drains, but still remain in lower depressional areas (with a maximum depth of S, as shown in Figure 2-12). When the ponded depth becomes less than S_1, water can no logner move freely over the surface, the depth of water ponded over

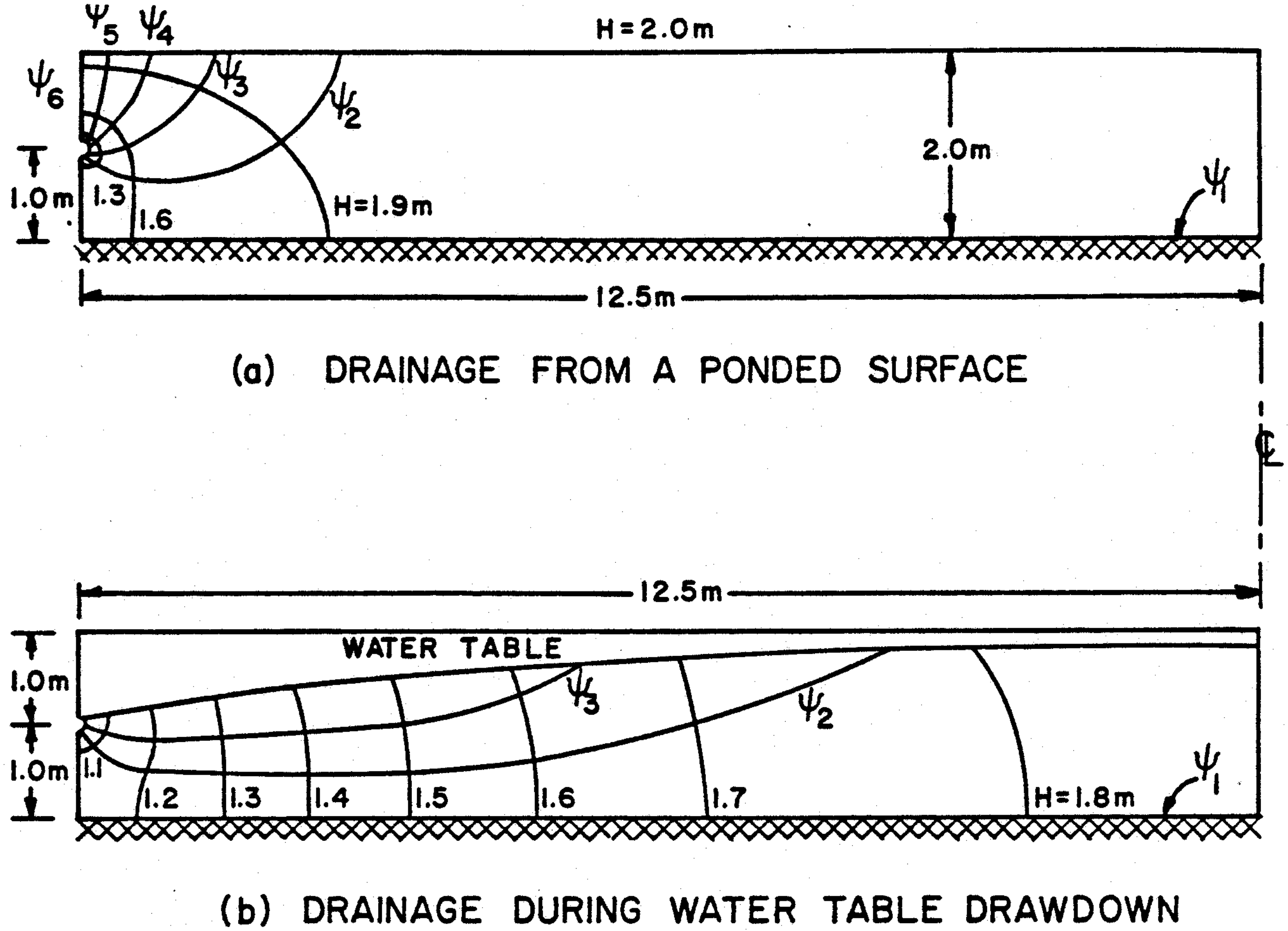

Figure 2-11. Equipotential H and streamlines Ψ for drainage from ponded surface and for drainage during water-table drawdown.

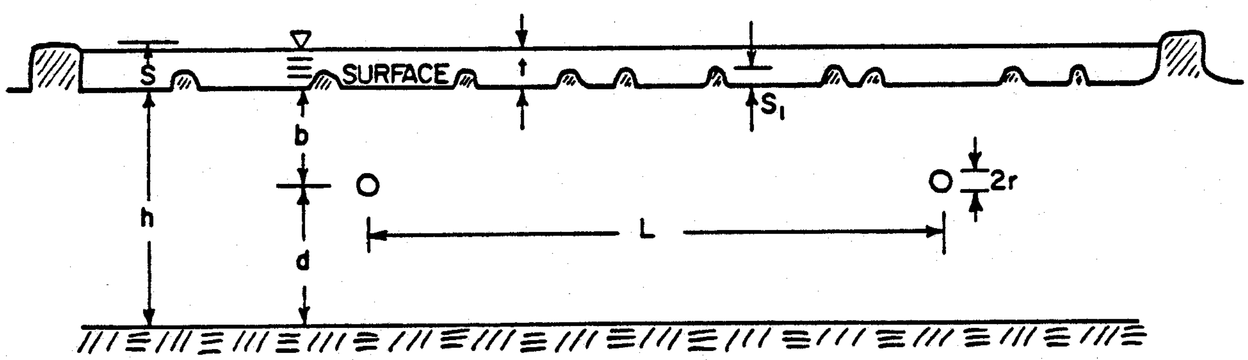

Figure 2-12. Schematic of drainage from a ponded surface. Water will move over the surface to the vicinity of the drains until the ponded depth becomes less than S_1. The maximum depressional storage is S.

the drains will decrease more rapidly than that near the midpoint and Equation 2-12 will provide a better estimate for drainage flux than will 2-17.

Use of equations 2-12 and 2-17 assume that drainage is limited by the rate of soil water movement to the lateral drains and not by the hydraulic capacity of the drain tubes or of the outlet. Usually, the sizes of the drain tubes are chosen to provide a design flow capacity, which is called the drainage coefficient, D.C. Typically, the D.C. may be 1 to 2 cm per day (about 3/8 to 3/4 inches per day) depending on the geographic location and crops to be grown. The D.C. for a given slope and size of drain (either lateral or main) can be obtained from the N.E.H. Section 16, Figures 4-36, or by direct use of the Manning equation. When the flux given by equations 2-12 or 2-17 exceeds the D.C., q is set equal to the D.C. in DRAINMOD as suggested by Chieng, et al, (1978). The water level in the main outlet (canal or river) may also limit the drainage flux in certain cases. However, the outlet water level is affected by surface and subsurface drainage from a much larger area than the field size areas analyzed in DRAINMOD. Such outlet limitations would depend on both the site and storm event and are not treated in the present version of DRAINMOD. That is, the outlet capacity is assumed to be adequate to carry the drainage and runoff from the fields.

In summary, the drainage flux should be calculated using a three-step approach as follows:

1. For water tables below the surface and for ponded depths < S_1, use Equation 2-12.

2. For ponded depths > S_1, use Equation 2-17.

3. When the flux predicted by the appropriate equation, either 2-12 or 2-17, is greater than the D.C., set the flux equal to the D.C.

Subirrigation

When subirrigation is used, water is raised in the drainage outlet so as to maintain a pressure head at the drain of h_o (refer to the broken curve in Figure 2-8). If the boundary condition $h = h_o$ at $x = o$ is used in solving Equation 2-10, the equation corresponding to Equation 2-12 for flux is,

$$q = \frac{4K}{L^2} (2\, h_o\, m + m^2) \qquad (2\text{-}19)$$

Where m is always defined as water table elevation midway between the drains minus the water table elevation at the drain, $(h_m - h_o)$, in this case (Figure 2-8). To correct for convergence, $h_o = y_o + d_e$ is the equivalent water table elevation at the drain and h_m is the equivalent water table elevation midway between the drains. For subirrigation, $h_o > h_m$ and both m and q are negative. Convergence losses, at the drain, are treated in the same manner as in drainage by using the equivalent depth to the impermeable layer, d_e, rather than the actual depth, d, to define h_o in equation 2-19. Equation 2-19 was derived by making the D-F assumptions and solving the resulting flow equation for steady evaporation from the field surface at rate q. The magnitude of q increases as m becomes more negative, i.e., as h_m becomes smaller, until the water table at the midpoint reaches the equivalent depth of the impermeable layer, $h_m = 0$. For deeper midpoint water table depths, which can occur because the actual depth to the impermeable layer is deeper than the equivalent depth, equation 2-19 predicts a decrease in the magnitude of q. Ernst (1975) observed that this is inconsistent with the physics of flow since the maximum subirrigation rate should occur when the midpoint water table reaches the impermeable layer. He derived an equation similar to Equation 2-19 to correct these deficienceis. The equation may be written in the present notation as,

$$q = \frac{4K\,m\,(2h_o + \frac{h_o}{D_o}\,m)}{L^2} \tag{2-20}$$

Where $D_o = y_o + d$, d is the distance from the drain to the impermeable layer, and h_o is the same as defined previously, $h_o = y_o + d_e$. Equation 2-20 is now used in DRAINMOD to predict subirrigation flux.

When controlled drainage is used, a weir is set at a given elevation in the drainage outlet. The actual water level in the drain is not fixed as it is with subirrigation, but depends on size of the outlet, previous drainage, etc. If the water table elevation in the field is higher than the water level in the drain, drainage will occur and the water level in the drain will increase. If it rises to the weir level, additional drainage water will spill over the weir and leave the system. When the water table in the field is lower than that in the drain, water will move into the field at a rate given by Equation 2-10 raising the water table in the field or supplying ET demands while reducing the water level in the drain. The amount of water stored in the drainage outlet and the water level in the outlet during subirrigation or controlled drainage is computed at each time increment by a DRAINMOD subroutine called YDITCH. This subroutine uses the geometry of the outlet, weir setting and drainage or subirrigation flux to determine the water level in the outlet at all times.

Evapotranspiration

The determination of evapotranspiration (ET) is a two-step process in the model. First, the daily potential evapotranspiration (PET) is calculated in terms of atmospheric data and is distributed on an hourly basis. The PET represents the maximum amount of water that will leave the soil system by evapotranspiration when there is a sufficient supply of soil water. The present version of the model distributes the PET at a uniform rate for the 12 hours between 6:00 a.m. and 6:00 p.m. In case of rainfall, hourly PET is set equal to zero for any hour in which rainfall occurs. After PET is calculated, checks are made to determine if ET is limited by soil water conditions. If soil water conditions are not limiting, ET is set equal to PET. When PET is higher than the amount of water that can be supplied from the soil system, ET is set equal to the smaller amount. Methods used for determining PET and the rate that water can be supplied from the soil water system are discussed below.

Potential ET depends on climatological factors which include net radiation, temperature, humidity, and wind velocity. Evapotranspiration can be directly measured with lysimeters or from water balance-soil water depletion methods. However, such measurements are rarely availabe for a given time and location and most PET values are obtained from climatological data using one of the many prediction methods. Jensen (1973) presented a thorough review of the consumptive use of water. He included detailed discussion and summary of the theory of evaporation and evapotranspiration (ET); engineering requirements for ET data; sources of ET data; evaluation of methods for estimating ET and utilization of ET data. Methods for predicting PET in humid regions were reviewed by McGuinness and Borden (1972) and Mohammad (1978). A summary of some of the methods, including required climatological input data is given in Table 2-1. Perhaps the most reliable method is the one developed by Penman (1948, 1956) which is based on an energy balance at the surface. The method requires net radiation, relative humidity, temperature, and wind speed, as input data. Additional methods that could be used include, among others, those by Jensen, et al, (1963), Stephens and Stewart (1963), Turc (1961), and van Bavel (1961). However, all of these equations require dairly solar or net radiation as input data and such data are available for only very few locations. Because we are interested in conducting simulations in many locations throughout the United States, it is necessary to estimate ET based on readily available input data.

The method selected for use in the model was the empirical method developed by Thornthwaite (1948). He expressed the monthly PET as,

$$e_j = c\,\overline{T}_j^{\,a} \tag{2-21}$$

Where e_j is the PET for month j and $\overline{T}_j$ is the monthly mean temperature (°C), c and a are constants which depend on location and temperatures. The coefficients a and c are calculated from the annual heat index, I, which is the sum of the monthly heat indexes, i_j, given by the eqation,

$$i_j = (\overline{T}_j/5)^{1.514} \tag{2-22}$$

$$I = \sum_{i=1}^{12} i_j \tag{2-23}$$

The heat index is computed from temperature records and the monthly PET calculated from Equation 2-21. Then, the monthly PET value is corrected for number of days in the month and the number of hours between sunrise and

Table 2-1. Summary of PET prediction methods for humid regions (from Mohammad, 1978).

Method	Climatological Factors													Formula Used
	TC	TA	RH	RI	H	U	e_s	e_d	DL	RT	S	PT	PD	
Penman		✓	✓		✓	✓	✓	✓			✓			PET = $(\Delta H + E_a \gamma)/(\Delta + \gamma)$ in mm/day
Jensen-Haise		✓		✓										PET = $[0.014(TA)-0.37]RI(0.000673$ in in/day
Stephens & Stewart		✓		✓										PET = $(0.0082\ TA - 0.19)(RI/1500)$ in in/day
Turc	✓			✓										PET = $0.40\ TC(RI + 50)/(TC + 15)$ in in/day
Grassi		✓		✓										PET = $KC_{RS}\ C_T\ C_{crc}\ F$ in in/day
Thornthwaite	✓													PET = $1.6\ (10\ TC/I)^a$ in cm/month
Blaney-Criddle		✓							✓					PET = $(0.0173\ TA - 0.314)KC \times TA(DL/4465.5)$ in in/day
Hamon											✓	✓		PET = $C\ S^2\ PT/100$ in in/day
Papadakis							✓	✓						PET = $0.5625\ (e_a - e_{d-2})$ in cm/month
Makkink	✓			✓										PET = $0.61\ RI[\Delta/(\Delta+\gamma)] - 0.12$ in mm/month
Christiansen		✓	✓			✓				✓	✓			PET = $0.473\ R_T\ C_T\ C_w\ C_H\ C_S\ C_E\ C_M$ in in/day
van Bavel		✓			✓	✓							✓	PET = $[(\Delta/\gamma)(H/L) + BV\ PD]/[(\Delta/\gamma) + 1]$ in in/day

PET = Potential evapotranspiration
TC = Mean air temperature in °C
TA = Mean air temperature in °F
RH = Relative humidity
RI = Solar radiation in langleys
H = Net radiation in langleys
U = Wind speed at a height of 2 meters
e_s = Saturated vapor pressure of the air in mm mercury
e_d = Actual vapor pressure of the air in mm mercury
DL = Day length in hours
L = Latent heat of vaporization of water

RT = Solar radiation at the top of the atmosphere in inches of evaporation equivalent
S = Possible hours of sunshine in units of 12 hours
PT = Saturated vapor density
PD = Vapor pressure deficit in mm
K = Constant (0.537)
C_{crc} = Plant cover coefficient (for meadow is 1.0)
F = Constant (for alfalfa is 1.09)
KC = Crop growth stage coefficient
C = Constant (0.55)
C_E = Coefficient for the elevation of the site
C_M = Monthly vegetative coefficient
a = $6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.792 \times 10^{2} I + 0.4924$
Δ = Slope of saturated vapor pressure curve.

sunset in the day by adjusting for the month and latitude. Daily values may be obtained from the monthly PET by using the daily mean temperature according to the methods given by Thornthwaite and Mather (1957).

The PET is computed in the main program of DRAINMOD from recorded daily maximum and minimum temperature values. The heat index must be determined and entered, along with the latitude of the site, separately. Adjustments for day length and number of days in the month are made in the program based on latitude and date. This version of the main program also inputs hourly rainfall from climatological records and is used for long-term simulations. Another version of the main program was developed to input climatological data obtained in experiments to test the model. The daily PET values were calculated separately and read into the model from cards. In this case, any method could be used to determine PET, although the Thornthwaite method was still used for all tests.

The approximate nature of the Thornthwaite equation for predicting daily PET should be emphasized. The following comments on the method were made by Taylor and Ashcroft (1972):

> "This equation, being based entirely upon a temperature relationship, has the disadvantage of a rather flimsy physical basis and has only weak theoretical justification. Since temperature and vapor pressure gradients are modified by the movement of air and by the heating of the soil and surroundings, the formula is not generally valid, but must be tested empirically whenever the climate is appreciably different from areas in which it has been tested. ... In spite of these shortcomings, the method had been widely used. Because it is based entirely on temperature data that are available in a large number of localities, it can be applied in situations where the basic data of the Penman method are not available."

Several of the methods listed in Table 2-1, as well as others not listed, will give more accurate estimates of PET than Thornthwaite. The Penman (1948) equation and the combination method by van Bavel (1966) are reliable methods, but reqire input data that are not available for many locations, especially for the long, continuous period of record needed in application of DRAINMOD. However, it is important to note that, if the input data can be obtained, these or other methods can be used in DRAINMOD by simply substituting for the Thornthwaite method in the main program. The necessary data for other methods may be available for some locations and it may be desirable to change the PET component for such applications. Measurements of net radiation, wind speed, RH, etc., are presently being conducted, analyzed and stored using modern micro computer technology. Thus, complete sets of required input data for the more sophisticated PET precediction equations may be available for many locations in the future.

In spite of the deficiency of the Thornthwaite method, it has given good results in some areas and it appears to be sufficiently accurate for drainage modeling in humid regions. Mohammad (1978) compared six methods for predicting PET for eastern North Carolina conditions. His study was closely associated with North Carolina State Univeristy experiments to test

DRAINMOD. Mohammad found that the PET values predicted by the Thornthwaite method were somewhat higher than that predicted from pan evaporation measurements and lower than predictions from the Penman method. Considering the difference in input requirements, the Thornthwaite method appears to provide an acceptable estimate of PET for North Carolina conditions.

An alternative method of estimating PET is to use measured daily pan evaporation corrected by a pan coefficient. The pan coefficient is usually taken to be about 0.7. Daily pan evaporation values can easily be read into DRAINMOD, if they are available. This method is reliable for a wider range of locations and conditions than the Thornthwaite method. The problem with its use is that the data may not be available for locations of interest.

Another method for estimating ET in terms of temperature and day length is the Blaney-Criddle formula. This method was developed by Blaney and Criddle (1947) for irrigated regions of the United States. The method has been modified by the SCS and is described, in detail, along with charts for consumptive-use and crop growth stage coefficients in Technical Release No. 21, "Irrigation Water Requirements." The Blaney-Criddle methods has been widely correlated with field experiments having been empirically developed for irrigated areas of the semi-arid and arid regions. According to Taylor and Ashroft (1972), the method gives an estimate of actual ET, rather than PET, because it is based on correlations with existing irrigation practice. This would cause some difficulty in using the Blaney-Criddle method in DRAINMOD where the effect of limiting soil water conditions is considered separately from PET calculations. Taylor and Ashcroft state that the method "is probably adequate for many estimates of seasonal ET under conditions similar to those for which crop coefficients and consumptive use factors have been determined. It has not proven reliable for shorter periods." Still, this may be a suitable alternative to the Thornthwaite method, especially for applications in the west, although it would require some modification of DRAINMOD.

Each ET calculation involves a check to determine if soil water conditions are limiting. When the water table is near the surface or when the upper layers of the soil profile have a high water contnet, ET will be equal to PET. However, for deep water tables and drier conditions, ET may be limited by the rate that water can be taken up by plant roots. Gardner (1958) analyzed the factors controlling steady evaporation from soils with shallow water tables by solving the governing equations for unsaturted upward water movement. For soils with a given functional relationship between unsaturated hydraulic conductivity and pressure head, $K = K(h)$, Gardner presented simplified expressions for the maximum evaporation rate in terms of water table depth and the conductivity function parameters. For steady unsaturated flow, the upward flux is constant everywhere and the governing equation may be written as,

$$\frac{d}{dz}\left[K(h)\frac{dh}{dz} - K(h)\right] = 0 \qquad (2\text{-}24)$$

Where h is the soil water pressure head and z is measured downward from the surface (Figure 2-13). For any given water table depth, the rate of upward water movement will increase with soil water suction (-h) at the surface. Therefore, the maximum evaporation rate for a given water table

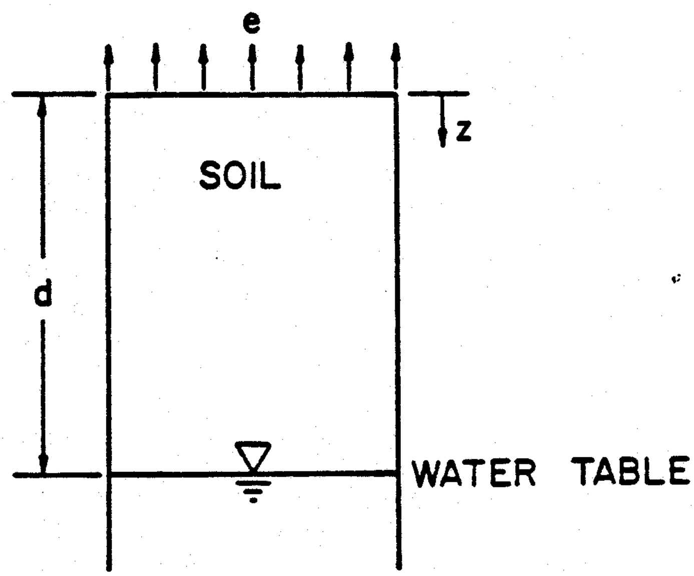

Figure 2-13. Schematic for upward water movement from a water table due to evaporation.

depth can be approximated by solving Equation 2-24, subject to a large negative h value, say h = -1000 cm, at the surface (z = 0) and h = 0 at z = d, the water table depth. Numerical solutions to Equation 2-24 can be obtained for layered soils and for functional or tabluated K(h) relationships (See Chapter 5 and Appendix F). By obtaining solutions for a range of water table depths, the relationship between maximum rate of upward water movement and water table depth can be developed. Such a relationship is shown in Figure 2-14 for the Wagram loamy sand studied by Wells and Skaggs (1976).

Relationships such as that shwon in Figure 2-14 are read as inputs to the model in tabular form. Then, if the PET is 5 mm/day, the ET demand could be satisfied directly from the water table for water table depths less than about 0.64 m. For deeper water tables, ET for that day would be less than 5 mm or the difference would have to be extracted from root zone storage. The root depth will be discussed in a later section. However, it should be pointed out that the roots are assumed to be concentrated within an effective root zone, and that the surface boundary condition may be shifted to the bottom of the root zone, as indicated by the abscissa label in Figure 2-14.

Methods used for determining whether ET is limited by soil water conditions can best be described by an example. Assume that the Wagram soil shown in Figure 2-14, the water table at the beginning of day k is 0.91 m between the bottom of the dry zone; the root zone depth is 10 cm and PET for

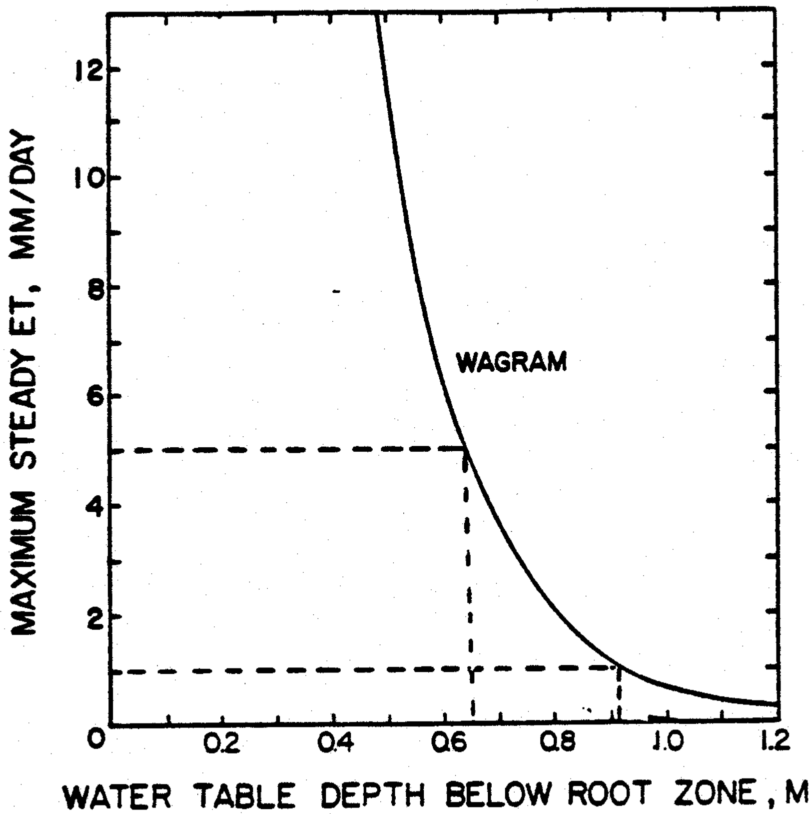

Figure 2-14. Relationship between maximum rate of upward water movement versus water table depth below the root zone for a Wagram loamy sand.

day x is 5 mm. From Figure 2-14, we find that 1 mm of the PET demand will be supplied from the water table, leaving a 4 mm deficit. This deficit can be supplied by water stored in the root zone, if it has not already been used up. Here it is assumed that the plant roots will extract water down to some lower limit water content, $\theta_{\ell\ell}$; the wilting point water content has been used for $\theta_{\ell\ell}$, but a larger value can be substituted if desired. For convenience, this water is assumed to be removed from a layer of soil starting at the surface and creating a dry zone which is limited to a maximum depth equal to the rooting depth. Taking a value of $\theta_{\ell\ell}$ of 0.15 and a saturated water content, θ_s, of 0.35 the 4 mm deficity would dry out a layer of thickness 0.4 cm/0.35 - 0.15) = 2 cm. Thus, the dry zone depth at the end of day k, would be incrased by 2 cm. Further, the total water table depth would be incrased by 2 cm in addition to the incrase resulting from the upward movement of the 1 mm of water. Under these conditions, ET for day k will be equal to the PET fo 5 mm. When the dry zone depth becomes equal to the rooting depth, ET is limited by soil water conditions and is set equal to the upward water movement. For example, if the dry zone at the beginning of day k was already 10 cm deep, the ET for day k would be limited to the rate of upward water movement of 1 mm, rather than 5 mm. The storage volume in the dry zone is accumulated separately from the rest of the unsaturated zone. It is updated on a day-to-day, hour-to-hour basis, and is assumed to be the first volume filled when rainfall or irrigation occurs.

One problem with the use of the methods discussed above for calculating ET, is the difficulty of obtaining reliable K(h) data needed to determine the relationship given in Figure 2-14 for many field soils. This is particularly true for multilayered soils and is discussed in detail in Chapter 5. A more approximate method was developed and may be used as an option in the model by estimating a single critical or limiting depth parameter. When this option is used, it is assumed that the potential ET rate will be supplied from the water table until the distance between the root zone and the water table becomes greater than the limiting depth. After the distance from the root zone and the water table reaches the limiting depth, it is assumed that water will be extracted from the root zone at a rate still equal to the potential ET rate, until the root zone water content reaches $\theta_{\ell\ell}$ in the same manner as was explained above when PET was greater than the rate of upward water movement. Thus, water is removed from the root zone from the surface downward until the depth of the resulting dry zone is equal to the rooting depth. Then, ET is assumed equal to zero. This option is considered more approximate than the alternative method and should be used only when the relationship between maximum upward flux and water table depth cannot be obtained.

Predictions of ET, as limited by soil water conditions, are shown schematically in Figure 2-15 for a period of constant PET. As discussed above, ET is assumed to be equal to PET, until the water content in the entire root zone falls to $\theta_{\ell\ell}$. Then, there is a steep drop in ET to a value equal to the upward flux from the water table. Such abrupt changes are very rare in natural situations and better methods can be devised to handle the transition, as water is removed from the root zone. Actually, the rate that water can be removed from the root zone is a function of soil water potential (Figure 2-16).

The rate, E_r, that water can be removed from the root zone to satisfy ET demand could be calculated from a relationship such as the one developed by Norero (1969):

$$E_r = PET/(1 + (\psi/\psi^*)^k) \qquad (2\text{-}25)$$

Where k is a constant that can be defined using methods given in Taylor and Ashcroft (1972) and Norero (1969), ψ is the soil water potential in the root zone which could be obtained from the soil water characteristic using the average root zone water content, and ψ^* is the value of ψ when $E_r = 0.5$ PET. Inclusion of Equation 2-24 or a similar method in DRAINMOD would likely improve predictions for periods when the dry zone approaches the root zone depth. However, these modifications have not been made, nor tested at this time.

Soil Water Distribution

The basic water balance equation for the soil profile (Equation 2-1) does not require knowledge of the distribution of the water within the profile. However, the methods used to evaluate the individual components, such as drainage and ET, depend on the position of the water table and the

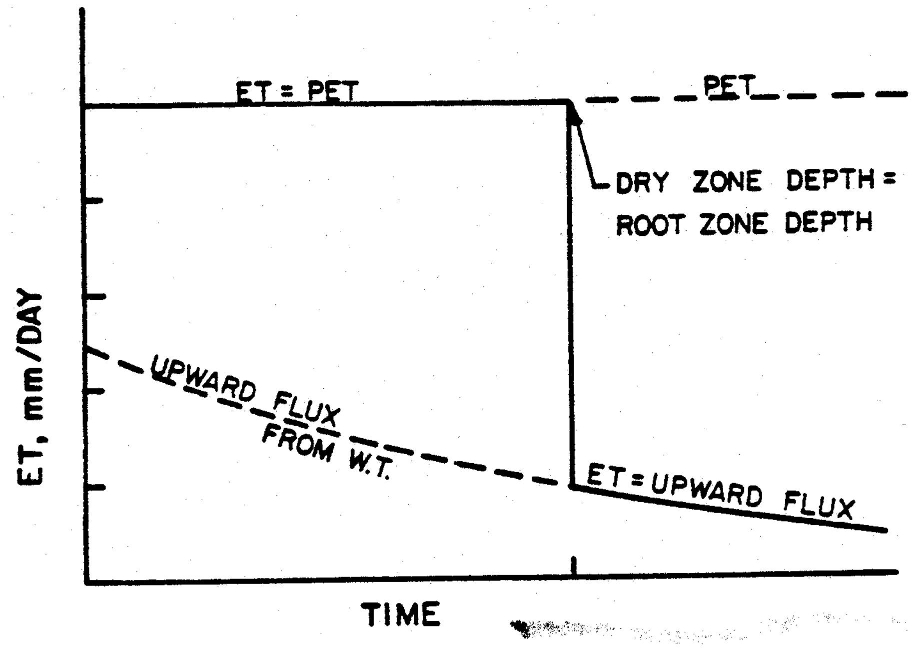

Figure 2-15. Schematic of the change in ET, with time for a constant PET as treated in the model. When the dry zone depth reaches the bottom of the root zone, ET is assumed to decline to the rate of upward flux.

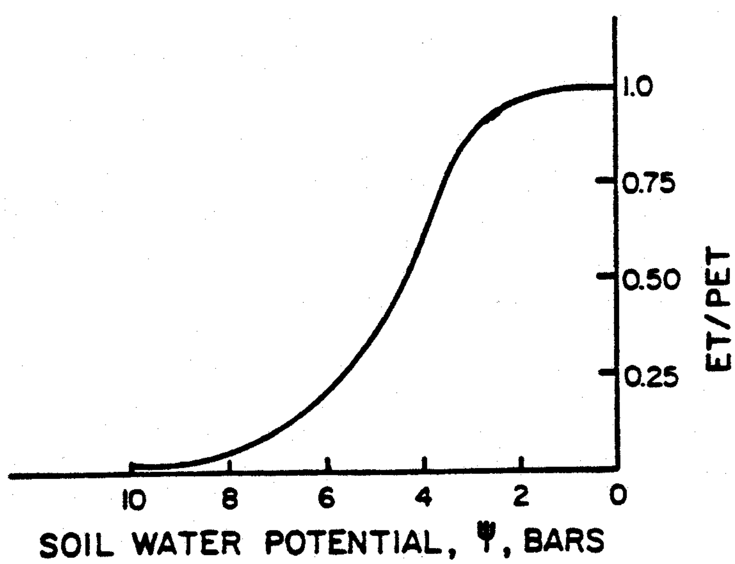

Figure 2-16. Schematic of relative evapotranspiration (ET/PET), as affected by soil water potential, ψ, in the root zone.

soil water distribution in the unsaturated zone. One of the key variables that is determined at the end of every water balance calculation in DRAINMOD is the water table depth. The soil water content below the water table is assumed to be essentially saturated; actually it is slightly less than the saturated value due to residual entrapped air in soils with fluctuating water tables. In some earlier models, the water content in the unsaturated zone was assumed to be constant and equal to the saturated value, less the drainable porosity. However, recent work (Skagges and Tang, 1976, 1978) has shown that, except for the region close to drains, the pressure head distribution above the water table during drainage may be assumed nearly hydrostatic for many field scale drainage systems. The soil water distribution under these conditions is the same as in a column of soil drained to equilibrium with a static water table. This is due to the fact that, in most cases in fields with artificial drains, the water table drawdown is slow and the unsaturated zone, in a sence, "keeps up" with the saturated zone. As a result, vertical hydraulic gradients are small. This is supported by the nearly verticial equipotential (H) lines in Figure 2-9 and Figure 2-17, which shows plots of pressure head versus depth at the drain, quarter and midpoints for drainage to open ditches spaced 20 m apart in a Panoche soil. The pressure head at the quarter and midpoints increase with depth in a 1:1 fashion indicating that the unsaturated zone is essentially drained to equilibrium with the water table (located where pressure head = 0), at all times after drainage begins.

The assumption of a hydrostatic condition above the water table during drainage will generally hold for conditions in which the D-F assumptions are valid. This will be true for situations where the ratio of the drin spacing to profile depth is large, but may cause errors for deep profiles, with narrow drain spacings.

Water is also removed from the profile by ET, which results in water table drawdraw and changes in the water content of the unsaturated rate. In this case, the vertical hydraulic gradient in the unsaturated zone is in the upward direction. However, when the water table is near the surface, the verticial gradient will be small and the water content distribution still close to the equilibrium distribution. Solutions for the water content distribution in a vertical column of soil under simultaneous drainage and evaporation are given in Figures 2-18 and 2-19. The solutions to the Richards equation for saturated and unsaturated flow were obtained using numerical methods described by Skaggs (1974). The water table was initially at the surface of the soil column and solutions were obtained for various evaporation rates and a drainage rate at the bottom of the column equal to that resulting from drains spaced 30 m apart and 1 m deep.

The results in Figure 2-18 indicate that, when the water table is 0.4 m from the surface, the water content distribution for this soil is independent of evaporation rates less than 4.8 mm/day. When the rate of evaporation from the surface was 0.0, the water table fell to the 0.4 m depth after 1 day of drainage; whereas, it reached the same depth in 0.74 days, when the evaporation rate was 4.8 mm/day. However, the water content distribution above the water table was the same for both cases; it was also the same for the intermediate evaporation rate of 2.4 mm/day. Figure 2-19

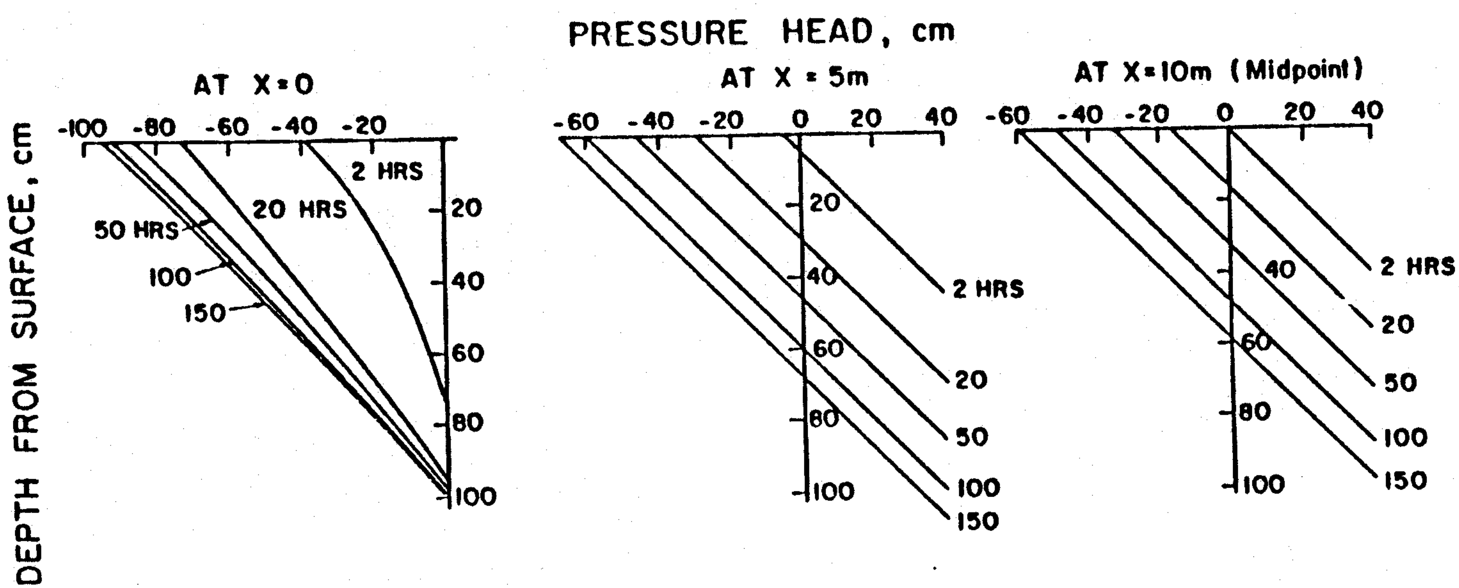

Figure 2-17. Pressure head distribution with depth at midpoint, quarter point and next to the drain for various times after drainage begins for a Panoche loam soil (after Skaggs and Tang, 1976).

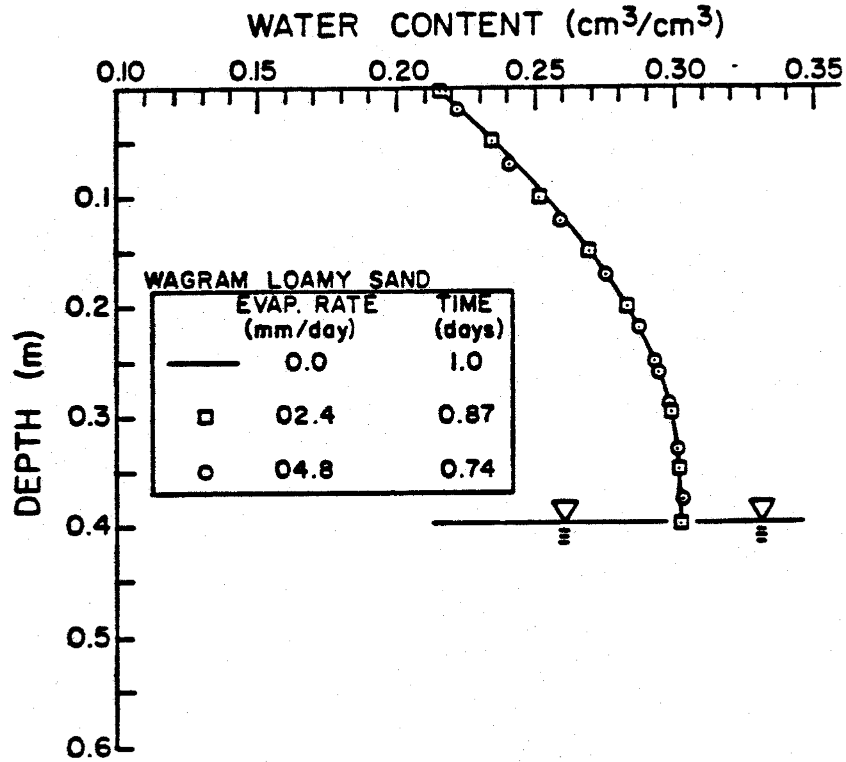

Figure 2-18. Soil water content distribution for a 0.4 m water table depth. The water table was initially at the surface and was drawn down by drainage and evaporation. Solutions are shown for three evaporation rates.

shows the distribution when the water table reached a depth of 0.7 m. Again, the soil water distribution was independent of the evaporation rate, except for the region close to the surface at the high evaporation rate (4.8 mm/day). The distribution for no evaporation is exactly the same as that which would result from the profile draining to equilibrium with a water table 0.7 m deep. Thus, the "drained to equilibrium" assumption, appears to provide a good approximation of the soil water distribution for this soil for both drainage and evaporation, when the water table depth is relatively shallow. Even when the water table is very deep, the soil water distribution for some distance above the water table will be approximately equal to the "equilibrium" distribution.

The zone directly above the water table is called the wet zone and the water content distribution is assumed to be independent of the means in which water was removed from the profile. Thus, the air volume or the volume of water leaving the profile by drainage, ET, and deep seepage, may be plotted as a function of water table depth as shown in Figure 2-20. Assuming hysteresis can be neglected, Figure 2-20 would allow the water

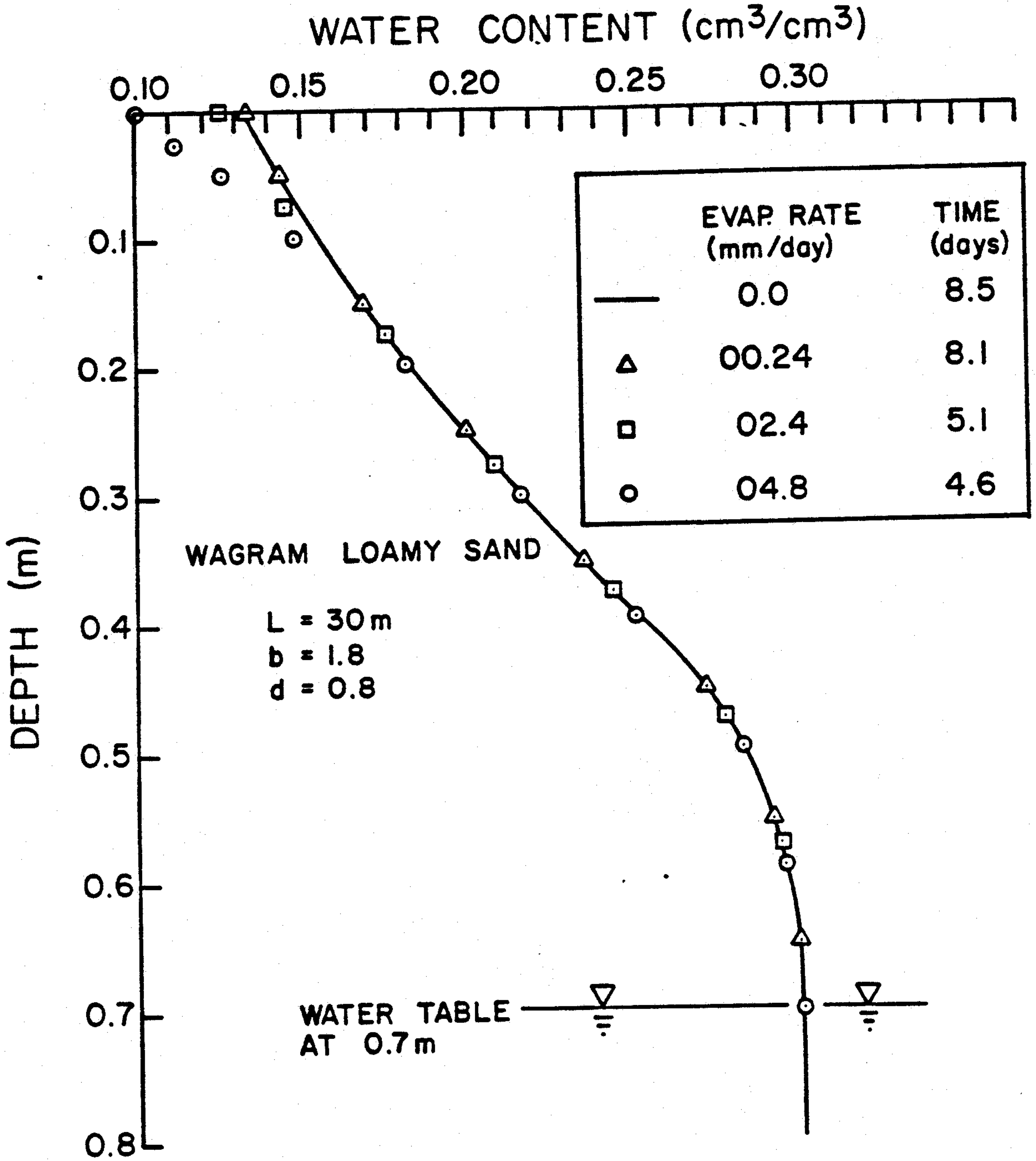

Figure 2-19. Soil water distribution for a water table depth of 0.7 m for various drainage and evaporation rates.

table depth to be determined simply from the volume of water that enters or is removed from the profile over an arbitrary period of time. For example, if the water table in the Wagram loamy sand of Figure 2-20 is initially at a depth of 0.6 m, the air volume above the water table would be V_a = 33 mm. Then, if drainage and ET removed 10 mm of water during the following day, the total V_a will be 43 mm and the depth of the wet zone, which is equal to the water table depth in this case, 0.66 m (from Figure 2-20). Subsequent infiltration of 25 mm would reduce the air volume to 18 mm and the water table depth to 0.48 m.

The maximum water table depth for which the approximatation of a drained to equilibrium water content distribution will hold depends on the hydraulic conductivity functions of the profile layers and the ET rate. The maximum depth will increase with the hydraulic conductivity of the soil and decrease with the ET rate. Because the unsaturated hydraulic conductivity decreases rapidly with water content, large upward gradients may develop near the surface, or near the bottom of the root zone, where the soil water

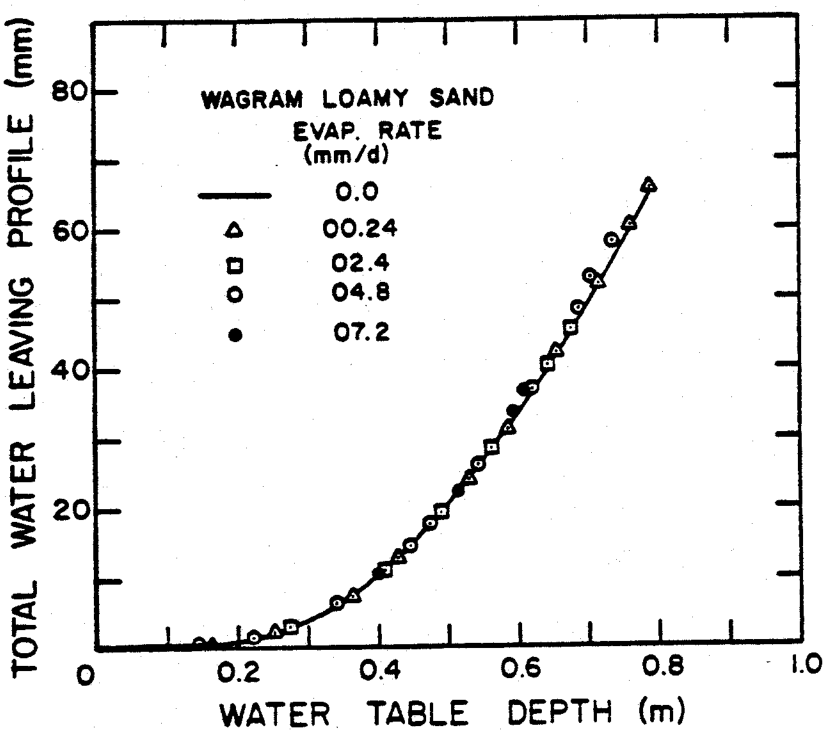

Figure 2-20. Volume of water leaving profiel (cm^3/cm^2) by drainage and evaporation versus water table depth. Solutions for five evaporation rates are given.

distribution departs from the equilibrium profile. At this point, the upward flux cannot be sustained for much deeper water table depths and additional water necessary to supply the ET demand would be extracted from storage in the root zone creating a dry zone as discussed in the ET section. This is shown schematically in Figure 2-21.

For purposes of calculation in DRAINMOD, the soil water is assumed to be distributed in two zones - a wet zone extending from the water table up to the root zone and possibly through the root zone to the surface, and a dry zone. The water content distribution in the wet zone is assumed to be that of a drained to equilibrium profile. When the maximum rate of upward water movement, determined as a function of the water table depth, is not sufficient to supply the ET demand, water is removed from root zone storage creating a dry zone as discussed in the ET section. The depth of the wet zone may continue to decrease due to drainage and some upward water movement. At the same time, the dry zone, with a constant water content of $\theta_{\ell\ell}$ may continue to increase to a maximum depth equal to that of the root

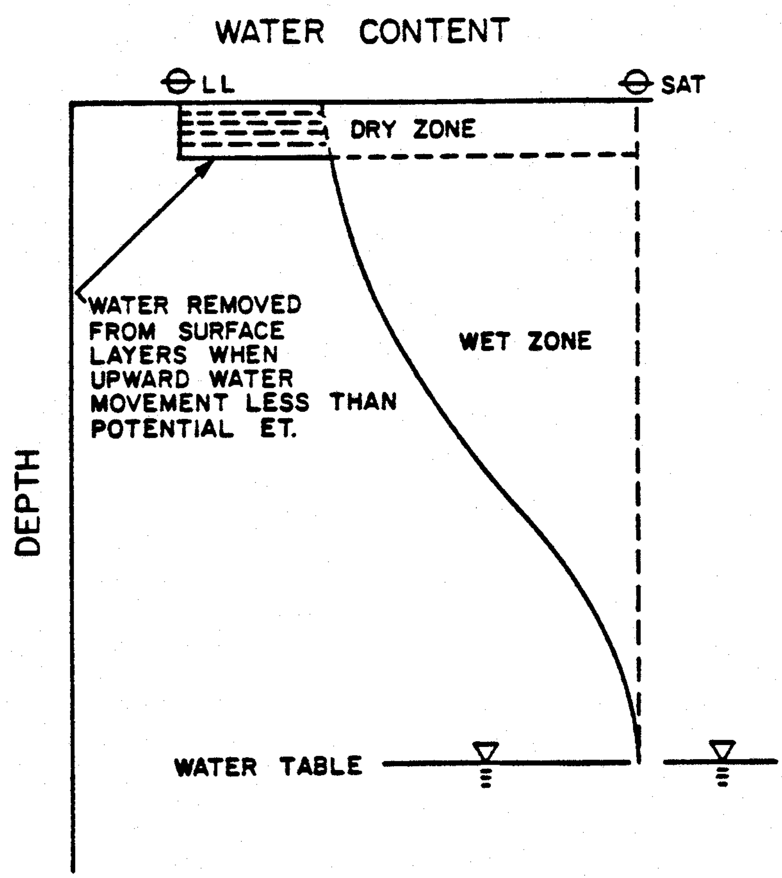

Figure 2-21. Schematic of soil water distribution when a dry zone is created near the surface.

zone. The water table depth is calculated as the sum of the depths of the wet and dry zones. When rainfall occurs, the storage volume in the dry zone, if one exists, is satisfied before any change in the wet zone is allowed. However, the depth to the water table will decrease by virtue of the reduction of the dry zone depth.

The assumptions made concerning soil water distribution may cause errors during periods of relatively dry conditions in soils with deep water tables and low K in the subsurface layers. Depp water tables may result from verticial seepage into an underlying aquifer or because of deep subsurface drains. For such conditions, the soil water at the top of the wet zone just beneath the root zone may be depleted by slow upward movement and by roots extending beyond the assumed depth of the concentrated root mass. Such conditions may cause the water content at the top of the wet zone to significantly depart from the drained to equilibrium distribution. However, this will not cause a problem for wet conditions and for most shallow water table soils for which the model was derived.

Rooting Depth

The effective rooting depth is used in the model to define the zone from which water can be removed as necessary to supply ET demands. Rooting depth is read into the model as a function of Julian date. Since the simulation process is usually continous for several years, an effective depth is defined for all periods. When the soil is fallow, the effective depth is defined as the depth of the thin layer that will dry out at the surface. When a second crop or a cover crop is grown, its respective rooting depth function is also included. The rooting depth function is read in as a table of effective rooting depth versus Julian date. The rooting depth for days other than those listed in the table is obtained by interpolation.

This method of treating the rooting depth is at best an approximation. The depth and distribution of plant roots is affected by many factors, in addition to crop species and date of planting. These factors included barriers, fertilizer distribution, tillage treatments, and others, as reviewed in detail by Allmaras, et al, (1973) and Danielson (1967). A good discussion of the effect of various factors on root growth and distribution, with effective graphic presentations, is given in Chapter 1, Section 15 of the SCS-NEH. One of the most important factors influencing root growth and distribution is soil water. This includes both depth and fluctuation of the water table as well as the distribution of soil water during dry periods. Since the purpose of the model is to predict the water table position and soil water content, a model which includes the complex plant growth processes would be required to accurately characterize the change of the root zone with time. Such models have been developed fro very specific situations, but their use is limited by input data and computational requirements at this time. Research is being conducted at North Carolina State University to develop root and plant growth models for use in DRAINMOD. Results of this and similar work at other locations should lead to future improvments in this component of the model.

The variation of root zone depths with time after planting may be approximated for some crops from experimental data reported in the literature. Studies of the depth and distribution of corn roots under field conditions were reported by Mengel and Barber (1974). Their data were collected on a silt loam soil which was drained, with drains placed 1 m deep and 20 m apart. They observed little evidence of root growth limitation by moisture or aeration stresses. The data of Mengel and Barber are plotted in Figure 2-22 for root zone depth versus time. Numbers on the curves indicate percentage of the total root length found at depths less than the value plotted. The broken sections of the curves were approximated by assuming that the effective root depth increases slowly for the first 20 days after planting, then more rapidly until the beginning of their measurements on day 30. The data of Mengel and Barber (1974) for the year 1971 showed the total root length reached a maximum 80 days after planting at about the silking stage, remained constant until day 94, then decreased until harvest at day 132. However, the percentage of roots less than a given depth remained relatively constant after about 80 days as shown in Figure 2-22.

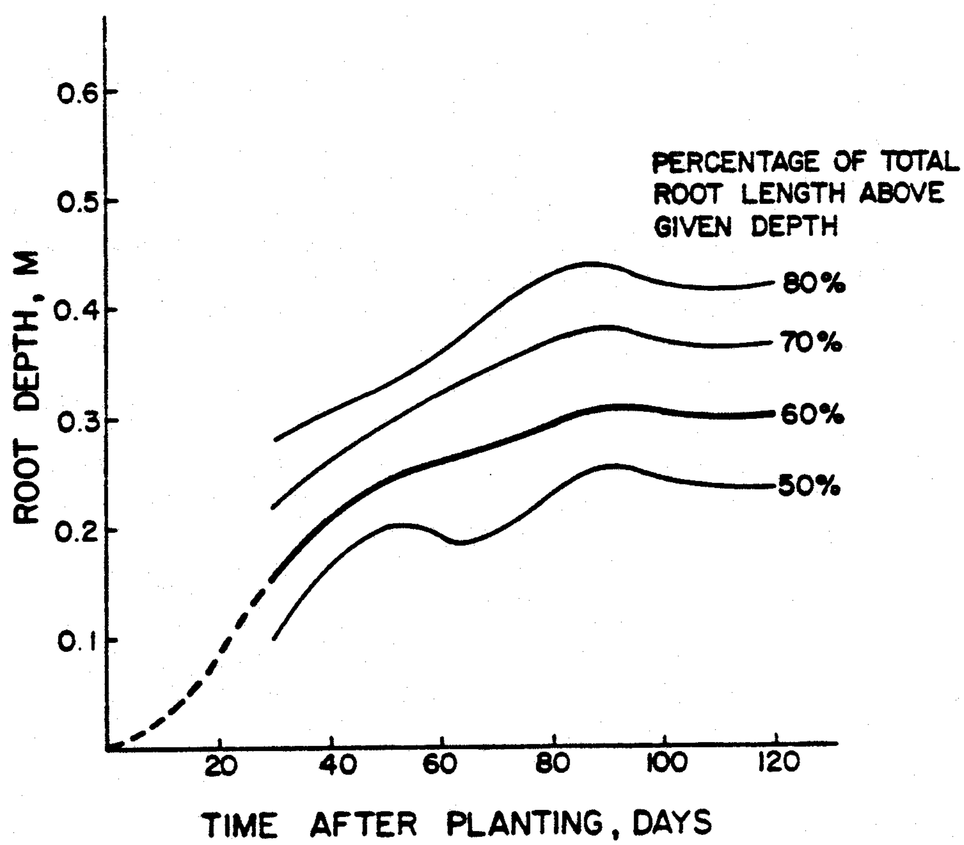

Figure 2-22. Relationships for depth above which 50, 60, 70, and 80 percent of the total root length exists versus time after planting for corn. From data given by Mengel and Barber (1974).

A similar study on the root distribution in corn was conducted by Foth (1962). Distribution plots based on root weights are given in Figure 2-23. The major differences between these results and those of Mengel and Barber were the shorter growing season (85 day versus 120 day corn) and smaller root depths, than those given in Figure 2-22. The total root dry weight is also plotted versus time in Figure 2-23. Foth found that root growth for plants less than 0.3 to 0.4 m reached a maximum by end of the vegetative growth stage 45 to 50 days after planting. After that date, there was a more rapid increase of roots, at deeper depths.

The following comments regarding mositure extraction patterns are made in the SCS-NEH (Section 16, Chapter 1, pages 1-30 and 1-33).

> "For most plants, the concentration of absorbing roots is greatest in the upper part of the root zone (usually in the top foot) and near the base of the plant. Extraction of water is most rapid in the zone of greatest root concentration and under the most favorable conditions of temperature and aeration. Since water also evaporates from the upper few inches of soil, moisture is withdrawn rapidly from the upper part of the soil. As the amount of moisture in this part of the root zone is diminished, soil-moisture tension incrases. Plants then get moisture from the lower parts of the root zone.
>
> In uniform soils that are fully supplied with available moisture, plants use water rapidly from the upper part of the root zone and slowly from the extreme lower part. Basic moisture-extraction curves indicate that almost all plants growing in a uniform soil with an adequate supply of available mositure have similar moisture-extraction patterns. The usual extraction pattern shows that about 40 percent of the extracted moisture comes from the upper quarter of the root zone, 30 percent from the second quarter, 20 percent from the third quarter, and 10 percent from the bottom quarter. Values for individual crops are within a range of ± 10 percent.

It is apparant that input data to DRAINMOD for the effective rooting depth-time relationship should not be based on the maximum depth of root penetration. Use of the 60 percent curve, as shown by the dark curve in Figure 2-22 has given good results in tests of the model. Relationships such as those given in Figures 2-22 and 2-23 for corn are not available for many crops. Values for a constant effective root zone depth are reported in the literature for many crops and are used in irrigation design. Bloodworth, et al, (1958) reported root distribution data for several mature crops. Methods for estimating the effective root zone depth-time relationship from single effective depth values given in the literature are discussed in Chapter 5.

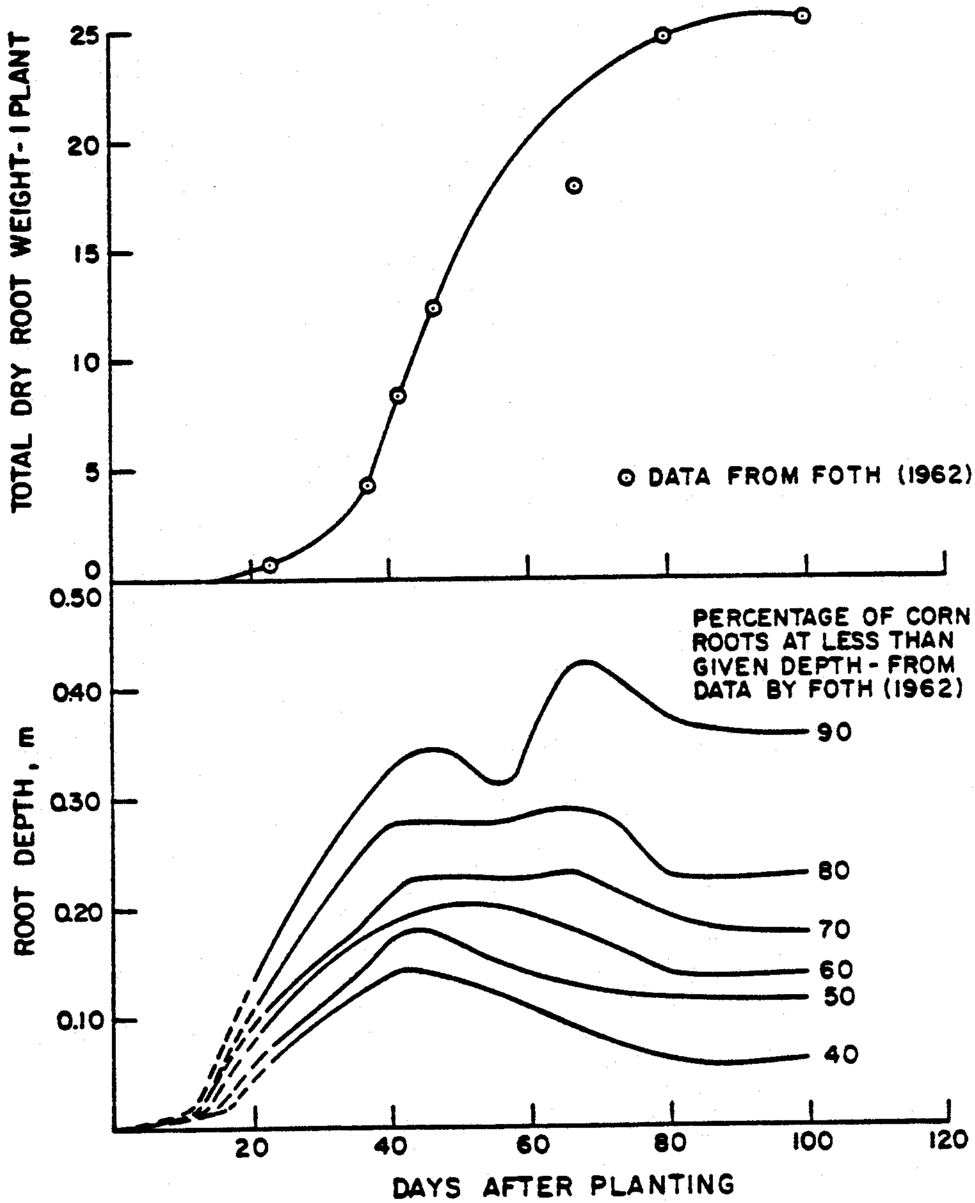

Figure 2-23. Root depths and total dry root weight versus times after planting for corn. From data given by Foth (1962).

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CHAPTER 3

WATER MANGEMENT SYSTEM OBJECTIVES

Agricultural water management systems may be installed to satisfy a variety of objectives. In most cases, the overall objective is to eliminate water related factors that limit crop production or to reduce those factors to an acceptable level. In the final analysis, the acceptable level depends on the cost of the required water management system in relation to the benefits that will result from its installation. Such benefits vary from year to year with both weather and economic conditions and are difficult to quantify because of the complex interrelationships of crop production processes. The selection or design of an optimum water management system for a given situation may also depend on the land owner. Some owners are willing to operate at a greater level of risk than others, so an acceptable level of drainage protection, for example, may be less for one owner than for another.

As more is learned about modeling plant growth, yields, and machinery-soil interactions (e.g. trafficability), it may be possible to simulate the entire crop production process, and thus to optimize the water management system design based on profit for a given enterprise. Lacking this knowledge at the present time, more intermediate or traditional objectives of water management systems must be used. Such objectives are easier to quantify and generally form the basis for system selection and design. For example, drainage systems in humid regions are usually installed to satisfy two functions: (a) to provide trafficable conditions for seedbed preparation in the spring and harvest in the fall, and (b) to insure suitable soil water conditions for the crop during the growing season. There may be a number of drainage system designs that will satisfy these objectives. For example, a system with good surface drainage and poor subsurface drainage may be adequate while a system with poor surface drainage and good subsurface drainage may serve the same purpose. Whether or not a given system will satisfy the objective depends on the location, crop, and soil properties. Of course, the objective itself may depend on the individual farmer's management capabilities, equipment, and manpower available, etc. For example, one farmer may require 10 working days for harvesting his crop while another farmer may need only 5 days for the same job. DRAINMOD can be used to simulate the performance of a given system design and evaluate the appropriate objective functions for a long period of climatological record. By making multiple simulations, the least expensive system that will satisfy the water management objectives for a given situation can be chosen.

Four objective functions are routinely computed in DRAINMOD and may be used for evaluating the adequacy of a given system design. These objective functions are:

1. Number of working days - this is used to characterize the ability of the water management system to insure trafficable conditions during specified periods.

2. SEW-30 - stands for sum of excess water at depths less than 30 cm and provides a measure of excessive soil water conditions during the growing season.

3. Number of dry days during growing season - quantifies the length of time when deficient soil water conditions exist.

4. Irrigation volume - when a water management system is designed for land disposal of waste water, the objective function is the allowable amount of irrigation for a specified time interval.

Working Day

A day is defined as a working day if the air volume (drained volume) in the profile exceeds some limiting value, AMIN; if the rainfall occurring that day is less than a minimum value, ROUTA; and if a minimum number of days, ROUTT, have elasped since that amount of rainfall occurred. It should be noted that ROUTA and ROUTT are assumed to be independent of AMIN and of the drainage system. For example, if conditions are very dry, with say an air volume of 150 mm in the profile, a 30 mm rainfall might still postpone field operations for 1 or 2 days even though the soil would normally be trafficable with an air volume of less than 150 - 30 = 120 mm. This is due to the fact that the surface wets up during rainfall and remains too wet for field operations until sufficient time for redistribution of the soil water has elapsed. Values for these limiting parameters are read into the model for two time periods which are specified by the beginning and ending Julian dates. The starting and stopping working hours (SWKHR and EWKHR) are also read in for each period and are used to compute partial working days. For example, let us assume that SWKHR = 0600 and EWKHR = 1800, (i.e., the working day is 12 hours long) for a given period. Then, if rain in excess of ROUTA occurs at 1400 hours, field work would be terminated at that point; and (1400 - 0600)/12 = 0.67 working days would be computed and stored for that day. The parameters AMIN, ROUTA, etc., are dependent on the soil and on the field operation to be conducted. These parameters have been obtained experimentally for some soils and are presented in Chapter 5, along with a discussion of methods for estimating the parameters for other soils.

SEW-30

The concept of SEW-30 was discussed by Wesseling (1974) and Bouwer (1974). It was originally defined by Sieben (1964) to evaluate the influence of high fluctuating water tables during the winter on cereal crops. It is used herein to quantify excessive soil water conditions during the growing season and may be expressed as,

$$\text{SEW-30} = \sum_{i=1}^{n} (30 - x_i) \qquad (3\text{-}1)$$

Where x_i is the water table depth on day i, with i = 1 being the first day and n the number of days in the growing season. The model actually calculates SEW-30 on an hourly, rather than a daily basis, so the SEW-30 as calculated by the model is more accurately expressed as,

$$\text{SEW-30} = \sum_{j=1}^{m} (30 - x_j)/24 \qquad (3\text{-}2)$$

Where x_j is the water table depth at the end of each hour and m is the total hours in the growing season. Negative terms inside the summation are neglected. The definition of SEW-30 is shown graphically by the cross-hatched area in Figure 3-1.

The relationship between crop yields and SEW-30 is shown schematically in Figure 3-2. Use of the SEW concept assumes that the effect on crop production of a 5 cm water table depth for a one day duration is the same as that of a 25 cm depth for five days. This seems unlikely as pointed out by Wesseling (1974). The severity of crop injury due to high water tables depends on the growth stage and time of year (Williamson and Kriz, 1970) as well as height of water table and time of exposure which determine the SEW-30 values. Probably, a better method of evaluating the quality of drainage during the growing season is the stress day index (SDI) concept advanced by Hiler (1969). This objective function was used by Ravelo (1977). He used DRAINMOD to evaluate alternative drainage system designs based on predicted excess water damage to grain sorghum. The crop susceptibility factors were defined for 3 growth stages from published experimental data (Howell, et al, 1976) and SEW-30 was used as the stress-day factor. This procedure allowed association of the amount of damage and the level of the stress-day-index. The slight modifications of the model necessary to use the stress-day-index are given by Ravelo (1977). However, the crop susceptibility factors are not available for other crops, so the SEW-30 value is used here as the objective function for quantifying excessive soil water conditions.

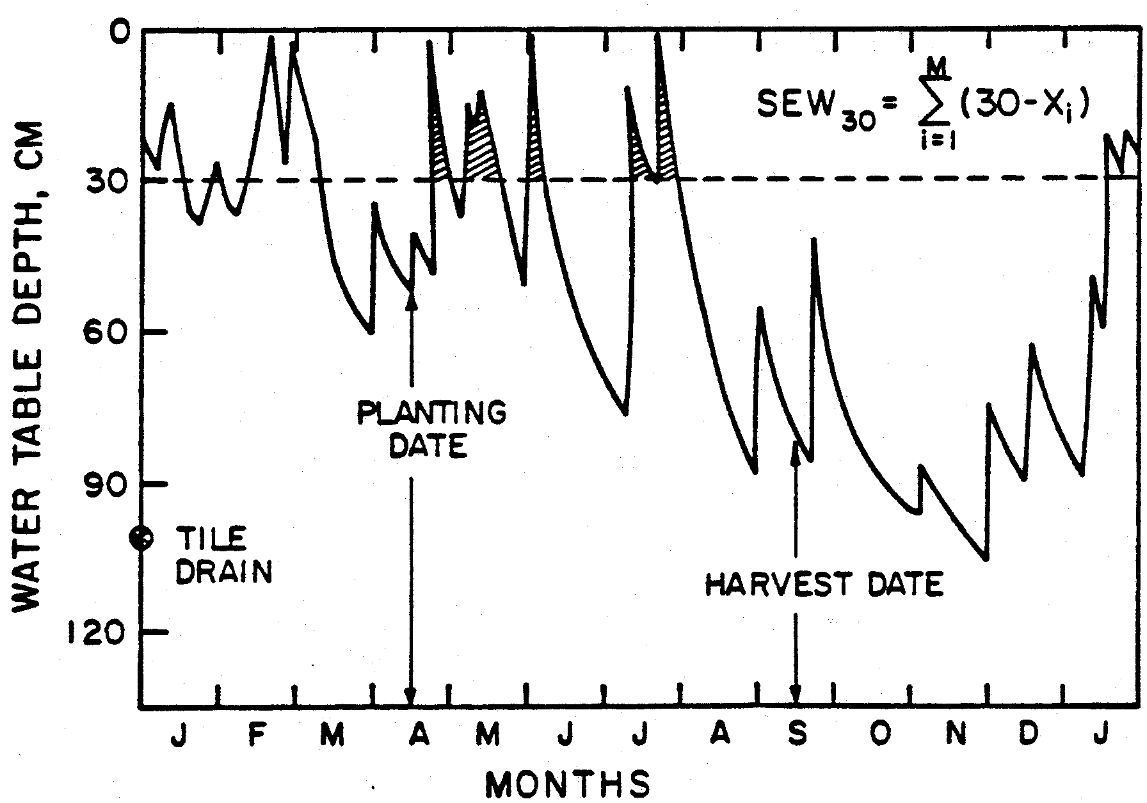

Figure 3-1. SEW-30 may be defined as the area between the water table and a depth of 30 cm (cross-hatched) during the growing season.

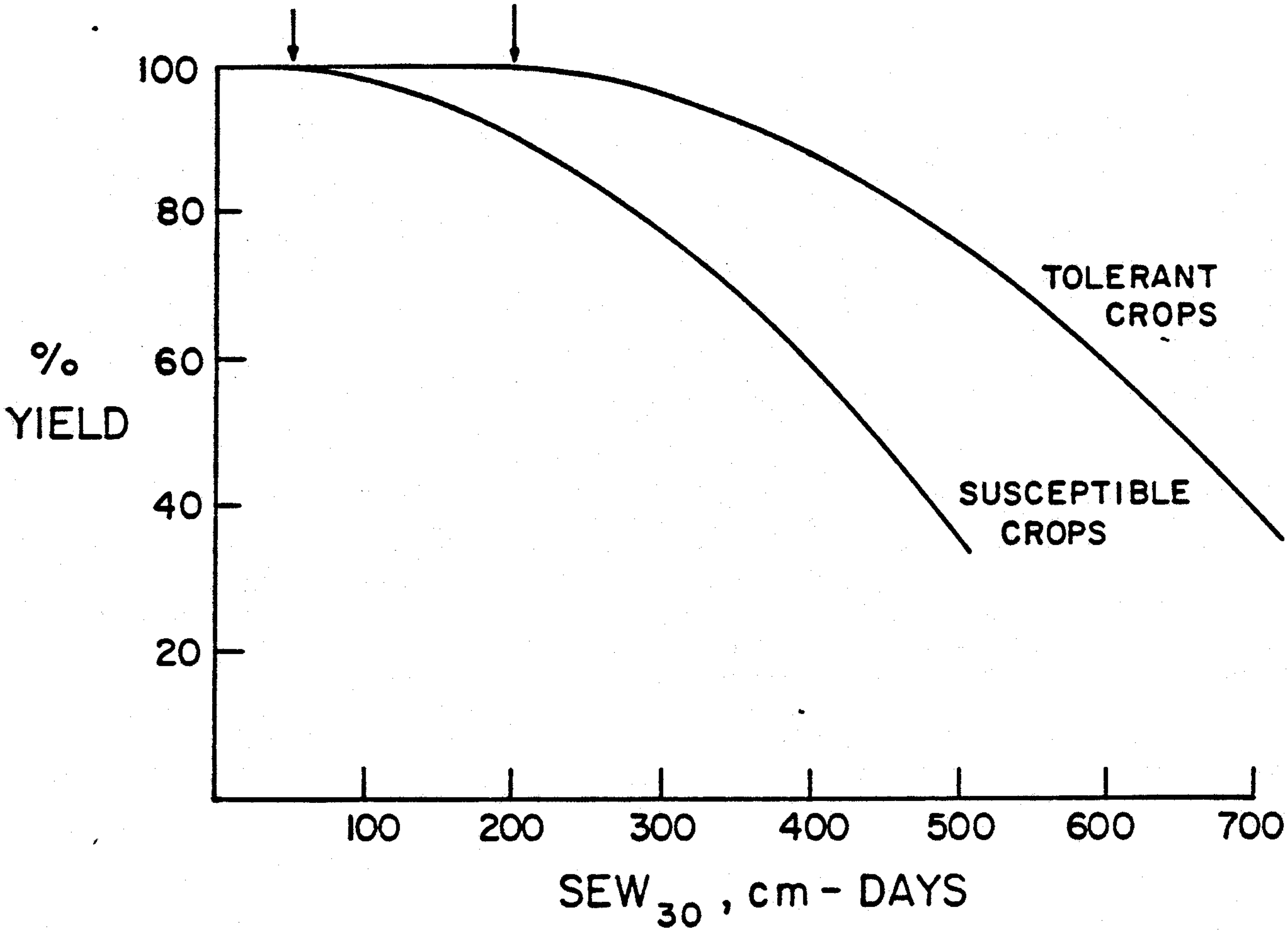

Figure 3-2. Schematic representation of the effect of SEW-30 on crop yields.

Although the SEW-30 concept has a number of weaknesses, it still provides a convenient method of approximating the quality of drainage. Sieben found that yields decreased for SEW-30 values greater than 100 to 200 cm-days. However, his values were calculated for the entire year, rather than just for the growing season as given here. Unless otherwise specified, it will be assumed that drainage is adequate to protect crops from excess water if the SEW-30 value is less than 100 cm-days. Obviously, some crops are more susceptible to poor drainage than others (Figure 3-1), so it may be desirable to adjust the critical SEW-30 value to fit the crop to be grown. Research is currently being conducted to better define the relationship between drainage and crop reponse.

Dry Days

A dry day is defined as a day in which ET is limited by soil water conditions. When the water table is at a shallow depth, water removed from the root zone by ET is replenished by upward movement from the wetter zones near the water table. After the water table is drawn down to a certain depth, the ET demand can no longer be sustained by upward movement alone and the root zone water will be depleted. ET will continue at a rate governed by atmospheric conditions until the soil water content in the root zone reaches some lower limit, $\theta_{\ell\ell}$, as discussed previously. When this condition occurs, ET will be limited to the rate water can move upward to the root zone from the vicinity of the water table. The limiting water content depends on the PET rate, as well as soil and crop properties, although the model assumes that it depends only on the soil (Figure 2-16). Days in which ET is less than the potential (PET) because of soil water conditions are presumed detrimental to optimum crop production and are counted as "dry days." A better method of quantifying stress due to dry conditions is the ratio of actual to potential transpiration, as used by Sudar, et al, (1979). This has not been included in the present version of the model, however.

Thus, the three parameters, working days, SEW-30, and dry days are used to quantify the performance of alternative agricultural water management systems. Ideally, a system would insure a given number of working days during the season when the crops are to be planted; SEW-30 values below a given maximum to prevent crop damage by excessive soil water; and a minimum number of dry days to prevent crop losses due to deficient soil water conditions.

Waste Water Irrigation Volume

DRAINMOD was also developed with the option to evaluate hydraulic loading limitations of land treatment of waste water. Waste water application to the surface may be scheduled at a specified interval, INTDAY, during a given period. If the drained volume in the profile is less than a given amount, REQDAR, irrigation of waste water may be posponed until the next day, at which time the drained volume will again be compared to REQDAR, or it may be skipped until the next scheduled period. If the parameter INSIRR = 0, the irrigation will be skipped. If INSIRR > 0, the irrigation will be postponed until the following day. If rainfall in excess of AMTRN occurs prior to time of scheduled irrigation, it is assumed to be 'rained out' and the event is postponed to the next day. If a scheduled irrigation is postponed more than twice, for whatever reason, it will be skipped until the next scheduled event. When land application systems are hydraulically, rather than nutrient limited, the objective is to apply as much waste water, as possible, without surface runoff. Maximum application reduces the land area required for the system, as well as the size of the irrigation system required. Thus, the objective function for evaluating a system design and irrigation scheme is the amount of wastewater than can be applied per unit area. This function may be evaluated on an annual basis to determine the size of the required system, and on a month basis to assess the waste water storage capacity that may be required during wet months. The amount of water irrigated at each application is read in to the model by specifying the beginning and end times of irrigation, IHRSTA and IHREND, and the application rate for each month AMTSIM (MO) (cm/hr). By specifying a negative value for AMTSIM (I), DRAINMOD will automatically apply the maximum amount of water that the profile will hold at irrigation, less the amount AMTSIM. That is, it will apply an amount TAV + AMTSIM(I) for every scheduled irrigation where AMTSIM(I) < 0.0. TAV is the total air volume in the profile at the time irrigation is scheduled to begin. Normally, a fixed amount of water will be applied at each scheduled irrigation. The option to apply the maximum amount of water that the profile will hold was added to evaluate situations where waste water would be stored during wet periods of the year and then applied at the maximum rate during dry periods.

In addition to determining the effects of a given drainage system design on the amount of waste water than can be applied per unit area of land, DRAINMOD can be used to compare the results of different irrigation strategies. For example, under the guidelines of only applying waste water when runoff will not occur, can more waste water be applied by scheduling two - 1 inch irrigations each week, one - 2 inch irrigation each week or one - 4 inch irrigation every two weeks? It turns out that, everything else being equal, more waste water can be applied by irrigating more frequently with smaller amounts of water. These alternatives are evaluated and discussed in some detail in an example given in Chapter 6.

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CHAPTER 4

SIMULATION OF WATER MANAGEMENT SYSTEMS - PROCEDURE

This section discusses the procedure for using DRAINMOD to simulate the performance of a water management system. As an example, the design of a drainage system is considered. The required input data and a representative example of the program output are presented. Sources of input data and methods used to determine them are discussed in Chapter 5. Other examples of the use of DRAINMOD for evaluation and design are given in Chapter 6. The purpose of this chapter is to demonstrate the simulation procedure and examine the form of the required inputs and simulation output.

Example - A combination surface-subsurface drainage system

The soil chosen for this hypothetical example is a Wagram loamy sand located near Wilson, North Carolina. This soil type is usually well drained in nature and does not require artificial drainage. In this case, however, it is flat and is underlain by a very slowly permeably layer at a 1.8 m depth. Corn is to be grown on a continuous basis. The seedbed is to be prepared after about March 15 and corn planted by April 15; the harvest period is September 1 to October 15. The purpose of the drainage system is to provide trafficable conditions in the spring and ruing the fall harvest season, and to prevent excessive soil water conditions during the growing season. The simulation will tell us whether or not the given design will accomplish this purpose and how often it may be expected to fail.

Input Data

The input data for this example are given in Appendix A as card images arranged in the order that they are fed into the computer. The sources of these data and more details concerning the inputs are discussed below.

Soil Property Inputs

The relationships between drainage volume (or effective air volume above the water table) and water table depth were determined from large field cores as discussed by Skaggs, et al, (1978), and are plotted along with similar relationships for other soils in Figure 5-4. The relationship between maximum rate of upward water movement to supply ET requirements and depth of the water table below the root zone is given in Figure 2-15 for the Wagram soil. A summary of the other soil property inputs is given in Table 4-1.

Crop Input Data

The growing season for corn is approximately 120 days from April 15 to about August 15. The effective root zone depth is assumed to be dependent on time after planting and is arbitrarily taken as that given by the 60 percent curve from the data of Mengel and Barber, Figure 2-22. Soil water from a shallow surface layer will be removed (i.e., dried out to some lower limit water content) by evaporation even when the land is fallow. Therefore, an effective root zone depth of 3 cm was assumed for the period before and after the growing season. Other crop related input data are given in Table 4-1.

Drainage System Input Parameters

The drainage system consists of subsurface 102 mm (4 inch) drains spaced 45 m apart and 1 m deep. The surface drainage is only fair with some shallow depressions and an average surface storage depth of 12.5 mm. Convergence near the drain is accounted for by defining an equivalent depth

Table 4-1. Summary of soil property and crop related input data for Wagram loamy sand.

Parameter	Program Variable Name	Value
Depth to restricting layer	DEPTH	180 cm
Hydraulic conductivity	CONK	6 cm/hr (uniform)
Volumetric water content at lower limit (wilting point)	WP	0.05
Initial water table depth	IDTWT	0.0 cm
Minimum soil air volume required for tillage operations during:		
first work period (spring)	AMIN1	3.7 cm
second work period (harvest)	AMIN2	3.0 cm
Minimum rain to stop field operations:		
spring seedbed prep.	ROUTA1	1.2 cm
fall harvest	ROUTA2	0.5 cm
Minimum time after rain before can till:		
spring seedbed prep.	ROUTT1	1 day
fall harvest	ROUTT2	1 day
Working period for seedbed prep.:		
starting day	BWKDY1	74
ending day	EWKDY1	104
Working period for harvest:		
starting day	BWKDY2	240
ending day	EWKDY2	270
Working hours during spring:		
starting time	SWKHR1	0800
ending time	EWKHR1	2000
Working hours during harvest:		
starting time	SWKHR2	0800
ending time	EWKHR2	1800
Growing season - starting date	ISEWMS/ISEWDS	4/15
- ending date	ISDWME/ISEWDE	8/15
Depth on which SEW calculations are based	SEWX	30 cm

Parameters for Green-Ampt infiltration equation:	W.T. Depth	A(hr^{-1})	B(cm hr^{-1})
	0 cm	0	0
	50	3.0	1.0
	100	5.5	2.0
	150	8.7	3.0
	200	11.5	3.0
	500	25.0	3.0

from the drain to the impermeable layer according to the methods given by Hooghoudt (van Schilfgaarde, 1974). Methods given elsewhere Skaggs (1978b), were used to find an effective radius of a completely open drain tube from data presented by Bravo and Schwab (1975), and then to determine the equivalent depth using equations given by Moody (1966). Input parameters describing the drainage system are summarized in Table 4-2.

Table 4-2. Summary of drainage system input parameters.

Parameter	Program Variable Name	Value
Drain spacing	SDRAIN	45 m
Drain depth	DDRAIN	1 m
Equivalent depth to impermeable layer	HDRAIN	0.68 m
*Equivalent profile depth	DEPTH	1.68 m
Maximum depth of surface storage	STMAX	12.5 mm
Drain radius	**	57 mm
Effective drain radius	**	5.1 mm

* The equivalent profile depth is the sum of DDRAIN and HDRAIN and is used as input for the variable DEPTH, rather than the actual profile depth in Table 1.

**These variables are not inputs to DRAINMOD, but are used to calculate HDRAIN.

Climatological Input Data

Hourly precipitation and daily temperature data were obtained for Wilson, North Carolina, from HISARS. Inputs identifying the station and specifying the heat index for ET calculations were given on the EXECUTE JCL card. These inputs are given in Table 4-3.

Table 4-3. Inputs for calling climatological data from HISARS and ET calculations.

Parameter	Program Variable Name	Value
Station ID for precipitation	ID1	319476
Station ID for daily temperatures	ID2	319476
Latitude for temperature station	LATT	35° 47'
Heat index	HET	75.0
Year and month simulation starts	START	1952-01
Year and month simulation ends	END	1971-12

Other Input Data

Irrigation is not considered in the example given here. However, input data for irrigation must be specified; values are selected such that no irrigation water will be applied. An example of the irrigation inputs required for simulating the use of the above system for application of waste water is given in Appendix A.

Simulation Results

Sample results of the computer output for each simulation are shown in Tables 4-4 through 4-7. A listing of the input parameters and soil properties is given in Table 4-4. Daily summaries for the month of July 1959 are given in Table 4-5 and monthly summaries for 1959, a relatively wet year with a total of 1553 mm of rainfall, infiltration (INFIL), ET, cumulative drainage (DRAIN), runoff, total water leaving the field through the outlet drain (WLOSS) and the amount of irrigated water (DMTSI). In addition, soil water conditions at the end of the day are given by values for air volume in the wet zone (AIR VOL), total drained volume (TVOL), depth of dry zone (DDZ), depth of wet zone (WETZ), depth of the water table (DTWT), depth of water stored on the surface at the end of the day (STOR), depth of water in the outlet (DRNSTO). The SEW-30 value is also given for each day.

The monthly summaries (Table 4-6) give the totals of rainfall, infiltration, runoff, drainage, ET, dry days, working days, water lost from the field through the drainage outlet, SEW-30, total irrigation (MIR), number of irrigation events (MCN), depth of water pumped for subirrigation (PUMP), and the number of scheduled irrigation events postponed (MPT) for each month. Sample output results for a year (1961) with a smaller amount of rainfall are given in the output section of Appendix A. Also given in Appendix A is an example of simulation output when this water management system is used for disposal of waste water at a planned sprinkler irrigation rate of 2.5 cm/week.

The simulation was conducted for a 20-year period (1952-1971). The summary and ranking of the objective functions, which is printed out at the end of the simulation is given in Table 4-7. A probability analysis can then be conducted on the results in Table 4-7 and on similar results for other sets of design parameters to develop relationships between the objective functions and design parameters such as those given in Chapter 6 (e.g. Figures 6-11 and 6-12).

Figure 4-4. An example of computer output - listing of inputs - Wagram soil.

```
INPUT PARAMETER VALUES USED IN THIS SIMULATION

DEPTH TO DRAIN=100.0CM
EFFECTIVE DEPTH FROM    DRAIN TO IMPERMEABLE LAYER = 68.0CM
DISTANCE BETWEEN        DRAINS = 4500.0CM
MAXIMUM DEPTH OF SURFACE PONDING = 0.25CM
EFFECTIVE  DEPTH IMPERMEABLE LAYER= 168.0CM
NUMBER OF DEPTH INCREMENTS=  33.
DRAINAGE COEFFICIENT(AS LIMITED BY SUBSURFACE OUTLET   )= 1.50CM/DAY
ACTUAL DEPTH FROM SURFACE TO IMPERMEABLE    LAYER=180.0CM
SURFACE STORAGE THAT MUST BE FILLED BEFORE WATER CAN   MOVE TO DRAIN (FIG.2-12) = 1.25CM
FACTOR -C- IN KIRKHAM   EQ. 2-17 =      21.70
MINIMUM AIR VOL REQUIRED FOR TRAFFICABILITY FOR FIRST  WORK PERIOD(AMIN1)= 3.70CM
MINIUM DAILY RAINFALL TO STOP FIELD OPERATIONS FOR FIRST PERIOD (ROUTA1)= 1.25CM
MINIMUM TIME AFTER RAIN BEFORE CAN TILL FIRST PERIOD (ROUTT1) =     1.DAYS
MINIMUM AIR VOL REQUIRED FOR TRAFFICABILITY FOR SECOND WORK  PERIOD (AMIN2)= 3.70CM
MINIUM DAILY RAINFALL TO STOP FIELD OPERATIONS FOR SECONDPERIOD (ROUTA2)= 1.25CM
MINIMUM TIME AFTER RAIN BEFORE CAN TILL SECOND PERIOD (ROUTT2)=    1.DAYS
JULIAN DATE TO BEGIN COUNTING WORK DAYS-FIRST PERIOD= 76
JULIAN DATE TO END COUNTING WORK DAYS- FIRST PERIOD=105
HOUR TO BEGIN WORK- FIRST PERIOD= 8
HOUR TO END WORK-FIRST PERIOD=20
JULIAN DATE TO BEGIN COUNTING WORK DAYS-SECOND PERIOD=368
JULIAN DATE TO END COUNTING WORK DAYS- SECOND PERIOD=368
HOUR TO BEGIN WORK- SECOND PERIOD= 8
HOUR TO END WORK- SECOND PERIOD=20
MAXIMUM ROOTING DEPTH= 30.0CM
CRITICAL DEPTH WET ZONE= 75.0CM
WILTING POINT= 0.05
INITIAL WATER TABLE DEPTH=  0.0
WIDTH OF DITCH BOTTOM= 60.0CM
SIDE SLOPES OF DITCH=  0.5:1
FIRST DAY OF SURFACE IRRIGATION= 1
INTERVAL BETWEEN SURFACE IRRIGATION DAYS=**
STARTING HOUR OF SURFACE IRRIGATION= 10
ENDING HOUR OF SURFACE IRRIGATION= 12
NO SURFACE IRRIGATION INTERVAL 1=   0     0
NO SURFACE IRRIGATION INTERVAL 2=   0     0
MINIMUM AIR REQUIRED TO HAVE SURFACE IRRIGATION=  3.50CM
AMOUNT OF RAIN TO POSTPONE SURFACE IRRIGATION=  1.00CM
SURFACE IRRIGATION FOR ONE HOUR=  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0 CM


        DEPTH          SATURATED HYDRAULIC CONDUCTIVITY

     0.0  -  100.00                 6.00000

     DEPTHS OF WIERS FROM THE SURFACE

DATE          1/ 0.   2/ 0.   3/ 0.   4/ 0.   5/ 0.   6/ 0.   7/ 0.   8/ 0.   9/ 0.   10/ 0.   11/ 0.   12/ 0.
WIER DEPTH    100.0   100.0   100.0   100.0   100.0   100.0   100.0   100.0   100.0   100.0    100.0    100.0

 INDICATER FOR DAILY SUMMERY=     0
 INDET=99WHEN INDET.GT. 0 USE READ IN VALUES TO DETERMINE ET WHEN LIMITED BY SOIL CONDITIONS
```

Table 4-4 (Cont.) An example of computer output - listing of inputs - Wagram soil.

SOIL WATER CHARACTERISTICS AND RELATIONSHIP
BETWEEN WATER TABLE DEPTH AND DRAINED(VOID) VOLUME

VOLUME OF VOIDS	WATER TABLE DEPTH
0.0	0.0
1.0000	43.3333
2.0000	54.2857
3.0000	61.1111
4.0000	66.6667
5.0000	71.6000
6.0000	75.6000
7.0000	79.6000
8.0000	83.1579
9.0000	86.6667
10.0000	90.1754
11.0000	93.6842
12.0000	97.1930
13.0000	100.5814
14.0000	103.4884
15.0000	106.3954
16.0000	109.3024
17.0000	112.2094
18.0000	115.1163
19.0000	118.0233
20.0000	120.9303
21.0000	123.8372
22.0000	126.7442
23.0000	129.6512
24.0000	132.5582
25.0000	135.4651
26.0000	138.3722
27.0000	141.2791
28.0000	144.1861
29.0000	147.0931
30.0000	150.0000
31.0000	166.3640
32.0000	182.7275
33.0000	199.0914
34.0000	215.4549
35.0000	231.8183
36.0000	248.1822
37.0000	264.5457
38.0000	280.9092
39.0000	297.2729
40.0000	313.6365
41.0000	330.0000
42.0000	346.3638
43.0000	362.7273
44.0000	379.0913
45.0000	395.4548
46.0000	411.8181
47.0000	428.1821
48.0000	444.5457
49.0000	460.9092

HEAD	WATER CONTENT	VOLUME VOIDS ABOVE W.T.	UPFLUX
0.0	0.3020	0.0	3.0000
10.0000	0.2990	0.1000	2.0000
20.0000	0.2850	0.2500	1.0000
30.0000	0.2540	0.5000	0.5000
40.0000	0.2180	0.8000	0.3000
50.0000	0.1835	1.4000	0.1460
60.0000	0.1540	2.8000	0.0350
70.0000	0.1320	4.6000	0.0150
80.0000	0.1170	7.1000	0.0090
90.0000	0.1080	9.9500	0.0060
100.0000	0.1030	12.8000	0.0030
110.0000	0.0998	16.2400	0.0020
120.0000	0.0966	19.6800	0.0010
130.0000	0.0934	23.1200	0.0007
140.0000	0.0902	26.5599	0.0003
150.0000	0.0870	30.0000	0.0000
160.0000	0.0840	30.6111	0.0000
170.0000	0.0810	31.2222	0.0000
180.0000	0.0780	31.8333	0.0000
190.0000	0.0750	32.4444	0.0000
200.0000	0.0720	33.0555	0.0000
210.0000	0.0711	33.6666	0.0000
220.0000	0.0703	34.2777	0.0000
230.0000	0.0694	34.8888	0.0000
240.0000	0.0686	35.5000	0.0000
250.0000	0.0677	36.1111	0.0000
260.0000	0.0669	36.7222	0.0000
270.0000	0.0660	37.3333	0.0000
280.0000	0.0652	37.9444	0.0000
290.0000	0.0643	38.5555	0.0000
300.0000	0.0635	39.1666	0.0000
310.0000	0.0626	39.7777	0.0000
320.0000	0.0618	40.3888	0.0000
330.0000	0.0609	41.0000	0.0000
340.0000	0.0601	41.6111	0.0000
350.0000	0.0592	42.2222	0.0000
360.0000	0.0584	42.8333	0.0000
370.0000	0.0575	43.4444	0.0000
380.0000	0.0567	44.0555	0.0000
390.0000	0.0558	44.6666	0.0000
400.0000	0.0550	45.2777	0.0000
410.0000	0.0546	45.8888	0.0000
420.0000	0.0542	46.5000	0.0000
430.0000	0.0538	47.1111	0.0000
440.0000	0.0534	47.7222	0.0000
450.0000	0.0530	48.3333	0.0000
460.0000	0.0526	48.9444	0.0000
470.0000	0.0522	49.5555	0.0000
480.0000	0.0518	50.1666	0.0000
[illegible].0000	0.0514	50.7777	

Table 4-4 (Cont.) An example of computer output - listing of inputs - Wagram soil.

GREEN AMPT INFILTRATION PARAMETERS

W.T.D.	A	B
0.0	0.0	0.0
50.000	3.000	1.000
100.000	5.500	2.000
150.000	8.700	3.000
200.000	11.500	3.000
500.000	25.000	3.000

VALUES READ IN

DAY	ROOT DEPTH
1	4.00
106	4.00
116	5.00
126	8.00
136	16.00
146	21.00
156	23.00
166	26.00
176	28.00
186	30.00
196	30.00
226	30.00
256	4.00
366	4.00

Table 4-5. An example of computer output for daily summaries - Wagram soil, July, 1959. All values given in cm.

1959 7

DAY	RAIN	INFIL	ET	DRAIN	AIR VOL	TVOL	DDZ	WETZ	DTWT	STOR	RUNOFF	WLOSS	YD	DRNSTO	SEW	DMTSI
1	2.90	2.90	0.52	0.0	12.75	16.88	16.40	99.82	116.22	0.0	0.00	0.00	0.0	0.00	0.0	0.0
2	0.38	0.38	0.61	0.0	12.79	17.11	17.15	99.95	117.10	0.0	0.00	0.0	0.0	0.00	0.0	0.0
3	0.13	0.13	0.41	0.0	12.82	17.39	18.14	100.07	118.21	0.0	0.0	0.00	0.0	0.00	0.0	0.0
4	0.0	0.0	0.42	0.0	12.89	17.81	19.53	100.27	119.80	0.0	0.0	0.0	0.0	0.00	0.0	0.0
5	0.0	0.0	0.46	0.0	12.96	18.27	21.05	100.48	121.53	0.0	0.0	0.0	0.0	0.00	0.0	0.0
6	1.19	1.19	0.53	0.0	13.00	17.60	18.26	100.59	118.85	0.0	0.00	0.00	0.0	0.0	0.0	0.0
7	0.0	0.0	0.53	0.0	13.07	18.13	20.08	100.79	120.88	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.47	0.0	13.14	18.61	21.68	100.99	122.68	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.71	0.71	0.31	0.0	13.18	18.21	19.96	101.10	121.06	0.0	0.00	0.0	0.0	0.00	0.0	0.0
10	2.24	2.24	0.34	0.0	13.21	16.31	12.30	101.20	113.50	0.0	0.00	0.00	0.0	0.0	0.0	0.0
11	3.53	3.53	0.28	0.0	13.06	13.06	0.0	100.77	100.77	0.0	0.00	0.00	0.0	0.0	0.0	0.0
12	2.26	2.26	0.30	0.01	11.11	11.11	0.0	94.06	94.06	0.0	0.0	0.01	0.0	0.0	0.0	0.0
13	8.00	7.72	0.20	0.12	3.70	3.70	0.0	65.00	65.00	0.0	0.28	0.39	0.0	0.0	0.0	0.0
14	1.70	1.70	0.22	0.19	2.41	2.41	0.0	57.20	57.20	0.0	0.00	0.19	0.0	0.0	0.0	0.0
15	3.68	2.95	0.20	0.34	0.00	0.00	0.0	0.00	0.00	0.11	0.63	0.97	0.0	0.0	7.50	0.0
16	5.03	0.45	0.42	0.55	0.53	0.53	0.0	30.91	30.91	0.22	4.47	5.03	0.0	0.0	15.70	0.0
17	0.53	0.75	0.42	0.40	0.59	0.59	0.0	33.14	33.14	0.0	0.00	0.40	0.0	0.0	1.32	0.0
18	0.15	0.15	0.48	0.32	1.24	1.24	0.0	47.41	47.41	0.0	0.00	0.32	0.0	0.0	0.0	0.0
19	0.53	0.53	0.47	0.27	1.45	1.45	0.0	50.37	50.37	0.0	0.00	0.27	0.0	0.0	0.0	0.0
20	1.14	1.14	0.41	0.28	1.00	1.00	0.0	43.35	43.35	0.0	0.0	0.28	0.0	0.0	0.0	0.0
21	0.51	0.51	0.37	0.30	1.16	1.16	0.0	46.01	46.01	0.0	0.00	0.30	0.0	0.0	0.0	0.0
22	0.0	0.0	0.57	0.26	1.99	1.99	0.0	54.19	54.19	0.0	0.0	0.26	0.0	0.0	0.0	0.0
23	0.0	0.0	0.56	0.22	2.77	2.77	0.0	59.80	59.80	0.0	0.0	0.22	0.0	0.0	0.0	0.0
24	0.0	0.0	0.56	0.19	3.53	3.53	0.0	64.03	64.03	0.0	0.0	0.19	0.0	0.0	0.0	0.0
25	2.62	2.62	0.56	0.17	1.64	1.64	0.0	51.74	51.74	0.0	0.0	0.17	0.0	0.0	0.0	0.0
26	3.20	2.46	0.46	0.36	0.00	0.00	0.0	0.00	0.00	0.08	0.65	1.01	0.0	0.0	9.26	0.0
27	4.95	0.20	0.47	0.47	0.74	0.74	0.0	38.02	38.02	0.21	4.63	5.10	0.0	0.0	8.71	0.0
28	0.10	0.31	0.43	0.33	1.19	1.19	0.0	46.49	46.49	0.0	0.00	0.33	0.0	0.0	0.0	0.0
29	0.10	0.10	0.46	0.26	1.81	1.81	0.0	52.91	52.91	0.0	0.00	0.26	0.0	0.0	0.0	0.0
30	0.74	0.74	0.58	0.23	1.88	1.88	0.0	53.43	53.43	0.0	0.00	0.23	0.0	0.0	0.0	0.0
31	0.05	0.05	0.48	0.23	2.54	2.54	0.0	58.15	58.15	0.0	0.00	0.23	0.0	0.0	0.0	0.0
	y Rainfall	Daily Infiltration	Daily ET	Daily Drainage	Air Volume in (or Drained Volume from) Wet Zone	Total Air Volume in Profile	Depth of Dry Zone	h of Wet Zone	Depth of Water Table	Depth of Water Stored on the Surface	Daily Runoff	Daily Water Leaving Outlet	Depth of Water in Outlet Ditch	Water Stored in Outlet-Equivalent Depth Over the Field	Daily SEW_{30}-cm Days	mount of Water rrigated

Table 4-6. An example of computer output for monthly summaries - Wagram soil, 1959.

MONTHLY VOLUMES IN CENTIMETERS FOR YEAR 1959

MONTH	RAINFALL	INFILTRATION	RUNOFF	DRAINAGE	ET	DRY DAYS	WRK DAYS	WATER LOSS	SEW	MIR	MCN	PUMP	MPT
1	5.97	5.97	0.00	5.50	1.19	0.0	0.0	5.50	0.0	0.0	1	0.0	0
2	10.59	9.24	1.35	6.71	1.45	0.0	0.0	8.06	0.0	0.0	0	0.0	0
3	12.17	10.69	1.48	7.39	2.48	0.0	5.46	8.87	0.0	0.0	0	0.0	0
4	18.77	13.53	5.24	8.94	6.53	0.0	1.58	14.17	40.81	0.0	0	0.0	0
5	4.93	4.93	0.00	1.81	11.02	0.0	0.0	1.82	0.0	0.0	0	0.0	0
6	6.93	6.93	0.00	0.16	13.72	0.0	0.0	0.17	0.0	0.0	0	0.0	0
7	46.38	35.72	10.66	5.51	13.49	0.0	0.0	16.17	42.50	0.0	0	0.0	0
8	12.88	12.88	0.00	3.42	11.41	1.00	0.0	3.42	0.0	0.0	0	0.0	0
9	6.53	6.53	0.00	2.72	8.97	0.0	0.0	2.72	0.0	0.0	0	0.0	0
10	17.12	17.12	0.00	4.56	5.55	0.0	0.0	4.56	0.0	0.0	0	0.0	0
11	6.10	6.10	0.00	5.40	2.61	0.0	0.0	5.40	0.0	0.0	0	0.0	0
12	6.93	6.93	0.00	5.25	1.29	0.0	0.0	5.25	0.0	0.0	1	0.0	0
TOTALS	155.30	136.57	18.73	57.35	79.72	1.00	7.04	76.10	83.31	0.0		0.0	

Table 4-7. Example of computer output of yearly summaries and ranking of objective functions - work days, SEW_{30} dry days and yearly irrigation for drainage.

RANK	WORK DAYS	YEAR	SEW	YEAR	DRY DAYS	YEAR	IRRIGATION	YEAR
1	29.65	1966	97.51	1953	50.00	1954	0.0	1951
2	28.67	1955	83.31	1959	38.00	1952	0.0	1952
3	28.00	1967	63.83	1967	32.00	1955	0.0	1953
4	25.33	1951	62.01	1965	26.00	1957	0.0	1954
5	23.10	1968	37.39	1960	24.00	1970	0.0	1955
6	18.50	1953	30.60	1958	22.00	1956	0.0	1956
7	13.32	1954	0.0	1951	21.00	1964	0.0	1957
8	13.28	1969	0.0	1952	15.00	1951	0.0	1958
9	13.24	1963	0.0	1954	10.00	1953	0.0	1959
10	10.99	1952	0.0	1955	10.00	1960	0.0	1960
11	10.92	1970	0.0	1956	8.00	1962	0.0	1961
12	10.68	1965	0.0	1957	6.00	1958	0.0	1962
13	10.58	1957	0.0	1961	4.00	1963	0.0	1963
14	8.61	1956	0.0	1962	4.00	1969	0.0	1964
15	7.04	1959	0.0	1963	2.00	1959	0.0	1965
16	5.50	1961	0.0	1964	2.00	1961	0.0	1966
17	4.94	1964	0.0	1966	2.00	1965	0.0	1967
18	4.23	1960	0.0	1968	2.00	1967	0.0	1968
19	1.06	1962	0.0	1969	0.0	1966	0.0	1969
20	0.0	1958	0.0	1970	0.0	1968	0.0	1970
AVERAGE	13.38		18.73		13.90		0.0	

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CHAPTER 5

INPUT DATA

The input data requirements for the water management model are discussed in this section. Data are required for soil properties, crop inputs, water management system parameters and climatological input data. The purpose of this chapter is to identify required inputs, discuss methods of measuring or calculating these data and identifying published and unpublished sources of data for different soils, crops, and locations.

In many cases, all of the input data needed in the model will not be available from conventional data sources. Furthermore, it may not be possible to measure, or otherwise directly determine, the data, and the needed inputs will have to be approximated. Where possible, methods of approximating the various input data are given in the chapter. When relationships, such as the hydraulic conductivity or upward flux have to be estimated from a meager amount of information, it is a good idea to test the sensitivity of the objective function to the relationship estimated. Some sensitivity analyses are presented in Chapter 7, but, when possible, such analyses should be conducted for the specific case of interest. If the objective function is not sensitive to the estimated inputs, the approximations may be used. When the results are sensitive to the estimations, it may be desirable to invest more time and money in determining the needed inputs.

Soil Property Inputs

The first step in obtaining soil property input data for a given area is to refer to a good soils map of the fields involved. The soils map will identify the different soil types and certain of the required input data can be obtained or estimated from the soil survey interpretations. The soil survey data will also serve as a guide for identifying layers, etc., and for making additional soil property measurements.

The model should be used to make a separate analysis for each major soil type involved in a given water management system design or analysis.

Hydraulic Conductivity - K.

The saturated hydraulic conductivity of each horizon above the restricting layer is an important input. Since artificial drainage and subirrigation usually involve lateral flow to and from drains, the effective horizontal K values are used. A rough estimate of K can be obtained from the SCS soil survey interpretations (Form #5 - blue sheets). These data are usually based on soil texture and structure and the judgment of soil scientists. The K values are normally not determined from measurements and are approximations of the vertical hydraulic conductivity. Field or laboratory measurements of K are occasionally made for a soil series by the SCS National Soil Survey Lab personnel or at universities in the various states. These data may be in the file for the given soil series at the state SCS office or at the respective National Technical Centers. They may also be available in publications from the state universities, usually from the departments of soil science or agricultural engineering. Hydraulic K data may also have been measured for a few locations by the SCS National Soil Mechanics Lab in Lincoln, Nebraska. These measurements would have been made on cores form dam site locations and would represent deep horizons. Such data would be available from the state SCS office.

In some cases, detailed in situ K measurements have been made for selected soil types (e.g., Schwab, et al, 1978) so a good estimate of saturated hydraulic conductivity can be made from knowledge of the soil type. K values have also been determined in the lab from undisturbed samples and tabulated by soil type and horizon for many soils. Some of the sources for these data, as well as for some field measurements of K are given in Table 5-1. K values determined from cores tend to be smaller than field effective values because the cores usually do not contain cracks, worm holes, etc., that may have a big effect on K. Also, care should be taken in using values from cores, in that these values usually represent vertical K while drainage rates depend more on horizontal K. Effective vertical and horizontal K values may be different by a factor of 10 for field soils. Furthermore, K values may very considerably within a given soil type. Therefore, on-site measurements should be made whenever possible.

Numerous methods have been developed for determining saturated hydraulic conductivity in the field (Bouwer and Jackson, 1974). They include the auger hole method (van Bavel and Kirkham 1949, Boast and Kirkham 1970, van Beers 1970); the slug test (Bouwer, 1978) the two-well method (Childs, et al, 1953); the four-well method (Kirkham 1955, Snell and van Schilfgaarde 1964); and the piezometer method (Kirkham 1946). Shady, et al, (1977) reported on experience in Canada with field production scale hydraulic measurements using the auger hole method. This method is the most commonly used and is described in the SCS-NEH (Section 16, Chapter 2). These methods offer the advantage of a rapid, relatively easy measurement, but the resulting K value represents a single point in the field and several measurements may be needed to determine a field effective K value (Dylla and Guitjens, 1970); Hore 1959).

Methods for determining field effective K values from water table drawdown measurements were presented by Hoffman and Schwab (1964) and Skaggs (1976, 1979). These methods are currently being used by Schwab, et al, (1978) to determine K for several soils in the midwest. The ratio of K to drainable porosity, f, is obtained by matching measured drawdown rates to those predicted from theoretical equations. By calculating f from drain outflow measurements (e.g. Hoffman and Schwab 1964) or from soil water characteristic data (Duke 1972; Skaggs, et al, 1978), hydraulic conductivity can be obtained from the K/f determinations. A major advantage of determining K/f from drawdown measurements is that the effects of profile heterogeneities, nonuniformities, and anisotropy tend to be lumped in such a way that they are properly represented in ultimate drain spacing calculations. In addition, errors made in estimating the effects of soil layering and determining the depth to the impermeable layer are incorporated in the K values obtained and result in smaller errors in predicted drain spacings than when K is measured independently. The main disadvantage is that these measurements require more time and effort than do the point methods.

Soil Water Characteristic h(θ).

This property is a measure of how tightly water is held in the soil matrix in the unsaturated state. In addition to being an input to DRAINMOD, h(θ) is used in determining other inputs such as the relationship between water table depth and drainage volume, upward flux, etc. When the water table depth-drainage volume relationship is not read in, it is computed in DRAINMOD from the h(θ) data. The soil water characteristic is a basic soil property which is second in importance to only hydraulic conductivity in modeling soil water movement.

The soil water characteristic is usually determined in the laboratory using tension tables or pressure plates. Details of apparatus and procedure are given by L. A. Richards (1965), Tanner, and Elrick (1958) and others. Soil water characteristics for soils representing several textural classes are plotted in Figure 5-1. Data are available for many soils from several sources and a national data set on soil water characteristics is being compiled by Rayls and Brakensiek (1979). A list of their data sources is given in Table 5-1. Holtan, et al, (1968) compiled a data set for h(θ) for several hundred soil horizons. Some of these data are plotted in Figure 5-2 (from Baver, et al, 1972). However the lowest tension represented in these data is 0.1 bar so they are not complete in the range needed for drainage modeling applications. They can still be used to get an approximation of the soil water characteristic. However, it will only be an approximation for drainage purposes. Additional h(θ) data may be available from the SCS Soil Survey Investigations Reports (SSIR) from each state. The SSIR's are available from the National Technical Centers and from individual state offices. The user should be aware that the data in the SSIR for a given soil type may be incomplete (e.g. volumetric water contents for only 2 or 3 tensions), or it may not be available at all. On the other hand, additional h(θ) data may be tabulated in the file that is maintained for each soil type at the SCS National Technical Centers, the National Soil Survey Lab, the state SCS offices, or in soil science departments at cooperating universities in various states. Because of the need for h(θ) data at low tensions in drainage modeling, it is desirable to increase the number of pressure steps that are used in standard tests run by the SCS National Soil Survey Lab. Water contents could be obtained at tensions of 5 cm, 50 cm, and 100 cm without much additional effort or expense. Such data would be extremely valuable for applications discussed herein, as well as in other water management uses.

The soil water characteristic relationship for only one layer is used as input data in the model. These data should represent the thickest layer between the surface and the drain line depth. Soil water characteristics for all the layers are needed to determine other required inputs.

Soil water characteristics for a given site should be measured whenever possible. The next best alternative is the tabulated h(θ) data in the literature (Table 5-1). If data for the soil is not available, h(θ) can be approximated for each horizon by matching the textural classes with those of soils that are tabulated. If possible, data should be obtained from soils in the same series and from the same geographic area. While h(θ) depends on texture, it is also heavily dependent on structure. So a well aggregated soil should be matched with a soil in the literature that is also well aggregated. Once h(θ) is determined for each horizon other inputs can be obtained.

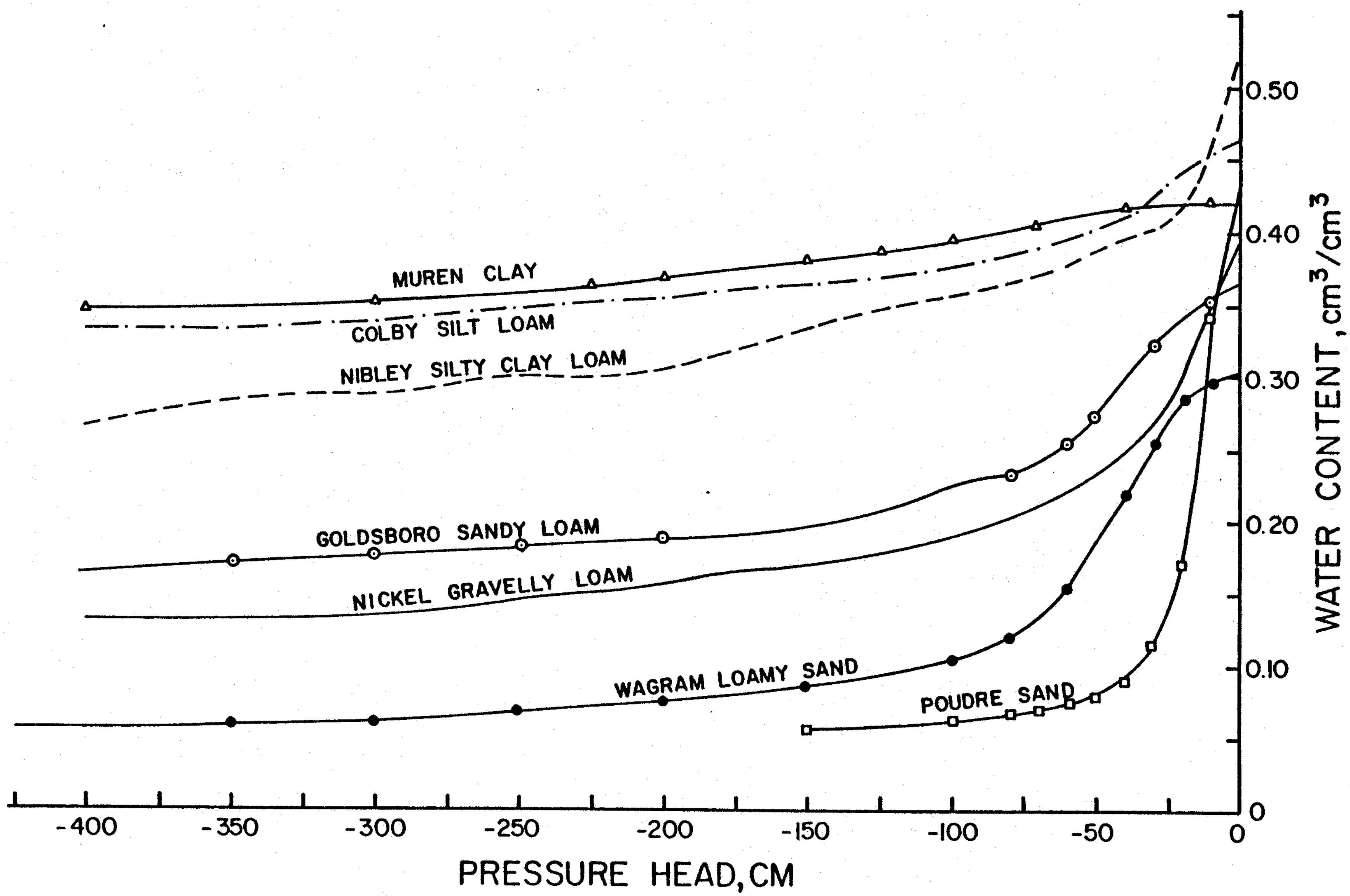

Figure 5-1. Soil water characteristics for 7 soils. Data for the Muren, Colby, Nibley, Nickel and Poudre soils were obtained from Smith (1972). Wagram and Goldsboro data are from Skaggs (1978a).

Methods for determining input h(θ) data may be ranked as follows:

1. Measurement of h(θ) from undisturbed field samples taken from each layer of the major soil types on the sites to be considered.

2. Obtain tabulated h(θ) data for the given soil types from literature sources.

3. Estimate h(θ) for each profile horizon by matching according to texture and structure with similar soils that have published or otherwise available h(θ) data.

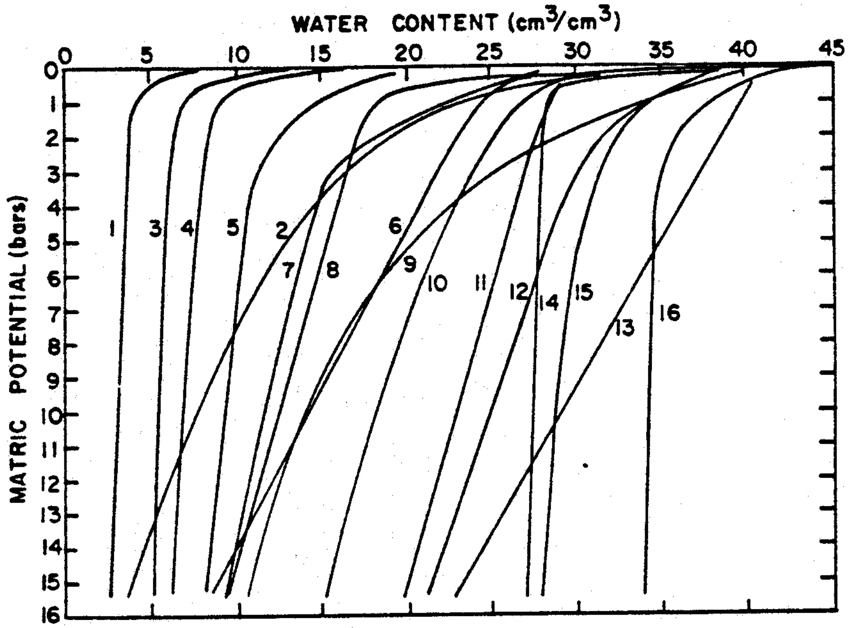

Figure 5-2. Desorption curves for various soils sketched from data at 0.1, 0.3, 0.6, 3, and 15 bars tension given by Holtan, et al, 1968.

1. Continental gravelly sandy loam, Arizona.
2. Sassafras sandy loam, Maryland.
3. Progresso fine sandy loam, New Mexico.
4. Vaucluse sandy loam, Georgia.
5. Albion loam, Oklahoma.
6. Abilene clay loam, Texas.
7. Hartsells loam, Ohio.
8. Palouse silt loam, Washington.
9. Fayette silt loam, Wisconsin.
10. Nellis gravelly loam, New York.
11. Lard-like silty clay loam, South Dakota.
12. Memphis silt loam, Mississippi.
13. Drummer silty clay loam, Illinois.
14. Auston silty clay, Texas.
15. Marshall silty clay loam, Iowa.
16. Bascom-like clay, South Dakota (from Baver, et al, 1972). Note that the curve between tensions of 0.0 and 9.1 bars may be very important for drainage applications and these data are missing in this data set.

Table 5-1. Sources of published soil water characteristic (or moisture tension), hydraulic conductivity and other soil property data (obtained by personal communication from Walter J. Rawls, USDA-SEA-AR).

Author or Investigator and Date	Location of Soils	Title of Article	Source
1. Holtan, et al, 1968	U.S.A.	Moisture tension data for selected soils on experimental watersheds	USDA, ARS Bulletin ARS 41-144, 609 pages
2. University of Illinois and USDA-ARS, 1979	North Central Region	Water infiltration into representative soils of the North Central Region	Illinois Agricultural Experiment Station Bulletin 760 and North Carolina Region Research Pub. 259 Urbana, Illinois, 119 pages
3. Long, et al, 1963	Lower Coastal Plains-Atlantic Coat	Soil moisture characteristics of some lower Coastal Plains soils	USDA, ARS Bulletin ARS 41-82, 22 pages
4. Elkins, et al, 1961	Southern Piedmont	Soil moisture characteristics of some Southern Piedmont soils	USDA, ARS ARS 41-54, 22 pages
5. Long, et al, 1969	Atlantic Coast Flatwoods	Morphological, chemical, and physical characteristics of eighteen representative soils of the Atlantic Coast Flatwoods	USDA, ARS, and University of Georgia Agriculture Experiment Station, Research Bulletin 59, Athens, Georgia, 74 pages
6. Lutz, J. F. 1970	North Carolina	Movement and storage of water in North Carolina soils	North Carolina State University Agricultural Research Service Soils Information Series No. 15, Raleigh, North Carolina, 29 pages
7. Carlisle, et al, 1978	Florida	Characterization data for selected Florida soils	IFAS, University of Florida, USDA, SCS, Soil Science Research Report No. 78-1, Gainesville, Florida, 335 pages

(Continued)
Table 5-1. Sources of published soil water characteristic (or moisture tension), hydraulic conductivity and other soil property data (obtained by personal communication from Walter J. Rawls, USDA-SEA-AR).

Author or Investigator and Date	Location of Soils	Title of Article	Source
8. Lund, Z. F. and Lofton, L. L., 1960	Louisiana	Physical characteristics of some Louisiana soils	USDA, ARS, ARS-41-33, 83 pages
9. Lund, et al, 1961	Louisiana	Supplement to physical characteristics of some Louisiana soils	USDA, ARS, ARS-41-33-1, 43 pages
10. Longwell, et al, 1963	Tennessee	Moisture characteristics of Tennessee soils	University of Tennessee Agr. Experiment Station and USDA, SCS Bulletin 367, Knoxville, Tennessee, 46 pages
11. Holt, et al, 1961	Minnesota	Soil moisture survey of some representative Minnesota soils	USDA, ARS Bulletin ARS 41-48, 43 pages
12. Hermsmeier, 1966	Minnesota	Hydraulic conductivity and other physical characteristics of some "wet" soils in SW Minnesota	USDA, ARS Bulletin ARS 41-127, 17 pages
13. Cassel and Sweeney, 1974	North Dakota	In situ soil water holding capacities of selected North Dakota soils	Bulletin 495, Agr. Experiment Station, North Dakota, State University, Fargo, North Dakota, 25 pages
14. Olson, 1970	South Dakota	Water storage characteristics of 21 soils in eastern North Dakota	USDA, ARS Bulletin ARS-41-166, 69 pages
15. Mathers, et al, 1963	Southern Great Plains	Some morphological physical, chemical, and mineralogical properties of 7 Southern Great Plains soils	USDA, ARS Bulletin ARS-41-85, 63 pages

(Continued)
Table 5-1. Sources of published soil water characteristic (or moisture tension), hydraulic conductivity and other soil property data (obtained by personal communication from Walter J. Rawls, USDA-SEA-AR).

Author or Investigator and Date	Location of Soils	Title of Article	Source
16. Krother, et al, 1960	Missouri	Soil moisture survey of some representative Missouri soil types	USDA, ARS Bulletin ARS-41-34, 57 pages
17. Post, et al, 1978	Arizona	Soils of the University of Arizona Experiment Station: Marana	USDA, SCS, Agri. Eng. & Soil Science, 78-1, University of Arizona, Tucson, Arizona
18. Kelley and Edwards 1975	Ohio	Soils of the North Appalachian experimental watershed	USDA, ARS, and SCS, Ohio Agri. Research & Development Center, M.S. Publication No. 1296, Washington, D.C., 145 pages
19. Epstein, et al, 1962	Maine	Soil moisture survey of some representative Maine soil types	USDA, ARS, ARS-41-57, 57 pages
20. Rourke, et al, 1969	Maine	Chemical and physical properties of the Charlton, Sutton, Paxton, and Woodbridge soil series	Maine Agr. Experiment Station Technical Bulletin 34, University of Maine, Orono, Maine, 8 pages
21. Rourke, et al, 1971	Maine	Chemical and physical properties of the Allagarh, Hermon, Howland, and Marlow soil mapping units	Agr. Experiment Station Technical Bulletin 46, University of Maine, Orono, 73 pages
22. Rourke and Bangs 1975	Maine	Chemical and physical properties of the Bangor, Dixmont, Caribou, Conant, Perhan, and Daigle soil mapping units	Agr. Experiment Station Technical Bulletin 75, University of Maine, Orotha, 102 pages

Drainage Volume - Water Table Depth Relationship

This relationship is used in the model to determine how far the water table falls or rises when a given amount of water is removed or added. The volume of water drained at various water table depths (sometimes called the water yield) can be measured directly from large soil cores (Skaggs, eta al. 1978). However, it is usually not convenient to collect a large core and the drainage volume - water table depth relationship may be calculated from the soil water characteristic.

In calculating the water yield from h(θ), it is assumed that the water table recedes such that the vertical hydraulic gradient above the water table is zero and the unsaturated zone is essentially 'drained to equilibrium' with the water table at all times. That is, it is assumed that the water content distribution at any time is the same as that which would result if the water table was stationary at a given position and the profile drained to equilibrium. Theoretical studies (Tang and Skaggs, 1978; Skaggs and Tang, 1976) indicate that this assumption is valid for most field scale drainage systems. Then, the volume drained per unit area, V_d, when the water table drops from the surface to depth y_1, may be expressed as,

$$V_d = \int_o^{y_1} (\theta_o(y) - \theta(y))\, dy, \tag{5-1}$$

Where $\theta_o(y)$ is the soil water content prior to drainage, usually assumed to be constant and equal to the saturated value*, and $\theta(y)$ is the equilibrium water content distribution which is obtained from the soil water characteristic for a water table depth of y_1. The water content distribution and V_d are shown schematically in Figure 5-3a for a uniform soil V_d is calculated for any depth, y, by numerically integrating the cross-hatched area in Figure 5-3a.

For layered profiles θ_o and $\theta(y)$ are obtained from the soil water characteristics for the respective layers, the drained volume for a layered profile is schematically shown in Figure 5-3b. If the water yield relationships of the soils in the top layer, V_{d1} (y), and in the bottom

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*Soils are rarely completely saturated in the field because of entrapped air. Thus, θ_o is the volumetric water content at residual air saturation which is usually not more than 90 to 95 percent of total porosity.

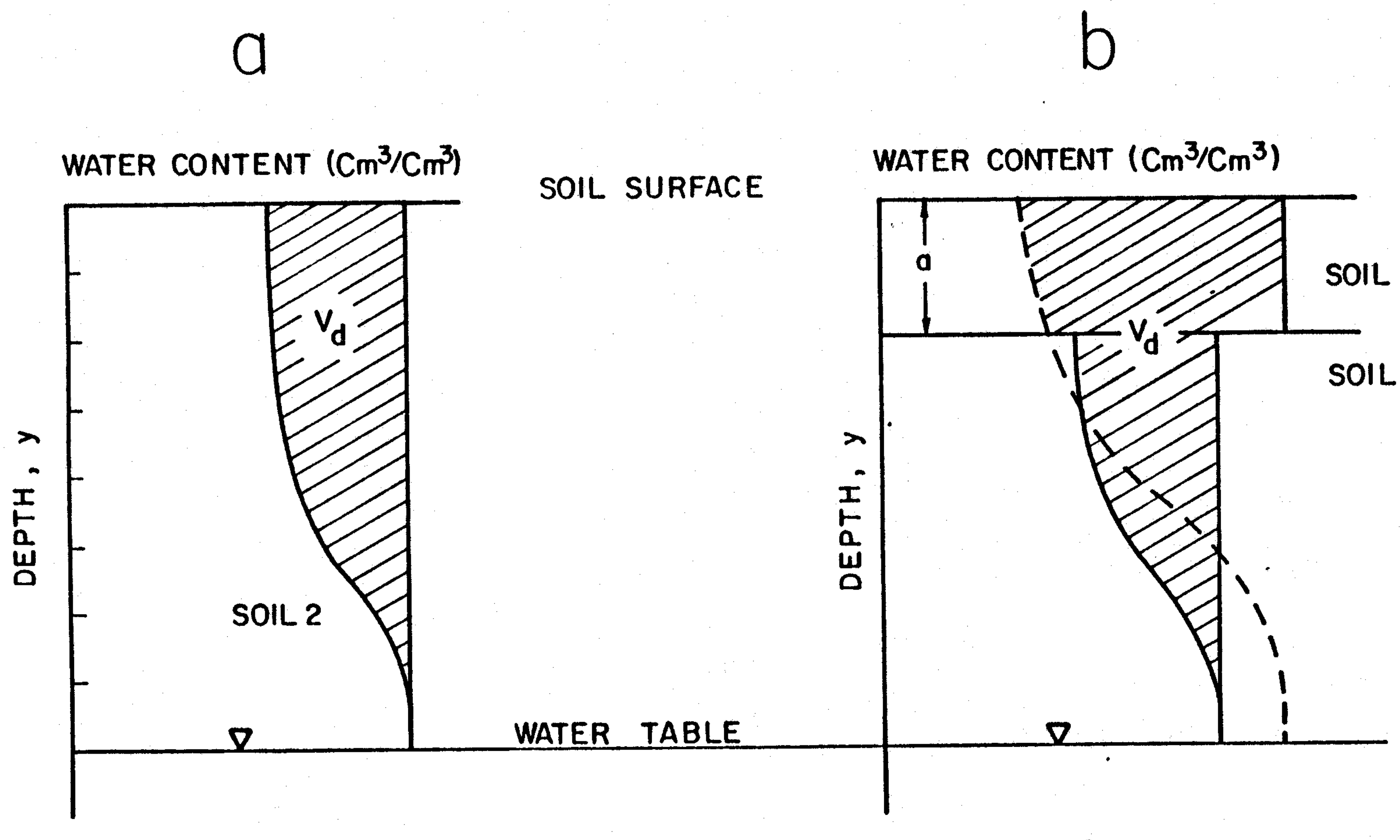

Figure 5-3. Soil water distribution for a uniform soil [a] and a layered soil [b] drained to equilibrium to a water table. The broken curve in [b] represents the soil water distribution for a uniform soil 1.

layer, V_{d2} (y), are first determined from the soil water characteristics, V_d can be easily computed for the layered soil as follows. For water table depths less than the depth, a, of the top layer,

$$V_d(y) = V_{d1}(y) \qquad (5\text{-}2)$$

For greater depths,

$$V_d(y) = V_{d1}(y) - V_{d1}(y-a) + V_{d2}(y-a) \qquad (5\text{-}3)$$

If the profile has a third layer starting at depth b, the water yield for depths greater than b may be computed by,

$$V_d(y) = V_{d1}(y) - V_{d1}(y-a) + V_{d2}(y-a) - V_{d2}(y-b) + V_{d3}(y-b) \qquad (5\text{-}4)$$

Where $V_{d3}(y)$ is the water yield relationship for the third layer.

A computer program to calculate the $V_d(y)$ relationship from the soil water characteristics of a soil profile with up to 5 layers was developed by Badr (1978) and is given, along with example input data and program results, in Appendix D.

Drainage volume - water table depth relationships are given in Figure 5-4 for 7 North Carolina soils. Others can be calculated from soil water characteristic data which are available for many soils as discussed in the previous section. The slope of a plot of drainage volume versus water table depth is the drainable porosity, f, also called the specific yield. So if f is known or can be approximated for each soil horizon $V_d(y)$ can be estimated. For example, consider a soil with a well aggregated surface layer (0 - 30 cm) which has a drainable porosity of approximately f = 0.12. The subsurface layer (B horizon; 30-120 cm deep) is a silt loam with f = 0.04. These drainable porosities imply the water yield relationships plotted in Figure 5-5 (broken lines) for each layer. Once the $V_d(y)$ relationships are estimated for each layer, the water yield for the entire profile can be obtained from equations 5-2 and 5-3. This relationship is plotted as the solid curve in Figure 5-5.

There are a number of methods of obtaining the input data for drainage volume versus water table depth as discussed above. These methods are ranked as follows with the most exact or best method listed first, the next best listed second, etc.

1. Measurement of $V_d(y)$ from large undisturbed soil cores. (Probably impractical for most situations.)

2. Calculation of $V_d(y)$ from soil water characteristics, $h(\theta)$, for each soil horizon.

3. Determination of $V_d(y)$ from estimated drainable porosities of each layer (e.g. Figure 5-5).

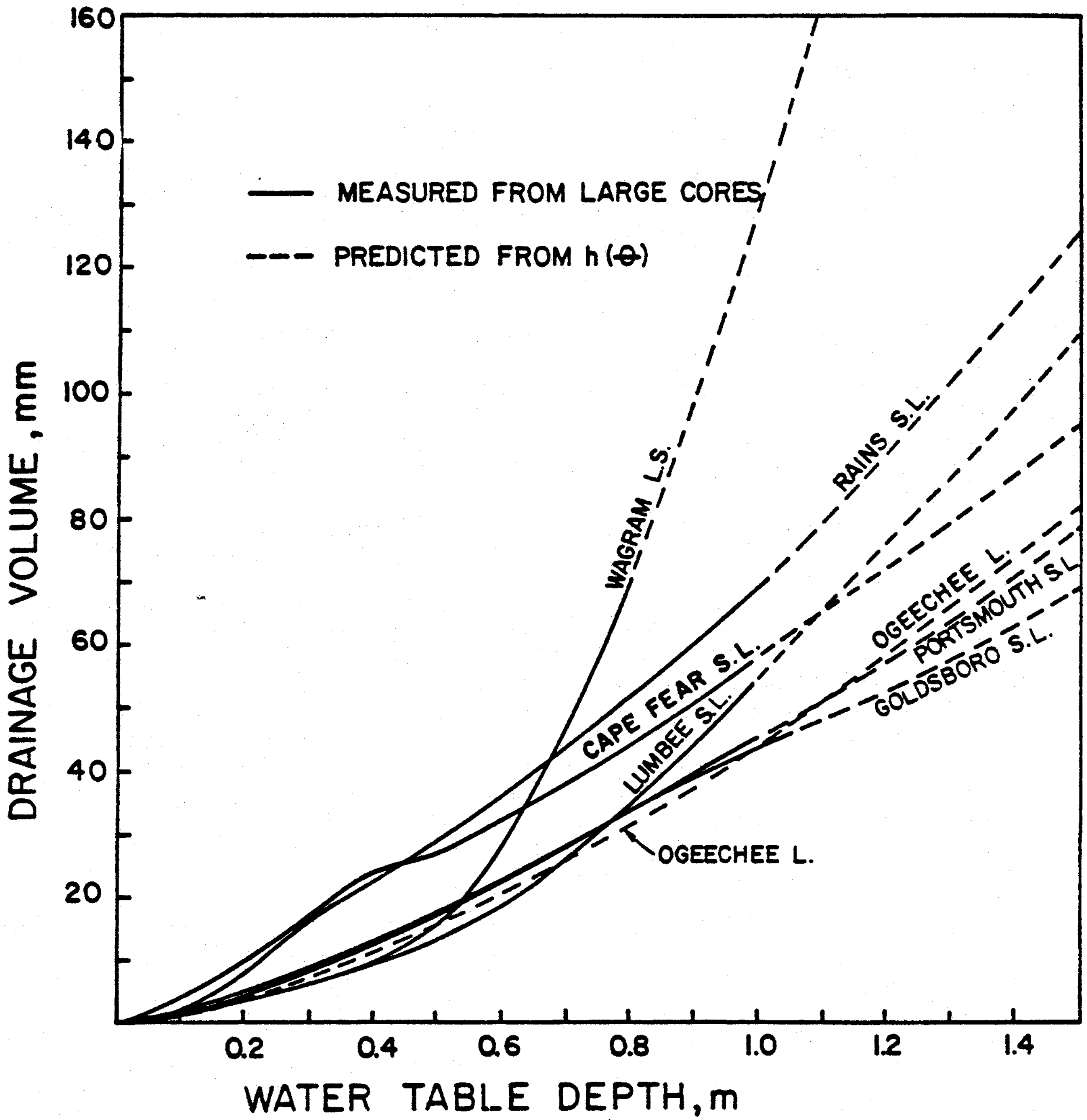

Figure 5-4. Drainage or air volume (mm^3/mm^2) as a function of water table depth for 7 North Carolina soils.

Upward Flux

There are several ways of estimating the relationship between upward flux and water table depth. The entire concept is approximate, as discussed in Chapter 2 because the relationship is defined for steady state conditions while the actual upward water movement process is transient. The easiest method is to obtain upward flux relationships directly from the literature. Such relationships are plotted for 8 North Carolina soils in Figure 5-6. Gardner (1958) obtained explicit unsaturated flux solutions for a given form of the unsaturated hydraulic conductivity function. Generally, however, upward flux relationships are not available and must be calculated from more basic soil properties. Numerical procedures may be used to calculate the water table depth for a given steady upward flux.

The equation for upward flux, at any point below the root zone, may be written from the Darcy-Buckingham equation as,

$$q = -K(h)\frac{dh}{dz} + K(h) \qquad (5\text{-}5)$$

Where q is flux, z is the vertical position coordinate which is positive in the downward direction, h is pressure head, and K(h) is the unsaturated hydraulic conductivity. By dividing the soil profile into increments of Δz (Figure 5-7), Equation 5-5 can be written in finite difference form as,

$$q = -K(h_i)\frac{h_i + 1 - h_i}{\Delta z} + K(h_i) \qquad (5\text{-}6)$$

Solving for h_{i+1} yields,

$$h_{i+1} = h_i + \Delta z - q\frac{\Delta z}{K(h_i)} \qquad (5\text{-}7)$$

For a given surface (or bottom of root zone) boundary condition h_1, say $h_1 = -500$ cm, and an assumed value of q, h_2 can be calculated from Equation (5-7) by looking up the K value corresponding to $h_1 = -500$ cm. Then, h_3 can be determined from (5-7) and so on for the entire column. The water table depth for the q value assumed is that depth at which h = 0. By repeating the solution for a range of q values, the relationship between upward flux and water table depth can be defined. The K(h) value for each node is obtained from the unsaturated hydraulic conductivity function of the appropriate layer. A computer program to solve Equation 5-7 for a profile with up to 5 layers is given together with example input and output data in Appendix E.

The most critical condition for upward water movement is when available water in the root zone has been used up. Then, the upper boundary is effectively at the bottom of the root zone. Since the root zone depth changes with time during the growing season, an average root depth should be defined and used as the surface boundary for calculating the upward flux. For example, if the root zone depth of corn varies from 2 to 28 cm, the upper boundary condition should be applied at a depth of (2 + 28)/2 = 15 cm. Then, if the soil profile has three layers: 0 - 25 cm with $K_1(h)$; 25-75 cm with $K_2(h)$; and 75-120 cm with $K_3(h)$, the solutions given above should be

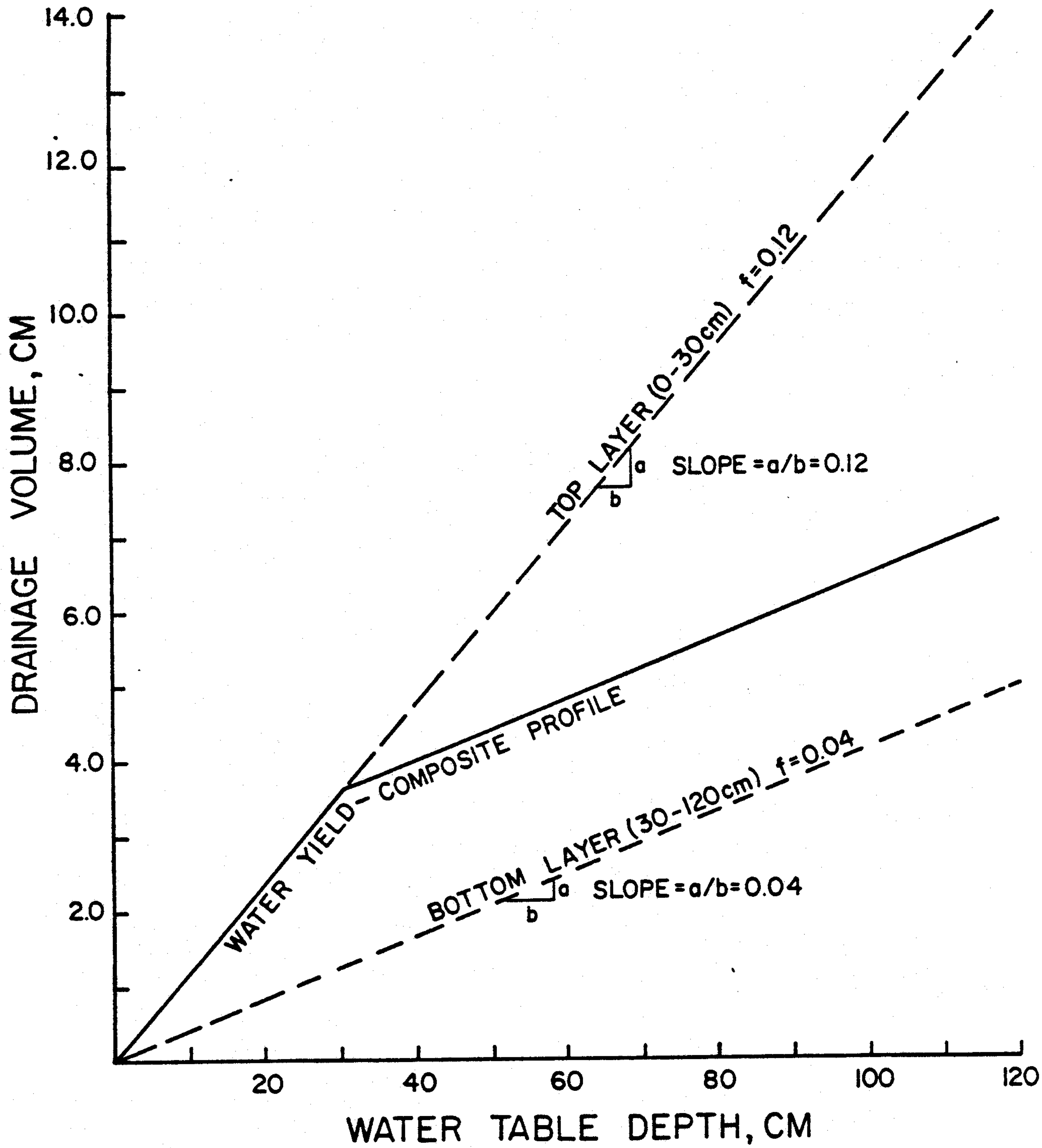

Figure 5-5. Drainage volume - water table depth relationships may be determined from estimated drainable porosity values.

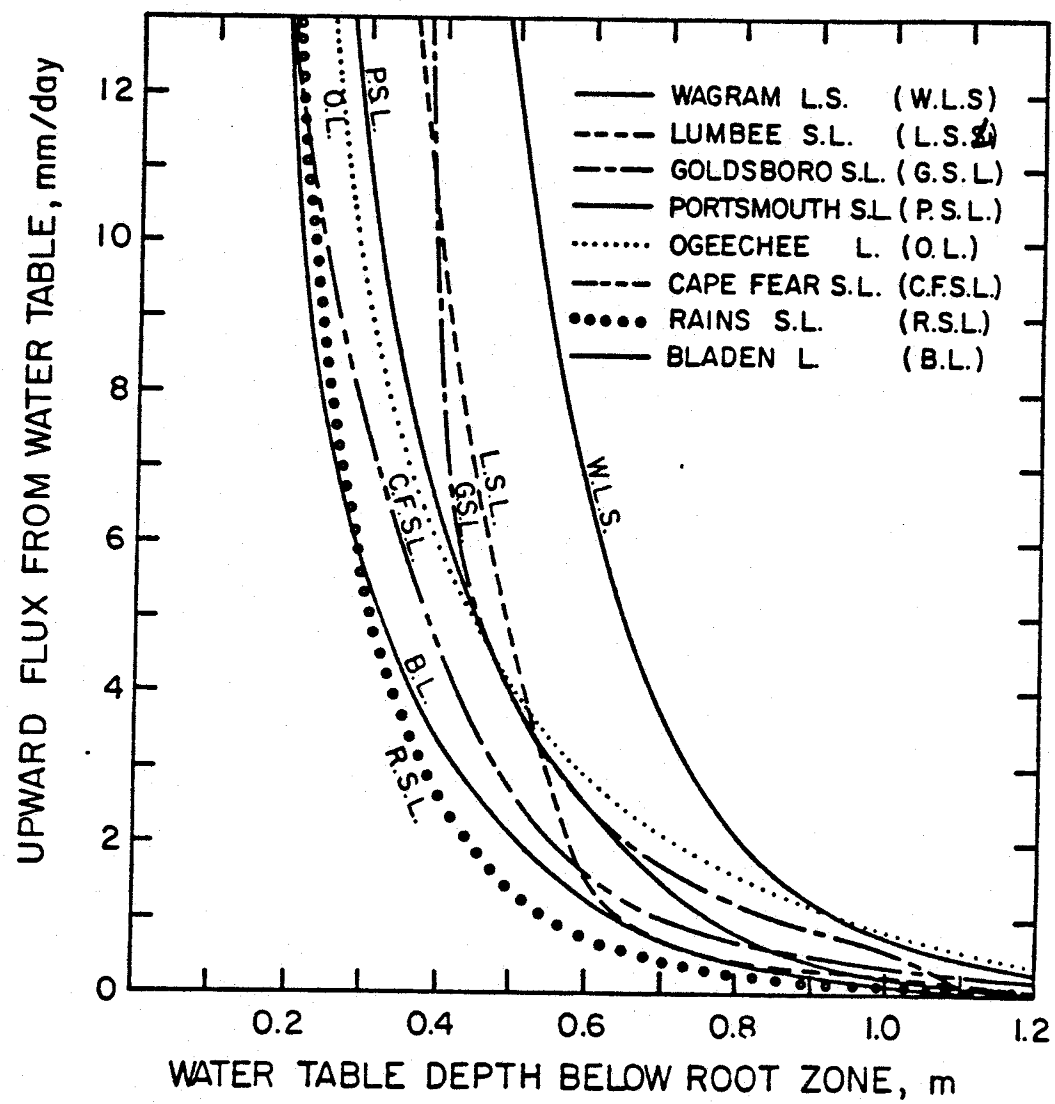

Figure 5-6. Upward flux - water table depth relationships for eight North Carolina soils.

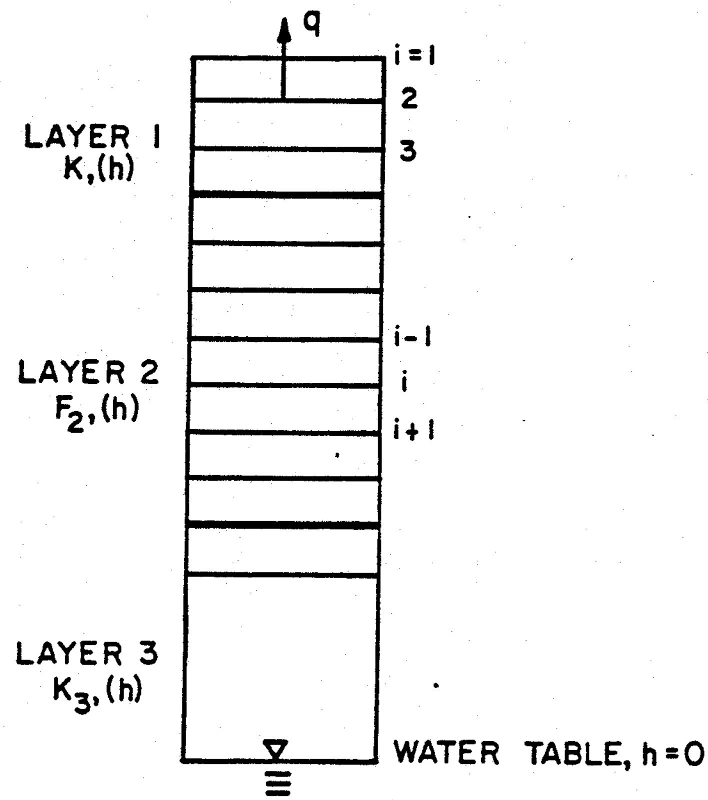

Figure 5-7. Finite difference grid for numerical solution for upward flux in a layered soil.

obtained for a profile starting at the 15 cm depth. That is, a profile with layer 1, 0 - 10 cm - $K_1(h)$; layer 2, 10-60 cm - $K_2(h)$; and layer 3, 60 - 105 cm - $K_3(h)$.

It is generally difficult to apply the above methods to determine upward flux relationships because of the unavailability of unsaturated hydraulic conductivity, K(h), data. Measured data are available for a few soils. Mualem (1978) cited sources of data for 50 soils. Other conductivity data may be obtained from some of the sources listed in Table 5-1. Unsaturated hydraulic conductivity, soil water characteristics and other properties are being measured in the field in several locations throughout the United States. The measurements are being made primarily by soil physicists at the Land Grant universities in the various states. A regional project entitled "Movement and Storage of Water and Solutes in Selected Southern Region Field Soils" is being conducted by researchers in 12 southern states. The project is sponsored by the Environmental Protection Agency and the Agricultural Experiment Stations in the individual states. The results from all states will be published in a bulletin when the project is completed (in 1982). Data may be published or available from individual researchers prior to that time.

What do you do if K(h) data are not available? Probably the next best alternative is to calculated K(h) from the soil water characteristic and saturated K. A number of prediction methods have been proposed and were reviewed by Bouwer and Jackson (1974). Experimental evaluations of the prediction methods have shown that best results are obtained when a matching factor is used to force the calculated and measured conductivities to agree at a given water content, usually saturation. Among the most frequently used methods are those predicted by Millington and Quirk (1961) and Marshall (1958). When the matching factor is based on the saturated conductivity, both the Millington and Quirk and Marshall equations can be written in the following form (Jackson, 1972).

$$K(\theta_i) = K_s \left(\frac{\theta_i}{\theta_s}\right)^p \frac{\sum_{j=1}^{m} (2j + 1 - 2i)/h_j^2}{\sum_{j=1}^{m} (2j - 1)/h_j^2} \qquad (5\text{-}8)$$

Where $K(\theta_i)$ is the calculated conductivity at water content θ_i, K_s is the saturated conductivity, θ_s is the water content at saturation, m is the number of water content increments used in the computation and j and i are indicies. The exponent p is 0 for the Marshall formulation and 4/3 for Millington and Quirk. A value of p = 1 can be used for most cases (Kunze, et al, 1968; Jackson 1972). Figure 5-8 shows a soil water characteristic divided into m equal water content increments. Usually m taken between 10 and 20 is adequate. The pressure head h_i is obtained from the midpoint of each increment. The water content, θ_i is the highest water content for the increment. A computer program to calculate K(θ) from Equation 5-8 is given in Appendix F. Once the K(h) relationship is defined, the numerical methods discussed above and in the computer program given in Appendix E can be used to determine the upward flux - water table depth relationship.

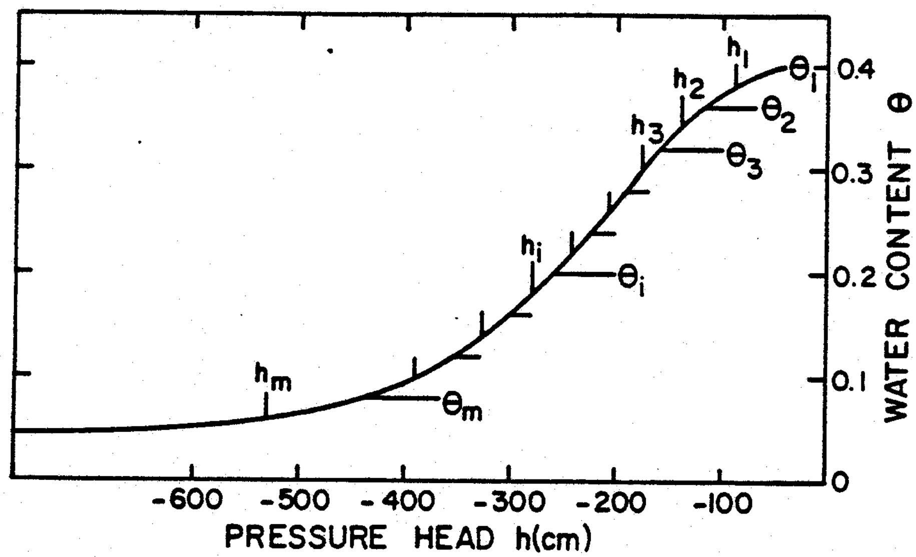

Figure 5-8. Hypothetical pressure head-water content relation showing equal water-content increments and corresponding pressure heads used to calculate the unsaturated conductivity by the methods of Marshall and of Millington and Quirk (after Bouwer and Jackson, 1974).

Often the soil water characteristic will not be known. Then, how do you determine the upward flux? It should be obvious that the less we know about the soil properties, the more approximate will be the inputs and the results. In the case where we know neither K(h) or h (θ), upward flux relationships can be estimated in terms of the soil texture and saturated hydraulic conductivity by assuming a form of the hydraulic conductivity function and selecting equation parameters based on the soil texture. Gardner (1958) suggested the following equation for the relationship between the hydraulic conductivity, K(h), and the pressure head, h.

$$K(h) = a\ [(-h)^n + b]^{-1} \tag{5-9}$$

Where a, b, and n are parameters that depend on the soil. Raats and Gardner (1974) wrote the equation as:

$$K(h) = K_s\ [(h/h_{0.5})^n + 1]$$

Where K_s is the vertical saturated hydraulic conductivity and $h_{0.5}$ is the pressure head at which $K(h) = K_s/2$.

Gardner (1958) solved Equation 5-5 for n values between 1.5 and 4 and expressed the maximum upward flux in terms of the water table depth and the parameters a, b, and n. Raats and Gardner (1974) showed that the solution for maximum upward flux could be written as,

$$q_{max} = K_s \left[\frac{-\pi\ h_{0.5}}{n\ \mathrm{Sin}\pi/n}\right]^n \quad y^n \tag{5-10}$$

Where y is the depth of the water table below the surface. For our purposes, we would assume that y is the depth below the root zone, as discussed on pages 5-20.

An equation similar to 5-10 was derived by Anat, et al, (1965) by assuming the Brooks and Corey (1964) form of the hydraulic conductivity function, which may be written as,

$$K = K_s \quad , \qquad h > h_b \tag{5-11a}$$

$$K = K_s \left(\frac{h_b}{h}\right)^\eta \qquad h < h_b \tag{5-11b}$$

Where η is a dimensionless constant for a given soil and h_b is the bubbling pressure head (remember that the pressure head is negative for unsaturated conditions, so $h < h_b$ corresponds to tensions greater than $-h_b$). Anat's equation for maximum upward flux may then be written as,

$$q = K_s\ \left[h_b + \frac{1.89\ h_b}{\eta^2 + 1}\right]^\eta /y^\eta \tag{5-12}$$

Brooks and Corey (1964) related η to the pore size distribution index, λ, as,

$$\eta = 2 + 3\lambda \tag{5-13}$$

They described graphical methods of determining λ from the soil water characteristic. It can be shown that $\eta = n$ in Equations 5-9 and 5-10.

The difficult part in applying either Equation 5-10 or Equation 5-12 is determination of the parameters η, h_b, and $h_{0.5}$. When better information cannot be obtained the parameters can be approximated in terms of the soil texture using results recently reported by Brakensiek, et al, (1980). These results build on the work of Clapp and Hornberger (1978) and Brakensiek (1979) to present, for textural classes of sand, sandy loam, silt loam, etc., average values of η, h_b, and other parameters that will be discussed in the section on infiltration. Values for η and h_b are given in Table 5-5. The values given by Brakensiek, et al, (1980) were derived from analyses of desorption data. Because upward flux may involve both desorption and imbibition processes (Anat, et al, 1965), estimates for the imbibition cycle should probably be used. Bouwer (1969) suggested that the bubbling pressure head for imbibition, which he called the water entry section, could be approximated as one-half the desorption h_b.

Another method of estimating the upward flux is to employ the results of Clapp and Hornberger (1978). They used a power curve to model the soil water characteristic and a relationship for K(h) originally derived by Cambell (1964). By examining soil properties for many soils, they obtained average parameters for various textural classes. Their results were used to calculate normalized upward flux relationships for each textural class using Equation 5-7 and the computer program in Appendix E. These normalized relationships are plotted in Figure 5-9. An input upward-flux relationship for a given soil can be estimated by multiplying the flux values on the approximate curve in Figure 5-9 by the saturated conductivity. A note of caution is necessary in using the values given in Table 5-5 and Figure 5-9. In both cases, the results are based on soil water characteristic data obtained by Holtan, et al, (1968). As already mentioned (page 5-4), these data are not complete for low tensions. Inaccuracies in this range may cause significant errors in predicting upward flux relationships so the results in Figure 5-9 and the data in Table 5-5 should only be used when measurements on the specific soils considered cannot be obtained.

For layered soils, the maximum upward flux-water table depth relationships can be constructed for each soil layer using Equation 5-10, Equation 5-12, or Figure 5-9. Then, a composite curve can be constructed, as shown in the example below.

Example. Analyses are to be conducted for a soil having the following profile description:

0 - 15 cm sandy loam, $K_s = 2.0$ cm/hr

15 - 55 cm sandy clay loam, $K_s = 0.5$ cm/hr

55 - 135 cm sandy clay, $K_s = 0.2$ cm/hr

Corn, with a time-average rooting depth of 15 cm is to be grown. Therefore, the upward flux relationship will be defined from profile characteristics from the 15 to 135 cm depth. Multiplying the ordinate values of the sandy clay loam and sandy clay curves in Figure 5-9 by 0.5 and 0.2 cm/hr,

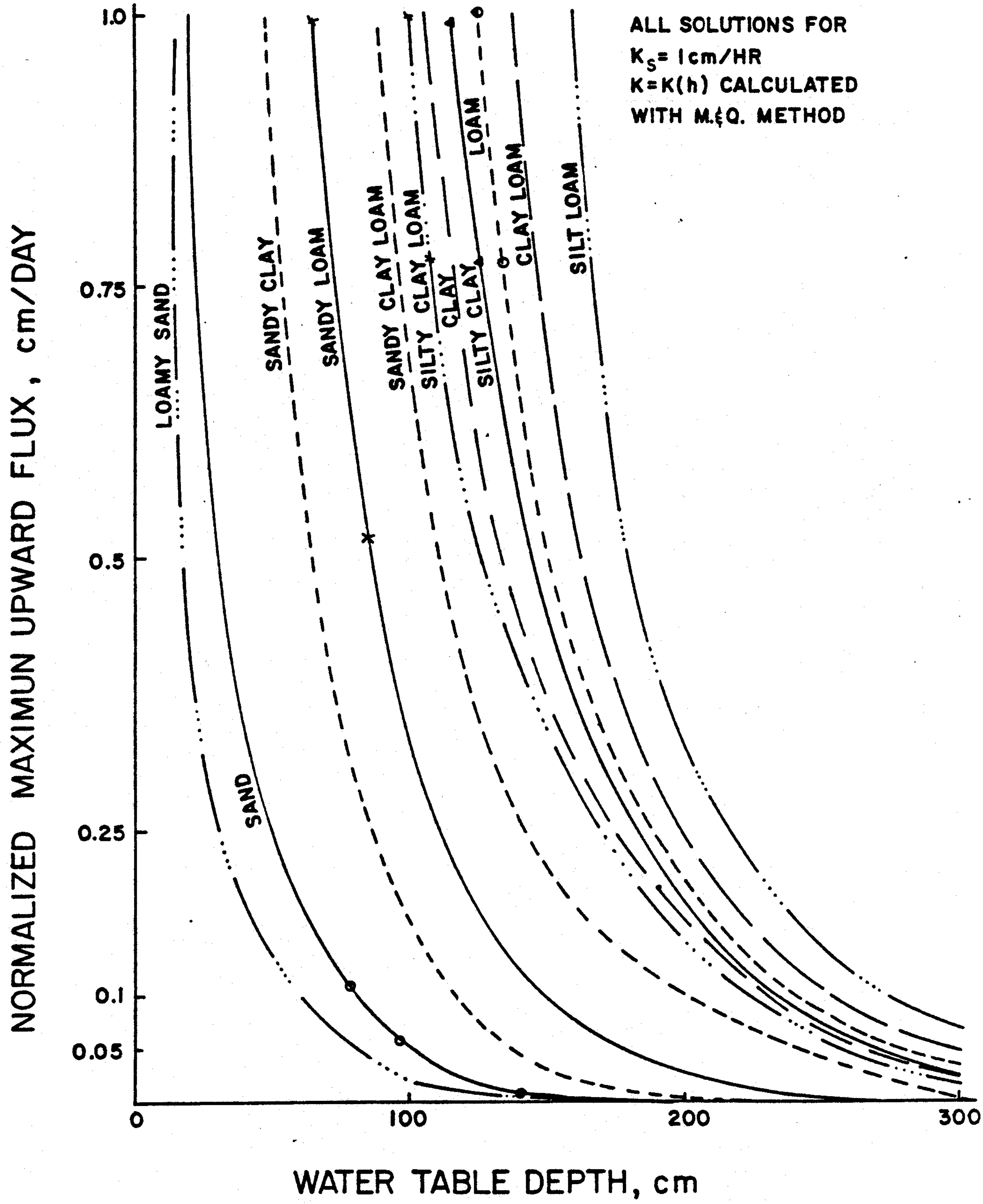

Figure 5-9. Approximate upward flux relationships for a range of textural classes. Upward flux was determined for saturated K of 1 cm/hr in all cases. Average h(θ) relationships were obtained from the results of Clapp and Hornberger (1978). K(h) was predicted from the Millington and Quirk method with K_s = 1.0 cm/hr and upward flux computed numerically (Equation 5-7 and Appendix E).

respectively, gives the broken curves in Figure 5-10. The sandy clay loam curve will represent the relationship for water table depths from 0 to 55 - 15 = 40 cm and the sandy clay curve for deeper depths. A transition curve is sketched in to smoothly connect the two relationships giving an approximate upward flux - water table depth relationship for the profile. If an upward flux relationship is to be calculated from Equation 5-12 or chosen from Figure 5-9 for a single layer, it should be based on the texture and K of the zone from the bottom of the plow layer to a depth of about 1 m.

The simplest (and most approximate) method of handling the upward flux is to define a critical limiting depth, CRITD, below which water will not be transferred to the root zone. That is, it is assumed that water will move upward from the water table at a rate equal to the potential ET rate until the distance between the water table and the root zone becomes greater than CRITD. The parameter CRITD can be approximated from a soil profile description based on the texture and hydraulic conductivity of each horizon. In some cases, this option may be preferable to approximating an upward flux - water table depth relationship. Consider the field description of an Oldsmar sand profile given in Table 5-2. For this particular case, the soil properties are given by Hammond, et al, (1971) and the upward flux relationship could be calculated using the numerical methods discussed above. However, if these data were not available, we would assume that upward water movement would be severely restricted by the tight layer at a depth of 86 cm. Then, subtracting the average root zone depth of 15 cm gives CRITD = 86 - 15 = 71 cm.

Alternative methods for determining input data for upward flux may be ranked as follows:

1. Obtain upward flux - water table depth relationship from plots or tables in the literature (e.g. Figure 5-6) or from explicit solutions such as those given by Gardner (1957). Such relationships are not available for many soils at this time, but could be developed for future use.

2. Calculate the relationship from K(h) using numerical methods (Equation 5-7 and Appendix F).

    a. With measured or tabulated K(h) for the given soils.

    b. With K(h) of each horizon computed from Millington and Quirk or other prediction methods (Appendix G). This requires the soil water characteristic, $h(\theta)$, and saturated K of each horizon.

3. Use the normalized relationships for different soil textures given in Figure 5-9 with saturated K for each horizon. Approximate for layered soils, as discussed in relation to Figure 5-10, <u>or</u> choose approximate η and h_b values from Table 5-5. Calculate upward flux relationship using Equations 5-10 or 5-12.

4. Use the critical depth concept. CRITD should usually not be greater than 90 cm and may be less depending on location of restricting horizons.

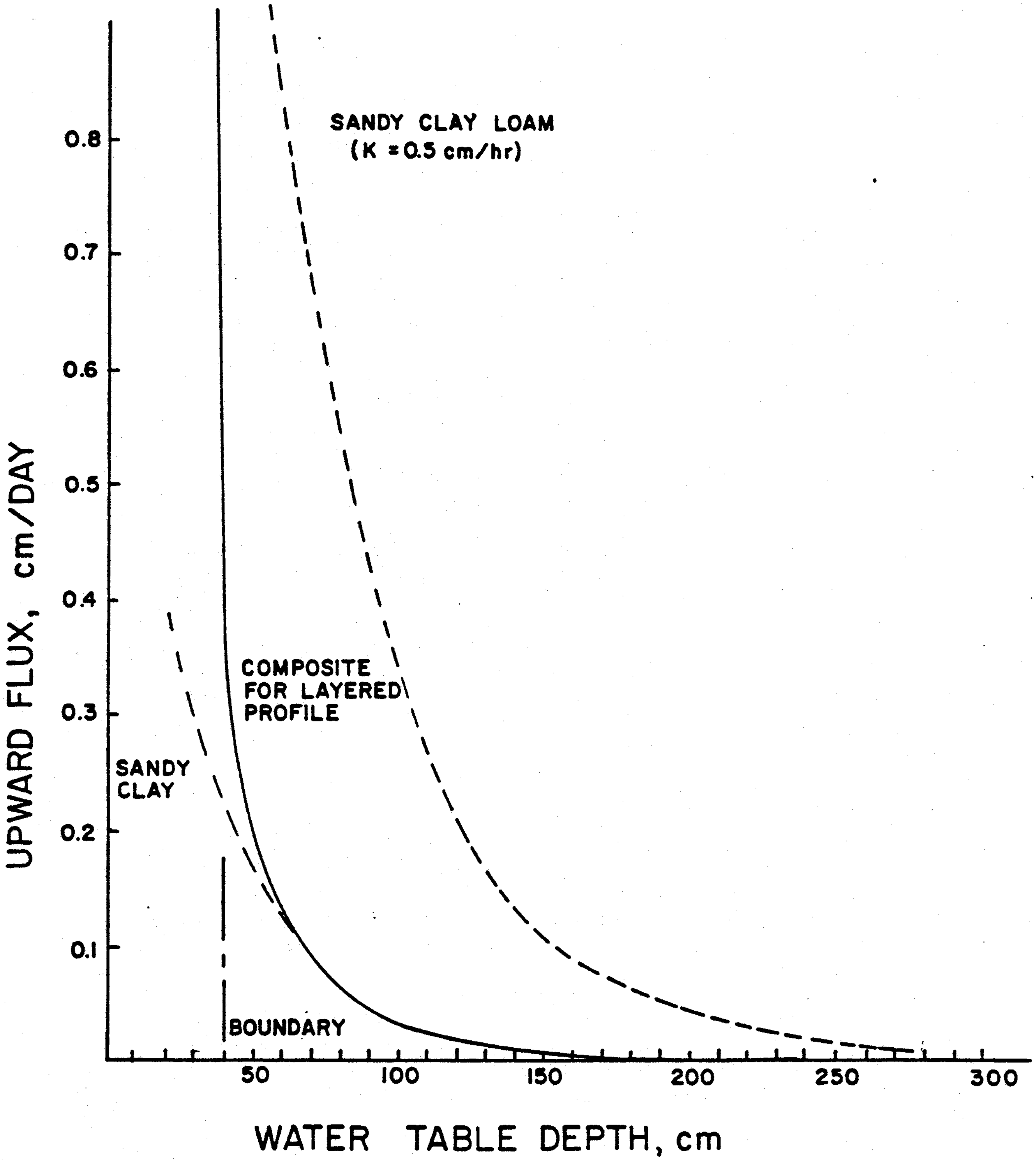

Figure 5-10. Upward flux relationships for a layered profile. The curves were approximated using the relationships in Figure 5-9, as explained in the example.

Table 5-2. Field description of an Oldsmar sand profile at the SWAP Experimental site at Fort Pierce (after Hammond, et al, 1971).

Horizon	Depth, cm	Morphology	K(cm/hr)
A1	0-13	Very dark gray (10 YR 3/1) sand; single grain structure; loose; gradual smooth boundary.	30.
A21	13-30	Gray (10 YR 5/1) sand; single grain structure; loose; gradual smooth boundary.	10.
A22	30-86	Light gray (10 YR 7/) sand; single grain structure; loose; abrupt wavy boundary.	10.
B2h	86-107	Black (10 YR 2/1) sand; massive structure; weekly cemented; gradual wavy boundary.	0.01
B21	107-127	Very dark grayish brown (10 YR 3/2) loamy sand; single grain structure; loose; gradual wavy boundary.	18.
B22tg	127-152	Very dark grayish brown (10 RY 3/2) sandy clay loam; sub-angular block structure; friable; gradual wavy boundary.	1
B23tg	152-218	Grayish brown (2.5 Y 5/2) to gray (10 YR 5/1) sandy clay loam; massive structure; friable; undetermined boundary.	0.1

Green-Ampt Equation Parameters

The flexibility of the Green-Ampt equations for describing infiltration under varied initial, boundary, and soil profile conditions makes it an attractive method for field applications. The fact that the equation parameters have physical significance and can be computed from soil properties is an added advantage. In practice, however, it will nearly always be advantageous to determine the equation parameters from field measurements by fitting measured infiltration data or from measurements such as those proposed by Bouwer (1966). Field infiltration measurements tend to lump the effects of such factors as heterogeneities, worm holes, and crusting in the equation parameters. This results in more reliable infiltration predictions than if the parameters are determined from basic soil property measurements.

Methods for measuring infiltration in the field are discussed briefly in Section 15, Chapter 1 of the SCS-NEH. Parr and Bertrand (1960) published a thorough review of field methods for measuring infiltration capacity. Basically, two types of devices have been used - sprinkling infiltrometers and flooding infiltrometers. While it would be advantageous to use a sprinkling infiltrometer to simulate rainfall conditions, the flooding devices are far more frequently used because they require less equipment and are easier to install and operate than the sprinkling type.

The most commonly used infiltrometer is probably the ring or cylindrical infiltrometer which was described in detail by Haise, et al, (1956). Bouwer (1963) and Wooding (1968) discussed methods of reducing and correcting for errors caused by lateral flow from the cylindrical infiltrometer. There are many types of sprinkling infiltrometers, as discussed by Parr and Bertrand (1960). Construction and operation of one such infiltrometer was presented, in detail, by Dixon and Peterson (1964). Sprinkling or spray infiltrometers usually consist of a plot surrounded by partially buried sheet metal barriers with facilities for measuring the rate of surface runoff. Water is sprinkled onto the plot surface at a constant intensity and the infiltration rate is determined from recorded runoff measurements. In most cases, the infiltration rate is determined by simply subtracting the runoff rate from the application intensity. However, the rate of surface storage during the initial stages of runoff should also be considered, as shown by Skaggs, et al, (1966) and Smith (1976). Another sprinkler irrigation method of measuring infiltration rates was described by Tovey and pair (1966). A shielded rotating sprinkler head is used to apply water to a circular section of soil at various rates depending on location. Application rates are measured and notes made as to whether the water is applied too fast, too slow, or equal to the infiltration capacity. The results can be used to plot a curve of infiltration capacity versus cumulative infiltration.

Regardless of the method used to measure the infiltration relationship, the next step is to determine the Green-Ampt equation parameters from the infiltration measurements. From Equation 2-7, the Green-Ampt equation may be written as,

$$f = A/F + B \qquad (2\text{-}7)$$

Where $A = K_s M S_{av}$ and $B = K_s$. A simple method for determining A and B is demonstrated in the example given below.

<u>Example</u>. Results of field infiltration measurements on a sandy loam soil are tabulated in Table 5-3 and plotted in FIgure 5-11. The infiltration rates were determined by drawing a smooth curve through the observed cumulative infiltration data and taking the slope at various times along the curve. The parameters A and B can be estimated from these data by first defining a variable $G = 1/F$ such that Equation 2-5 may be written,

$$f = AG + B \qquad (5\text{-}14)$$

The variable G is also tabulated in Table 5-3. Then, A and B can be determined from a plot of f vs. G (Figure 5-12) by simply drawing a straight line (eyeball fit) through the data and determining the slope and intercept. In this example, $A = 1.25\ cm^2/hr$ and $B = 0.50\ cm/hr$.

Table 5-3. Results of sprinkler infiltrometer measurements on a sandy loam soil. The application rate was 5.0 cm/hr.

Time min	Cumulative Infiltration, F (cm)	Infiltration Rate, f (cm/hr)	$G = 1/F$ cm^{-1}
0	0	5.0	0
3 (time of surface ponding)	0.25	5.0	4.0
5	0.45	3.6	2.22
10	0.60	2.4	1.67
20	1.0	1.7	1.0
40	1.55	1.2	0.645
60	1.80	1.08	0.555
90	2.25	0.95	0.444
120	3.0	0.88	0.333
150	3.25	0.81	0.308
180	3.75	0.78	0.267
210	4.10	0.75	0.244

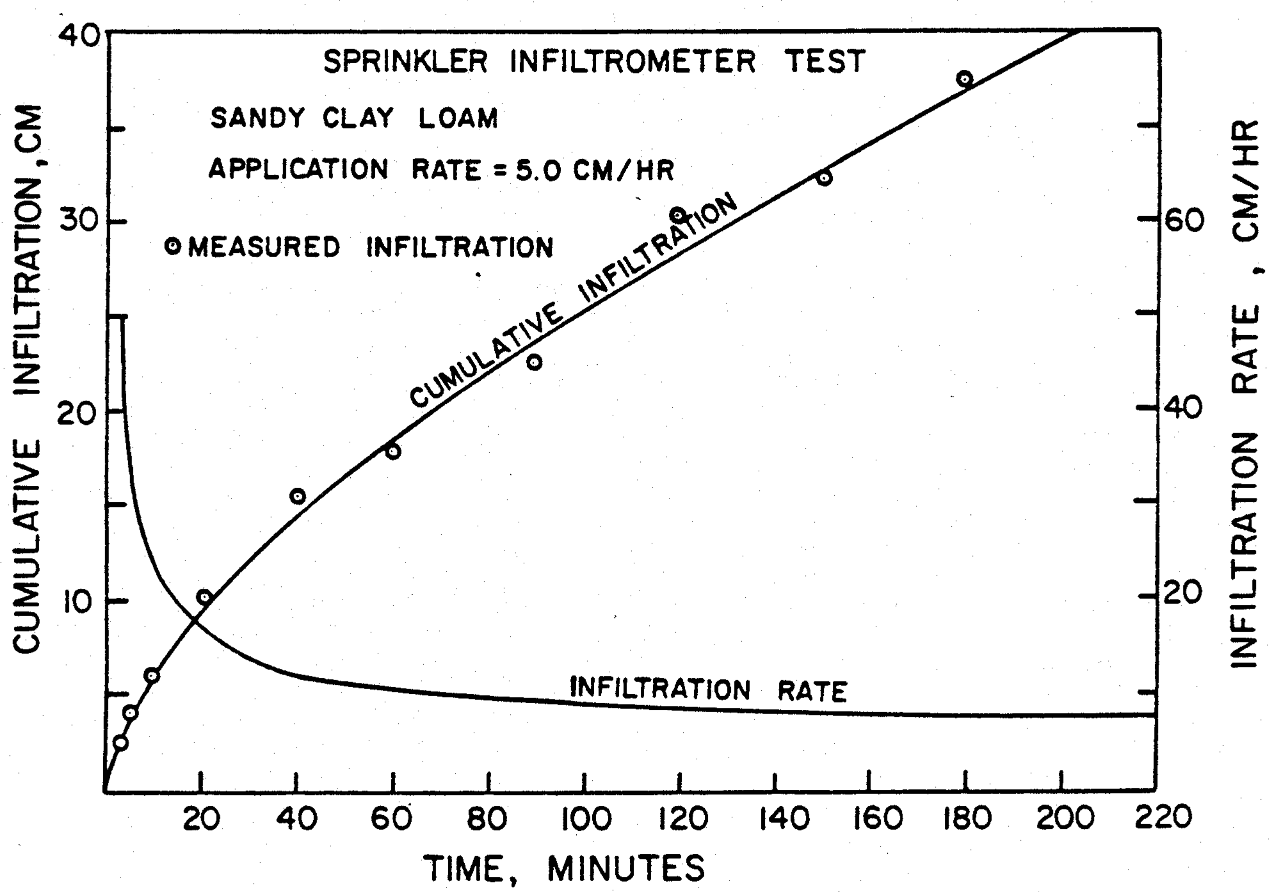

Figure 5-11. Cumulative infiltration determined from sprinkler infiltrometer measurements and calculated infiltration rates as a function of time.

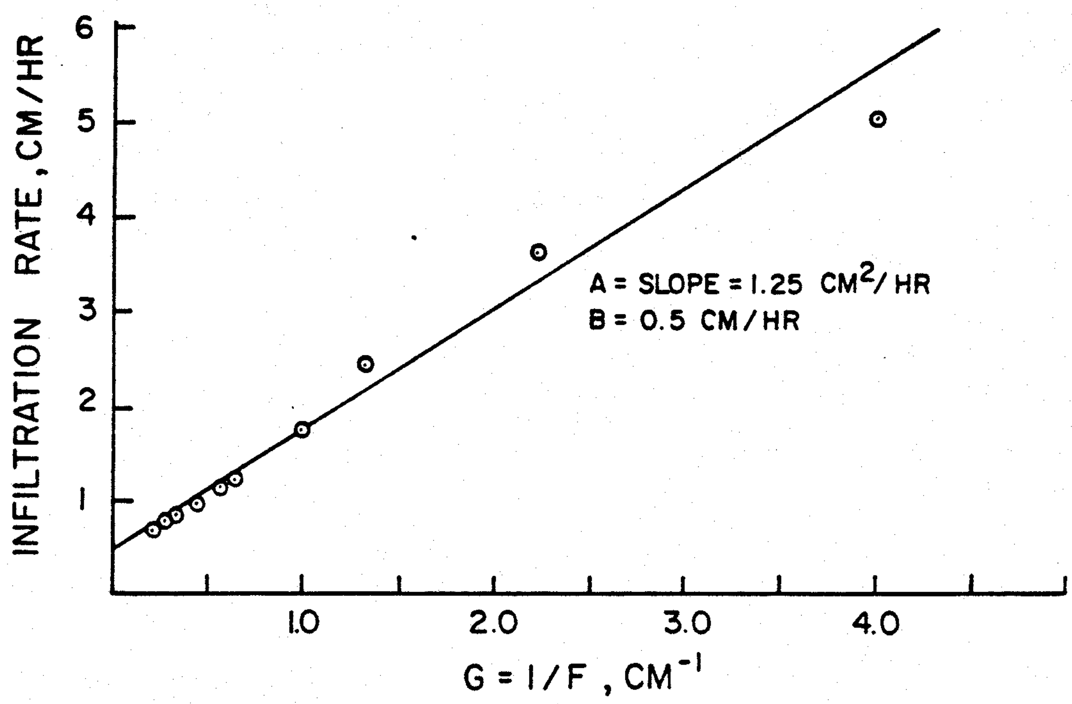

Figure 5-12. Graphical procedure for estimating parameters A and B from measured infiltration data.

Nothing has been said so far about the initial conditions for the above test. Let us assume that the water table was at a depth of 150 cm when the above test was run and the water content at the soil surface was $\theta_i = 0.25$ cm^3/cm^3. The maximum water content (saturation less entrapped air) is $\theta_s = 0.45\ cm^3/cm^3$. Therefore, M = 0.45 - 0.25 = 0.20 and since $K_s = B = 0.5$ cm/hr, $S_{av} = A/K_sM = 12.5$ cm. The values of A and B can be determined for other initial water table depths by repeating the experiment for the different conditions. Alternatively, B can be assumed constant at 0.5 cm/hr and A can be estimated by determining the appropriate value of M for each water table depth. For example, if the initial water table depth is 50 cm, the water content at the surface may be obtained from the soil water characteristic (corresponding to h = -50 cm) as, say 0.36 cm^3/cm^3. Then, M = 0.45 - 0.36 = 0.09 and A = 0.5 X 0.09 X 12.5 = 0.56 cm^2/hr.

More sophisticated methods for determining A and B by fitting infiltrometer data using regression methods were presented by Brakensiek and Onstad (1977). They considered spatial variation of the estimated parameters and presented methods for averaging the values to give lumped parameter values for watershed modeling. A sensitivity analysis for the equation parameters showed that predicted infiltration and runoff amounts and rates were most sensitive to the errors in fillable porosity, M, and K_s, and less sensitive to errors in S_{av}.

When field infiltration measurements are not available, the Green-Ampt equation parameters can be estimated from basic soil properties. Bouwer (1966, 1969) showed that the hydraulic conductivity parameter in the Green-Ampt equation should be less than the saturated value, K_o, because of entrapped air. He described an air-entry permeameter which can be used in the field for measuring K_s, the conductivity at residual air saturation, and the air entry suction. When measured values are not available, Bouwer (1966) suggested that K_s may be approximated as $K_s = 0.5\ K_o$. Thus, an estimate of K_s can be obtained from K_o values in the standard soil survey interpretation forms.

The effective suction at the wetting front, S_{av}, is somewhat more difficult to determine. Bouwer (1969) used the water entry suction, h_{ce}, for S_{av} in Equation 2-7 and suggested that it can be approximated as one-half of the air entry value. Main and Larson (1973) used the unsaturated hydraulic conductivity as a weighting factor and defined the average suction at the wetting front as,

$$S_{av} = \int_o^1 h\ dk_r = -\int_o^{h_i} k_r\ dh \qquad (5\text{-}15)$$

Where h is the soil water pressure head, h_i is the pressure head at the initial water content, θ_i, and k_r is the relative hydraulic conductivity, $k_r = K(h)/K_s$. The effective matric drive, H_c, introduced by Morel-Seytoux and Khanji (1974) is dependent on the relative conductivities of both air and water. However, for most cases, the value of S_{av} given by Equation 5-15 is a reasonable approximation of H_c (Morel-Seytoux and Khanji, 1974).

One of the problems of using Equation 5-15 to obtain S_{av} is the requirement of the unsaturated hydraulic conductivity function K(h). Some investigators have used prediction methods (e.g. Equation 5-8 and Appendix G) to estimate K(h) and then determine S_{av} from Equation 5-15. Brakensiek (1977) used methods of Brooks and Corey (1964) and Jackson (1972) to determine S_{av} for the five soils originally investigated by Mein and Larson (1973). He showed that, for the Brooks and Corey (1964) model, Equation 5-15 may be integrated to give,

$$S_{av} = h_{ce}\ \eta/(\eta-1) \qquad (5\text{-}16)$$

Where h_{ce} is approximately one-half the bubbling pressure. The bubbling pressure, P_b, and the parameter η may be obtained from the soil water characteristic by using graphical procedures given by Brooks and Corey (1964). The procedures are demonstrated in an example given below. Brakensiek (1977) found that S_{av} values computed from Equation 5-16 and from Equation 5-15 with k_r given by Equation 5-8 were in good agreement with the original values of Mein and Larson for actual k_r data and with the H_c values computed by Morel-Seytoux and Khanji (1974) for the same five soils. Brakensiek (1977) also found that the simple equation,

$$S_{av} = 0.76\ P_b, \qquad (5\text{-}17)$$

Where P_b is the desorption bubbling pressure, is an acceptable approximation for the soils he investigated.

<u>Example</u>. The soil water characteristic for a sandy clay loam soil is plotted in Figure 5-13. To use the method of Brooks and Corey (1964), we first define saturation as $S = \theta/\theta_s$ where θ_s = saturated water content. The residual saturation, S_r is determined from Figure 5-13, or a similar plot of S vs. h, as the horizontal asymptote. In this case, $\theta_r = 0.21$ and $S_r = 0.21/0.42 = 0.50$. Then, the effective saturation,

$$S_e = \frac{S - S_r}{1 - S_r}$$

is calculated for a number of points as shown in Table 5-4. Then, log S_e is plotted versus log (-h) on log-log paper (Figure 5-14).

The value of P_b is determined from the straight line intercept of the -h axis. From Figure 5-14, P_b = 32 cm and $\eta = 2 + 3\lambda = 2 + 3 \times 0.57 = 3.71$. Then, the value of S_{av} may be estimated from Equation 5-16 as,

$$S_{av} = \frac{32}{2} \times 3.71/(3.71 - 1) = 21.9 \text{ cm}.$$

Using Equation 5-17 gives $S_{av} = 0.76 \times 32 = 24.3$ cm. Thus, S_{av} can be estimated from the soil water characteristic when it is available.

Table 5-4. Effective saturation and pressure head values for a sandy clay loam. (S_r = 0.50).

θ cm^3/cm^3	S_e $(S-S_r)/(1-S_r)$	h cm
0.42	1.0	0.0
0.41	0.95	-30
0.40	0.90	-40
0.38	0.81	-61
0.36	0.71	-92
0.34	0.62	-138
0.32	0.52	-200
0.30	0.43	-295
0.28	0.33	-550
0.26	0.24	-1,000

When the soil water characteristic cannot be obtained for a given soil, it may be estimated by matching the soil texture with that of a soil for which h(θ) is known, as discussed earlier in this chapter. Then, S_{av} could be estimated using the methods discussed above. The results of Brakensiek, eta al. (1980) and Clapp and Hernberger (1978) can be used to estimate soil property values for various textural classes as discussed earlier in this chapter. Brakensiek's, et al, (1980) results for saturated water content, θ_s, η, h_b, and S_{av} are given in Table 5-5. Brakensiek's (1979) estimates for S_{av} are also given in the table.

Table 5-5. Average values of θ_s, η, h_b, and S_{av} for 10 textural classes of soils (after Brakensiek, et al, 1980). Note: There may be wide variation of S_{av} within a textural class and these values should be regarded, as approximate.

Soil Texture	Average θ_s	(Std. Dev.)	η	h_b (cm)	S_{av} (cm)	Average S_{av}* (cm)
Sand	0.35	(0.11)	3.6	17	10	10
Loamy sand	0.41	(0.06)	3.3	10	7	7
Sandy loam	0.42	(0.08)	3.1	17	12	18
Silt loam	0.48	(0.06)	2.6	43	35	64
Loam	0.45	(0.07)	2.7	23	18	39
Sandy clay loam	0.41	(0.05)	3.0	26	19	25
Silty clay loam	0.47	(0.05)	2.5	37	30	31
Clay loam	0.48	(0.05)	2.8	28	21	55
Sandy clay	0.42	(0.06)	2.7**	28**		14
Silty clay	0.48	(0.06)	2.5	27	20	44
Clay	0.48	(0.05)	2.5	33	26	36

* From Brakensiek's (1979) comment on the Clapp and Hornberger (1978) paper.

** Estimated.

Note: The values given in Table 5-5 are average values and that $h(\theta)$ (and hence S_{av}) depends on soil structure and other factors, as well as texture. Therefore, the values tabulated in Table 5-5 should be treated, as estimates, to be used only when better data cannot be obtained.

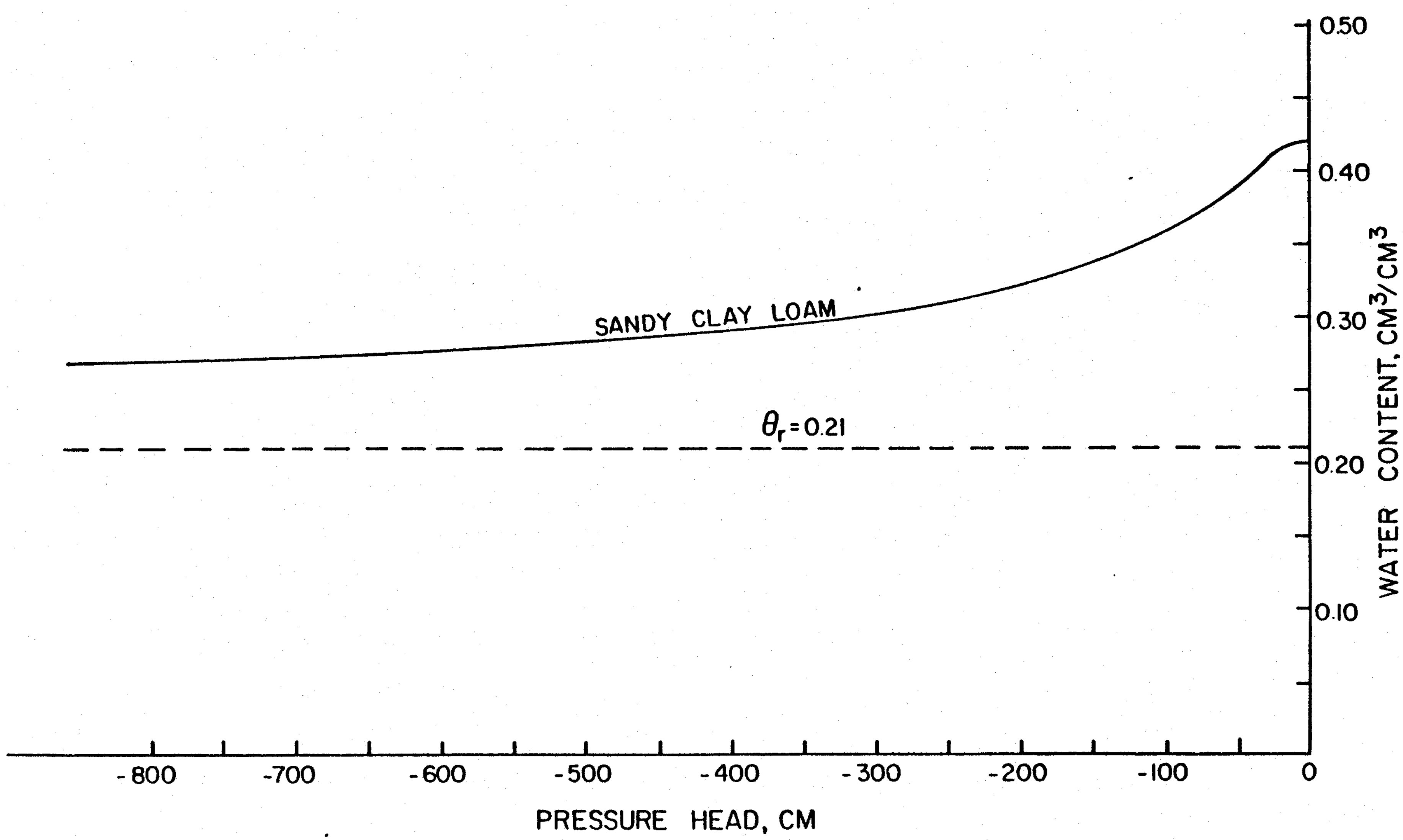

Figure 5-13. Soil water characteristic for a sandy clay loam.

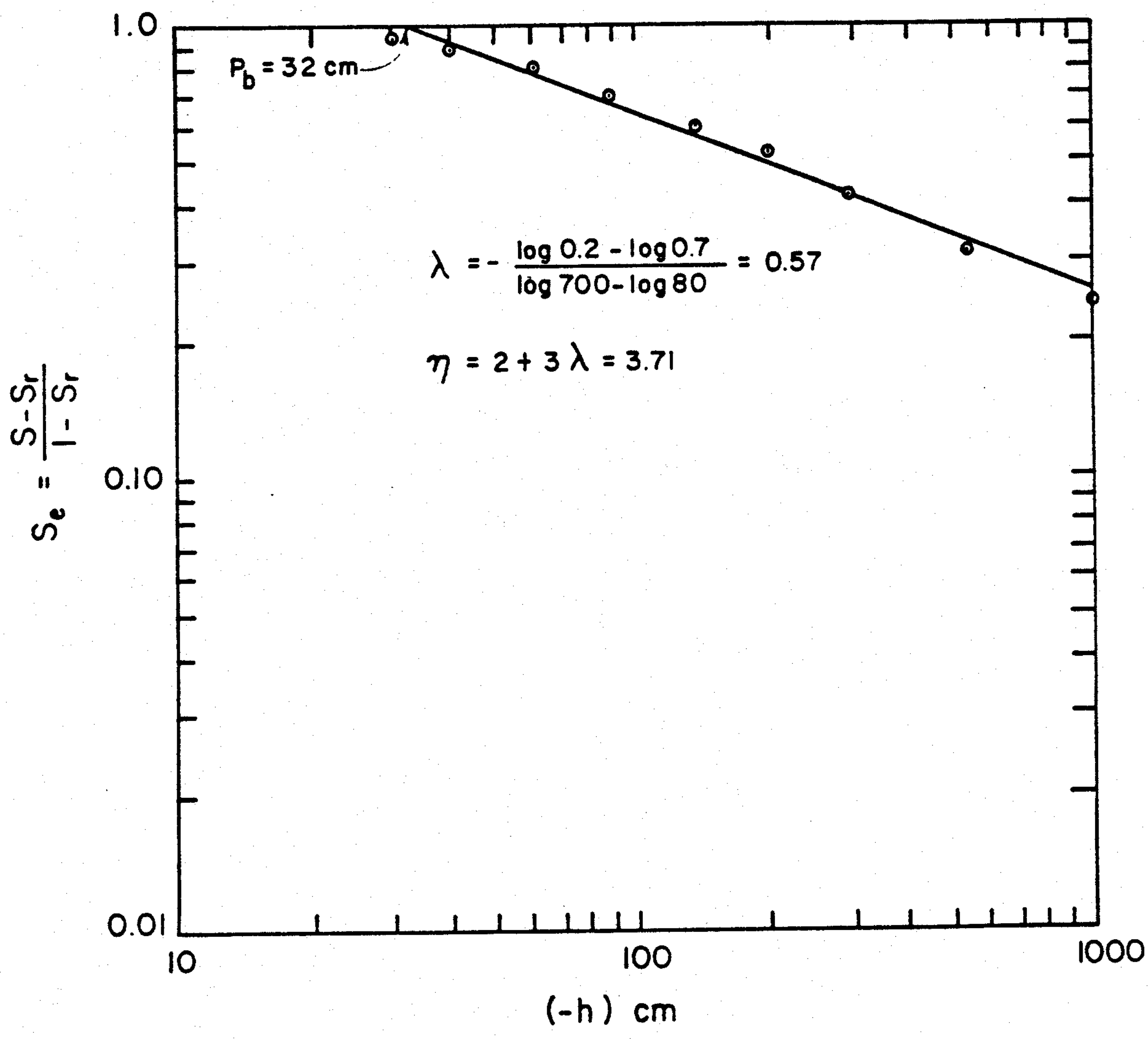

Figure 5-14. Determination of bubbling pressure, P_b, and η from the effective saturation, S_e, - pressure head relationship.

For a layered soil, S_{av} should usually be based on properties of the surface horizon. The value of K_s in the surface layer may be used for shallow initial water table depths, while K_s of underlying layers or average K_s values may be used when the water table is deeper. Consider a profile made up of 30 cm of the sandy clay loam of the above example (with $K_s = 2$ cm/hr) over 170 cm of silty clay loam with $K_s = 1$ cm/hr. We need input data for DRAINMOD for a range of initial water table depths (IWTD). From above $S_{av} = 22$ cm.* For IWTD = 30 cm, $K_s = 2$ cm/hr. From Figure 5-13, $\theta_s = 0.42$ and $\theta_i = 0.41$ (corresponding to $h = -30$ cm). Then, $M = 0.42 - 0.41 = 0.01$, $A = 0.01 \times 2$ cm/hr $\times 22$ cm $= 0.44$ cm^2/hr and $B = K_s = 2.0$. For IWTD = 120 cm, $\theta_i = .345$ (Figure 5-13), $M = .075$, $K_s = (30 \times 2 + 90 \times 1)/120 = 1.25$ cm/hr so $B = 1.25$ cm/hr and $A = 1.25 \times 0.075 \times 22 = 2.06$ cm^2/hr. For water table depths greater than 150 cm, a dry zone normally develops at the surface with an assumed $\theta_{\ell\ell} = 0.22$. Then, $M = 0.42 - 0.22 = 0.20$, $B = 1.25$ cm/hr and $A = 5.28$ cm^2/hr. Using these methods for other IWTD values, the input data for infiltration parameters could then be written as follows:

IWTD (cm)	A(cm^2/hr)	B cm/hr
0	0.	2.0
30	0.44	2.0
60	1.32	1.5
120	2.06	1.25
150	5.28	1.25
500	5.28	1.25

Methods for determining the Green-Ampt equation parameters may be ranked as follows:

1. Determination from field infiltration measurements.

2. Field measurement of S_{av} and K_s using methods such as those proposed by Bouwer (1966).

3. Calculation of S_{av} from measured k_r (h) and h(θ) data.

4. Calculation of S_{av} using prediction equations for k_r and measured h(θ) data. That is, use of Equations 5-16, 5-17, 4-18, and others. Obtain K_s from field measurements or estimate from soil survey interpretations.

5. Estimate S_{av} based on soil texture from Table 5-5. Get K_s from soil survey interpretations.

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* $S_{av} = 22$ cm was obtained from data for this specific soil and is used rather than the value for sandy clay loam in Table 5-5. If h(θ) data were not available, $S_{av} = 11.7$ cm could have been estimated from Table 5-5.

Trafficability Parameters

Three parameters are used in DRAINMOD to determine if field conditions are suitable for tillage or harvesting operations. The parameters are: (1) minimum water free pore volume (air volume) (cm) required for trafficability, AMIN; (2) minimum precipitation (cm) required to stop field operations, ROUTA; and (3) minimum time after rain before field operations can begin (days), ROUTT. Two sets of the parameters are read in DRAINMOD; one set represents values required for tillage operations (seedbed preparation, etc.) in the spring and the other set is for harvesting conditions in the fall. Spring conditions are called working period 1 and the trafficability inputs are designated as AMIN1, ROUTA1, and ROUTT1, while AMIN2, etc., are used for working period 2 in the fall. Times that the working day begins and ends are also inputs to the model in order to determine fractional working days as discussed in Chapter 3.

Trafficability parameters were approximated for several research sites in North Carolina by field observations during the spring period of seedbed preparation. Field conditions were monitored by experienced technicians in coordination with farmers and research station personnel. When the soil reached a condition that was just dry enough to plow and prepare seedbed, samples were taken at 10 and 20 cm depths and the water contents determined. Drainage volumes corresponding to the measured water contents were estimated from the soil water characteristics and drainage-volume water table depth relationship. For example, the volumetric water content for Goldsboro s.l. was 0.23 at the point that it was just dry enough to plow. This corresponds to a pressure head of -75 cm (Figure 5-1). A suction head of at least 75 cm at the surface would result from a 75 cm water table depth. This would give a water free pore volume (air volume) of 3.2 cm (Figure 5-4). Thus, AMIN1 = 3.2 cm for Goldsboro s.l. soil. Trafficability parameters for the seedbed preparation period are given in Table 5-6 for eight North Carolina soils.

Table 5-6. Trafficability parameters for plowing and seedbed preparation for some North Carolina soils.

Soil	Water content in plow layer* (cm^3/cm^3)	Corresponding pressure head in plow layer (cm)	AMIN (cm)	ROUTA (cm)	ROUTT (days)
Cape Fear l.	0.395	-65	3.3	1.2	2
Lumbee s.l.	0.265	-70	2.8	1.5	1
Coxville-Ogeechee l.	0.39	-80	3.4	1.2	2
Goldsboro s.l.	0.23	-80	3.2	1.5	1
Rains s.l.	0.25	-70	3.9	1.2	2
Wagram l.s.	0.15	-65	3.5	1.5	1
Bladen s.l.	0.40	-60	3.0	1.0	2
Portsmouth s.l.	0.32	-75	3.0	1.2	2

* Water content in plow layer when soil is just dry enough for plowing and seedbed preparation.

The water contents given in Table 5-6 corresponded to pressure heads between -60 and -80 cm of water. For a 10 cm depth at the point of measurement, these pressure heads would result for water table depths between 70 and 90 cm from the surface. Grossman (1979)* measured the minimum water tension at which tillage operations could be initiated in the spring. He measured the tension at a 15 cm depth in a Sharpsburg (typic Argiudall, fine) in southeastern Nebraska and a Mexico (Udollic Ochraqualf, fine) in central Missouri. The tensions ranged from 40 to 170 cm with most below 100 cm of water. These results are consistent with those given in Table 5-6. Similar measurements are needed on many more soils throughout the humid region to provide a data base for predicting trafficability. In the absence of specific data, it is suggested that suitable conditions for seedbed preparation may be assumed when the soil tension at the 15 cm depth is at least 60 cm. This will occur for a profile drained to equilibrium to a water table 75 cm deep. Then, AMIN1 can be obtained directly from the drainage volume - water table depth relationship.

The other trafficability parameters, ROUTA and ROUTT, can be selected by a technician or farmer who is familiar with the soil being analyzed. Assuming very dry initial conditions, ROUTA is the minimum amount of rain that would prohibit field operations because of wet or slick soil conditions. The air volume in the profile may be greater than AMIN at that time, but field operations would be limited because the surface soil is too wet. Then, ROUTT is the time (in days) required for the soil water at the surface to redistribute in the profile so that field operations can resume.

Crop Input Data

Crop input data include the relationship between effective rooting depth and time and the dates to initiate and stop SEW and Dry Day computation. The main input is the effective rooting depth-time relationship which was discussed in some detail in Chapter 2 (pages 2-47 through 2-52). Data of the type given in Figures 2-22 and 2-23 will not be available for most crops so the relationships will have to be approximated from other data. Depths of roots that extract soil water at the peak stage of growth are given for several crops and locations in Table 1-4 of the SCS-NEH, Section 15, Chapter 1. The depth of plant feeder roots for various crops is also given in the Sprinkler Irrigation Handbook published by Rain Bird Manufacturing Corporation and listed in Table 5-7.

Because most of the water will be extracted near the surface, as discussed in Chapter 2, the maximum effective root depth used in DRAINMOD should be approximated as 50 to 60 percent of the depth given in Table 5-7 or in Table 1-4 of the SCS-NEH. The maximum rooting depth depends on factors such as physical and chemical barriers to root growth, as well as soil water conditions. Values given in the tables may require modification because of the influence of such factors.

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* Unpublished data obtained by personal communication from R. B. Grossman, Research Soil Scientist, SCS National Soil Survey Laboratory, Lincoln, Nebraska.

Table 5-7. Plant feeder root depths* (from Sprinkler Irrigation Handbook, Rain Bird Manufacturing Corporation, Glendora, California).

Crop	Root Depth	Crop	Root Depth
Alfalfa	3 to 6 feet	Nuts	3 to 6 feet
Beans	2 feet	Onions	1 1/2 feet
Beets	2 to 3 feet	Orchard	3 to 5 feet
Berries (Cane)	3 feet	Pasture (Grasses only)	1 1/2 feet
Cabbage	1 1/2 to 2 feet	Pasture (with Clover)	2 feet
Carrots	1 1/2 to 2 feet	Peanuts	1 1/2 feet
Corn	2 1/2 feet	Peas	2 1/2 feet
Cotton	4 feet	Potatoes	2 feet
Cucumbers	1 1/2 to 2 feet	Soy Beans	2 feet
Grain	2 to 2 1/2 feet	Strawberries	1 to 1 1/2 feet
Grain, Sorghum	2 1/2 feet	Sweet Potatoes	3 feet
Grapes	3 to 6 feet	Tobacco	2 1/2 feet
Lettuce	1 foot	Tomatoes	1 to 2 feet
Melons	2 1/2 to 3 feet		

* Majority of feeder roots.

The change in the effective root depth with time can be estimated by Crop Growth Stage Coefficients (K_c) given in the SCS Technical Release No. 21, "Irrigation Water Requirements." The K_c was introduced to account for the growth stage in predicting ET by the Blaney-Criddle method. K_c values are plotted as a function of percent of growing season for several crops in the SCS-TR 21. Because K_c indicates the rate that the crop can use water, it should also be proportional to the stage of development of the plant and root growth. Use of the K_c to estimate the change in effective root depth with time is demonstrated in the following example. Note that the K_c was not derived for this purpose. Further, the procedure has not been verified experimentally and should be viewed only as a method of obtaining a rough estimate of the root depth distribution with time.

Example. Irish potatoes are to be planted on March 10 and harvested June 28 in eastern North Carolina. Estimate the root depth-time relationship during that period. From Table 5-7, the maximum depth of feeder roots for potatoes is 2 feet. Taking an effective depth of 50 percent of maximum gives 0.5 x 2 ft = 1 ft = 30 cm. We can estimate the root depth at any time during the growing season by assuming that it is linearly related to K_c as, $R_d = aK_c + b$ where R_d is root depth and a and b are coefficients. K_c values for Irish potatoes are given as curve No. 18 in the SCS-TR 21. Assuming that water may be removed from the surface 3 cm by evaporation when the soil is fallow implies an effective root depth of 3 cm at the beginning of the growing season when $K_c = 0.33$ (curve No. 18). The maximum effective root depth of 30 cm would correspond to a maximum K_c of 1.37. Substituting these values in the above equation and solving for a and b gives $R_d = 26\ K_c - 5.62$. After 20 percent of the growing season (growing season length = 110 days, so 20 percent = day 22), $K_c = 0.51$. Then, $R_d = 7.6$ cm 22 days after planting. Repeating this procedure for several times during the growing season gives the following values for root depth versus time:

Table 5-8. Effective root depth versus days after planting for potatoes, as estimated from published crop growth stage coefficients.

Percent of Growing Season	Days after Planting	K_c	Root Depth
0 percent	0	0.33	3 cm
10	11	0.40	4.8
20	22	0.51	7.6
30	33	0.72	13.1
40	44	0.96	19.3
50	55	1.18	25.1
60	66	1.31	28.4
70	77	1.37	30.0
80	88	1.36	30.0
90	99	1.30	28.1
100	110	1.22	26.1

Drainage System Parameters

Surface Drainage

Most of the input data for drainage system parameters such as drain spacing and depth are easy to define. The depressional storage parameter used to quantify surface drainage is somewhat more difficult. Depressional storage has been measured under various field conditions in eastern North Carolina (Gayle and Skaggs, 1978). The following subjective guidelines are offered for estimating surface storage:

Table 5-9. General guidelines for estimating field surface depressional storage.

Field Surface Drainage Quality	Field Description	Depressional Storage
Good	Surface relatively smooth and on grade so that water does not remain ponded in field after heavy rainfall. No potholes - adequate outlets.	0.1 - 0.5 cm
Fair	Some shallow depressions, water remains in a few shallow pools after heavy rainfall. Micro-storage caused by disking or cultivation may cause surface drainage to be only fair, even when field surface is on grade.	0.6 - 1.5 cm

Table 5-9. General guidelines for estimating field surface depressional storage. (continued)

Field Surface Drainage Quality	Field Description	Depressional Storage
Poor	Many depressions or potholes of varying depth. Widespread ponding of water after heavy rainfall or inadequate surface outlets, such as berms around field ditches or very rough surface, such as directly after plowing.	1.6 - 2.5 cm or greater

Effective Drain Radius

The effective drain radius, r_e, is used in Equation 2-13 to calculate the equivalent depth from the drain tube to the impermeable layer. The effective radius is considerably smaller than the actual drain tube radius to account for the resistance to inflow due to a finite number of openings in an otherwise impervious wall, as discussed in Chapter 2. The determination of r_e is based on research by Bravo and Schwab (1977). They used an electric analog to determine the effect of openings on radial flow to corrugated drain tubes. Envelopes increase the effective size of the drain by allowing free movement of water to the drain openings. When gravel envelopes are placed around the drain in a cylindrical shape, the effective radius may be taken as the outside radius of the envelope. For a more commonly used square envelope cross-section of length 2a on each side, r_e can be approximated from the results of Kirkham and Selin (1973) as r_e = 1.77a. Fabric wrap envelopes tend to prevent drain tube corrugations from filling with soil and therefore increase the effective radius to some degree. However, the effective radius with a fabric wrap material would still be less than the actual tube radius. The effective radii of some conventional drain tubes are given in Table 5-10. These values were approximated from Bravo and Schwabs (1977) work and from related work by Skaggs (1978a). Research is continuing in this subject and the values given in Table 5-10 are subject to revision.

Table 5-10. Effective radii for various size drain tubes.

Drain	Diameter (O.D.)	r_e
3-in corrugated*	89 mm	3.5 mm
4-in corrugated*	114	5.1
5-in corrugated*	140	10.3
6-in corrugated*	165	14.7
4-in clay - 1/16 in crack between joints	127	3.0
4-in clay - 1/8 in crack between joints	127	4.8
Drain tube surrounded by gravel envelope with square cross-section of length 2a on each side	2a	1.177a

* Based on 5 rows of slots with total opening amount to 1.5 to 2 percent of the wall area.

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CHAPTER 6

APPLICATION OF DRAINMOD - EXAMPLES

The purpose of this chapter is to present examples of the use of DRAINMOD for designing and evaluating water management systems. Four sets of examples will be considered. First, alternative designs of a combination surface-subsurface drainage system are analyzed for four soils at three locations. The results are presented such that the least expensive alternative can be selected for each case. The use of a drainage system for controlled drainage or subirrigation is considered in the second example set. In the third example, DRAINMOD is used to determine the amount of waste water that can be applied to a disposal site that has surface and subsurface drainage. The storage capacity required to hold waste water which cannot be applied during the wet season of the year until the summer months when it can be irrigated is also determined. Finally, the model is used to show the effects of root depth on the occurrence and frequency of drought stress on crops in North Carolina. The purpose of this example is to demonstrate the potential effects of removing physical and chemical barriers to root growth on water availability to plants and the frequency of drought stress.

Example Set 1 - Combination surface-subsurface drainage systems

Combination surface-subsurface drainage systems are analyzed for four soils at three locations: Wilmington, North Carolina, Columbus, Ohio, and Jacksonville, Florida. The results in this example were presented as an ASAE paper (Skaggs, 1978c). The soils used at all locations are North Carolina soils and may not be typical of soils at Columbus or Jacksonville. The analyses for these locations show the affects of changes in climate and planting dates on the drainage system design needs.

Soils

Four soils were chose for analysis in this example: Bladen loam, Lumbee sandy loam, Rains sandy loam, and Wagram loamy sand. The soil properties were determined in a study to test the validity of the model (Skaggs, 1978b). Methods for determining the properties and the soils are discussed in more detail in Chapter 10. All soils are assumed to have relatively flat surfaces with poor drainage in their natural states. The Bladen and Wagram soils have relatively uniform profiles while Lumbee and Rains have layered profiles. As noted in Chapter 4, the Wagram soil is normally well drained in its natural state and does not require artificial drainage. However, the loamy sand considered here has a nearly level surface and is underlain by a heavy subsoil that may be assumed impermeable so artificial drainage is needed. Downward water movement in all soils is restricted by an impermeable layer at a uniform depth; the depth of the layer is soil dependent and is within 3 m of the surface for the soils considered herein. Soil properties used as inputs in DRAINMOD are tabulated in Table 6-1. The soil water characteristic and the relationship between water table depth and upward water movement are given in Table 10-5 and Figures 5-4 and 5-6, respectively. The relationship given in Figure 5-4 for Portsmouth s.l. was used for the Bladen soil.

Table 6-1. Summary of input soil property data used in examples in this chapter.

Soil	Bladen l.	Lumbee s.l.		Rains s.l.		Wagram l.s.	Portsmouth s.l.
Depth to restricting layer (m)	3.0	1.7		1.4		1.8	2.0
Saturated hydraulic conductivity layer depth (m)	uniform	0 - 1.0	1.0 - 1.5	0 - 1.1	1.1 - 1.4	uniform	uniform
K (mm/hr)	10	10	30	43	10	60	30
Saturated water content (cm^3/cm^3)	0.41	0.34		0.37		0.30	0.40
Water content at lower limit available to plants (cm^3/cm^3)	0.15	0.12		0.09		0.05	0.13
Minimum water-free pore space for tillage (spring) (mm)	30	28		39		35	30
Minimum daily rain to stop field operations (spring) (mm)	10	15		12		15	12
Minimum time after rain before it is possible to restart tillage (spring) (days)	2	1		2		1	2

Crop Data

It was assumed that corn was to be grown on a continuous basis in all simulations conducted. The growing season was assumed to be 120 days in duration with the planting and harvesting dates dependent on location as shown in Table 6-2. Although the depth and distribution of plant roots depend on many factors including soil type, water content, fertility, physical and chemical barriers in the soil, and others, the effective root zone depth is assumed here to depend only on time after planting. The root distribution given by the 60 percent curve in Figure 2-22 (with a minor correction so that the minimum root depth was 3 cm to account for the thin surface layer that can be dried by evaporation) was used for all soils and locations.

Drainage System Parameters

Three field surface drainage intensities corresponding to the average surface storage depths o 2.5, 12.5, and 25 mm were considered in the simulations. This range is consistent with the results of field studies of surface storages on fields with and without improved surface drainage in eastern North Carolina. The subsurface drainage component was provided by parallel 102 mm (4 inch) drain tubes placed at a range of depths and spacings as given in Table 6-3. Convergence near the drains was accounted for by defining an equivalent depth as discussed in Chapter 2. An effective drain tube radius of 5.1 mm (0.51 cm) was used in calculating d_e. Simulations were conducted for four drain depths and five spacings for each soil at each location, as indicated in Table 6-3. Table 6-3 gives the values of drain depths, spacings, surface drainage, soils, and locations used in the simulations. Simulations were conducted for all combinations of these variables.

Table 6-2. Planting and harvesting dates for corn that were used in the simulations for three locations.

	Jacksonville, Florida	Wilmington, North Carolina	Columbus, Ohio
Planting date	March 3	April 15	May 5
Harvesting date	July 3	August 15	September 5
Seedbed preparation period	February 1 - March 2	March 15 - April 15	April 15 - May 5

Table 6-3. Range of drainage system parameters, soils, and locations for which simulations were conducted.

Drain depths (m)	0.75	1.0	1.25	1.50*	
Drain spacing					
Wagram (m)	15	30	45	60	90
Bladen (m)	7.5	15	30	60	90
Lumbee and Rains (m)	7.5	15	30	45	60
Surface depression storage (mm)	2.5	12.5	25		
Soils	Bladen l, Lumbee s.l., Rains s.l., Wagram l.s.				
Locations	Columbus, OH; Wilmington, NC; Jacksonville, FL				

* The greatest drain depth for the Rains soil was the depth of the restrictive layer, 1.4 m, rather than the 1.5 m used for the other soils.

Climatological input data consisted of hourly precipitation records and maximum and minimum daily temperatures. These data were obtained from storage in HISARS (Wiser, 1975) for Wilmington, North Carolina, for the 26-year period, 1950-1975. Data from Jacksonville, Florida, and Columbus, Ohio, were obtained from the National Climatic Center, Asheville, North Carolina, and stored in HISARS format for automatic retrieval by DRAINMOD. Simulations for Jacksonville and Columbus were conducted for 25 years of record (1949 to 1973).

Results - Alternative Drainage System Designs

Results of the simulations were analyzed to identify alternatives of surface and subsurface systems that would satisfy trafficability and crop protection requirements.

Trafficability

The effect of drain spacing on the number of working days during the 1-month period (March 15 - April 15) prior to planting is shown in Figure 6-1 for two soils at Wilmington, North Carolina. Relationships are plotted on a 5-year recurrence interval (5 YRI) basis for both good (s = 2.5 mm) and poor (s = 25 mm) surface drainage. The results show that trafficability is strongly dependent on the drain spacing. The effect of surface drainage on the number of working days during the seedbed preparation period depends on the soil and the drain spacing. For example, a drain spacing of 21 m on the Lumbee soil would give 10 working days on a 5 YRI basis for poor surface drainage as compared to 13 working days for good surface drainage (Figure 6-1). On the other hand, improving the field surface drainage for the Wagram soil with a 40 m drain spacing would only increase the working days

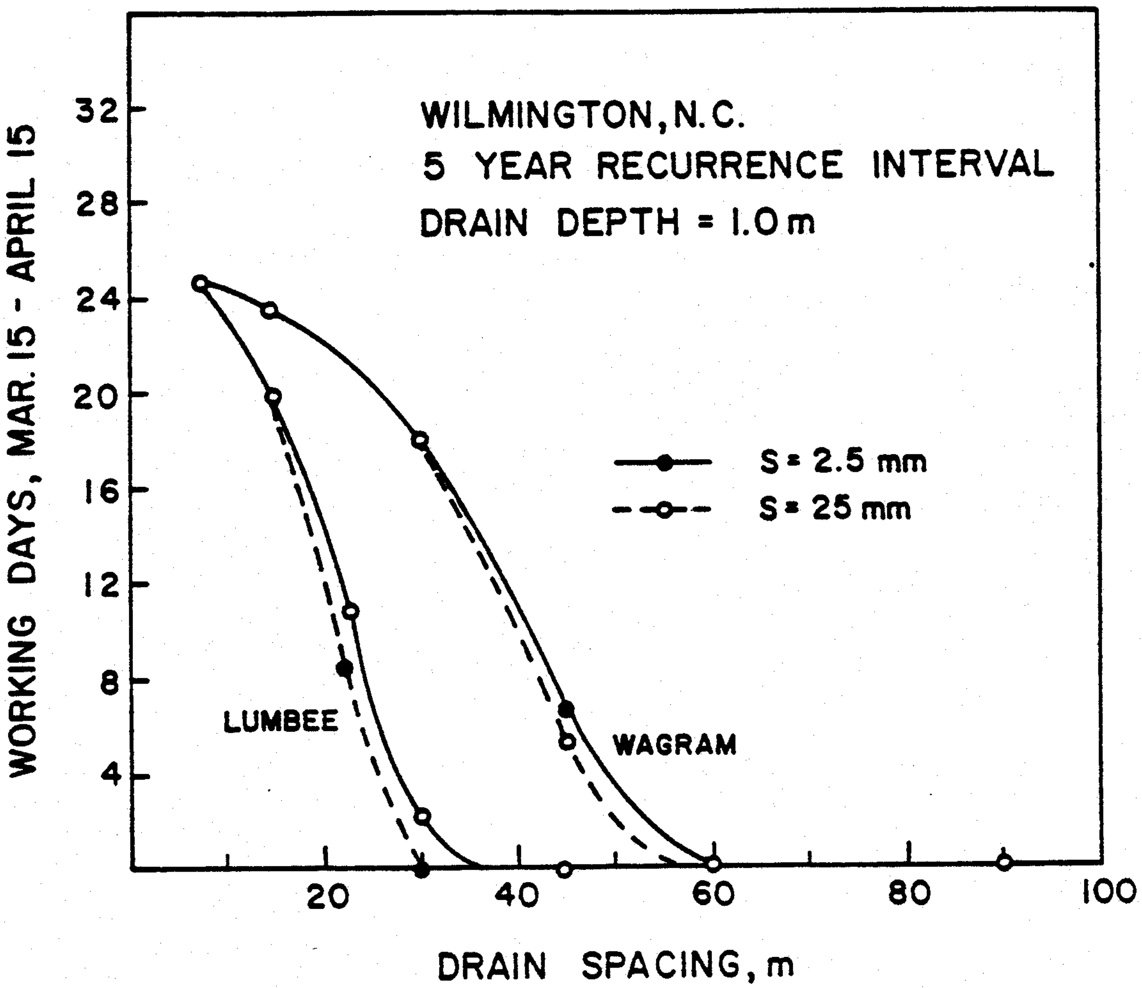

Figure 6-1. Working days on Lumbee sandy loam and Wagram loamy sand during the month prior to corn planting at Wilmington, North Carolina, as a function of drain spacing for good (s = 2.5 mm) and poor (s = 25 mm) surface drainage.

from 10 to 11 on a 5 YRI basis. In general, the effect of field surface drainage on trafficability will be larger for the tighter soils with close drain spacings than for soils that require less intensive subsurface drainage. However, the results plotted in Figure 6-1 show clearly that the quality of surface drainage has only a small effect of the drain spacing required to insure a given number of working days during the seedbed preparation period. In the above example, the 21 m spacing required to provide 10 working days with poor surface drainage on Lumbee could only be increased to 23 m for good surface drainage. Similar results for the effect of field surface drainage were observed for all soils at all locations. In order for trafficable conditions to exist, there must be a minimum air volume (water-free pore space) in the profile. Because seedbed preparation follows the winter period when water tables are often high, trafficable conditions depend on the rate that water can be removed from the profile. ET is relatively low during this period so the major pathway for water removal is subsurface drainage. Surface drainage is only effective in removing water from the surface before it can infiltrate into the profile and in reducing the water stored on the surface after rainfall ceases. Land forming and smoothing to provide good surface drainage does not remove water from the soil profile; it only affects the amount of water that must be removed from the soil surface before water table drawdown can begin. Thus, trafficability has a strong dependence on subsurface drainage and only a weak dependence on surface drainage on these soils.

Subsurface drainage for a given soil depends primarily on the depth and spacing of drains. Working days for the Lumbee soil at Wilmington, North Carolina, are plotted versus drain spacing for several drain depths in Figure 6-2. These results show that the drain spacing can be considerably increased by increasing the depth. For example, the 23 m spacing required at a 1.0 m depth to give 10 working days (5 YRI basis) could be increased by 30 percent to 30 m by increasing the depth to 1.25 m. A depth of 1.5 m would allow a 34 m spacing (48 percent increase) for the same number of working days. These results indicate that the drains should be placed as deep as possible so as to increase spacings and decrease costs. However, the drain depth may be limited by the depth of restricting layers or the elevation of the drainage outlet. For the Lumbee soil, a layer of higher K exists below a 1 m depth. However, in many soils, the conductivity decreases with depth so there is less advantage of increasing the drain depth. Another factor that may be important for some soils is the possibility of excess drainage when very deep drains are used. Results of

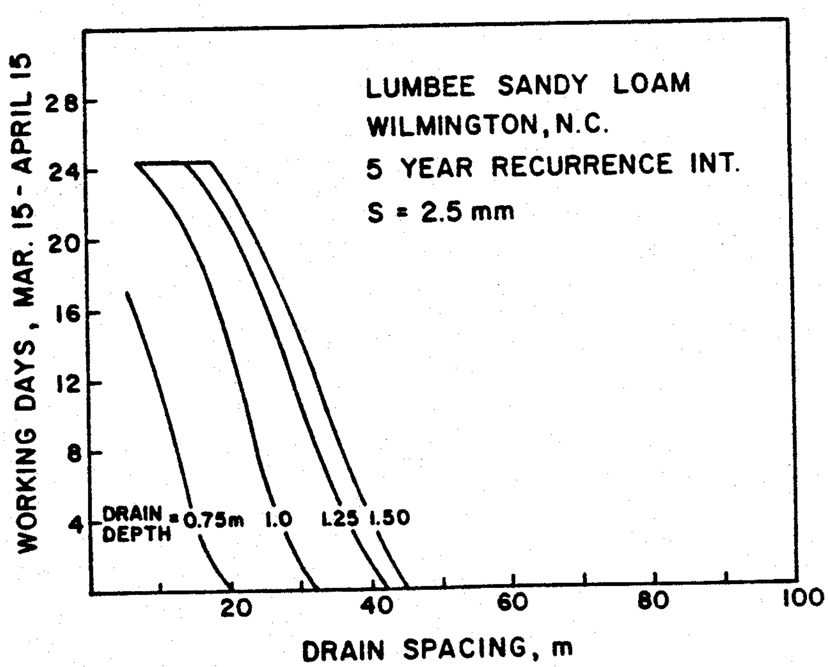

Figure 6-2. Working days versus drain spacing for four drain depths on a Lumbee sandy loam soil with good surface drainage at Wilmington, North Carolina.

the simulations showed that excess drainage was not a problem with the Lumbee soil as the number of drought days were only increased from 34 to 37 (again on a 5 YRI basis) by increasing the drain depth 0.75 to 1.5 m. However, this will not always be the case and the possibility of excessive drainage should be considered when deep drains are proposed.

Relationships between the number of working days and drain spacings are plotted in Figure 6-3 for Wagram and Bladen soils at all three locations. The relationships for the three locations were surprisingly close for all soils, as indicated by the results given in Figure 6-3. The drain spacings required to provide 10 working days were less than 2 m different among the three locations for both Bladen and Wagram soils. It is important to recall that the planting dates are different for each location so that working days are determined for the period February 1 to March 2 for Jacksonville compared to April 5 to May 5 for Columbus. If the planting dates were the same, there would be considerable difference in the working day relationships between locations, as shown by the dotted curve in Figure 6-3, which was obtained for the Jacksonville location using the planting date and growing season from Columbus.

Working day - drain spacing relationships for all four soils are plotted in Figure 6-4 for the Columbus, Ohio location. Similar relationships for the Lumbee and Wagram soils at Wilmington, North Carolina, are plotted in Figure 6-5 for recurrence intervals of 5, 10, and 25 years. An interesting point here is the relatively small differences in drain spacing among the three recurrence intervals. Taking 10 working days on the Lumbee soil, as an example, a drain spacing of 23 m would be required for design on a 5 YRI basis while the 25 YRI basis would require an 18 m spacing.

The results presented in Figures 6-1 through 6-5 show that trafficability during the seedbed preparation period is heavily dependent on the factors controlling the rate of subsurface drainage: drain spacing, depth, and soil properties. While surface drainage may have a significant effect on the number of working days for a given soil and drain spacing, it has a relatively small effect on the subsurface drainage intensity required to insure a given number of working days on a 5 year recurrence interval basis. Location had a relatively small effect for the cases considered. It is clear, however, that, in general, drainage requirements for trafficability depend heavily on the local climate, planting date (Figure 6-3), and the level of protection desired (Figure 6-5).

SEW-30

The effect of drain spacing and surface drainage on SEW-30 is shown in Figure 6-6 for Lumbee and Wagram soils. The quality of surface drainage has a much greater effect on SEW-30 than on trafficability as can be seen by comparing Figures 6-1 and 6-6. The results given in Figure 6-6 show three combinations of surface and subsurface drainage that will provide a given level of SEW-30 on a 5 YRI basis. Consider the Lumbee soil, for example. A SEW-30 value of 100 cm days can be obtained with drain spacings of 23, 16, or 12 m for surface drainage corresponding to depressional storage values of s = 2.5, 12.5, or 25 mm, respectively. All of these combinations would provide 10 or more working days for seedbed preparation (Figure 6-1), so the

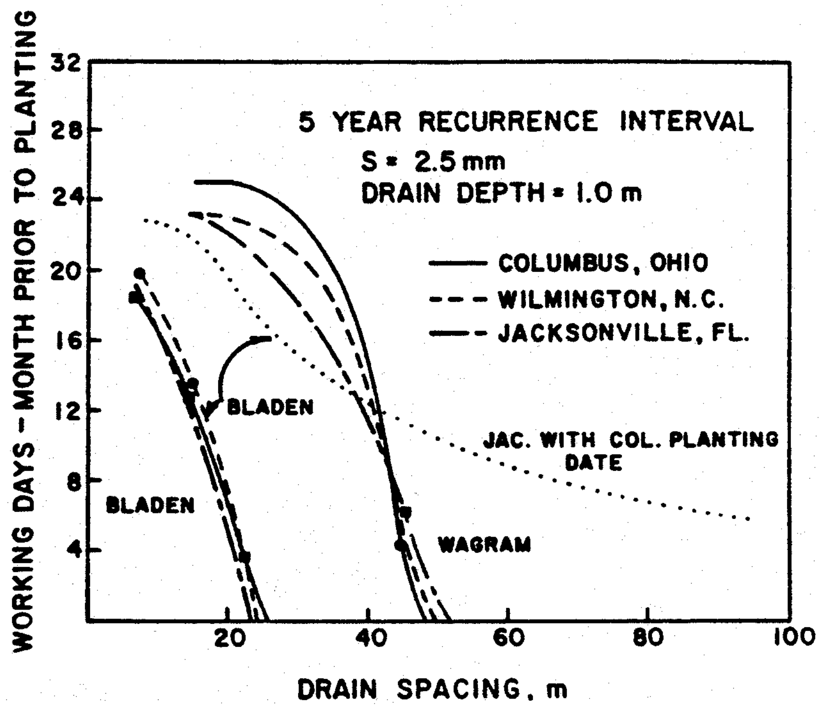

Figure 6-3. Working days during the 1-month period prior to planting versus drain spacing for two soils at all three locations. The dotted curve (...) is the relationship obtained for Jacksonville, when planting dates and growing season from Columbus, Ohio, are used.

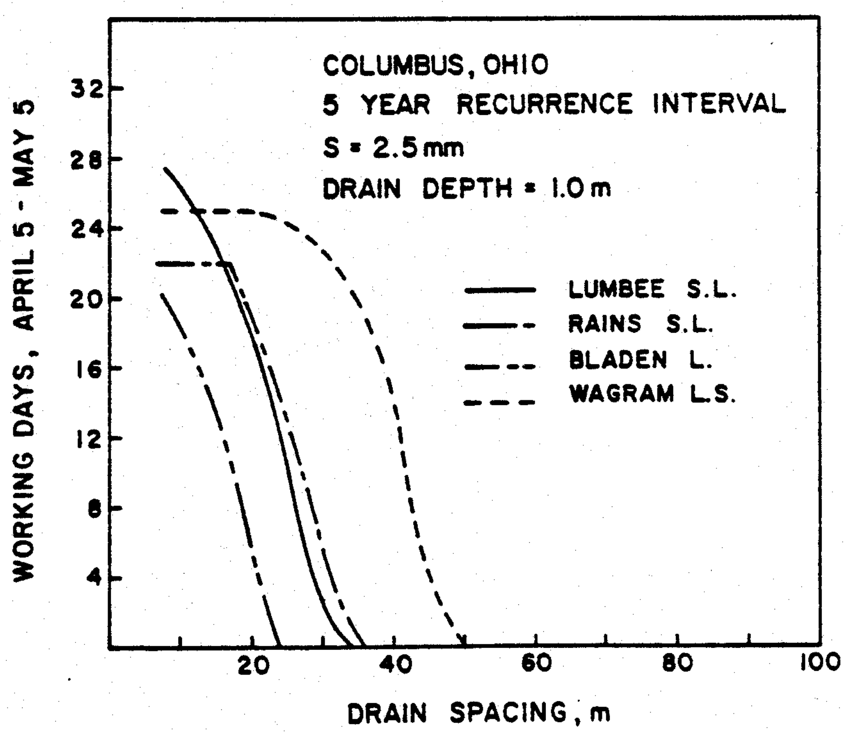

Figure 6-4. Working days versus drain spacing for all four soils at Columbus, Ohio.

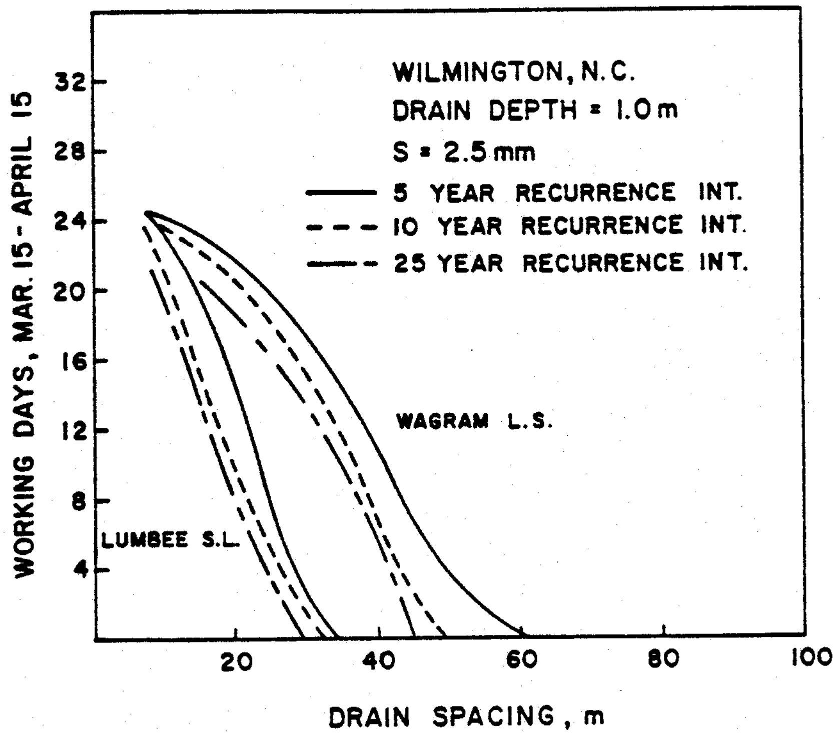

Figure 6-5. Working days versus drain spacing for recurrence intervals of 5, 10, and 25 years on Lumbee and Wagram soils at Wilmington, North Carolina.

least cost system could be selected. If a different number of working days or SEW-30 values are required, the appropriate combinations of surface and subsurface drainage can be selected from Figures 6-1 and 6-6.

The results for the Lumbee soil demonstrate the utility of using DRAINMOD to evaluate alternative designs of combination surface-subsurface drainage systems. The required number of working days and drainage protection for crop growth as indicated by SEW-30 values can be provided with a drain spacing of 12 m and poor surface drainage (s = 25 mm) or with a spacing of 23 m and good surface drainage (s = 2.5 mm). Both systems will do the required job so the farmer can choose the alternative that requires the least investment, although other factors such as maintenance costs and compatibility with the farming operation must also be considered. Another parameter that must be considered is drain depth (Figure 6-7). By placing the drains at a depth of 1.5 m rather than 1.0 m, the spacing could be increased from 23 m to 30 m for good surface drainage (s = 2.5 mm). This alternative would also be satisfactory from the trafficability aspect as it would result in 14 working days on a 5 YRI basis (Figure 6-2). Again, it is emphasized that the drain depth may be limited by other factors such as restrictive layers and the depth of the drainage outlet. Of course, possible increased costs of placing drains at a deeper depth must also be considered.

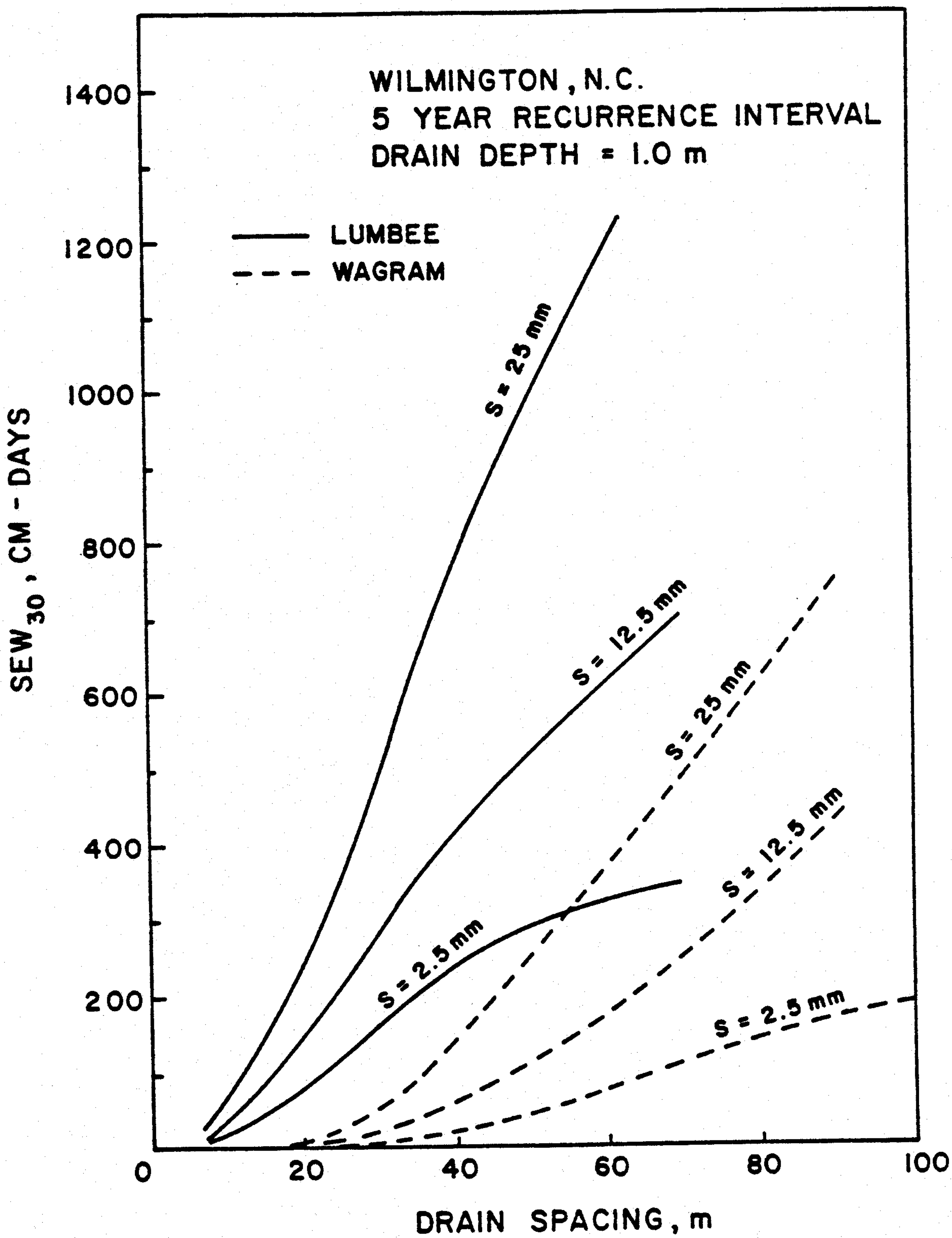

Figure 6-6. SEW-30 versus drain spacing for 3 levels of surface drainage on Lumbee and Wagram soils at Wilmington, North Carolina.

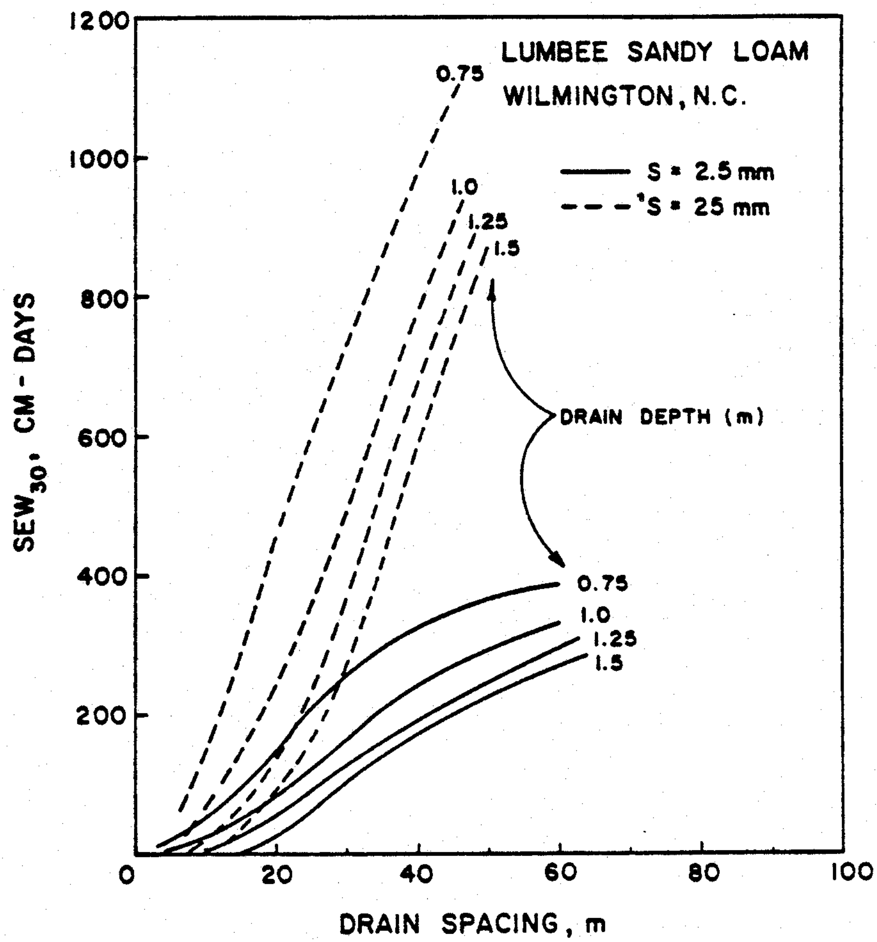

Figure 6-7. The effect of drain spacing and depth on SEW-30 values for a Lumbee soil at Wilmington, North Carolina. Relationships are given for both good (s = 2.5 mm) and poor (s = 25 mm) surface drainage.

Relationships between SEW-30 and drain spacing are plotted in Figure 6-8 for all four soils at Columbus, Ohio. Drain spacings required for a given SEW-30 value were somewhat greater at Columbus than at Wilmington or Jacksonville (Figure 6-9). This was true for all four soils and simply results from the fact that the precipitation is greater at Jacksonville and Wilmington than at Columbus. The average precipitation during the 4-month growing season was 440 mm at Jacksonville, 410 mm at Wilmington, and 370 mm at Columbus.

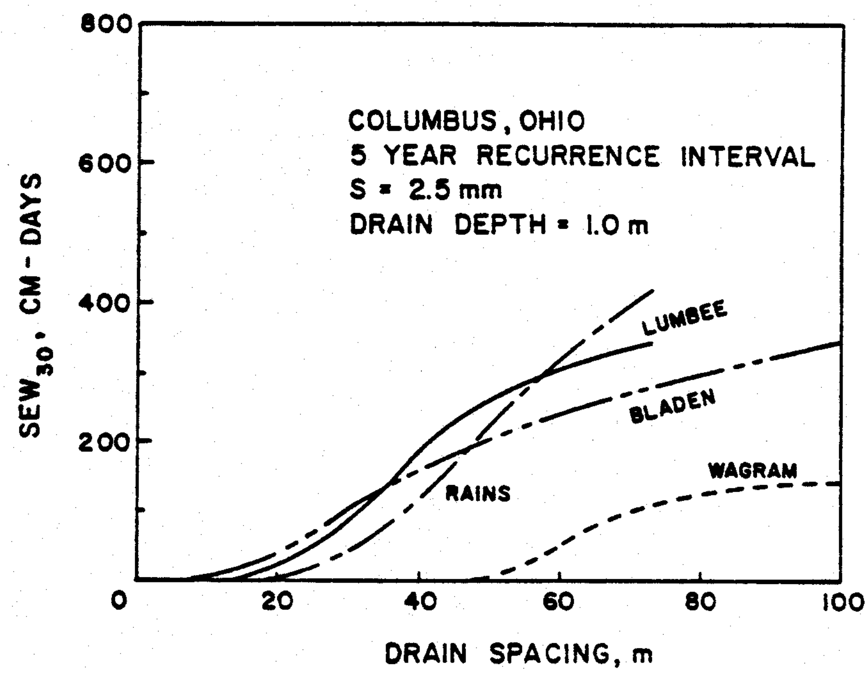

Figure 6-8. The effect of drain spacing on SEW-30 values for good surface drainage on four soils at Columbus, Ohio.

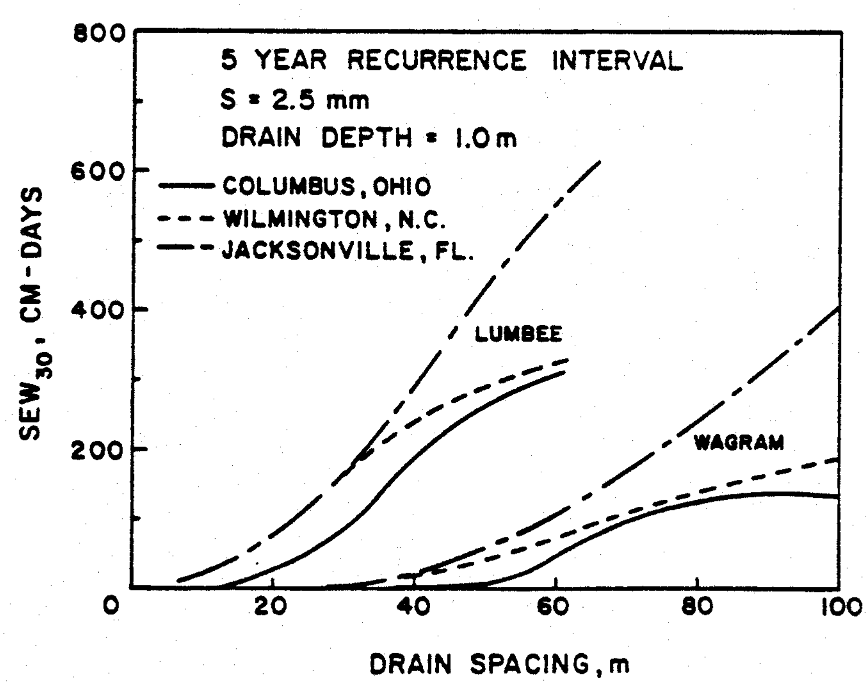

Figure 6-9. SEW-30 versus drain spacing for Lumbee and Wagram soils at all three locations.

Example Set 2 - Subirrigation and Controlled Drainage

The soils considered in Example 1 are relatively flat so water table control via subirrigation or controlled drainage should be considered. Outlet conditions for drainage, controlled drainage and subirrigation are shown schematically in Figure 6-10. When subirrigation is used, a weir is placed in the drainage outlet and water is pumped into the outlet as required to maintain a constant water level. For controlled drainage a weir

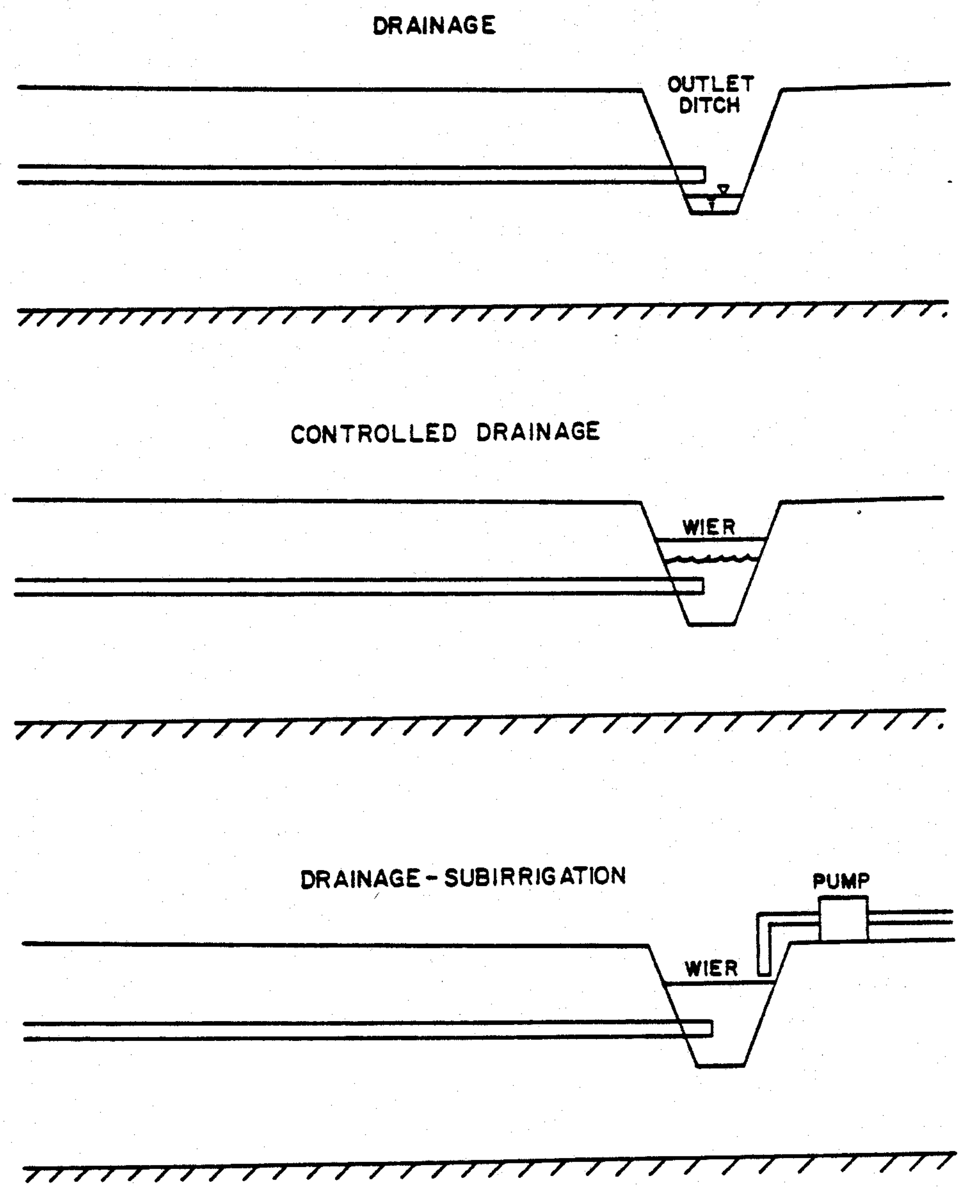

Figure 6-10. Schematic of three possible modes of operation for a subsurface drainage system.

is also placed in the drainage outlet, but no water is pumped in. This reduces the drainage rate and allows plant use of some runoff and drainage water that would be lost from the system under conventional drainage practices. In the analysis of controlled drainage systems, it is assumed that water in the outlet comes only from the field being drained and not an upstream source. Therefore, controlled drainage is not expected to provide assistance during dry years when drainage water is not available.

Simulations were conducted for subirrigation and controlled drainage on the Bladen and Wagram soils analyzed above for drainage and on a Portsmouth sandy loam. The input soil properties for Portsmouth are given in Tables 6-1 and 10-5 and Figures 5-4 and 5-6. Analyses were conducted for only the North Carolina site with the crop being continuous corn as discussed above. A drain depth of 1.0 m was used for all soils. Additional simulations were made for a drain depth of 1.5 m on the Portsmouth soil.

Results - Subirrigation and Controlled Drainage

The effect of drainage, controlled drainage, and subirrigation on the number of dry days during the growing season is shown in Figure 6-11 for the Wagram loamy sand. The relationship plotted for drainage shows clearly that drainage systems should not be over designed. For example, a drain spacing of 40 m would give, on the average, 35 or more dry days in one year out of five. Closer spacings, which are not required for trafficability (Figure 6-1) nor for crop protection (Figure 6-6) could increase the number of dry days and have detrimental effects on crop growth.* Recall that a dry day does not mean that there is no water available to growing plants, but that ET is limited by soil water conditions. The relationships plotted in Figure 6-11 were derived for good surface drainage (s = 0.25 cm). Surface drainage had little effect on the number of dry days and similar relationships were obtained for the other surface drainage treatments.

When subirrigation is used, water is pumped into the drainage outlet such that the water level is held constant at a depth of 60 cm below the soil surface during the growing season. The water table depth directly over the drain tubes during subirrigation will be approximately equal to that in the drainage outlet, but will increase with distance away from the drain during dry periods because of ET (Fox, et al, 1956). The 60 cm depth was chosen so that the water table would not be too close to the surface directly over the drain tubes. Williamson and Kirz (1970) reported that a 60 cm steady water table depth caused a 15 percent reduction in yield from the optimum depth of 76 cm for a loam soil. Yield reduction for the area directly over the drains is expected to be less for the lighter Wagram loamy sand. Results plotted in Figure 6-11 for subirrigation show that a drain

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* Note that it was assumed that the effective root depth depends on time alone, although it clearly is also dependent on soil water conditions during the growing season. Thus, good drainage, early in the season, may allow a better developed, deeper root system, which may counteract the over drainage effects shown in Figure 6-11.

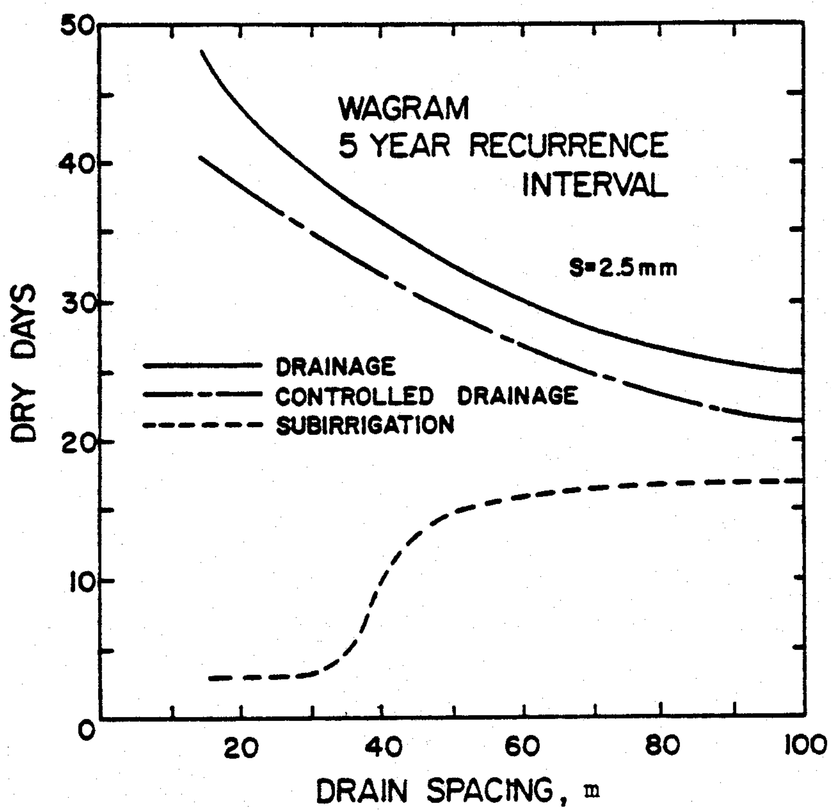

Figure 6-11. Dry days, during the growing season, as a function of drain spacing for three water management methods on Wagram soil.

spacing of 30 m or less will provide sufficient water table control to allow only 3 dry days on a 5 YRI basis. For spacings between 30 and 60 m, the number of dry days increases to 16. Further examination of the results of simulations show that, for L = 30 m, the three dry days occurred immediately after planting when rooting depths were negligible and subirrigation had just been initiated. Under these conditions, three dry days appeared to be acceptable and a drain spacing of 30 m sufficient for subirrigation on the loamy sand. These results are subject to the assumption that the water level is held constant in the drains at the 60 cm depth. This level may fall due to equipment failure or operator error. Therefore, the time required to raise the water table back to its steady state position may be critical and should be checked using the procedures given in Chapter 8.

One of the major concerns in using subirrigation in humid regions is that a high water table reduces storage available for infiltrating rainfall and may result in frequent conditions of excessive soil water. The effect of subirrigation on SEW-30 values is shown in Figure 6-12. These results show the importance of good surface drainage if subirrigation is to be used. A 30 m drain spacing gives a SEW-30 value of 210 cm days for poor surface drainage (s = 25 mm). Additional simulations showed that a SEW-30 value of less than 100 cm days can be obtained with only moderate surface drainage (s = 7.5 mm). When a 30 m spacing is used with good surface drainage (s = 2.5 mm), the 5 YRI SEW-30 value exceeded 100 cm days only once, in 20 years, and that value was only 114 cm days.

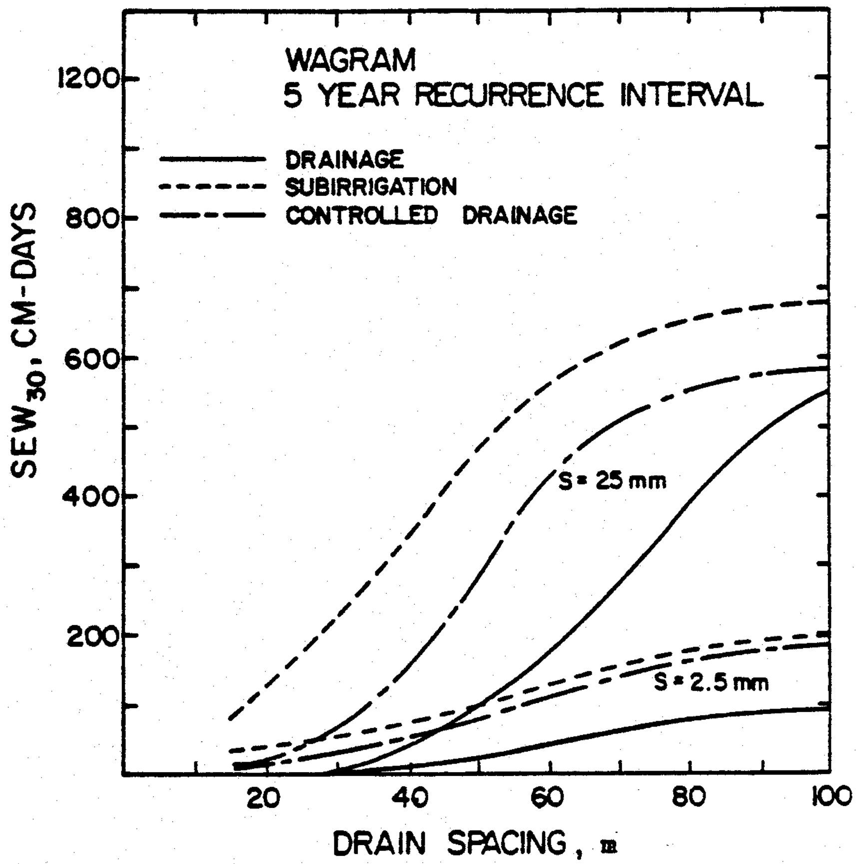

Figure 6-12. SEW-30, as a function of drain spacing for conventional drainage, subirrigation, and controlled drainage on Wagram soil. Results are plotted for two levels of surface drainage.

The results presented for Wagram loamy sand indicate that, if subirrigation is used, a drain spacing of 30 m with good surface drainage will satisfy both drainage and irrigation requirements. If subirrigation is not used, a drain spacing of 40 m will satisfy drainage requirements for both trafficability and plant growth, regardless of surface drainage. However, unless irrigation water is applied through other means, we can expect at least 35 dry days during the growing season on an average frequency of once every 5 years. The number of dry days can be reduced somewhat by using controlled drainage. Simulations were conducted for controlled drainage by assuming a weir is placed in the drainage outlet at a depth of 60 cm below the soil surface. From Figure 6-11, we see that this practice reduced the number of dry days on a 5 YRI basis by only 4, from 35 to 31. Obviously, this provides very little assistance for dry years and cannot replace an irrigation system. However, for wetter years, controlled drainage did provide some assistance. For example, a 40 m drain spacing gave fewer than 10 dry days in a growing season in 16 of 20 years of simulation when controlled drainage was used, versus only 7 of the 20 years when it was not used. When good surface drainage is provided, controlled drainage will not cause a problem with inadequate drainage during wet years, as shown in Figure 6-12.

The effect of the various water management alternatives on the number of dry days is plotted in Figure 6-13 for the Bladen soil. The relationships given in Figure 6-13 were obtained for good surface drainage, s = 2.5 mm, but the quality of surface drainage had little effect on the number of dry days. Subsurface drainage had only a small effect on number of dry days, as shown by the fact that the number of dry days decreased from 50 to only 40 when the drain spacing is increased from 7.5 to 60 m. The number of dry days during the growing season for drainage seems high, even on the basis of a 5 YRI. This may be due to assuming a root zone depth which is too shallow. Spot checks using a 75, rather than 60 percent curve in Figure 2-22 for the root zone depth, showed a reduction in the number of dry days for a 30 m spacing to about 30.

The relatively high number of dry days is consistent with the reputation that Bladen soils have for being droughty. This is caused by the low hydraulic conductivity which decreases rapidly with water content for unsaturated conditions so that the rate of upward water movement from wetter regions is slow (Figure 5-6). Thus, plants must obtain their water from a relatively shallow zone which extends only a small distance below the root zone. These soils have severe water shortages during dry years, as indicated by Figure 6-13 and it is not uncommon to experience large reductions in yield every three or four years, if irrigation is not used.

The relationship given for subirrigation if Figure 6-13 was obtained for a water level in the drainage outlet of 60 cm below the surface. In order to use subirrigation on this soil, the drains would have to be spaced about 5 m apart to provide (on a 5 YRI basis), less than 10 dry days during

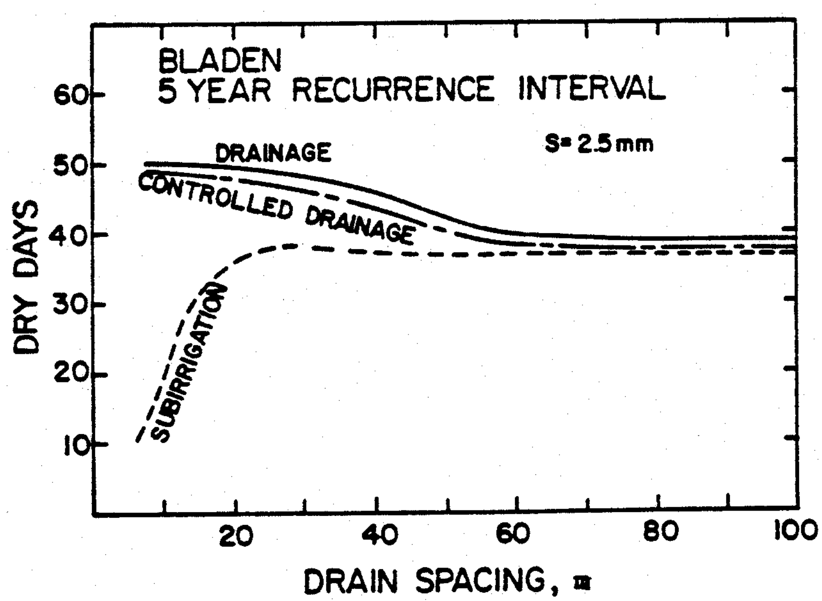

Figure 6-13. Dry days, during the growing season, for three water management methods on Bladen soil.

the growing season. Furthermore, it would be necessary to have good surface drainage in order to insure that the soil is adequately drained during wet periods (Figure 6-14). Such close drain spacings are not economically feasible and other methods of applying irrigation water should be used on this soil. For example, a drain spacing of 5 m rather than the 20 m necessary to meet trafficability (Figure 6-3) and crop requirements for conventional drainage would require 2,000 m/ha of tubing, as compared to 500 m/ha for conventional drainage. At an assumed cost of $2.50/m (installed), the tubing cost alone would be $5,000/ha ($2,000/ac) for subirrigation versus $1,250/ha ($500/ac) for conventional drainage. One possibility of increasing the drain spacing for subirrigation is to hold the water level in the drainage outlet closer to the surface. A water table depth at the drain of 40, rather than 60 cm was tried, but could not be used because of high SEW-30 values during wet years. In order to meet both subirrigation and drainage requirements, it was still necessary to have drain spacings of about 5-7 m.

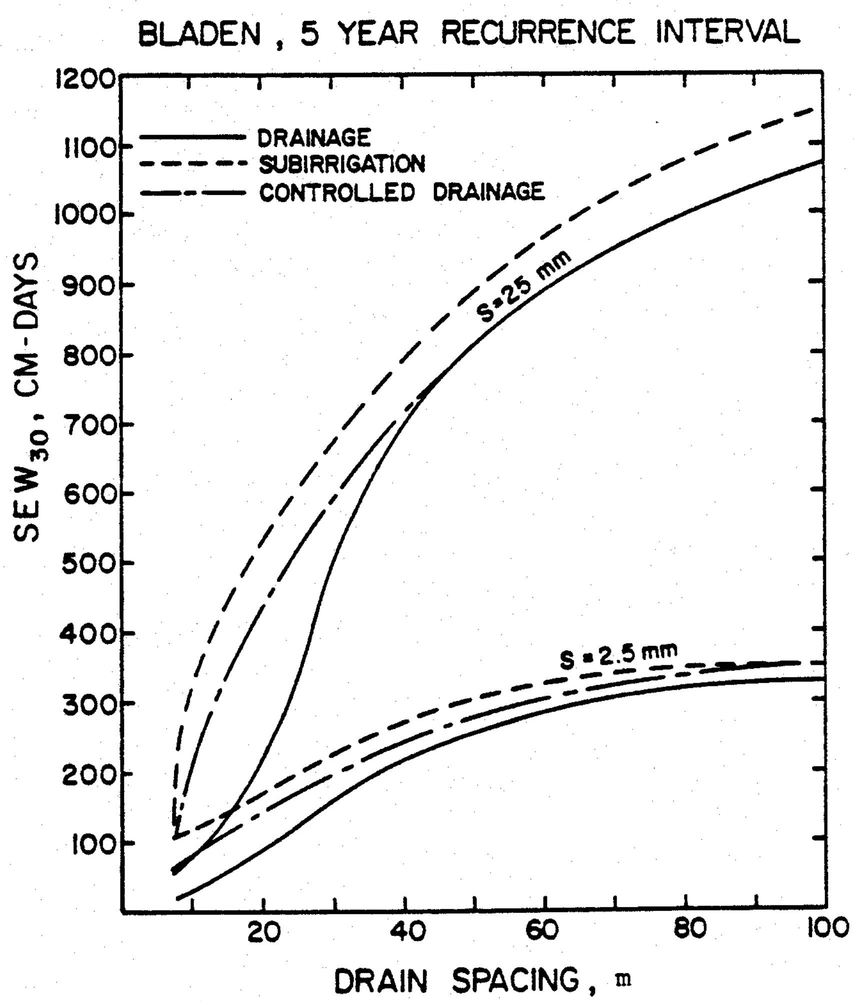

Figure 6-14. SEW-30, as a function of drain spacing for conventional drainage, subirrigation, and controlled drainage on Bladen soil. Results are plotted for two levels of surface drainage.

Controlled drainage is not attractive for this soil either. Use of controlled drainage reduced the number of dry days by only 2 on a 5 YRI basis (Figure 6-13). Thus, neither subirrigation nor controlled drainage appear feasible for the Bladen soil.

The above examples considered a soil (Wagram) with a relatively high K where subirrigation is feasible and a tight soil (Bladen) where subirrigation is impractical. A third soil, Portsmouth sandy loam with intermediate conductivity of K = 3 cm/hr, is analyzed in the following example. This same soil is also used in examples in Chapter 8 to demonstrate methods for predicting the time necessary to raise the water table at the beginning of the subirrigation process. The position of the water table during subirrigation with steady state ET conditions is also considered in Chapter 8.

A subirrigation system is to be designed for a Portsmouth sandy loam soil located near Wilson, North Carolina. Corn is to be grown on a continuous basis. The soil is flat, but good surface drainage can be provided by filling potholes in the field and smoothing the surface. Some of the soil properties and site parameters are given in Table 6-1. The soil water characteristic is given in Table 10-5 and the drainage volume and upward flux relationships in Figures 5-4 and 5-6, respectively. Example calculations in Chapter 8 showed that a steady ET rate of 0.5 cm/day could be supplied by either of the following combinations of drain spacing and drain water elevations:

1. L = 25 m with water level at drain = 30 cm deep

2. L = 17 m with water level at drain = 50 cm deep

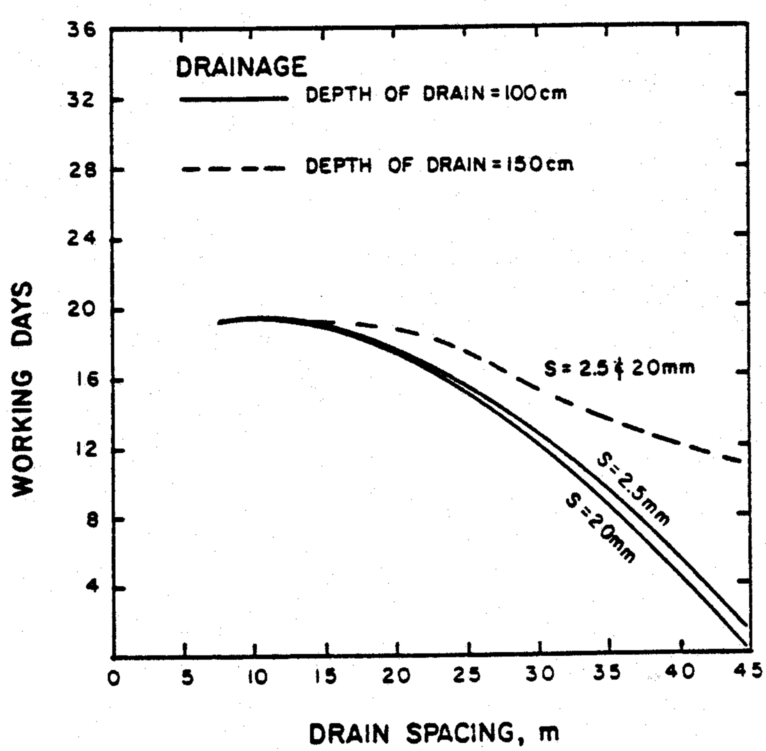

Figure 6-15. Working days on a Portsmouth s.l., as affected by drain spacing and depth and by surface drainage. Results are plotted for a 5 year recurrence interval.

Both combinations assumed a constant midpoint water table depth of 76 cm. With the 17 m drain spacing, the water table could be raised to a subirrigation position in 2.3 days (c.f. example in Chapter 8), but an excessive length of time (10 days) was required for the 25 m spacing. Therefore, a drain spacing of about 17 m is expected to do the job so far as meeting the irrigation requirement. DRAINMOD was used to determine if both irrigation and drainage requirements can be met by this on other alternative system designs.

Simulations were conducted for two drain depths (100 and 150 cm) at drain spacings of 7.5, 15, 22.5, 30, and 45 m. After planting (about April 15), the water level was raised in the drain to within 30 cm of the surface where it was held for the growing season. Simulations were also conducted for the drain water level 50 cm from the surface during the growing season.

Working days during the month prior to planting (March 15 to April 15), are plotted versus drain spacing in Figure 6-15. These relationships would be the same whether the system is used for subirrigation or for conventional drainage. Based on these results, 10 working days could be provided on a 5 YRI with a drain spacing of 32 m for a depth of 100 cm or a spacing of 45 m for a 150 cm drain depth. As in previous examples, surface drainage had a small effect on working days. SEW-30 for drainage without subirrigation is plotted in Figure 6-16. These results show that a threshold value of 100 cm days on a 5 YRI basis can be maintained with a spacing of about 35 m if the surface drainage is good (s = 2.5 mm). For poor surface drainage (s = 20 mm) drain spacings of 17 and 22 m would be required for depths of 100 and 150 cm, respectively.

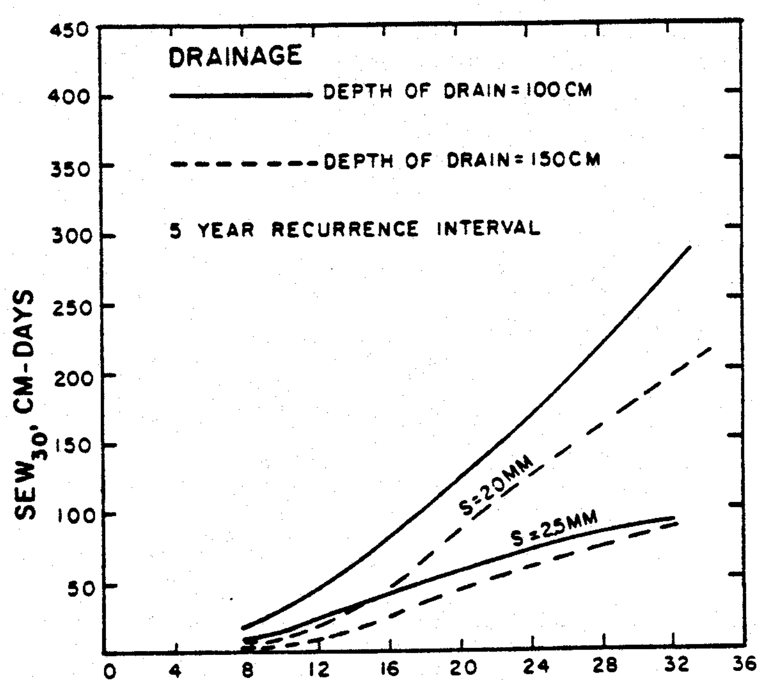

Figure 6-16. SEW-30, as a function of drain spacing for two surface drainage treatments and two drain depths on Portsmouth s.l. The system is used for conventional drainage without subirrigation, in this case.

The number of dry days on a 5 YRI basis are plotted in Figure 6-17. For conventional drainage, about 40 to 50 dry days can be expected in one year out of five. When subirrigation is used, the number of dry days depends on the drain spacing and the depth that water is held in the drains (weir depth). For a drain spacing of 15 m, about 4 dry days (5 YRI) would result for a weir depth of 30 cm and 10 dry days for a weir depth of 50 cm. However, a 30 cm weir depth and L = 15 m would result in SEW-30 values in excess of 300 (5 YRI) during the growing season (Figure 6-18). A 50 cm weir depth would have 5 YRI SEW-30 values of about 140 cm days for good surface drainage. There is no advantage in placing the drains at a depth of 150, rather than 100 cm, if subirrigation is used. At a spacing of 15 m, the 100 cm drain depth is sufficient to provide trafficable conditions for seedbed preparation (Figure 6-15), as well as protection for crop growth (Figures 6-16 and 6-18). Close inspection of the simulation for subirrigation with L = 15 m showed that most of the 10 dry days occurred during start-up immediately after planting, as observed earlier for the Wagram soil. This number can be reduced to 4 or 5 days by raising the weir to within 30 cm of the surface during start-up and then lowering to a 50 cm depth for the remainder of the growing season.

A summary of results for the Portsmouth soil shows that drainage and irrigation requirements could be provided with the alternatives given in Table 6-4. It is interesting that the factor limiting the drain spacing for a combination drainage-subirrigation system on this soil is the drainage requirement. For example, the irrigation requirement could be satisfied with a drain spacing of 25 m and a weir depth of 30 cm (Figure 6-17). However, this would give an unacceptable SEW-30 value of 450 cm days (Figure 6-18).

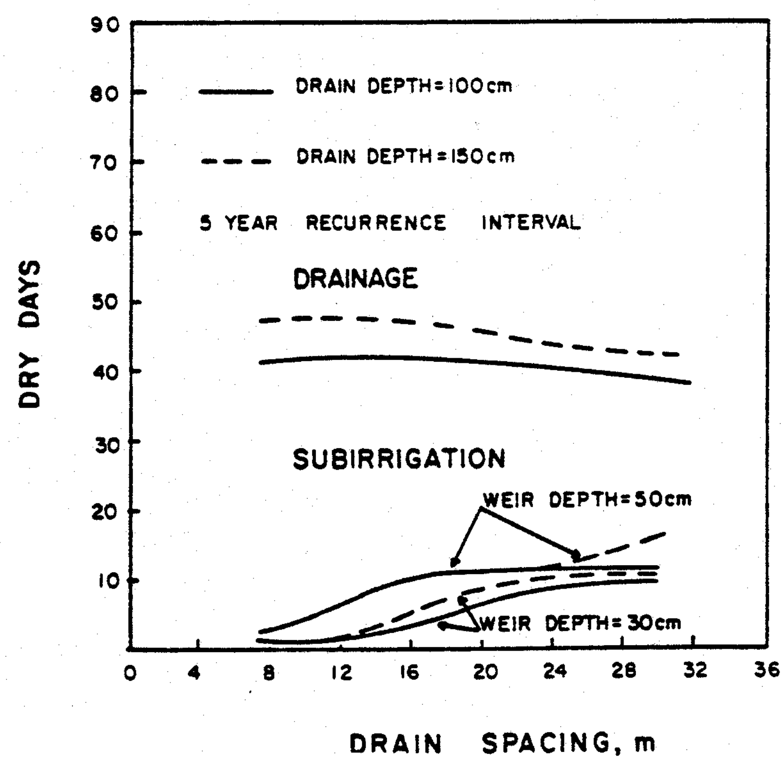

Figure 6-17. Dry days, as affected by drain spacing for conventional drainage and for subirrigation with weir depths during the growing season of 30 and 50 cm. Drain depths of both 100 and 150 cm are considered.

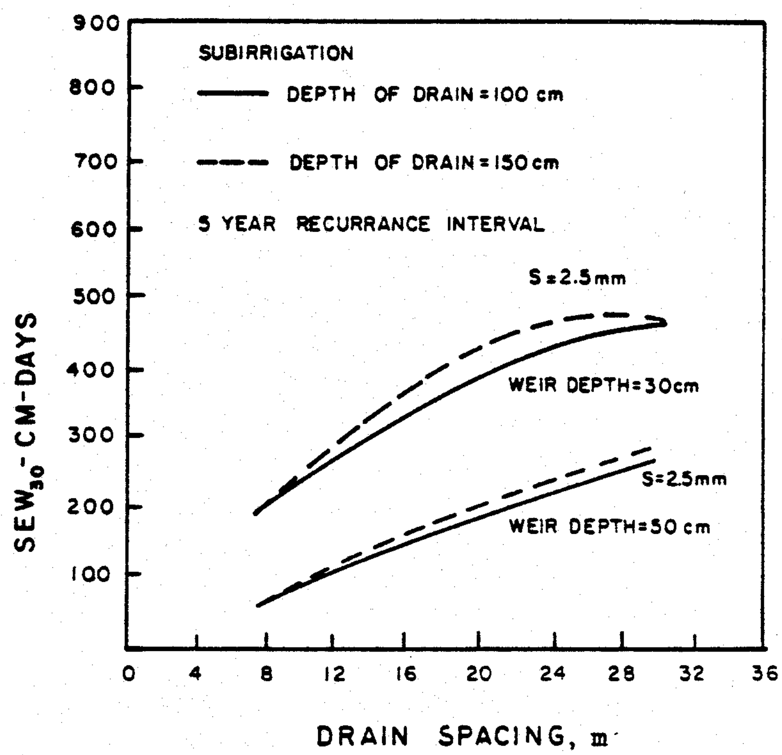

Figure 6-18. Effect of drain spacing on SEW-30 during the growing season for subirrigation with weir depths of 30 and 50 cm.

Table 6-4. Drain spacings required to meet drainage* and irrigation** requirements for a Portsmouth sandy loam near Wilson, North Carolina.

	Surface Drainage	
Drain Depth	Good (s = 2.5 mm)	Poor (s = 20 mm)
	DRAINAGE ALONE	
100 cm	34 m	17 m
150 cm	36 m	21 m
Weir Depth	DRAINAGE AND SUBIRRIGATION	
30 cm	05 m	05 m
50 cm	15 m	7 m

* The drainage requirement is assumed to be at least 10 working days during the month prior to planting and SEW-30 values less than 100 cm days.

** The irrigation requirement is assumed to be 10 or fewer dry days during the growing season.

Example Set 3 - Waste Water Application on Drained Lands

Land application of agricultural, municipal, processing, or industrial waste water, with appropriate pretreatment, is an economically and technically feasible alternative to conventional waste disposal methods for many situations. A major step in designing a land application system is determining the permissible loading rate for a given site. In some cases, the loading rate is limited by the pollutants in the waste water. In others, the application rate is limited hydraulically by drainage conditions of the site. In the latter cases, it may be feasible to provide subsurface drainage to increase the amount of waste water that can be applied to a given site and reduce the land area required. Since the costs of land and irrigation systems to apply waste water are relatively high, increasing the application rate by the use of artificial drainage could significantly lower the costs of a land disposal system.

In this example, we consider waste water application to the Wagram loamy sand discussed in example sets 1 and 2 above. The hypothetical site is located near Wilson, North Carolina. Fescue is grown year around and waste water from a processing plant pretreatment lagoon is to be applied (sprinkler irrigation) onto the surface. Consideration of the nutrient levels in the water limit the application rate to 25 mm/week in this example. The water may be applied at any irrigation frequency, but the average must not exceed 25 mm/week. Higher loading rates of 50 mm/week and 100 mm/week will be considered in another example. As discussed in example set 1, the soil surface is flat and a restrictive layer exists at a depth of 1.8 m so that drainage under natural conditions is slow. Outlet conditions limit the depth of the drain tube to 1.25 m, which is considered deep enough to prevent short-circuiting of the waste water directly into the drain.

The objective in this example is to determine the effect of surface and subsurface drainage on the amount of water that can be applied without causing surface runoff. The effect of application frequency (e.g. one irrigation per week of 25 mm versus one application of 50 mm every 2 weeks), on the total permissible annual application will also be considered. Simulations were conducted for good surface drainage, s = 2.5 mm, poor surface drainage, s = 25 mm, and very poor surface drainage, s = 150 mm. The very poor surface drainage was considered because it may be desirable in some cases to construct dikes or otherwise artificially shape the surface to prevent runoff during high rainfall intensities. This would prevent pollutants deposited on the surface, grass cover, etc., from washing off the site with runoff water. Simulations were conducted for five drain spacings and for 3 application strategies as follows: (1) 10.5 mm every 3 days; (2) 25 mm every 7 days; (3) 50 mm every 14 days. All 3 strategies would give an average application rate of 25 mm/week. As discussed in Chapter 3, waste water application is simulated by DRAINMOD on the application interval, INTDAY, if the drained volume (air volume) in the profile is greater than a given amount, REQDAR, and if rainfall occurring on the scheduled day is less than AMTRN. Parameter values used to determine whether an application will be skipped or postponed are listed in Table 6-5 for the cases considered in this example. In all cases, the required drained volume, REQDAR, was 10 mm greater than the amount of water to be irrigated.

Table 6-5. Application parameter values used in Example 3.

Application interval, INTDAY	3 days	7 days	14 days
Irrigation amount	10.5 mm	25 mm	50 mm
Time irrigation starts	1000	1000	1000
Time irrigation ends	1200	1200	1200
Drained (air) volume required in the profile, REQDAR	20.5 mm	35 mm	60 mm
Amount of rain to postpone irrigation, AMTRN	10 mm	10 mm	10 mm

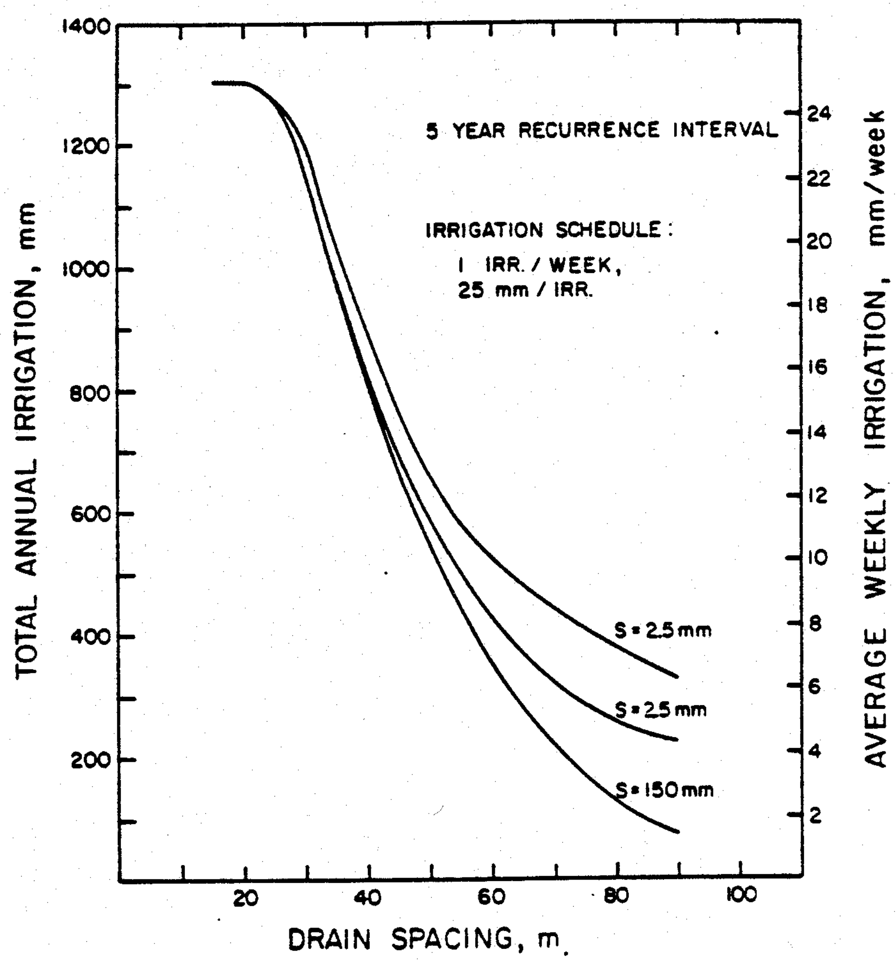

Figure 6-19. Effects of drain spacing and surface storage on amount of waste water treated annually for irrigation scheduled once per week, 25 mm per application.

All simulations were conducted a 25-year period and the results analyzed to determine the total annual irrigation on a 5-year recurrence interval basis. The results are plotted in Figure 6-19 for the 7-day application frequency and all three surface drainage treatments. The results show that, for drain spacings of 25 m or less, water could be applied at every scheduled application for a total of 1300 mm (52 weeks x 25 mm/week) on a 5 YRI basis. In some weeks, waste water application may have to be postponed for one or more days due to rainfall, but the scheduled amount could be applied in all cases. For larger drain spacings, many of the scheduled irrigations could not be applied because there was insufficient water-free (drained) volume in the profile. When this happened, application was canceled for that period and conditions were checked on the next scheduled day. For example, only 770 mm could be applied (5 YRI basis) for a drain spacing of 45 m and good surface drainage. Closer inspection of the simulation results showed that most of the cancellations due to wet conditions occurred in the winter and early spring when ET is low. The results plotted in Figure 6-19 show that the amount of water that can be applied is more dependent on subsurface drainage, as indicated by the drain spacing, than on surface drainage. However, when subsurface drainage is poor (large drain spacings), the amount of waste water that can be treated is heavily dependent on surface drainage. When surface drainage is poor, water may be stored on the surface after periods of high rainfall and can be removed only by evaporation or subsurface drainage. Time required for removal of this surface water may cause the next scheduled waste water application to be canceled due to wet soil conditions.

The effect of the application interval on annual amount applied is shown in Figure 6-20. Recall that the intervals and amounts to be applied were selected so that the average application rate was 25 mm/week for all three combinations simulated. This is obvious for good subsurface drainage where 1300 cm could be treated for all three irrigation frequencies. For slower subsurface drainage (i.e., drain spacings greater than 25 m), the results in Figure 6-20 indicate that more water can be treated by applying smaller amounts on a more frequent basis. For example, if drains are spaced 45 m apart, 950 mm of water could be treated (on a 5 YRI basis) by applying 10.6 mm every 3 days, while only 650 mm could be treated by scheduling 50 mm every 14 days. The reason for the difference is that, due to random occurrence of rainfall, it is more difficult to get the required water free (drained) volume for larger, less frequent irrigations. For the 14-day application interval, a water-free pore volume of 60 mm was required in order to apply waste water at the scheduled time. This volume may be available on the 12th day, but rainfall on the 13th day could cause conditions to be too wet for application at the scheduled time on day 14. For the 3-day interval, on the other hand, the same rainfall conditions would cause cancellation of only one or perhaps none of the 4 scheduled smaller waste water applications during the same period.

The results discussed above assumed that a given amount of waste water is applied at a schedule time providing that soil water and rainfall conditions are not limiting. For a given drainage system, soil water conditions are more likely to be limiting in the winter and early spring because of lower ET rates, as mentioned above. However, it may also be

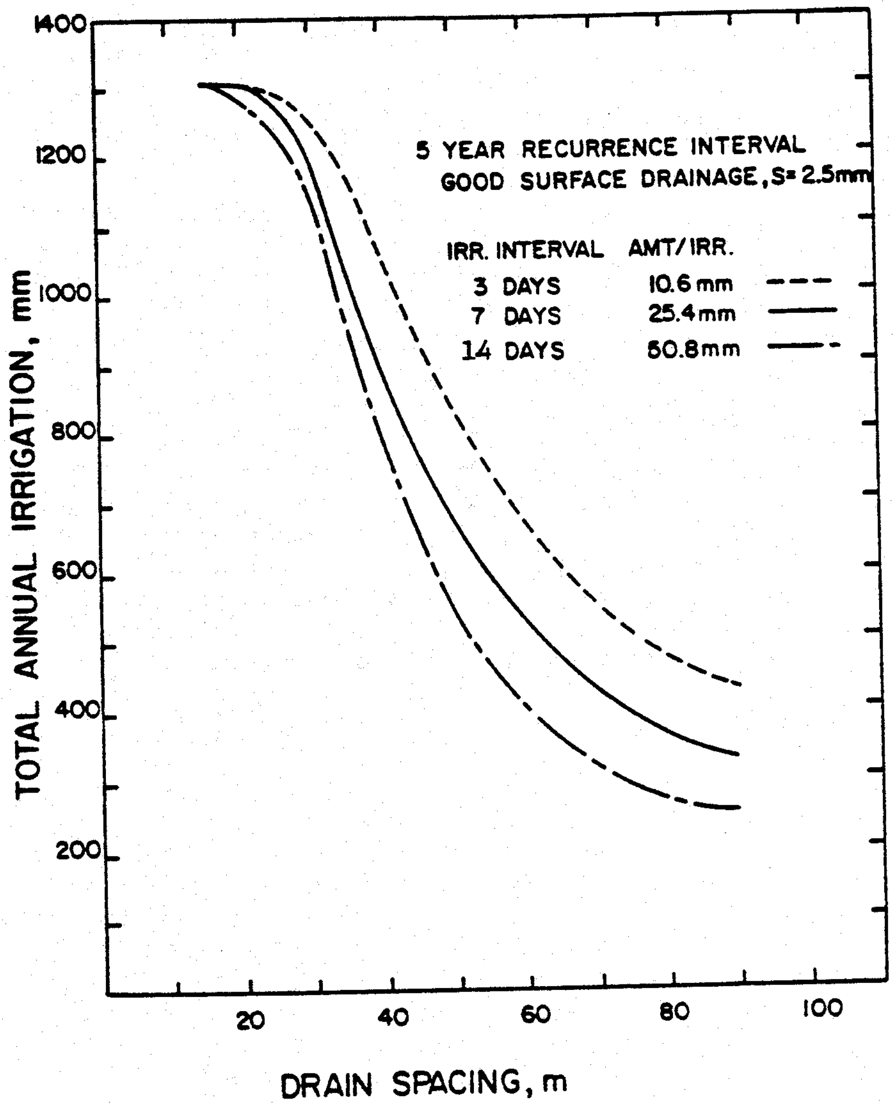

Figure 6-20. Effect of drain spacing and application frequency on total annual waste water treated for a Wagram loamy sand.

possible to increase the amount applied during the late spring and summer months because of the relatively high ET rates during this season. Thus, it would be possible to increase the annual application over that shown in Figures 6-19 and 6-20 by storing the water in a reservoir during periods when irrigation is not possible and increasing the application rate during the summer. In this case, it is important to determine the amount of storage that would be required for a given drainage system and application strategy. Storage required for the alternative systems considered here is shown in Figure 6-21 for drain spacings up to 45 m. The values given represent the storage required (5 YRI basis) to permit land treatment of an

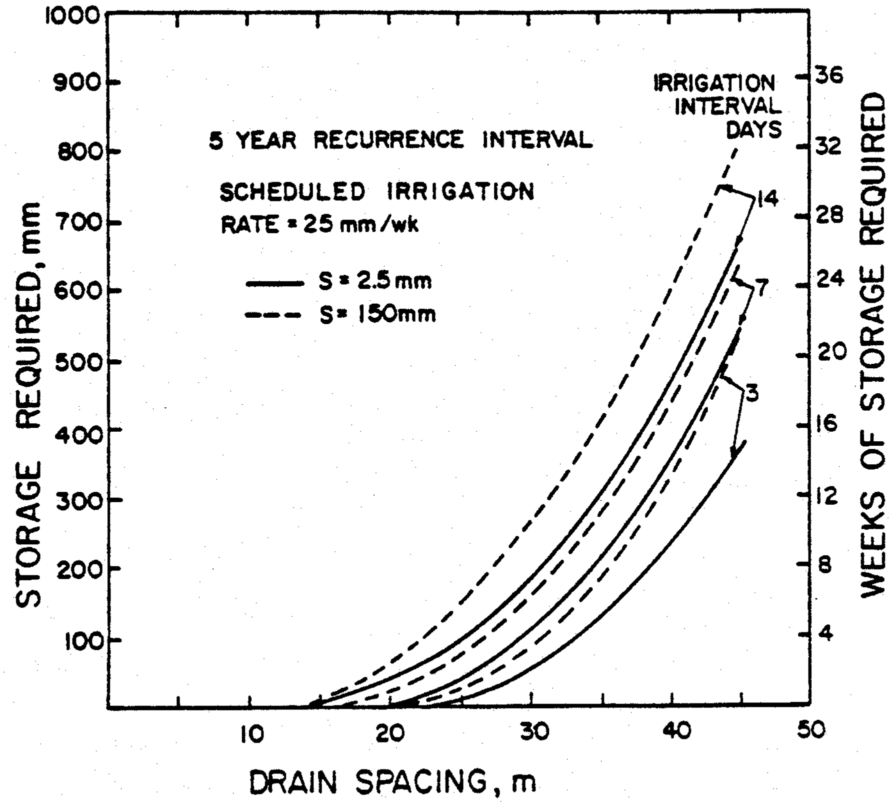

Figure 6-21. Effect of drain spacing, surface drainage, and application frequency on storage volume required for application of an average of 25 mm/week on a Wagram loamy sand.

average of 25 mm per week for 52 weeks per year. For example, a drain spacing of 45 m, with good surface drainage, would require storage capacity for 350 mm of waste water. This amounts to 13 weeks of irrigation at 25 mm per week.

The results of this example show that DRAINMOD can be used to determine the amount of waste water than can be applied to drained soils. The storage volume required because application is not possible during wet periods can also be assessed. Since simulations are made with actual weather data, designs can be made on a probabilistic basis. By considering alternative systems, DRAINMOD can be used to select the most economical system that will meet the design requirements for a given situation.

In many cases, concentrations of potential pollutants in waste waters are very low and the amount of water than can be applied to a disposal site depends on hydraulic limitations only. The following hypothetical example considers the effect of drainage system design and loading rates on the total amount of water than can be applied to the same Wagram soil discussed above.

A processing plant needs to treat above 11,000 m^3 (3,000,000 gallons) of waste water per week during the 8-month period from March 15 to November 15. The waste has a low concentration of pollutants and could be applied to the soil at rates up to 10 cm/week as far as the pollutant load is concerned. What size land disposal site will be required and how is the size dependent on the drainage system design?

The size of the land area required will obviously depend on the loading rate. If 2.5 cm of water can be applied every week, an area of 44 ha (110 acres) will be required. For loading rates of 5 and 10 cm/week, areas of 22 ha (55 acres) and 11 ha (27 acres) would be needed respectively. However, land application of the waste water would be limited during some weeks because of natural rainfall. Application may also be frequently restricted by wet soil conditions if the soil is not adequately drained. Simulations were conducted for planned loading rates of 2.5, 5, and 10 cm/week. A 3-day application interval was used in all cases with the amount

Table 6-6. Irrigation parameter values for three different loading rates on Wagram l.s.

Loading rate*		2.5 cm/week	5.0 cm/week	10.0 cm/week
Application interval (INTDAY)		3 days	3 days	3 days
Irrigation amount* (per application)		1.07 cm	2.14 cm	4.28 cm
Time irrigation starts (IHRST)		10	10	10
Time irrigation ends (IHREND)		12	12	12
Intervals when no irrigation is applied:				
Interval 1	NOIRR1	1 (Jan 1)	1	1
	NOIRR2	74 (Mar 15)	74	74
Interval 2	NOIRR3	314 (Nov 15)	314	314
	NOIRR4	365 (Dec 31)	366	366
Drained (air) volume required in profile, REQDAR		2.07 cm	3.14 cm	5.28 cm
Amount rain to postpone irrigation, AMTRN		1 cm	1 cm	1 cm
Irrigation rate**		0.53 cm/hr	1.07 cm/hr	2.14 cm/hr

* Not a direct input to this model.
** Constant for all months in which waste water is to be applied.

of water at each application adjusted to give the required weekly loading. The irrigation parameter values used in this example are given in Table 6-6. As in the previous example, subsurface drainage is provided by 4-inch drains placed at a depth of 1.25 m in the Wagram soil. Also, the required drainage volume was set at 10 mm greater than the amount of waste water to be applied. However, in this example, it is assumed that good surface drainage (s = 2.5 mm) will be provided for all cases. A good stand of fescue, with an effective rooting depth of 30 cm, will be grown on the site.

All simulations were run for a 25-year period and the results analyzed to determine the annual waste water applied on a 5 YRI basis. The results are plotted in Figure 6-21 for all three loading rates. In this case, the 5 YRI means that the total waste water application, taken from Figure 6-22 could be applied four years out of five on the average.

Results given in Figure 6-22 show that, for narrow drain spacings, the amount of waste water than can be applied during the 8-month season is directly dependent on the planned loading rate. For example, a 15 m drain spacing would permit an irrigation total of 85 cm, 170 cm, and 325 cm for planned loading rates of 2.5, 5, and 10 cm/week, respectively. For wider drain spacings, the drainage rate limits the application of irrigation water and there is much less difference in the amount of water that can be applied at the different loading rates. At a 30 m drain spacing, both 5 and 10 cm/week loading rates will apply a total of 140 cm of water while the 2.5 cm/week rate will still result in a total application of 85 cm. Clearly, the drainage system should be designed to fit the loading rate desired. For example, if the loading rate is restricted to 2.5 cm/week, the total amount of water applied cannot be increased by placing the drains closer together than 30 m. Likewise, a 10 m spacing would allow the maximum amount of irrigation to be applied if a 10 cm/week loading rate is used.

The relationship plotted in Figure 6-22 can be used to determine the optimum drain spacing and size of the land disposal site for a given application rate. Assuming a land cost of \$3,000/ha (\$1,200/ac), irrigation system (pipe, sprinkler, installation, etc.) costs of \$2,000/ha (\$800/ac) and drainage system costs (installed) of \$2.50/m (\$0.78/ft), the initial cost of a land disposal system can be calculated, as follows, for a planned application rate of 5. cm/week.

An average waste load of 11,000 m^3/week gives a total of 477,400 m^3 to be applied over the 8-month period. For an application rate of 5 cm/wk and a 10 m drain spacing, 170 cm of water can be applied (Figure 6-21). Then, the area required is:

$$\text{Area} = \frac{377{,}300 \text{ m}^3}{1.7 \text{ m}} \times \frac{1 \text{ ha}}{10{,}000 \text{ m}^2} = 22.2 \text{ ha}$$

The total drain length = 22.2 ha x 10,000 m^2/ha/10 m = 22,200 m. Then, the total land cost is 22.2 ha x \$3,000/ha = \$66,600; the irrigation system cost is 22.2 ha x 2,000/ha = \$44,400 and the drain cost is 22,200 m x 2.50/m = \$55,500. Initial costs for land, irrigation, and drainage systems are tabulated in Table 6-7 for drain spacings of 10, 20, and 30 m.

Table 6-7. Initial costs for a land disposal system with subsurface drainage to treat 11,000 m^3 (3,000,000 gallons) per week. These calculations are based on a planned application rate of 5 cm/week.

Drain spacing	10 m	20 m	30 m
Total seasonal loading (Figure 6-21)	170 cm	167 cm	144 cm
Land area required	22.2 ha	22.6 ha	26.2 ha
Total drain length	22,200 m	11,300 m	8,700 m
Land cost*	$66,600	$67,800	$78,600
Irrigation system cost**	$44,400	$45,200	$52,400
Drain cost	$55,500	$28,200	$21,800
Total cost	$166,500	$141,200	$152,800

* Land cost calculated at $3,000/ha ($1,200/ac)

** Irrigation system costs assumed to be $2,000/ha ($800/ac)

*** Drainage cost (installed) calculated at $2.50/m ($0.78/ft)

The initial cost of land, irrigation, and drainage system considered above are plotted in Figure 6-23 for all three loading rates. These results show that the minimum cost will be obtained by using the loading rate of 10 cm/week and a drain spacing of 15 m. If the loading rates are restricted, due to pollutant concentration or for other reasons to 5 or 2.5 cm/week, initial costs can be minimized by using drain spacings of 23 m and 30 m, respectively. Pumping, maintenance, and other operational costs have not been considered and the analysis is therefore incomplete. However, this example demonstrates the use of the model in optimizing the design of an under-drained land disposal system.

Example Set 4 - Effect of Root Depth on the Number and Frequency of Dry Days

Root depths are limited in many North Carolina soils due to the physical barriers caused by hard pans or layering and by chemical barriers, such as a low pH below a given depth. In other cases, root depths are limited by high water table conditions which frequently prune back deeper roots. Some varieties of a given crop have more shallow rooting depths than others. Thus, increasing the rooting depth for a given crop may be a matter of variety selection, providing good drainage, or removing physical and chemical barriers to root growth. Because increasing the rooting depth

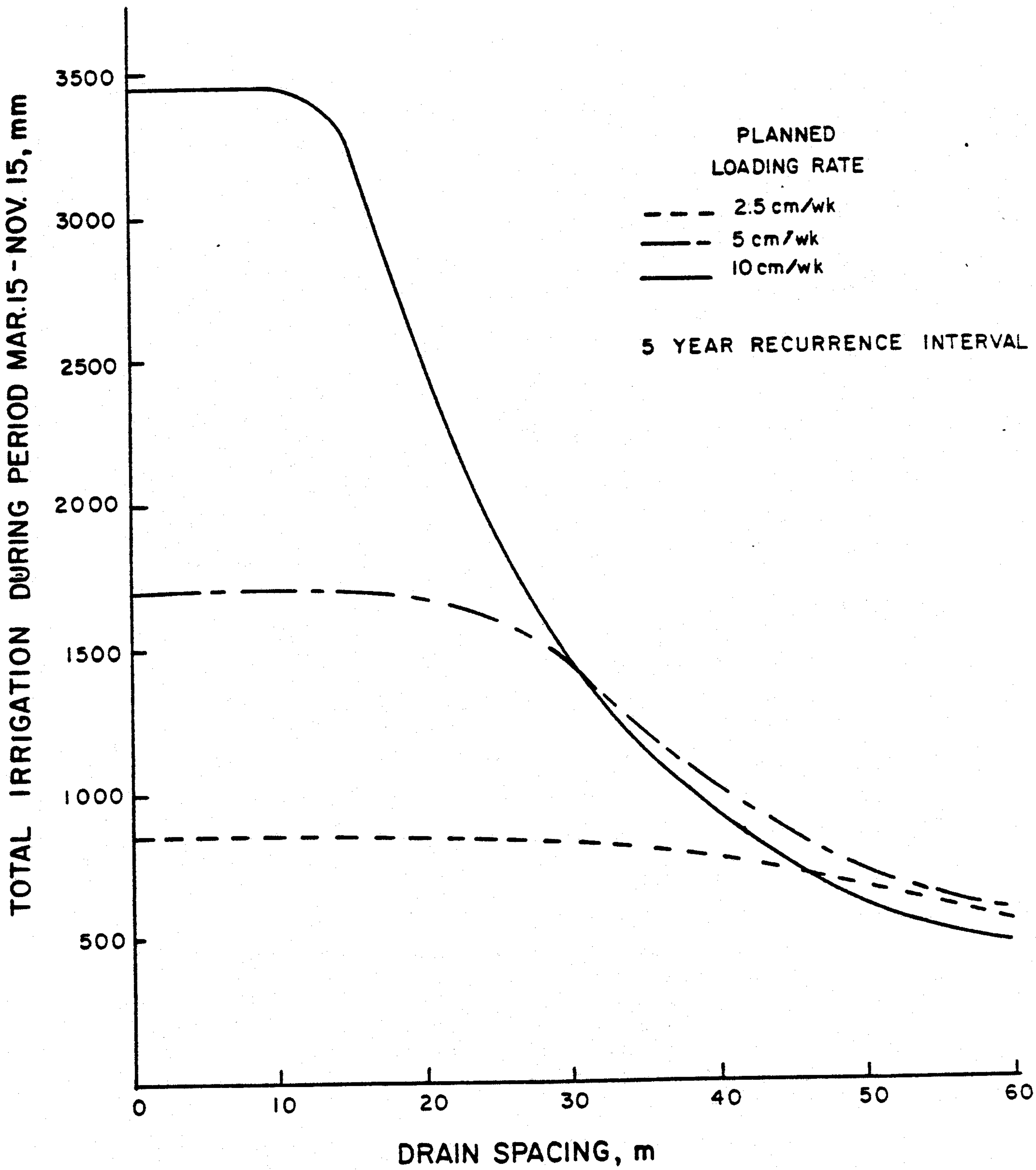

Figure 6-22. Effect of drain spacing and planned loading rate on total volume of water that can be treated on a Wagram l.s. soil near Wilson, North Carolina.

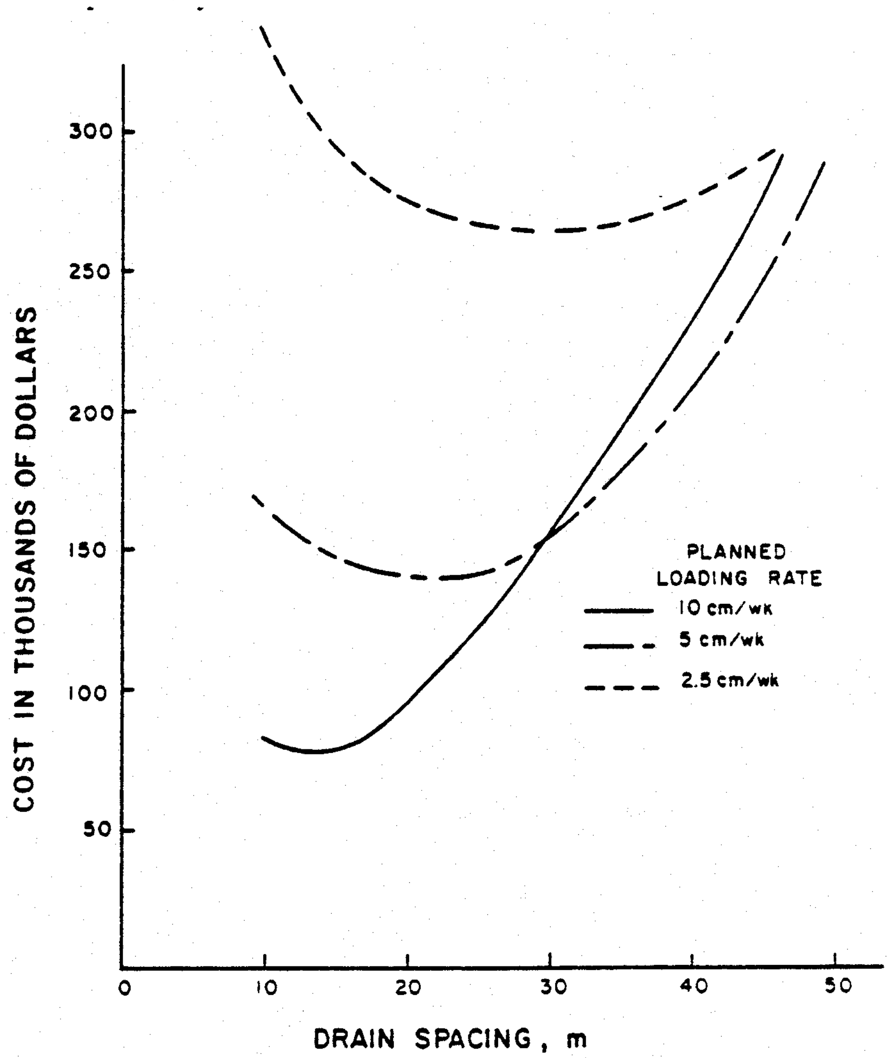

Figure 6-23. Initial costs (sum of land, irrigation equipment, and subsurface drainage costs) versus drain spacing for three loading rates.

directly increases the water available for plant use, there has been much interest in removing barriers to root growth and in developing plant varieties with deeper rooting systems. The purpose of this example is to examine the effect of root depth on the number of days that the plant is under stress due to dry conditions. A day when plants are under stress due to dry conditions is assumed here to be a dry day and is defined in Chapter 3 as a day in which ET is limited by soil water conditions.

The soils, Bladen loam and Wagram loamy sand, and drainage systems considered here were used in previous examples (Example Sets 1 and 2). The drainage system for the Bladen soil is composed of parallel drains buried 1 m deep and placed 20 m apart with good surface drainage (s = 2.5 mm). For the Wagram soil, the drain spacing is 43 m with poor surface drainage (s = 25 mm). Conventional drainage is assumed without controlled drainage or subirrigation. Simulations were conducted for 20 years of climatological data for Greenville, North Carolina. It was assumed that corn was to be grown on a continuous basis and the maximum effective rooting depth was varied from 0.1 m to 0.6 m to determine the effects on number of dry days. The basic relationship for rooting depth versus time was the same as used in the previous examples and is given by the 60 percent curve in Figure 2-22, which has a maximum depth of 0.3 m. When the value given in Figure 2-22 was greater than the maximum rooting depth chosen, the rooting depth was set equal to the maximum. For maximum rooting depths greater than 0.3 m, the values given by the 60 percent curve in Figure 2-22 were increased by the ratio M/.30 where M is the maximum depth.

The results of the simulations are plotted in Figure 6-24 for 5-year and 2-year recurrence intervals for both Bladen and Wagram soils. An example interpretation of these results yields the following for a Wagram soil with a limiting root depth of 0.15 m. On a 5 YRI basis, we should expect to have 38 or more dry days during the growing season in one year out of 5 when the root depth is limited to 0.15 m. However, if the barrier to root growth is removed and the maximum effective depth reaches 0.3 m, the expected dry days (once in 5 years) would be 23. From another point of view, we can say that 23 or fewer dry days would be expected in 4 years out of 5 when the maximum effective root depth is 0.3 m. If the effective maximum root depth could be further increased to 60 cm, the expected number of dry days in 4 years out of 5 would be 7 or fewer.

Use of the model, as in this example allows an evaluation of the potential benefit of operations to increase rooting depths, such as chisel plowing to break hardpans or deep incorporation of lime to raise subsoil pH. Potential benefits of research to develop varieties with deeper rooting systems could also be evaluated.

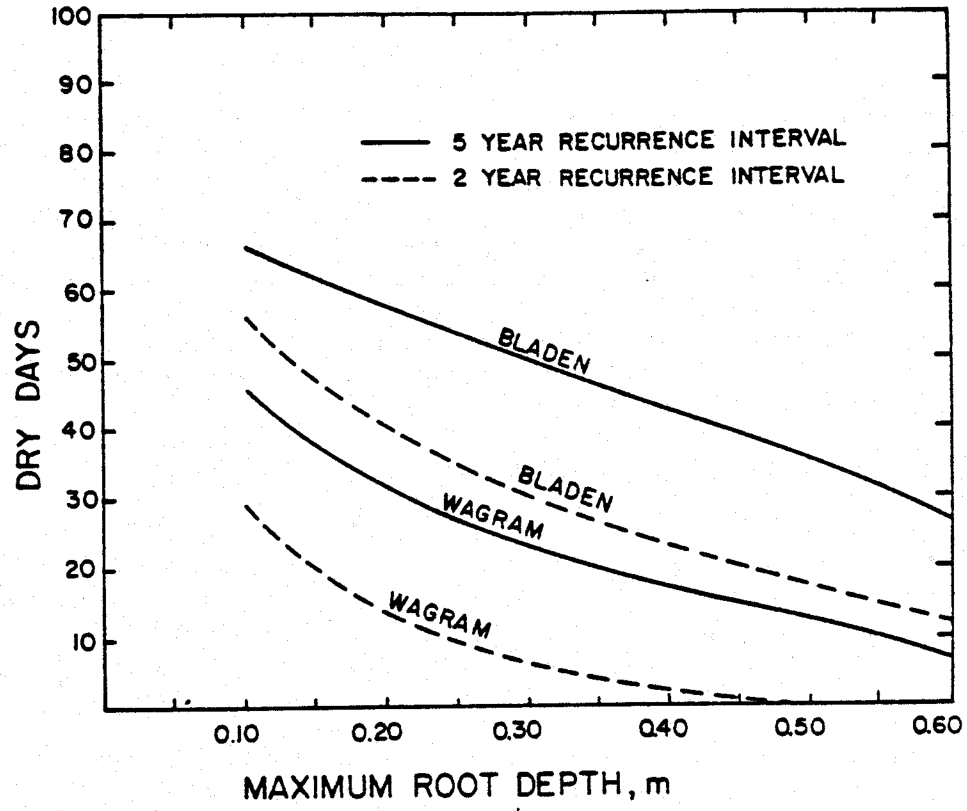

Figure 6-24. Effect of maximum root depth on number of dry days, 2 and 5 years recurrence intervals.

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CHAPTER 7

SENSITIVITY ANALYSIS

Simulation of a water management system requires input information for soil properties, climatological data, plant relationships, and system parameters, as discussed in Chapter 4. Various methods can be used to measure or approximate these inputs (Chapter 5). The accuracy of the input data will usually be proportional to the time and resources invested in their determination. However, exact values for the required inputs will rarely be available in practice because of measurement errors and field variation of soil properties and other parameters. Results of simulations both in terms of the day-to-day predictions and objective function values (Chapter 3) will obviously be affected by errors in the inputs. Furthermore, the results will probably be affected more by errors in some inputs than others. Therefore, the sensitivity of simulations to errors in the individual inputs is needed in order to establish where priorities should be placed in determining required input data. The purpose of this chapter is to examine the sensitivity of the objective functions to errors in input data for several water management systems.

Procedure

Sensitivity analyses were conducted for the following soils and water management systems:

1. Conventional surface and subsurface drainage on a Lumbee sandy loam at Wilmington, North Carolina.

2. Conventional surface and subsurface drainage on a Toledo silty clay at Columbus, Ohio.

3. Drainage and subirrigation on a Portsmouth sandy loam at Wilmington, North Carolina.

4. Waste water application to a Wagram loamy sand with surface and subsurface drainage near Wilson, North Carolina.

Simulations were conducted and the results presented elsewhere in this report for each of the above cases. Sensitivity analyses are presented in this chapter for a single water management system and operational procedure for each case. That is, only one drain spacing, drain depth, and depressional storage is considered for each soil and location. Drainage system parameters and certain additional input data that were used in sensitivity analyses are summarized in Table 7-1.

Table 7-1. Summary of certain water management system parameters used in sensitivity analyses.

Soil	Location*	Drain Spacing (m)	Drain Depth (m)	Weir Depth** (m)	Depressional Storage (mm)	Reference to Soil Property Information
Lumbee s.l.	Wilmington, N. Carolina	15	1.0	1.0	2.5	Chapter 6, Example Set 1
Toledo sl. cl.	Columbus, Ohio	12.2	0.9	0.9	2.5	Chapter 10, pages 10-37 to 10-44
Portsmouth s.l.	Wilmington, N. Carolina	15	1.0	0.50	2.5	Chapter 6, Example Set 2
Wagram l.s.	Wilson, N. Carolina	30	1.25	1.25	2.5	Chapter 6, Example Set 3

* Location refers to the place that the weather data used in the simulations were obtained. Soil property data may have been obtained from a different location.

** Weir depth is the depth of a weir in the outlet during the growing season. A weir was only used for the Portsmouth soil in the examples considered in this chapter.

Sensitivity analyses were conducted by changing a given input by a predetermined amount, and, with the other inputs held at their correct values, running a simulation for 20 or 25 years of record. Then, values of the objective functions for a 5-year recurrence interval were obtained from the simulation results and plotted as a function of input error. Analyses were made for hydraulic conductivity, water content at the lower limit (or wilting point), upward flux - water table depth relationship, drainage volume - water table depth relationship, root depth, and potential evapotranspiration (PET). For each input parameter, simulations were conducted for the correct value(s) ±10 percent, ±25 percent, ±50 percent, -95 percent, +100 percent, and +200 percent. For example, the hydraulic conductivity for Portsmouth s.l. is (Chapter 6), K = 3.0 cm/hr. Simulations were conducted for K = 3.0 cm/h, 3.3 cm/hr., 2.7 cm/hr, 3.75 cm/hr., 2.25 cm/hr, etc. For layered soils, the conductivity (or other soil property) of each layer was increased or decreased by the given percentage error. Functional relationships, such as drainage volume versus water table depth, were likewise increased or decreased by the given percentage for all levels of the independent variable (water table depth, in this case).

Results

Working Days

Sensitivity of the number of working days predicted by the model to errors in the input data are plotted in Figure 7-1 for Lumbee sandy loam and in Figure 7-2 for Portsmouth sandy loam. Corn production, near Wilmington, North Carolina, was considered in both cases with the seedbed preparation period being from March 15 to April 15, as discussed in the examples in Chapter 6. It may be concluded from Figures 7-1 and 7-2 that errors in hydraulic conductivity (K) have the greatest effect on predicted working days.

An error of +50 percent, in K for the Lumbee soil, would have resulted in a prediction of 17 working days on a 5 YRI, rather than the 11 days that should have been obtained. For the Lumbee soil (Figure 7-1), the sensitivity of predicted working days to errors in drainage (air) volume, PET, and depth to the impermeable layer was of the same order as hydraulic conductivity. Practiced results were not noticeably affected by errors in wilting point or the upward flux relationship. Results for Portsmouth s.l. were only sensitive to negative errors in K and, to a lesser degree, depth to the impermeable layer. The 15 m drain spacing used on the Portsmouth s.l. was chosen to meet both drainage and subirrigation objectives. Actually, a 32 m spacing would have been sufficient to meet the trafficability requirement of 10 working days (Figure 6-15). Because the system is operated in the conventional drainage mode during and prior to seedbed preparation, the maximum number of working days (19), as limited by soil water conditions, was predicted (c.f. Figure 6-15). The other 11 days (30 - 19 = 11) cannot be working days (on a 5 YRI), because of rainfall on those days. Thus, an error causing the K to be too high had no effect on predicted working days for this case. Rapid subsurface drainage provided by the close drain spacing also nullified potential effects of errors in PET, drainage volume, and depth to the impermeable layer.

SEW-30

Effects of errors in soil properties and other inputs on SEW-30 are shown in Figures 7-3, 7-4, and 7-5 for the Lumbee, Toledo, and Portsmouth soils, respectively. In all three cases, SEW-30 was more sensitive to errors in K and PET than to any of the other input parameters. Errors in upward flux and air volume - water table depth relationship had relatively small effects on predicted SEW-30. However, the effects were somewhat greater for subirrigation (Figure 7-5) than for conventional drainage. This is a fortuitous result because the upward flux relationship is usually the most difficult to characterize, and therefore, subject to the greatest error of all the model inputs. The effect of root depth, another input parameter that is difficult to define, also has a relatively small effect on SEW-30 (Figures 7-4 and 7-5).

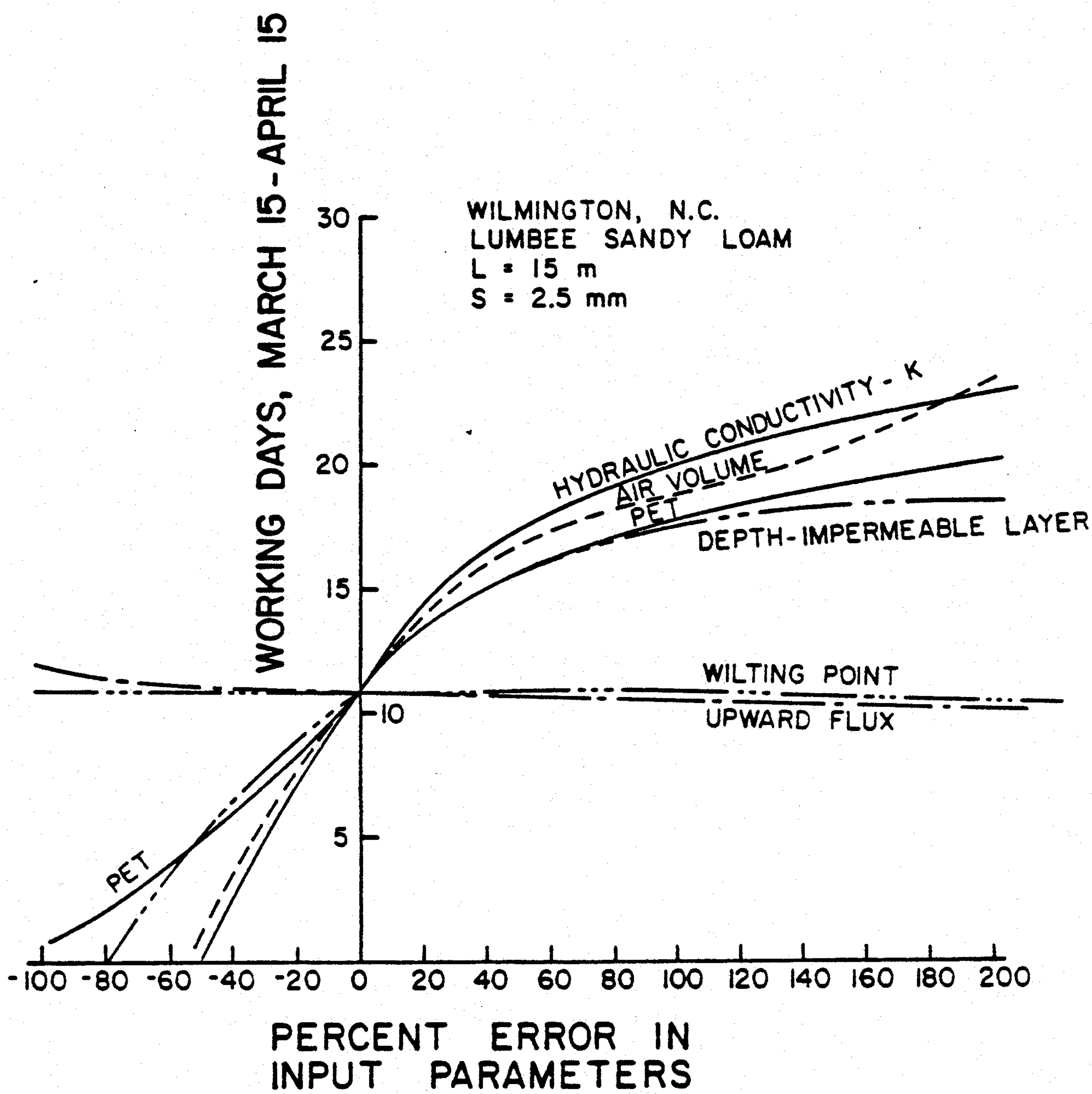

Figure 7-1. Effect of errors in input data on number of working days predicted for the period March 15 to April 15, on a 5-year recurrence interval (5 YRI). Simulations were conducted for a Lumbee sandy loam at Wilmington, North Carolina.

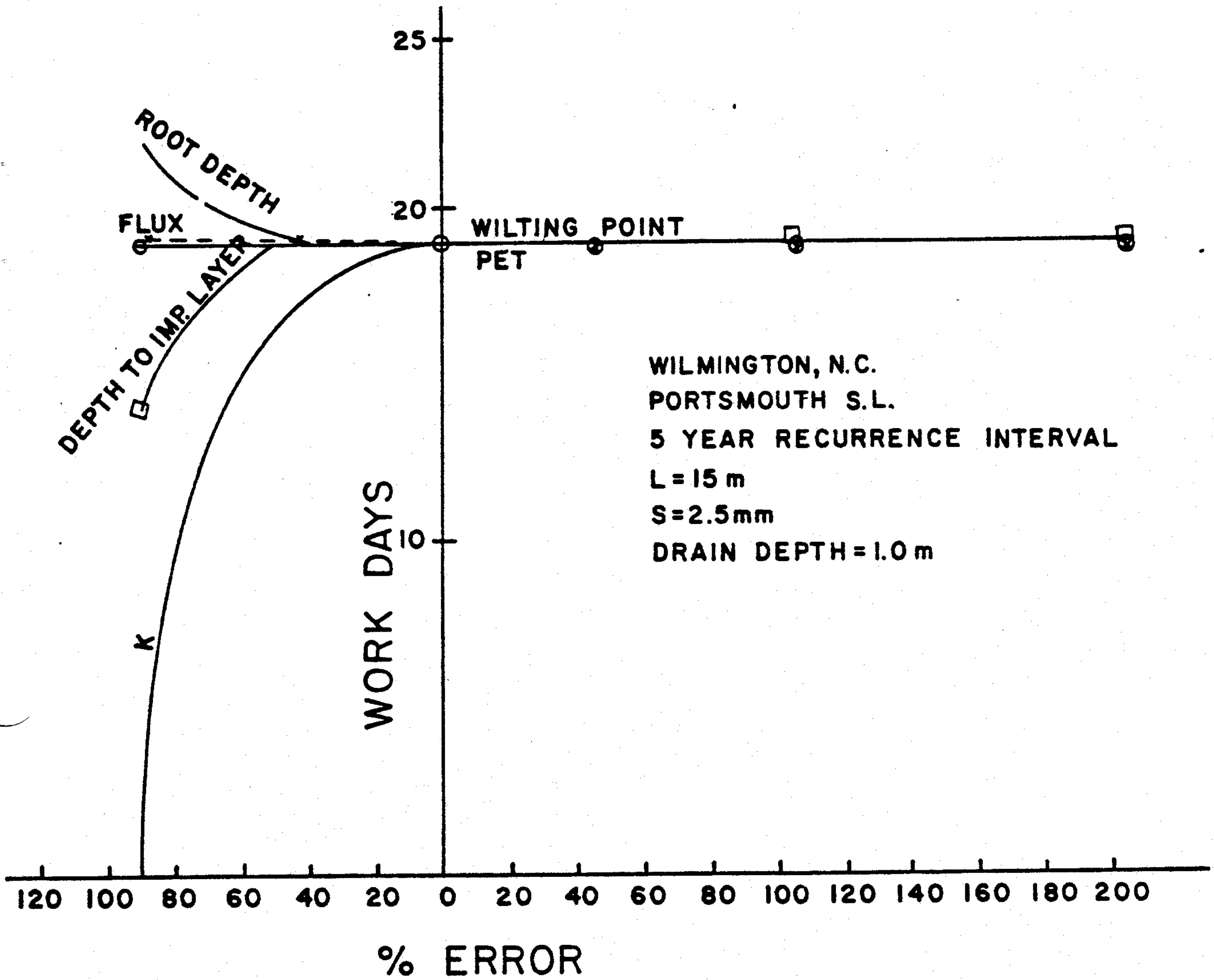

Figure 7-2. Effect of errors in input data on predicted working days for period March 15 to April 15, for Portsmouth sandy loam, at Wilmington, North Carolina.

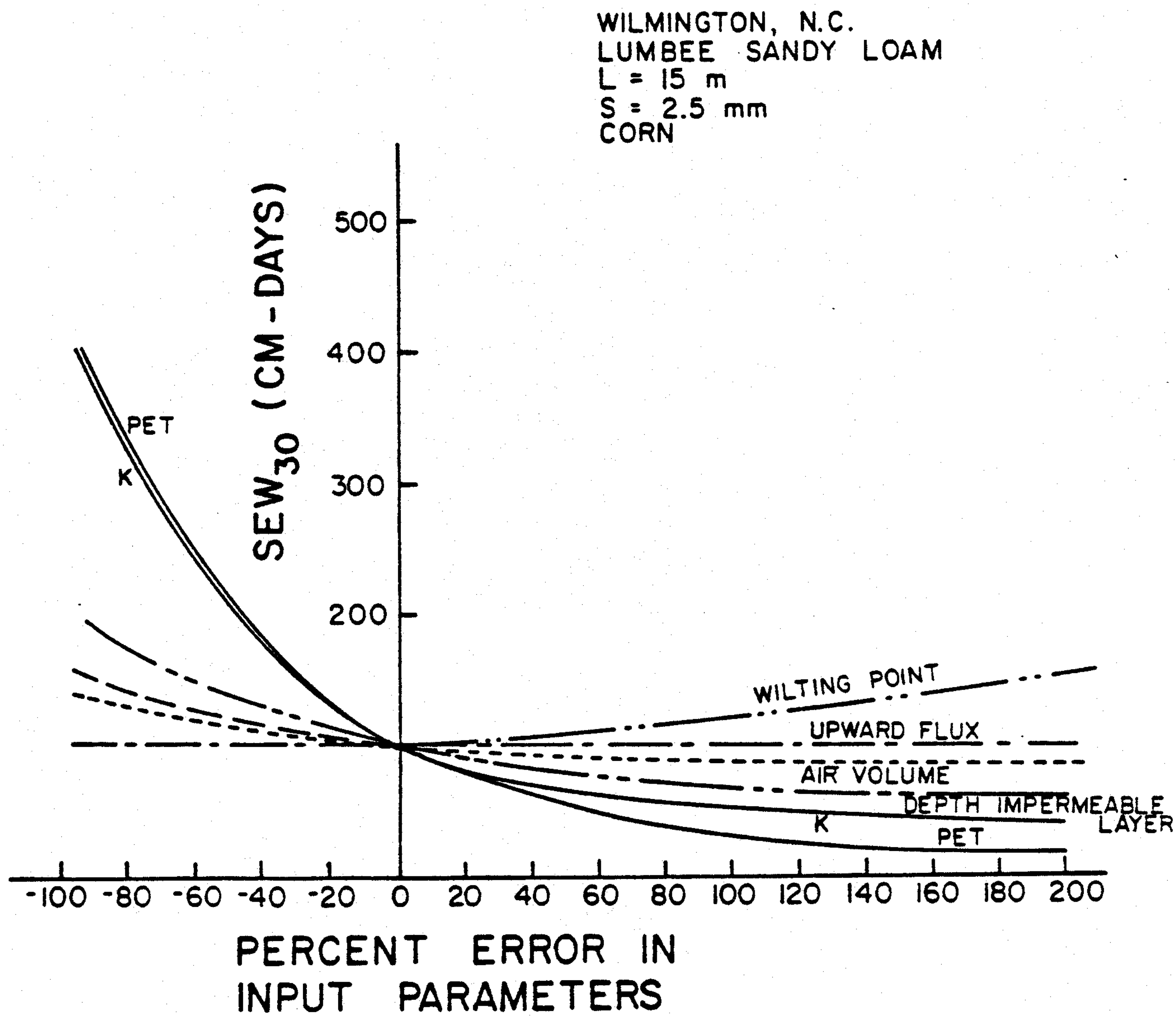

Figure 7-3. Sensitivity of predicted growing season SEW-30 (5 YRI values) to errors in input data for a Lumbee sandy loam, near Wilmington, North Carolina. The water management system was designed for conventional drainage.

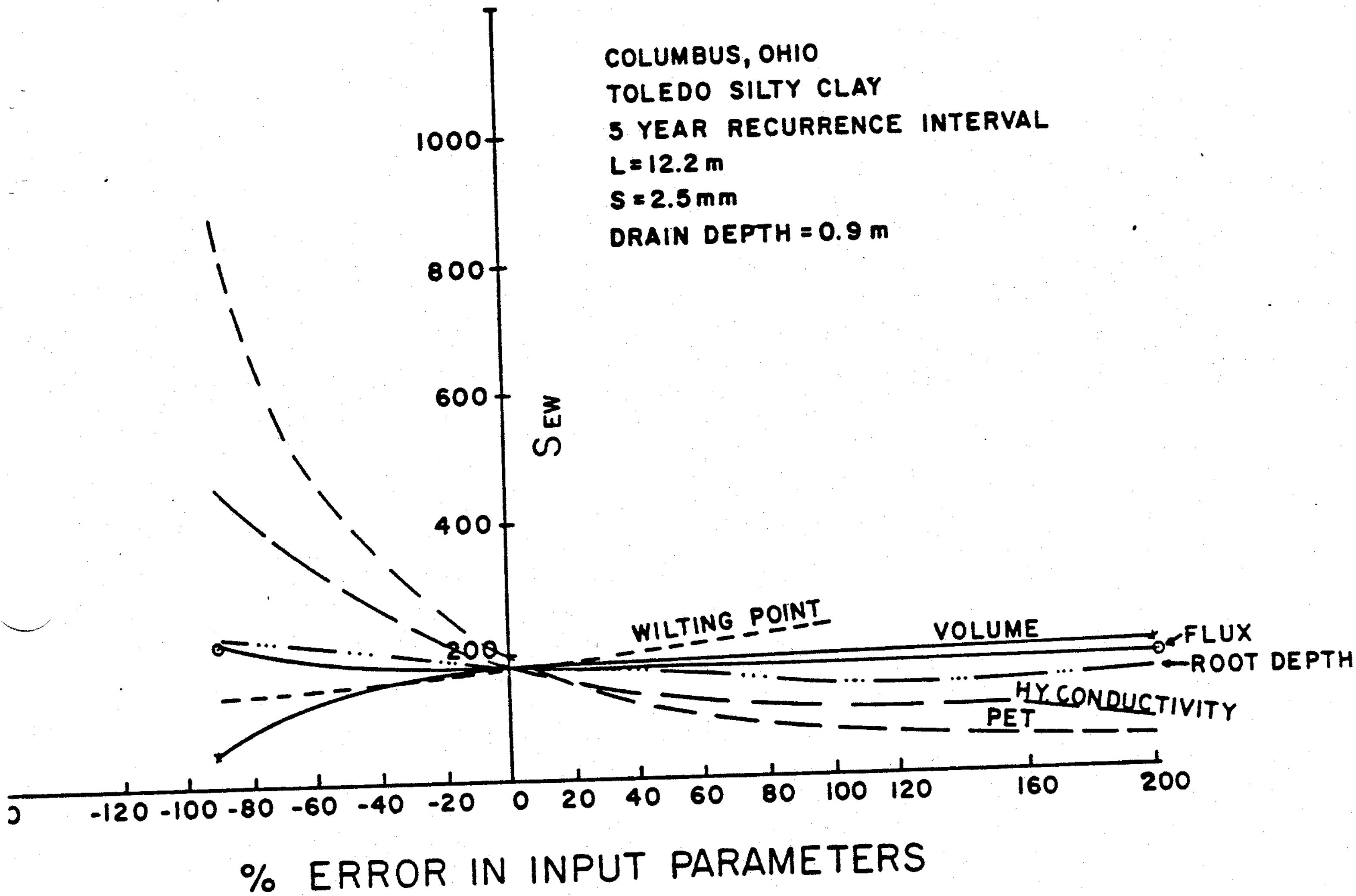

Figure 7-4. Sensitivity of predicted SEW-30 (5 YRI values) to errors in input data for Toledo sl. c., near Columbus, Ohio.

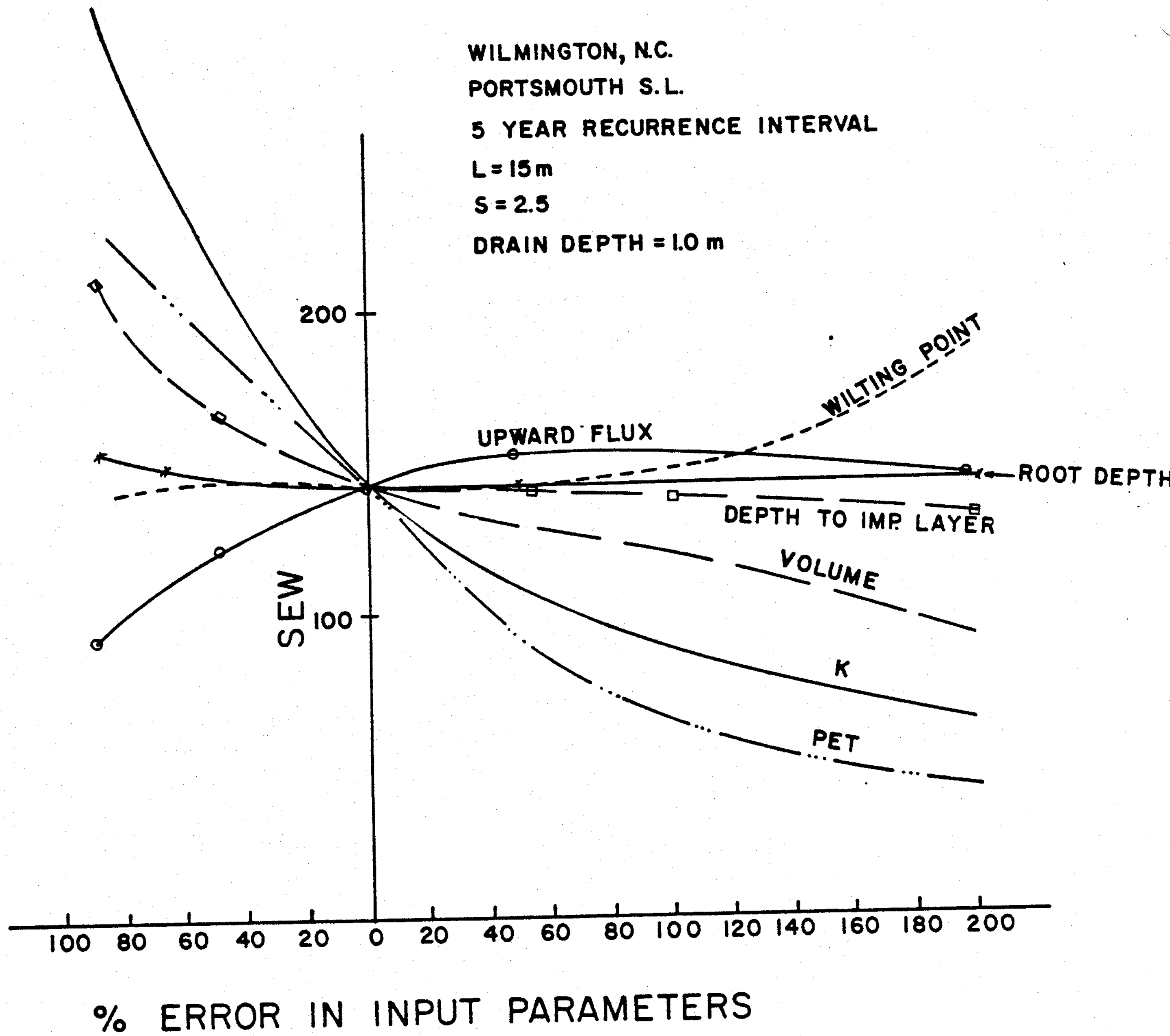

Figure 7-5. Sensitivity of predicted SEW-30 (5 YRI basis) to errors in input data for Portsmouth sandy loam, near Wilmington, North Carolina. Subirrigation was used during the growing season for this case.

Based on the results plotted for working days and SEW-30, effort in defining the model inputs should be concentrated on accurately determining field effective K values and PET. This is especially true when the model is used to analyze conventional surface-subsurface drainage systems. This is not to say, however, that the user can be sloppy in determining the other inputs. The sensitivity analyses presented represent only a limited number of soils, locations, and water management systems. In other situations, the results may be more sensitive to other parameters so all inputs should be specified as accurately as possible.

Dry Days

The sensitivity of the predicted number of dry days to errors in various input parameters is demonstrated in Figure 7-6 for the Lumbee soil near Wilmington, North Carolina, and in Figure 7-7 for the Toledo soil at Columbus, Ohio. In both of these cases, the drainage systems were used for conventional surface and subsurface drainage. The same relationships are plotted in Figure 7-8 for subirrigation on the Portsmouth soil considered in Example Set 2, Chapter 6. The number of dry days are less dependent on K than either working days or SEW-30 for all cases considered. The sensitivity of predicted dry days to errors in root depth and PET was greater than the other parameters tested. For example, there were 36 dry days predicted (5 YRI basis) for the Lumbee soil. If the methods for predicting PET had been 40 percent too high (error of +40 percent), 60 dry days would have been predicted. An error of the same magnitude in effective root depth would have resulted in a prediction of 21 dry days. The effects of errors in root depth were not as great for the Toledo soil or for Portsmouth sandy loam, under subirrigation, as for the Lumbee. Still, the dry days were more sensitive to root depth than any other parameter, except PET.

Dry days were also quite sensitive to errors in the water content at the lower limit (wilting point), except for the case of subirrigation where sufficient water was supplied from the water table so the wilting point selection was not critical. Errors in the upward flux relationship had a significant effect on dry days for Lumbee and Portsmouth soils, but not on the Toledo soil (Figure 7-7). In the latter case, the drainable porosity in the subsoil was small and the water table was often greater than 1 m during dry periods. Since upward flux is small for deep water tables (Figure 10-31), increasing it by as much as 200 percent had only a small effect on the number of dry days. Errors in drainage volume and depth to the impermeable layer had only a small effect on number of dry days predicted.

Waste Water Application

Effects of errors in the model inputs on the predicted annual amount of waste water that can be applied are shown in Figure 7-9 for the Wagram soil considered in Example Set 3, of Chapter 6. The drain spacing is 30 m and irrigation is planned once per week at a rate of 2.54 cm per application. Therefore, the maximum amount that could be applied is 2.54 cm per application. Therefore, the maximum amount that could be applied is 2.54 cm/wk x 52 weeks = 132 cm. The 30 m drain spacing permitted an application of 122 cm on a 5 YRI basis (Figure 6-19), as shown for zero error in Figure 7-9.

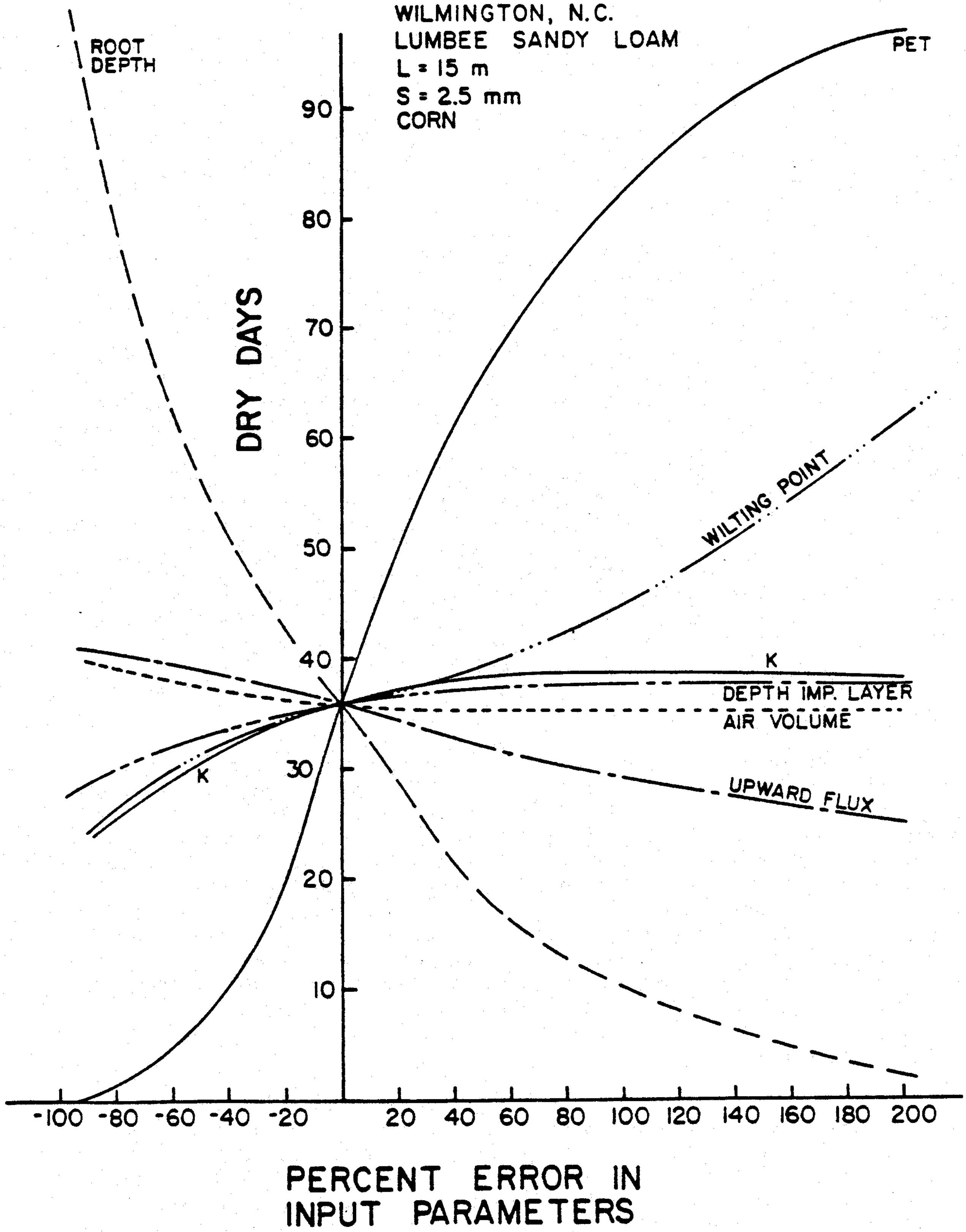

Figure 7-6. Effects of errors in the input data on predicted number of dry days (5 YRI basis) for a Lumbee sandy loam, near Wilmington, North Carolina.

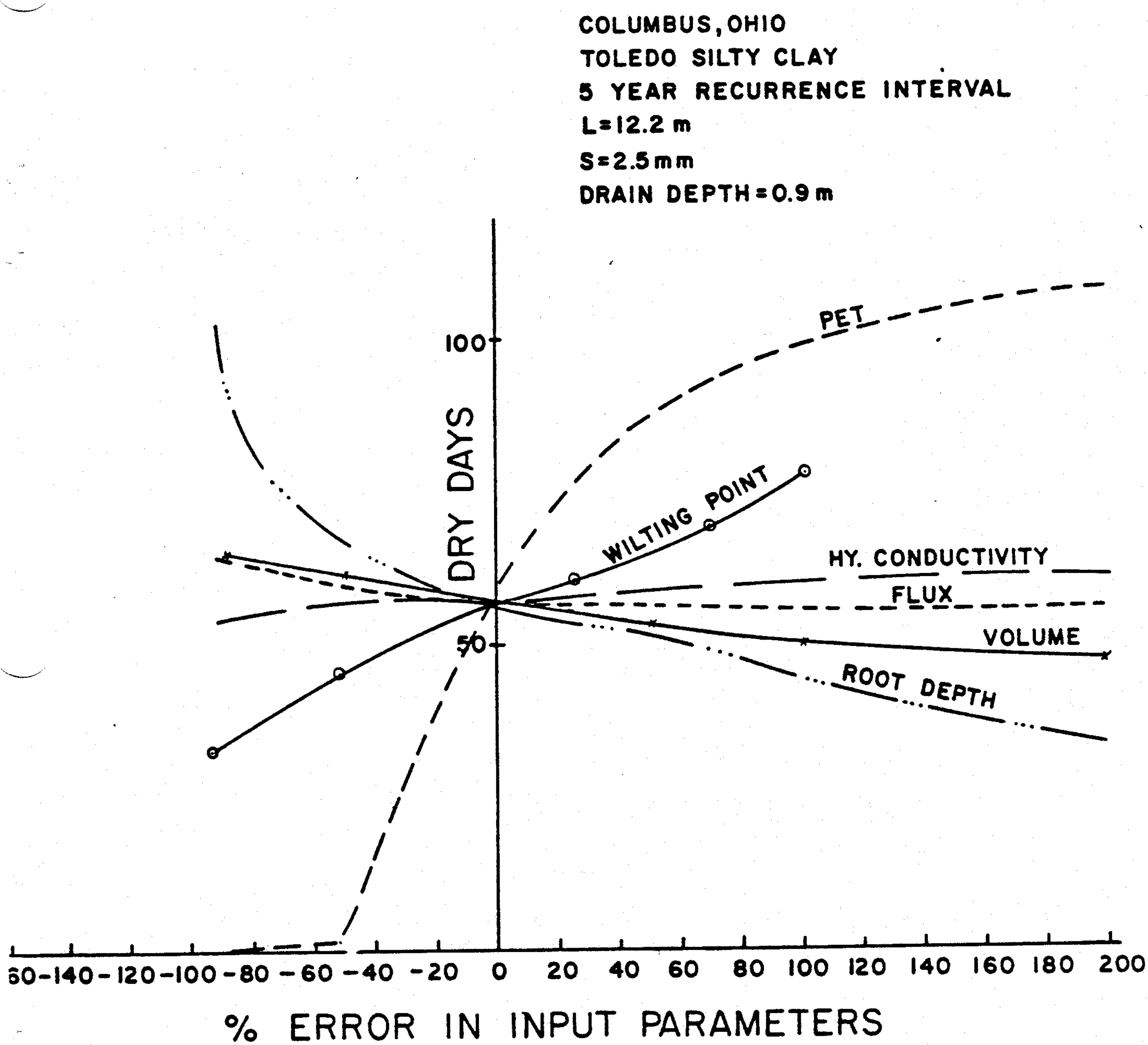

Figure 7-7. Effects of errors in the input data on predicted number of dry days (5 YRI basis) for a Toledo sl. c. located near Columbus, Ohio.

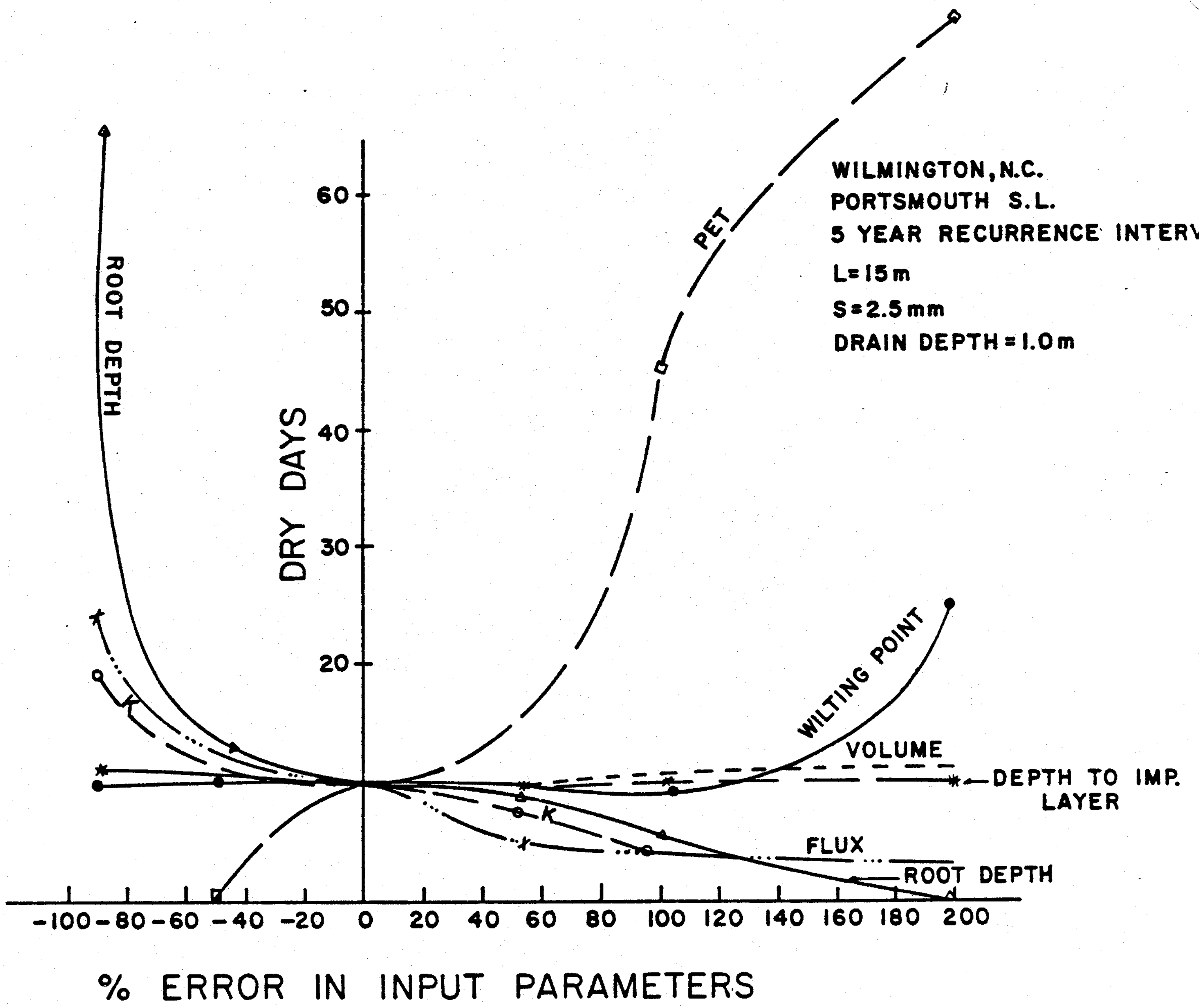

Figure 7-8. Effect of errors in the input data on predicted number of dry days (5 YRI basis) for subirrigation on a Portsmouth sandy loam, near Wilmington, North Carolina.

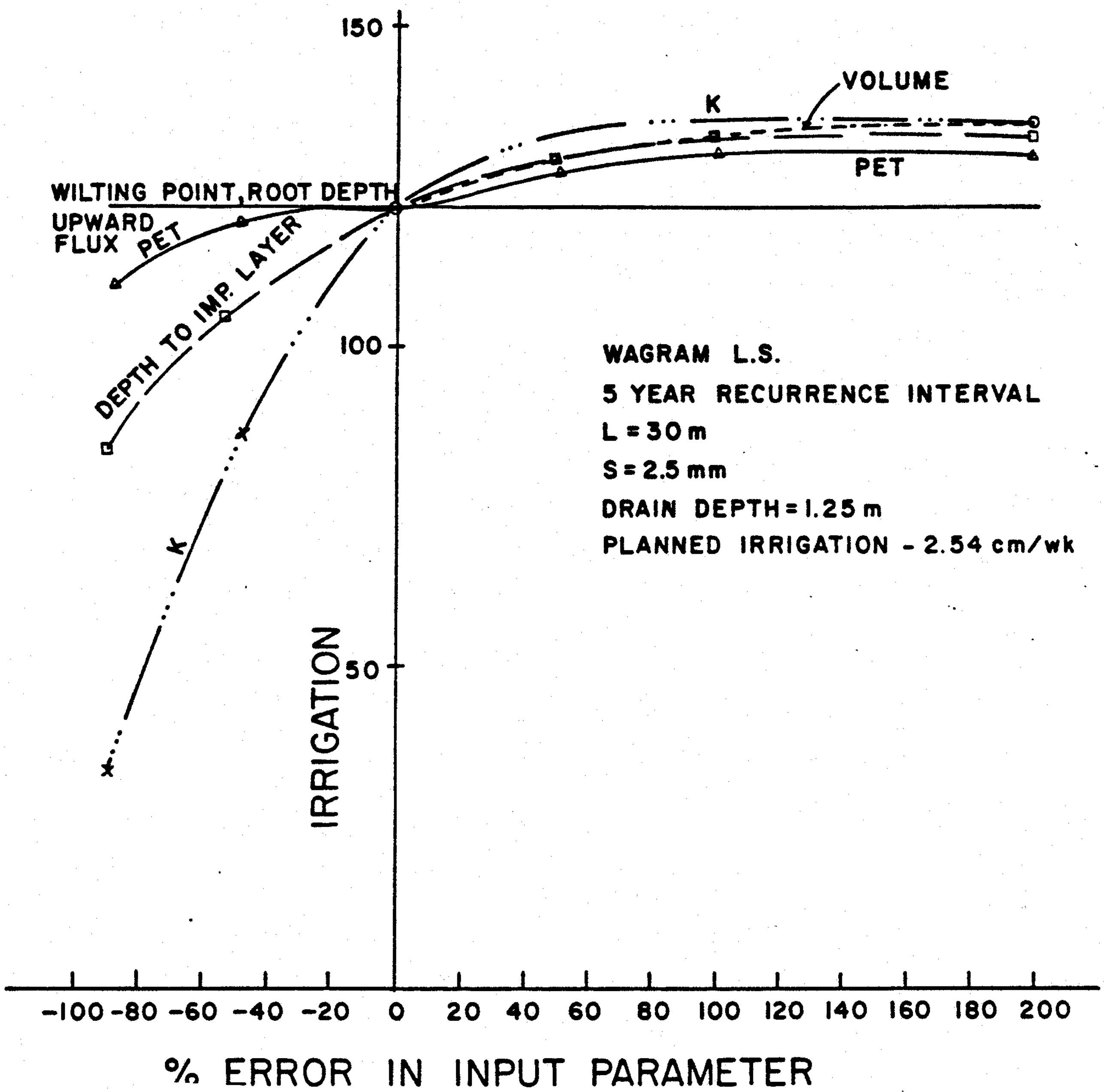

Figure 7-9. Effect of errors in model inputs on predicted total annual waste water applied (5 YRI basis) for a Wagram l.s. soil near Wilson, North Carolina. Application of waste water is scheduled for once per week at 2.54 cm per application.

This waste water treatment system involves application of as much as 2.5 cm per week of water in addition to natural rainfall. Therefore, the soil is relatively wet all year long and the effects of errors in wilting point, root depth, and upward flux relationships on annual waste water application are negligible. Errors in K had the largest effect on the predicted total allowable application. Depth to impermeable layer and PET were the next most sensitive parameters. An error of -50 percent in K (3 cm/hr, rather than 6 cm/hr) would have resulted in a predicted annual application of 86 cm. The same error in depth to the impermeable layer and PET would have given annual amounts of 105 and 128 cm respectively. Thus, if the model is to be used to predict annual waste water application, effort should be concentrated toward determining those input data controlling the rate that the water is removed from the profile: K, depth to the impermeable layer, and PET.

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CHAPTER 8

SUBIRRIGATION

The purpose of this chapter is to examine factors affecting water movement in a subirrigation system. Methods are presented making certain preliminary design calculations to supplement results obtained from DRAINMOD and improve the efficiency of its application. Examples to demonstrate the use of these methods are presented and discussed.

There are basically two operational procedures for subirrigation systems. The most common procedure is to maintain a constant water level elevation in the tile outlet (Figure 8-1). Water is periodically pumped from a well, stream, or other water supply to replenish water which moves from the drains into the soil to supply ET demands and seepage losses from the system. During dry periods, this procedure results in a water table profile which is more or less in steady state. The drain spacing necessary to satisfy crop ET demands depends on the hydraulic conductivity of the soil, peak ET, or consumptive use, height of the water level in the drain, etc. Methods for determining the drain spacing for steady state operation are discussed in the following section.

Another procedure for operating subirrigation systems is to place a weir in the outlet that extends to near the soil surface and, by pumping for an extended period, raise the water table into the root zone of the profile. Then, pumping is topped and the water table is allowed to fall as water is removed by ET and seepage. Pumping is initiated again when the water table reaches a predetermined depth and the process is repeated. Water table profiles for this unsteady state subirrigation process are process are shown schematically in Figure 8-2. Determination of design parameters, such as drain spacing in this situation depends on the time required to raise the water table to the desired elevation. Methods for predicting the time required to raise the water table in terms of drain spacing, hydraulic conductivity, and other factors are given in a subsequent section of this chapter.

Steady State Operation

The position and shape of the water table for steady-state subirrigation can be approximated by making the Dupuit-Forchheimer (D-F) assumptions and using the approach of Fox, et al, (1956). By neglecting water movement in the unsaturated zone, the flow rate in the horizontal direction per unit length of drain may be expressed as:

$$Q_x = - K h \frac{dh}{dx} \qquad (8\text{-}1)$$

Where, referring to Figure 8-1, Q_x is the horizontal flow rate (cm^3/hr cm) and h is the height of the water table above the impermeable layer which depends on the horizontal position, x, (i.e., h = h(x)). At any position, x, Q_x must be equal to the rate that water leaves the profile by ET in the section x to x = L/2. That is,

$$Q_x = e(L/2 - x) \qquad (8\text{-}2)$$

Then,

$$-K h \frac{dh}{dx} = e\ (L/2 - x) \qquad (8\text{-}3)$$

Separating variables and integrating subject to the boundary condition of $h = h_o$ at x = 0 yields an expression for the water table position in terms of x:

$$h^2 = \frac{e}{K} x^2 - \frac{e\,L}{K} x + h_o^2 \qquad (8\text{-}4)$$

Thus, the water table assumes an elliptical shape under steady ET conditions. The derivation of Equation 8-4 assumes that water can move vertically from the water table by unsaturated flow to supply the ET demand. The maximum upward rate of water movement is dependent on water table depth as well as soil properties as discussed in Chapter 2. Therefore, the drains should be placed close enough together to maintain some minimum water table elevation at the midpoint (x = L/2) during a period of maximum ET demand. This spacing can be estimated from Equation 8-4 by specifying a water table elevation of h_1 at x - L/2 and solving for L:

$$L = [4\ K(h_o^2 - h_1^2)/e]^{1/2} \qquad (8\text{-}5)$$

The effective horizontal hydraulic conductivity should be used for K in Equation 8-5, while the maximum permissible water table elevation at the drains, h_o, will depend on the root zone depth, crop sensitivity and site parameters.

As discussed above, Equations 8-2 to 8-5 are subject to the D-F assumptions and do not consider convergence losses near the drain. These losses can be accounted for by substituting an effective depth to the impermeable layer, d_e, for d in Figure 8-1, as discussed in Chapter 2 (pages 2-13 to 2-15) for drainage. The h values are adjusted accordingly. The value of d_e can be computed from Equations 2-13 and 2-14. Because d_e depends on the drain spacing, L, an iteration process is required to compute L from Equation 8-5. First, a trial value of L is calculated from Equation 8-5 using h values based on the actual value of d. Then, d_e is computed from Equation 2-13 or Equation 2-15 and the h_o and h_1 are adjusted. Then, a new value of L is determined from Equation 8-5. A new value of d_e is computed and the process is repeated until L remains constant. Usually, one iteration is sufficient for convergence.

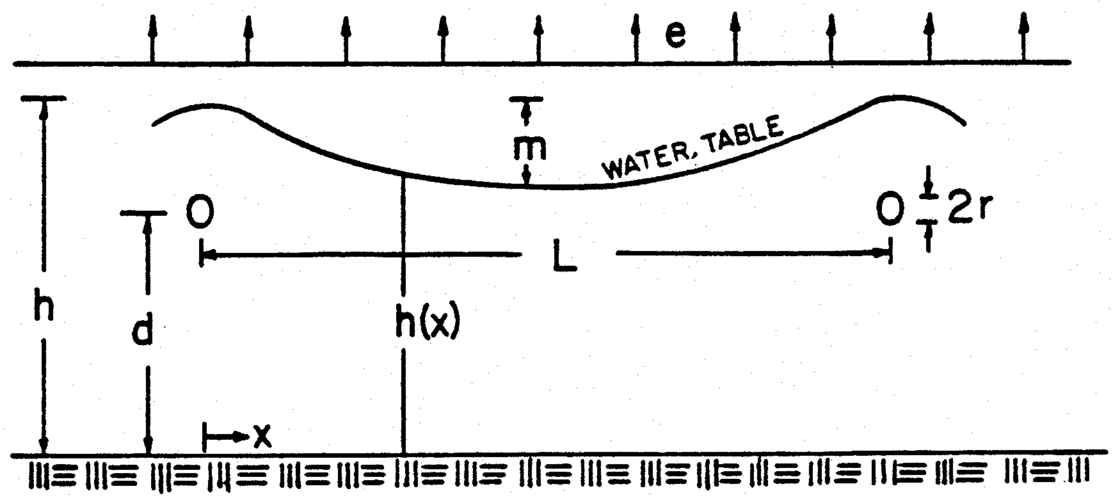

Figure 8-1. Water table profile for subirrigation under steady state conditions with an ET rate of e.

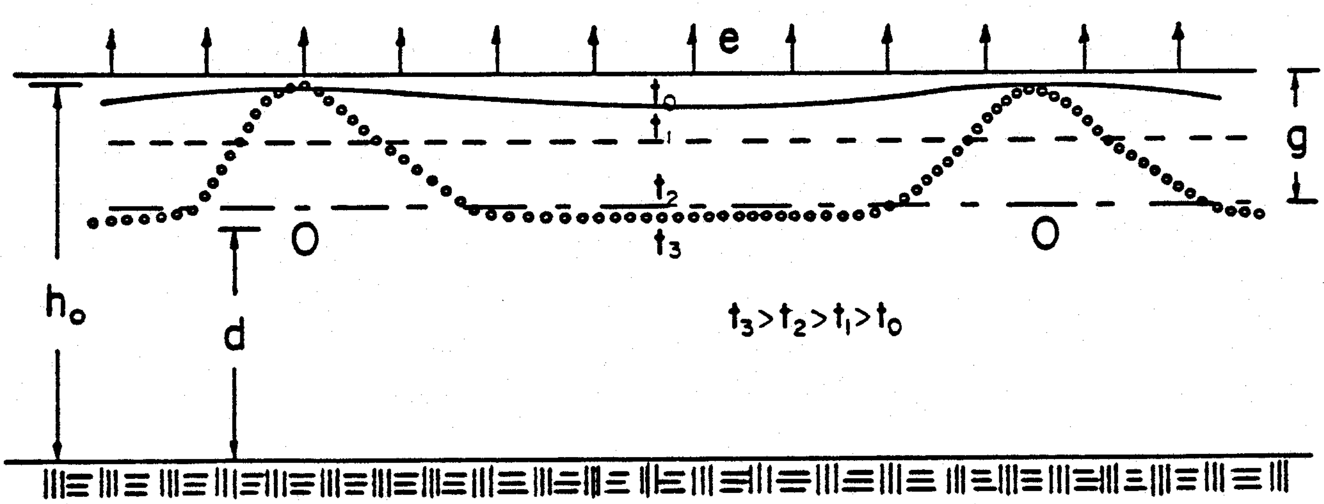

Figure 8-2. Water table profiles for unsteady state operation of a subirrigation system. The water table is raised to near the surface at time, t_o. Then, pumping is stopped and the water table recedes due to ET, as shown for times t_1 and t_2. When the water table reaches some depth, g, pumping is initiated to raise the water table back to its initial position.

Example 1 - Steady State Subirrigation

A Portsmouth sandy loam has a hydraulic conductivity of 3 cm/hr and a profile depth to a restrictive layer of 2.0 m. Drains are placed at a 1 m depth as shown in Figure 8-3 with the main in the direction of the surface slope of 0.5 percent. Corn is to be grown with an effective rooting depth of 30 cm (1 ft.). Roots cannot penetrate much below this depth because of acid subsoil. The drains to be used have a diameter of 10 cm (4 inches) with a completely open effective radius of 0.51 cm. Determine the drain spacing necessary for subirrigation during dry periods in the summer when the peak ET demand is 0.5 cm/day.

Because the root zone is 30 cm deep, the water level in the laterals should not be held closer than 30 cm to the surface. A given depth in the lateral can be maintained in a sloping situation by placing a water level control structure such as those shown in Figure 8-4 immediately below each lateral. One design of such structures is described in detail in an SCS technical note (TECH NOTE ENG-FL-11) from the SCS Florida State Office (dated April 1977). Depending on the slope, it may be possible to service several laterals with a single control structure (Figure 8-3). However, in this case, we will assume that the water level is controlled exactly 30 cm from the surface in each lateral so that $h_o = 100 - 30 + d_e$. Assuming $d_e = d = 100$ cm for the first trial, gives $h_o = 170$ cm. To determine h_1, we use the curve in Figure 5-6 for Portsmouth. It gives a water table depth below the root zone of 46 cm for a steady upward flux of 0.5 cm/day. The root zone is 30 cm deep so $h_1 = d + 100 - (30 + 46) = 100 + 24 = 124$ cm. Applying Equation 8-5 gives a first estimate for the drain spacing of:

$$L_1 = [4 \times 3 \text{ cm/hr } (170^2 \text{ cm}^2 - 124 \text{ cm}^2)/(0.5 \text{ cm/day} \cdot \frac{1 \text{ day}}{24 \text{ hr}})]^{1/2}$$

$$L_1 = 27.9 \text{ m (91 ft)}$$

The equivalent depth to the impermeable layer is then calculated using Equation 2-18 with $r = r_e = 0.51$ cm as:

$$d_e = \frac{100}{1 + \frac{100}{2,790} \{\frac{8}{\pi} \ln \frac{100}{0.51} - 3.4\}} = 74 \text{ cm}$$

With this value of d_e, $h_o = 74 + 70 = 144$ and $h_1 = 74 + 24 = 98$. Then,

$$L_2 = [4 \times 3 (144^2 - 98^2)/(0.5/24)] = 25.3 \text{ m} \quad \text{(83 ft)}$$

Recalculating d_e from Equation 2-18 gives $d_e = 72$ cm which is close enough to the 74 cm assumed in the above calculation of L. Therefore, a drain spacing of $L = L_2 = 25.3$ m (83 ft) would be sufficient to supply an ET rate of 0.5 cm/day, if the water level in the drain is held 30 cm from the surface.

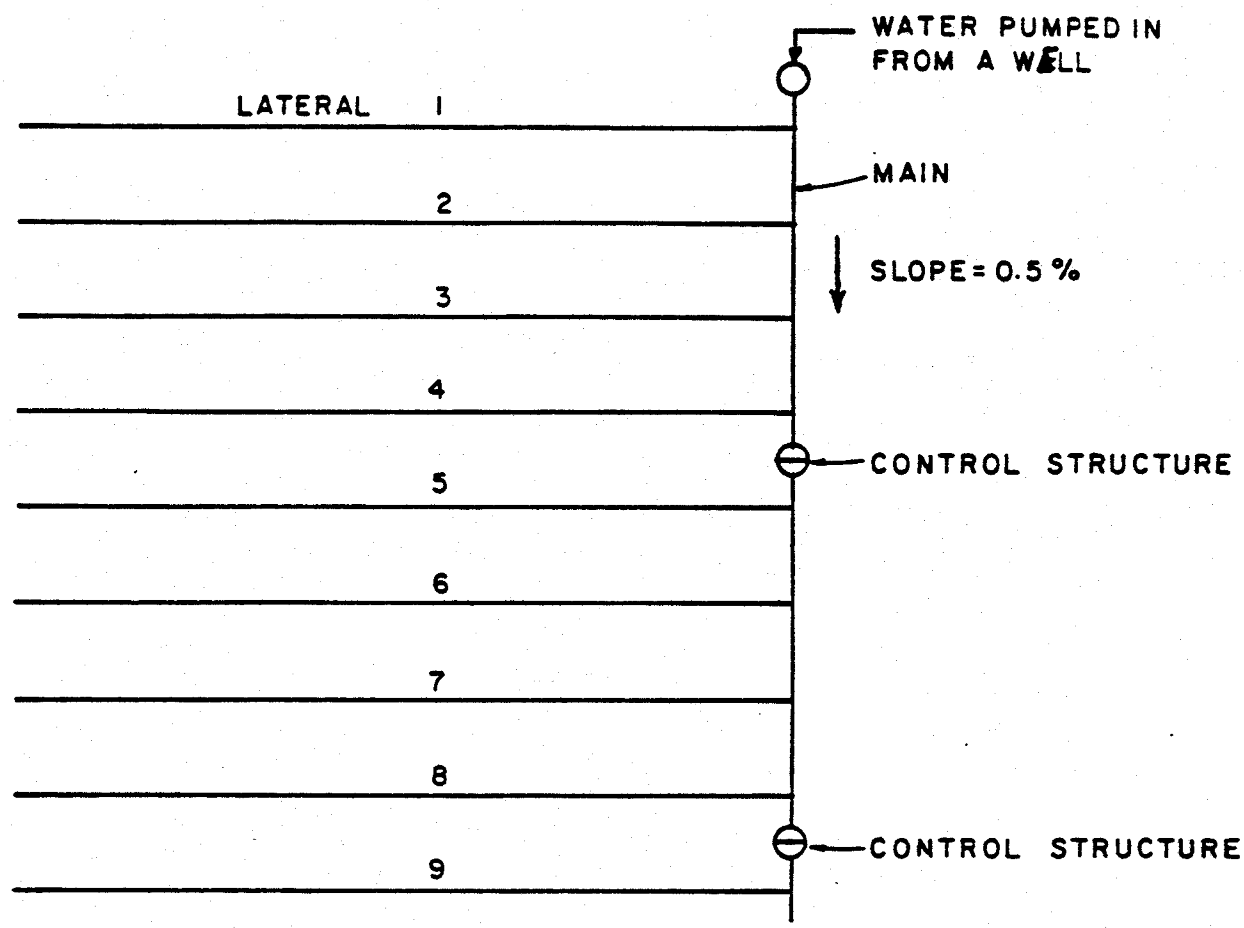

Figure 8-3. Layout of laterals and main with water level control structures.

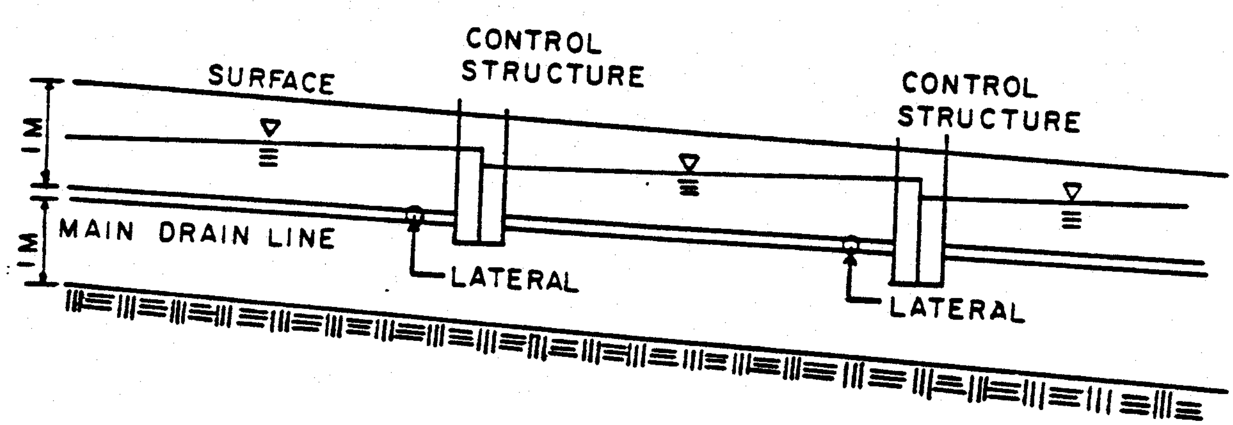

Figure 8-4. Profile view of main drain line with water within a given distance of the surface at the drain lines.

What if the minimum tolerable water table depth is 50 cm, rather than 30, as assumed above? Then, starting with an assumed d_e of 70 cm, we would have h_o = 70 + (100 - 50) = 120 cm and h_1 = 70 + (100 - 30 - 46) = 94 cm. From Equation 8-5, L_1 = 17.9 m. Recalculating d_e gives d_e = 64 cm so h_o = 64 + 50 = 114 and h_1 = 64 + 24 = 88. Then, L_2 = 17.4 m and the new d_e is d_e = 63 cm, which is close to the assumed value of 64 cm. Therefore, if the water level in the drain line is maintained at a depth of 50 cm, a drain spacing of L = 17.4 (57 ft) would be needed, as opposed to the 25 m spacing for a 30 cm depth.

Water Table Rise During Subirrigation

The time required to raise the water table to a height sufficient to supply crop ET demands may be the limiting factor in the design of a subirrigation system. The need to consider this aspect is obvious for operations where the water table is raised to the root zone and then allowed to fall as water is removed from the profile by ET. These systems function in an unsteady state mode and it is extremely important to be able to raise the water table rapidly enough to maintain a supply of water to the crop. The time required to raise the water table is also important for steady state operation. Ignoring this aspect of the operation could result in a prohibitive length of time to raise the water table at the beginning of the growing season or when irrigation is initiated.

Methods for predicting water table rise for both initially horizontal and draining profiles were presented in a previous paper (Skaggs, 1973). The methods are described here and new graphical solutions are presented for the convenience of the user.

Equation 8-1 for horizontal flow rate may be combined with the principle of conservation of mass to obtain the following governing equation for unsteady conditions (van Schilfgaarde, 1974).

$$f \frac{\partial h}{\partial t} = K \frac{\partial}{\partial x} [h \frac{\partial h}{\partial x}] + e \qquad (8\text{-}6)$$

Where, referring to Figures 8-1 and 8-2, h = h(x,t) is the distance of the water table above the impermeable layer, t is time, f is effective or fillable porosity, and e is the rate water is added to the soil by rainfall and is negative for losses by ET or deep seepage. If the water table is initially flat at some distance, h_i above the impermeable layer, the boundary and initial conditions may be written as:

$$h = h_o \,, \quad x = 0 \,, \quad t > 0 \qquad (8\text{-}7a)$$

$$h = h_o \,, \quad x = L \,, \quad t > 0 \qquad (8\text{-}7b)$$

$$h = h_i \,, \quad 0 \leq x \leq L, \quad t = 0 \qquad (8\text{-}7c)$$

Equation 8-6 can be expressed in nondimensional form as:

$$\frac{\partial H}{\partial \tau} = \frac{\partial}{\partial \xi} (H \frac{\partial H}{\partial \xi}) + \mu \qquad (8\text{-}8)$$

Where $H = h/h_o$, $\xi = x/L$, $\mu = eL^2/Kh_o^2$, and $\tau = \frac{K h_o}{f L^2} t$. Then, the boundary conditions may be written,

$$H = 1,\ \xi = 0,\ \tau > 0 \quad (8\text{-}9a)$$

$$H = 1,\ \xi = 1,\ \tau > 0 \quad (8\text{-}9b)$$

$$H = D = h_i/h_o,\ 0 \leq \xi \leq,\ \tau = 0 \quad (8\text{-}9c)$$

The D-F assumptions are not valid for regions near the drain tube, as discussed earlier, so d_e should be substituted for d in Figures 8-1 and 8-2. The values of h_o and h_i should be adjusted accordingly to compensate for convergence losses near the drain.

Solutions

Numerical solutions to Equation 8-8 were obtained by writing the equation in finite difference form and solving on the digital computer. The numerical methods are described elsewhere (Skaggs, 1975). Solutions for the H vs. τ are given for a point midway between the drain ($\xi = x/L = 0.5$) in Figures 8-5 through 8-8 for μ values of 0, -1, -2, and -3, respectively. The solutions in each figure are plotted for a range of $D = h_1/h_o$ values from D = 0.0 to D - 0.95. Solutions for D and μ values not given can be obtained by interpolation.

The final or steady state values of H are constant for a given μ value, as shown in Figures 8-5 through 8-8. The steady state value of H can be obtained by solving Equation 8-8 with $\partial H/\partial \tau = 0$. Then,

$$\frac{\partial}{\partial \xi}\left(H \frac{\partial H}{\partial \xi}\right) + \mu = 0 \quad (8\text{-}10)$$

Separating variables and integrating subject to the boundary conditions:

$$\partial H/\partial \xi = 0 \text{ at } \xi = 1/2 \quad (8\text{-}11a)$$

and

$$H = 1 \text{ at } \xi = 0 \quad (8\text{-}11b)$$

gives

$$H^2 = -\mu\xi^2 + \mu\xi + 1 \quad (8\text{-}12)$$

At the midpoint, $\xi = 1/2$ and $H_m^2 = \mu/4 + 1$ (8-13)

Then, for example, if $\mu = -1$, the midplane H value should approach H_m = 0.87 after some period of time. This is consistent with results given in Figure 8-6, which shows that the steady state position of H = 0.87 is attained at $\tau = 0.8$ for all D values. Note that for $\mu = -4$, $H_m = 0$

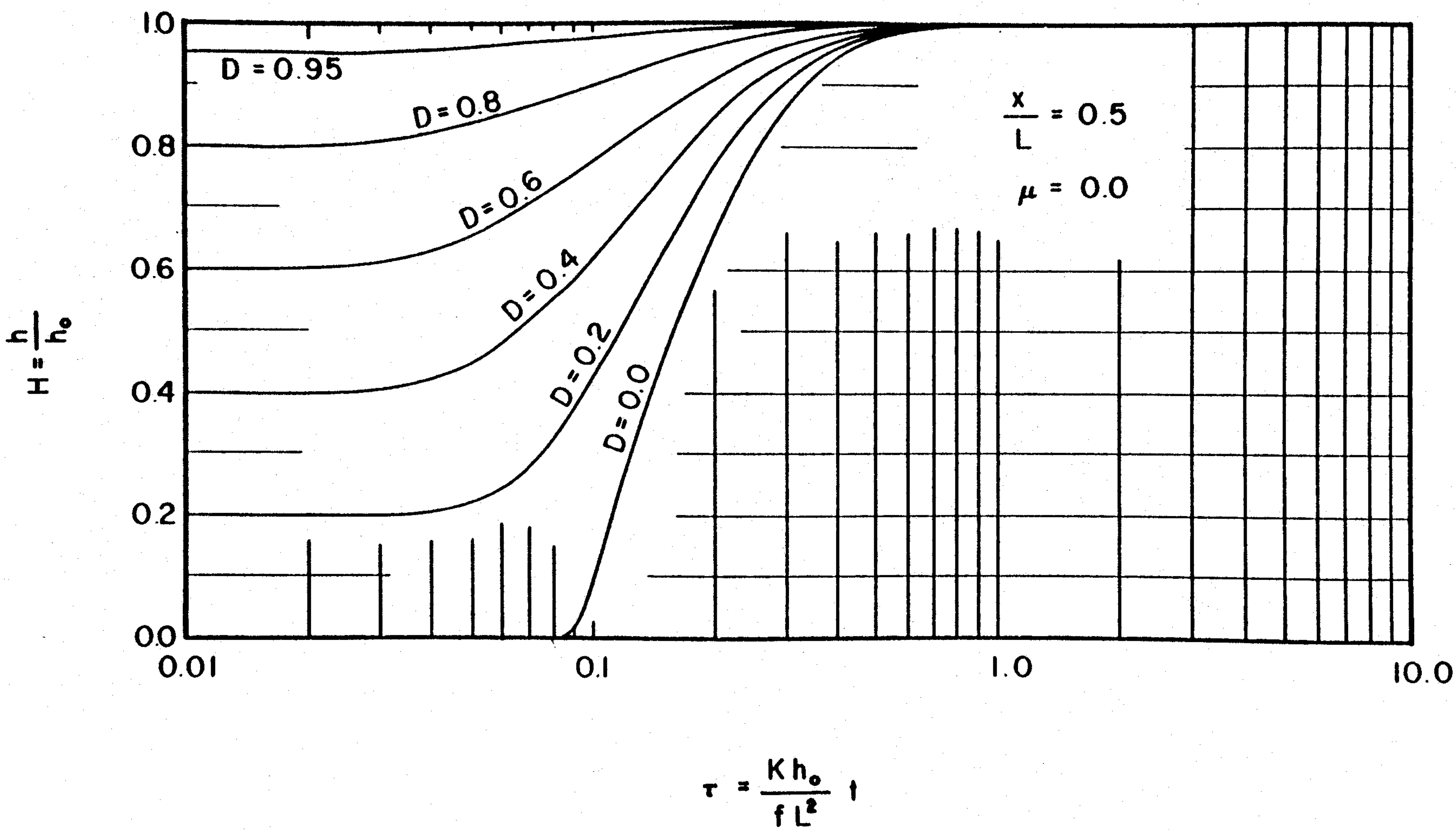

Figure 8-5. Solutions for water table movement at a point midway between the drains when the water table elevation is raised to h_o in the drains. The initial water table is horizontal at an elevation of h_i and $D = h_i/h_o$. The nondimensional vertical loss rate is $\mu = 0$.

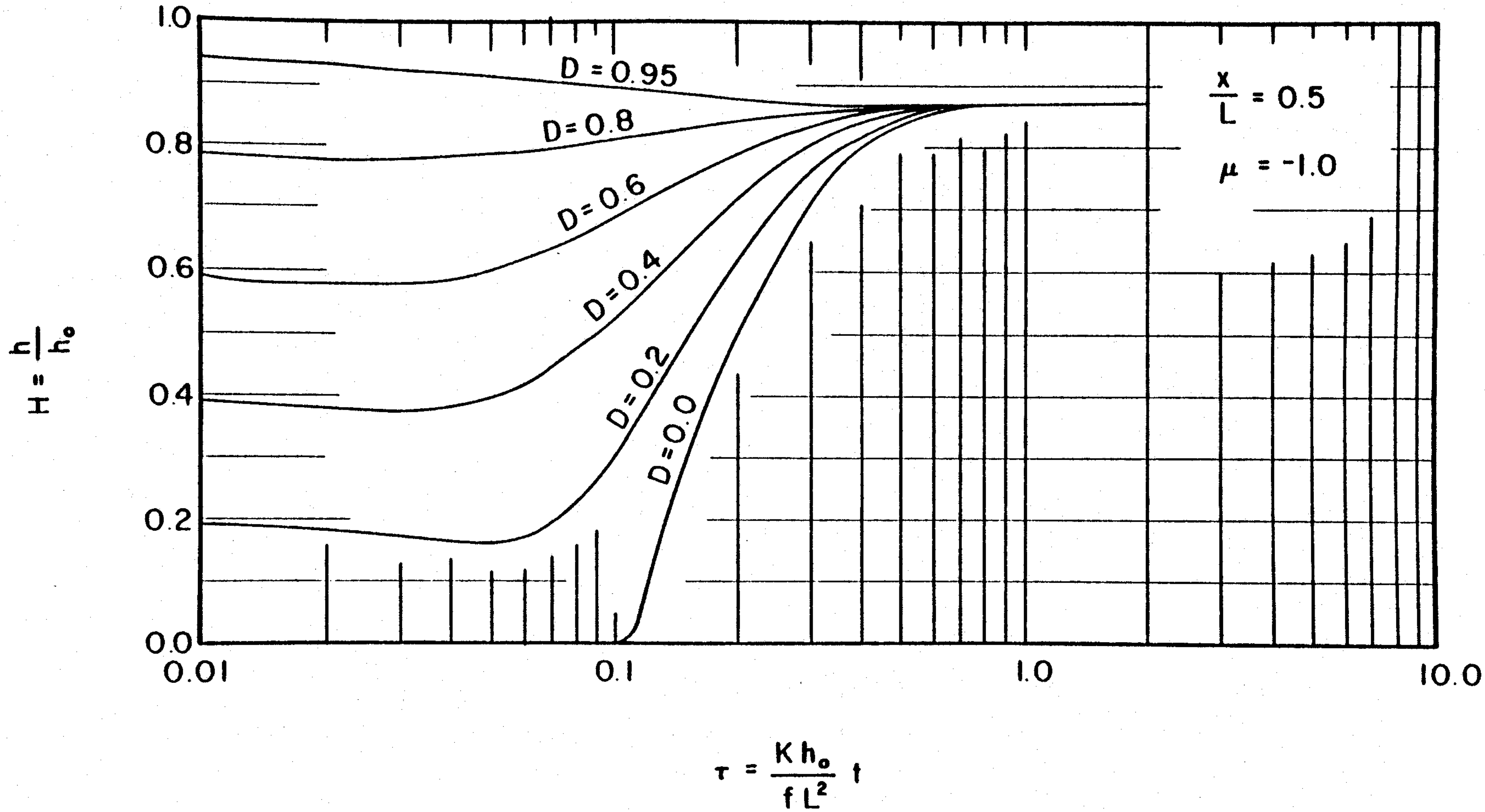

Figure 8-6. Solutions for water table movement at a point midway between the drains when the water table elevation is raised to h_o in the drains. The initial water table is horizontal at an elevation of h_i and $D = h_i/h_o$. The nondimensional vertical loss rate is $\mu = -1.0$.

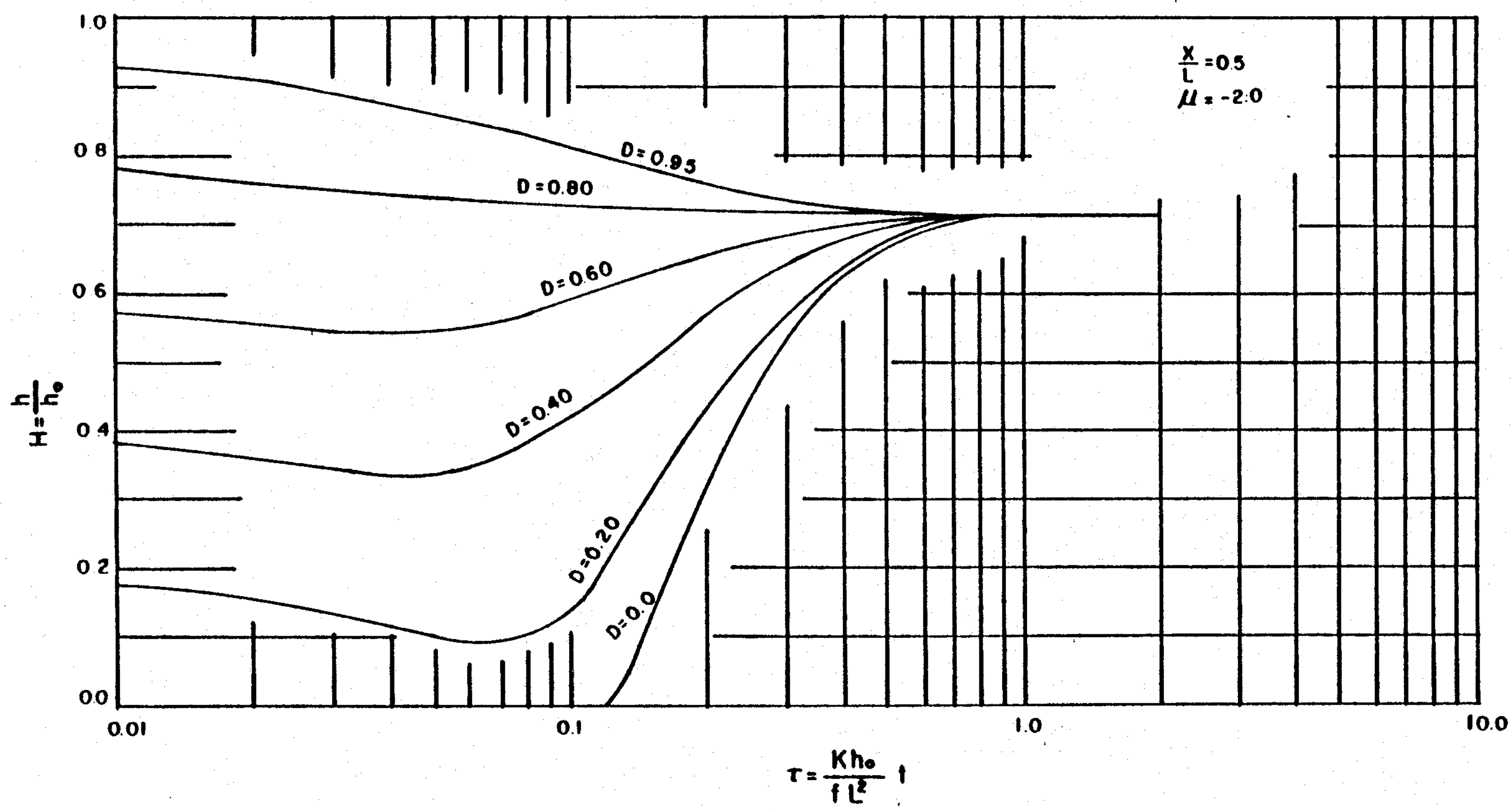

Figure 8-7. Solutions for water table movement at a point midway between the drains when the water table elevation is raised to h_o in the drains. The initial water table is horizontal at an elevation of h_i and $D = h_i/h_o$. The nondimensional vertical loss rate is $\mu = -2.0$.

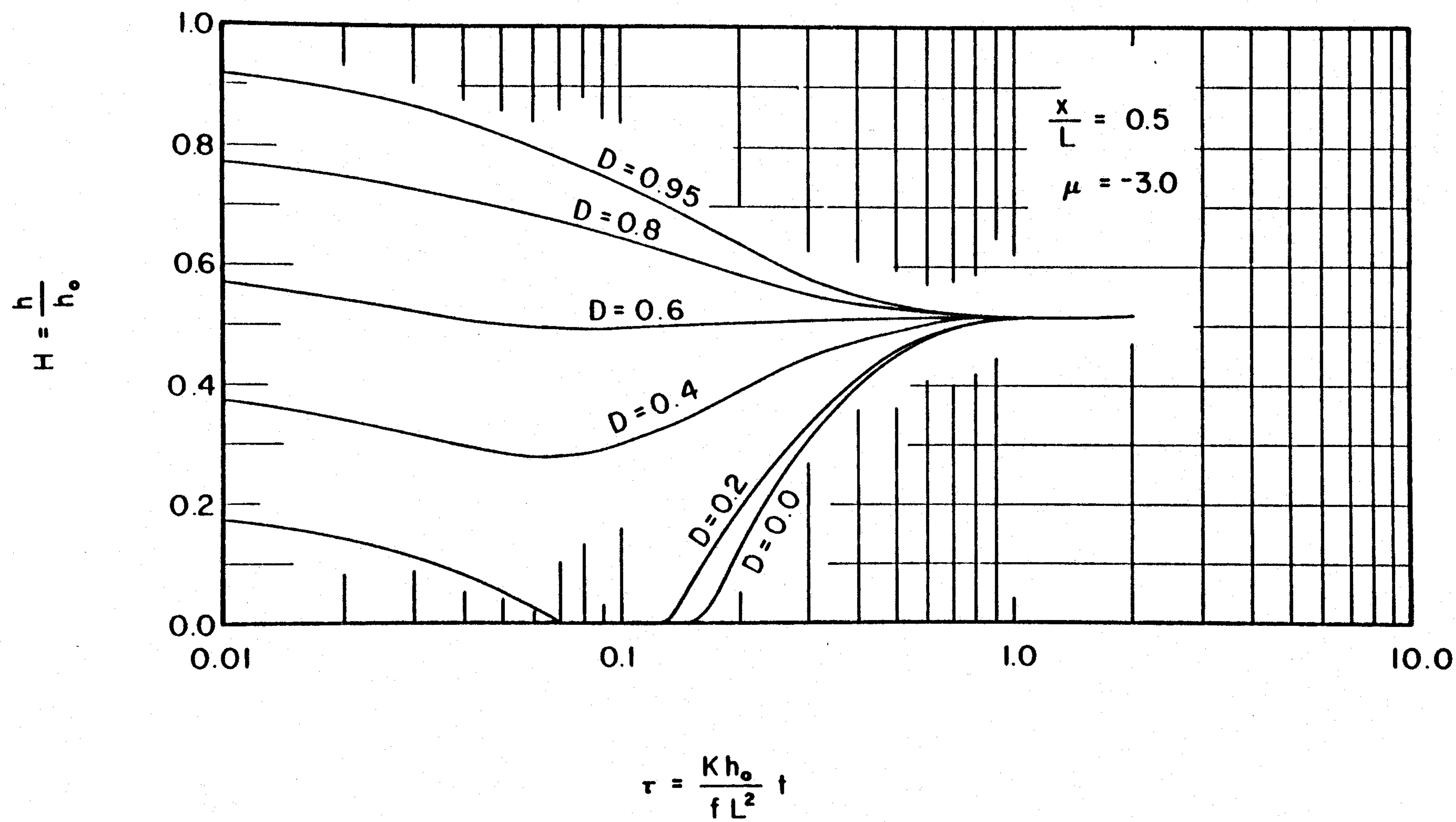

Figure 8-8. Solutions for water table movement at a point midway between the drains when the water table elevation is raised to h_o in the drains. The initial water table is horizontal at an elevation of h_i and $D = h_i/h_o$. The nondimensional vertical loss rate is $\mu = -3.0$.

(Equation 8-13). This simply means that the water table elevation at the midpoint will be drawn down to the impermeable layer by the ET losses when $\mu = eL^2/Kh_o^2 = -4$. This assumes, of course, that the ET rate of e occurs uniformly across the field and is not restricted by the deep water table. In fact, it may be restricted, but this would represent a point of failure for the subirrigation system. In any case, solutions for $\mu < -4$ are not needed as it is not possible to maintain a steady state midplane water table above the impermeable layer for these values.

It may seem unusual that the midplane water table decreases after the water level is raised in the drains (e.g., the solution for D = 0.8, $\mu = -3$ in Figure 8-8). This can occur when the initial water table is higher than the steady state water table depth; i.e., $D > H_m$. In other cases, the midplane water table may decrease for a while then increase (e.g., the solutions for D = 0.4 and 0.2 in Figure 8-8). This happens because some time is required for the water table midway between the drains to react to a change in the water level at the drains. However, vertical losses due to ET (and deep seepage, if it occurs), have an immediate effect. So the midplane water table may fall at first due to ET losses, then increase as water arrives from the drain.

Example 2 - Water Table Rise During Startup

The water table in Example 1 is initially horizontal at a depth of 1 m when the crop is planted and the water level in the drain is raised to within 30 cm of the surface. If the drain spacing is 25 m (from Example 1) and the evaporation rate is assumed to be zero during the period just after planting, how much time will be required to raise the midpoint water table to the design elevation of 76 cm from the surface?

Since e = 0, $\mu = 0$, and Figure 8-5 can be used to calculate the time required. From calculations in Example 1, d_e = 72 cm for L = 25 m, so h_o = 72 + (100 - 30) = 142 cm, h_i = 72/142 = 0.51. The water table at the midpoint is to be raised to h_1 = 72 + (100 - 76) = 96 cm. Then, $H = h_1/h_o$ = 96/142 = 0.676. The effective porosity for Portsmouth s.l. can be estimated from the slope of the drainage volume - water table depth curve given in Figure 5-4. The slope between water table depths of 1.0 m and 0.75 m is f = 0.06. Substituting H = 0.68 in Figure 5-5 and interpolating for D = 0.51 gives $\tau = 0.089$. Then,

$$\tau = \frac{K h_o}{f\, l^2}\, t = 0.089$$

$$t = \frac{0.089\, f\, L^2}{K h_o} = \frac{0.089 \times 0.06 \times 2500^2\ \text{cm}^2}{3\ \text{cm/hr} \times 142} = \underline{78\ \text{hours}}$$

Thus, 78 hours will be required to raise the water table to the design elevation, if evaporation from the surface is negligible.

What time will be required for the same situation if the ET rate is a relatively modest 0.20 cm/day? For this case, $\mu = -eL_o^2/K h_o^2 = -0.20$ cm/d x 2500^2 $cm^2/(3$ cm/hr x 142^2 cm^2 x 24 hr/day) $\mu = -0.86$. Substituting H = 0.68 in Figure 5-6 ($\mu = -1$) gives $\tau_{-1} = 0.137$ and from above $\tau_o = 0.089$. Interpolation for $\mu = -0.86$ yield $\tau_{-0.86} = 0.130$. Solving for t, as shown above, yields:

$$t = \frac{0.130 \times 0.06 \times 2500^2}{3 \times 142} = \underline{114 \text{ hours}}$$

This example shows that a substantial length of time may be required to raise the water table, especially when water is lost by ET from the surface. The time increases sharply with e, as shown in FIgure 8-10, for L = 25 m. The 25 m spacing was determined from steady state considerations in Example 1 such that a water table depth of 76 cm at a point midway between the drains would result if the water level in the drains is held at an elevation 30 cm from the surface and the steady ET = 0.5 cm/day. However, the above results and those given in Figure 8-10, show that a long time would be required to raise the water table to the desired steady state position. For example, if the water table is allowed to drop to a depth of 100 cm for some reason (equipment failure, operator error, assumption that it is going to be a wet year and irrigation will not be needed), about 240 hours would be required to raise the water table to its steady state position, if e = 0.4 cm/day. The irrigation requirement would not be met during that period and substantial yield reductions could result. Therefore, a smaller drain spacing than calculated from the steady state analysis may be desirable to reduce the time required to raise the water table during the growing season.

The time required to raise the midplane water table, as affected by the vertical loss rate, e, is also plotted for L = 17.4 m in Figure 8-10. Only 57 hours would be required to raise the water table for this spacing when e = 0.4 cm/day. Then, the water level at the drains could be allowed to fall to a depth of 50 cm and still supply a steady ET rate of e = 0.5 cm/day (Example 1). This would allow a smaller variation in the steady state water table depth (from 50 cm at the drain, to a depth of 76 cm at the midplane). At the same time, the smaller spacing would provide system that is responsive to adjustments in the outlet water level during the growing season.

The effects of rainfall and of available water stored in the unsaturated zone are not considered in this chapter. The effects of such factors on drain spacing and operational procedures of a subirrigation system can be analyzed best by using DRAINMOD to simulate the performance of the system. However, the methods discussed herein can be used to make a first cut design of the subirrigation system. The methods may also be used to check the final design for the time required to raise the water table to an operational position. Interruptions of subirrigation due to equipment breakdowns or other problems, are not planned so they are not usually simulated when DRAINMOD is used to analyze a given design. Thus, the time required to "restart" the subirrigation process should be checked for all systems designs.

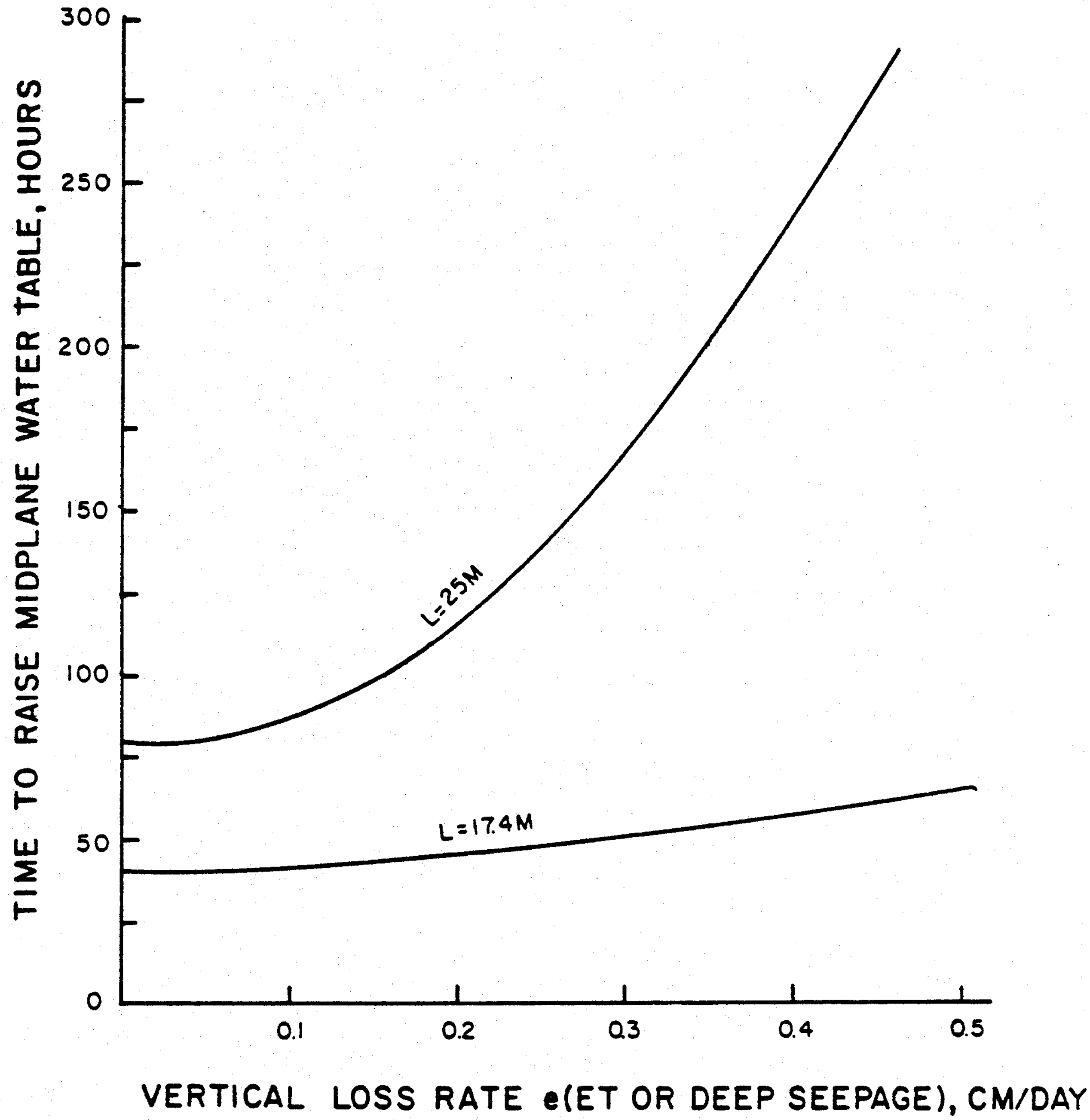

Figure 8-9. Effect of vertical loss rate e on time to raise the midplane water table from a depth of 100 cm to 76 cm for two drain spacings in a Portsmouth s.l. soil. The water level in the drains is raised to within 30 cm of the surface for both drain spacings.

DRAINMOD REFERENCE REPORT

CHAPTER 9

SEEPAGE LOSSES FROM SUBIRRIGATION AND WATER TABLE CONTROL SYSTEMS

Introduction

One of the most important components of a subirrigation system is the development of a water supply with adequate capacity to meet plant use requirements, plus replenish water lost from the system by seepage. When the water table is raised during subirrigation, the hydraulic head in the field is higher than that in surrounding areas and water is lost from the system by lateral seepage. The rate of deep seepage or vertical water movement from the soil profile may also be increased. The magnitude of seepage losses depend on the hydraulic conductivity of the soil and depth to restricting layers. It also depends on boundary conditions such as the elevation of the controlled water table in relation to surrounding water table depths and the distance to drains or canals that are not controlled. Methods for characterizing seepage losses from subirrigated fields are presented in the following sections. The methods used are similar in concept to those described by Hall (1976) for computing reservoir water losses, as affected by ground water mounds. However, water tables are usually high for subirrigation systems and seepage losses can be computed by considering flow in one or two dimensions, whereas, the reservoir seepage problem is normally a two or three dimensional problem.

Seepage Losses to Nearby Drains or Canals

Methods for quantifying steady seepage losses in the lateral direction can be developed by considering the case shown in Figure 9-1. Using the Dupuit-Forchheimer (D-F) assumptions, the seepage rate may be expressed as,

$$q = = - Kh \frac{dh}{dx} \qquad (9\text{-}1)$$

Where q is the seepage rate per unit length of the drainage ditch (or per unit thickness into the paper (cm^3/cm hr or ft^3/ft hr)). K is the effective lateral hydraulic conductivity (cm/hr). h is the water table elevation above the impermeable layer (cm or ft), which is a function of the horizontal position, x. If evapotranspiration from the surface is assumed negligible, q is constant for all x and Equation (9-1) can be solved, subject to the boundary conditions,

$$h = h_1 \text{ at } x = 0 \qquad (9\text{-}2)$$

$$h = h_2 \text{ at } x = s \qquad (9\text{-}3)$$

The solution for h may be written as,

$$h^2 = - \frac{h_1^2 - h_2^2}{S} x + h_1^2 \qquad (9\text{-}4)$$

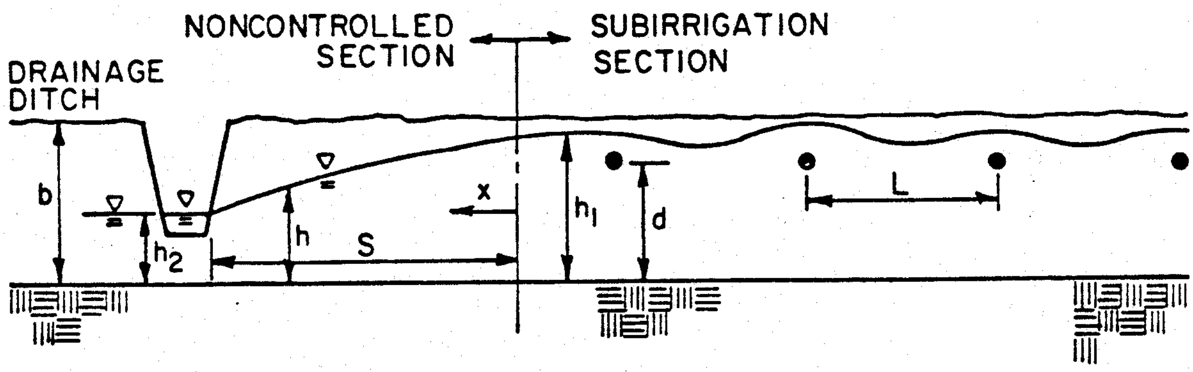

Figure 9-1. Water table profile for seepage from a subirrigated field to a drainage ditch.

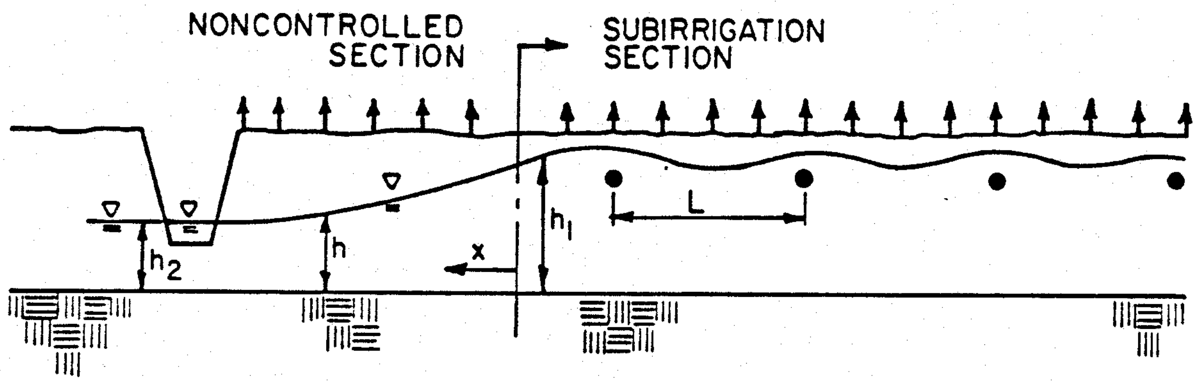

Figure 9-2. Water table profile for seepage from a subirrigated field to a drainage ditch. ET losses are considered.

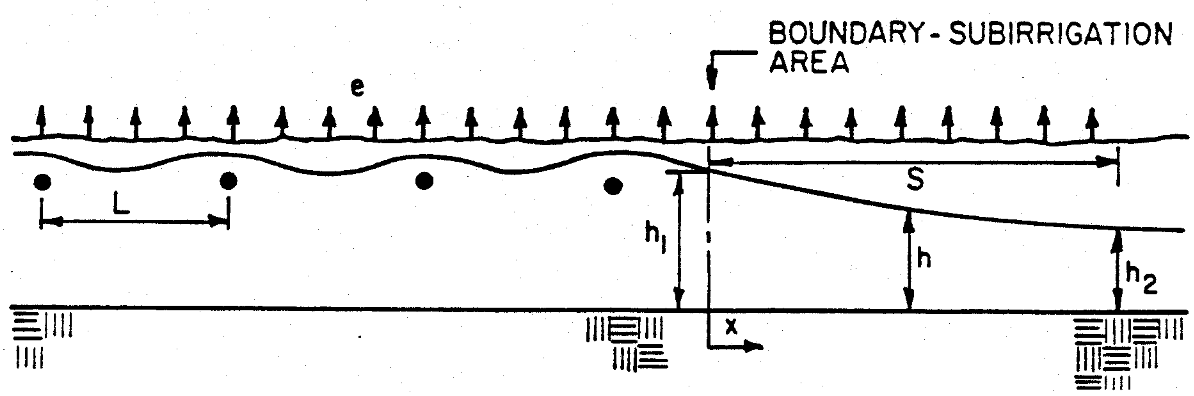

Figure 9-3. Seepage from a subirrigated field to an adjacent nonirrigated field which has water table drawdown due to ET.

Differentiating Equation (9-4) and substituting back into (9-1) gives,

$$q = \frac{K}{2S} (h_1^2 - h_2^2) \tag{9-5}$$

Then, if the length of the field (into the paper) is ℓ, the seepage loss from that side of the field may be calculated as,

$$Q = q\,\ell = \frac{K\ell}{2S} (h_1^2 - h_2^2) \tag{9-6}$$

Vertical water losses due to ET along the field boundaries increase the hydraulic gradients in the horizontal direction and, thus, seepage losses (Figure 9-2). In this case, the flux, q, may still be expressed by Equation (9-1), but rather than the flux being constant we may write, according to Harr (1962),

$$\frac{dq}{dx} = -e \tag{9-7}$$

Where e is the ET rate.

Then, substituting Equation 9-1 for q,

$$\frac{d}{dx} [h \frac{dh}{dx}] = \frac{e}{K} \tag{9-8}$$

Solving (9-8), subject to boundary conditions (9-2) and (9-3) gives,

$$h^2 = \frac{e}{K} x^2 + \frac{(h_2^2 - h_1^2 - \frac{e}{K} S^2)}{S} x + h_1^2 \tag{9-9}$$

Again, differentiating and evaluating dh/dx at x = 0 and substituting into (9-1) yields,

$$q = \frac{K (h_1^2 - h_2^2) + e\,S^2}{2S} \tag{9-10}$$

Notice that for no ET (e = 0), Equations (9-9) and (9-10) reduce to (9-4), and (9-5), respectively, as they should.

Seepage Losses to Adjacent Undrained Lands

Subirrigation systems are often located next to forest or cropland that is not drained. However, seepage losses may still occur along these boundaries because of low water tables in the undrained areas. Why would water tables be low in surrounding areas if they are not drained? Remember that subirrigation is used during dry period so water tables would be drawn down due to ET. Such a situation is shown schematically in Figure 9-3. The problem here, as opposed to the cases above is that neither h_2 nor S is known. The relationship between the rate of steady upward water movement and water table depth was discussed in an earlier section (pages 5-13 to 5-23). For purposes of this problem, it is assumed that water will not move to the surface (or to the root zone) at a rate sufficient to support an ET rate of e for water table elevations less than h_2. Then, from principles of conservation of mass, we may write for any point, x,

$$q(x) = (S-x)\ e \qquad (9\text{-}11)$$

Where q(x) is the flowrate per unit length of the field (into the paper) expressed as a function of x, e is the steady ET rate, S is the limiting distance where $h = h_2$, the limiting water table elevation that will allow upward water movement to the surface at rate e.

Substituting Equation 9-1 for q gives,

$$-\,Kh\frac{dh}{dx} = (S - x)\ e \qquad (9\text{-}12)$$

Separating variables and integrating subject to the condition $h = h_1$ at $x = 0$, yields the following expression for h,

$$h^2 = \frac{ex^2}{K} - \frac{2\ S\ ex}{K} + h_1^2 \qquad (9\text{-}13)$$

Then, S can be determined by substituting $h = h_2$ at $x = S$, which after simplifying results in,

$$S = \sqrt{\frac{(h_1^2 - h_2^2)\ K}{e}} \qquad (9\text{-}14)$$

Then, the seepage loss per unit length of the field may be evaluated from Equation (9-11) at x = 0 as,

$$q = \sqrt{\frac{(h_1^2 - h_2^2)\ K}{e}}\ e \qquad (9\text{-}15)$$

or

$$q = \sqrt{(h_1^2 - h_2^2)\ K\ e} \qquad (9\text{-}16)$$

Normally, seepage losses to surrounding undrained areas would be highest during peak consumptive use periods. The value of h_1 would depend on the water level held in the subirrigation system. The value of h_2 would depend on the soil profile and could be chosen from relationships for maximum upward flux versus water table depth (Figure 9-6). To be on the safe side h_2 should be chosen so that the depth of the water table is at least 1.0 m at x = S.

Vertical or Deep Seepage

Subirrigation and water table control systems are usually located on soils with tight underlying layers and/or high natural water tables so that vertical losses are not excessive. When evaluating a potential site for a subirrigation system, vertical seepage losses under a raised water table condition should be estimated even though a natural high water table is known to exist. These losses should be added to lateral seepage estimates to determine the water supply capacity needed in addition to that required to meet ET demands.

Deep seepage can be estimated for soils with restricting layers at a relatively shallow depth by a straight-forward application of Darcy's law. Referring to Figure 9-4, the vertical seepage flux may be estimated as,

$$q_v = K_v \frac{h_1 - h_2}{D} \tag{9-17}$$

Where q_v is the flux (m/day), K_v is the effective vertical hydraulic conductivity of the restricting layer, h_1 is the average distance from the bottom of the restricting layer to the water table, h_2 is the hydraulic head in the ground water aquifer referenced to the bottom of the restricting layer, and D is the thickness of the restricting layer.

The hydraulic head in the ground water aquifer may be estimated from the water level in wells in the vicinity. It may be necessary to install piezometers to the depth of the ground water aquifer in order to accurately determine the hydraulic head in the aquifer. Methods for installing the piezometers are discussed in Section 16 of NEH (pages 81-87). The thickness and hydraulic conductivity of the restricting layer may be determined from deep borings in the field. Data from such borings should be logged in accordance with the procedures given in Section 16 of NEH (pages 63-70). The vertical hydraulic conductivity, K_v, of restricting layers can be determined from in-field pumping tests using the piezometer method (see Bouwer and Jackson, 1974). Laboratory tests on undisturbed cores can also be used to determine K_v; however, field tests are preferred, when possible.

The restricting strata is often composed of several layers of different conductivities and thicknesses rather than a single layer. In this case, K_v in Equation (9-17), is replaced by the effective vertical hydraulic conductivity K_{ve}. The effective conductivity can be calculated for flow perpendicular to a series of layers (Harr, 1922) as,

$$K_{ve} = \frac{D}{\frac{D_1}{K_{v1}} + \frac{D_2}{K_{v2}} + \frac{D_3}{K_{v3}} + \ldots} \tag{9-18}$$

Where D_1, D_2, D_3, ... are the thicknesses, and K_{v1}, K_{v2}, K_{v3}, ... are the vertical hydraulic conductivities of the individual layers.

Examples

An example layout of a subirrigation system is shown in Figure 9-5. Drains are placed 20 m apart and the water level directly above the drains is held to within 50 cm of the surface during the growing season. Seepage losses occur along all four boundaries of the field. The effective lateral hydraulic conductivity is 2.0 m/day for the field and surrounding areas, except for the compacted roadway south of the field where K = 0.5 m/day.

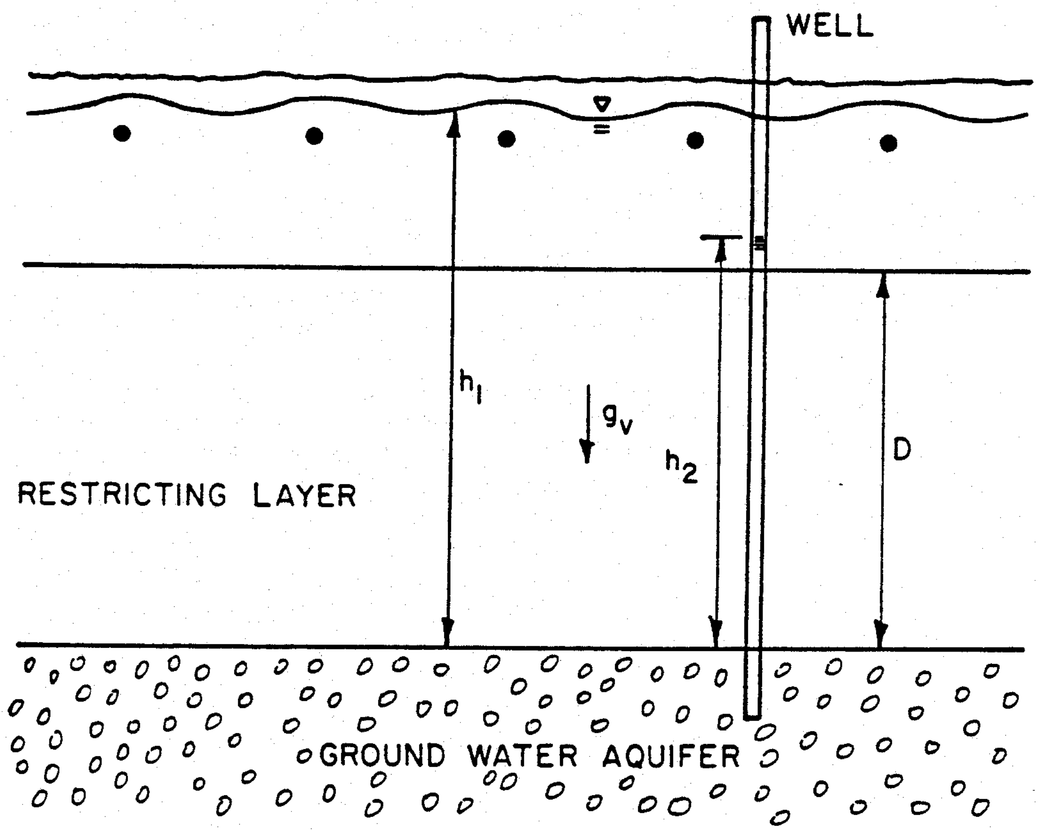

Figure 9-4. Vertical seepage to a ground water aquifer during subirrigation.

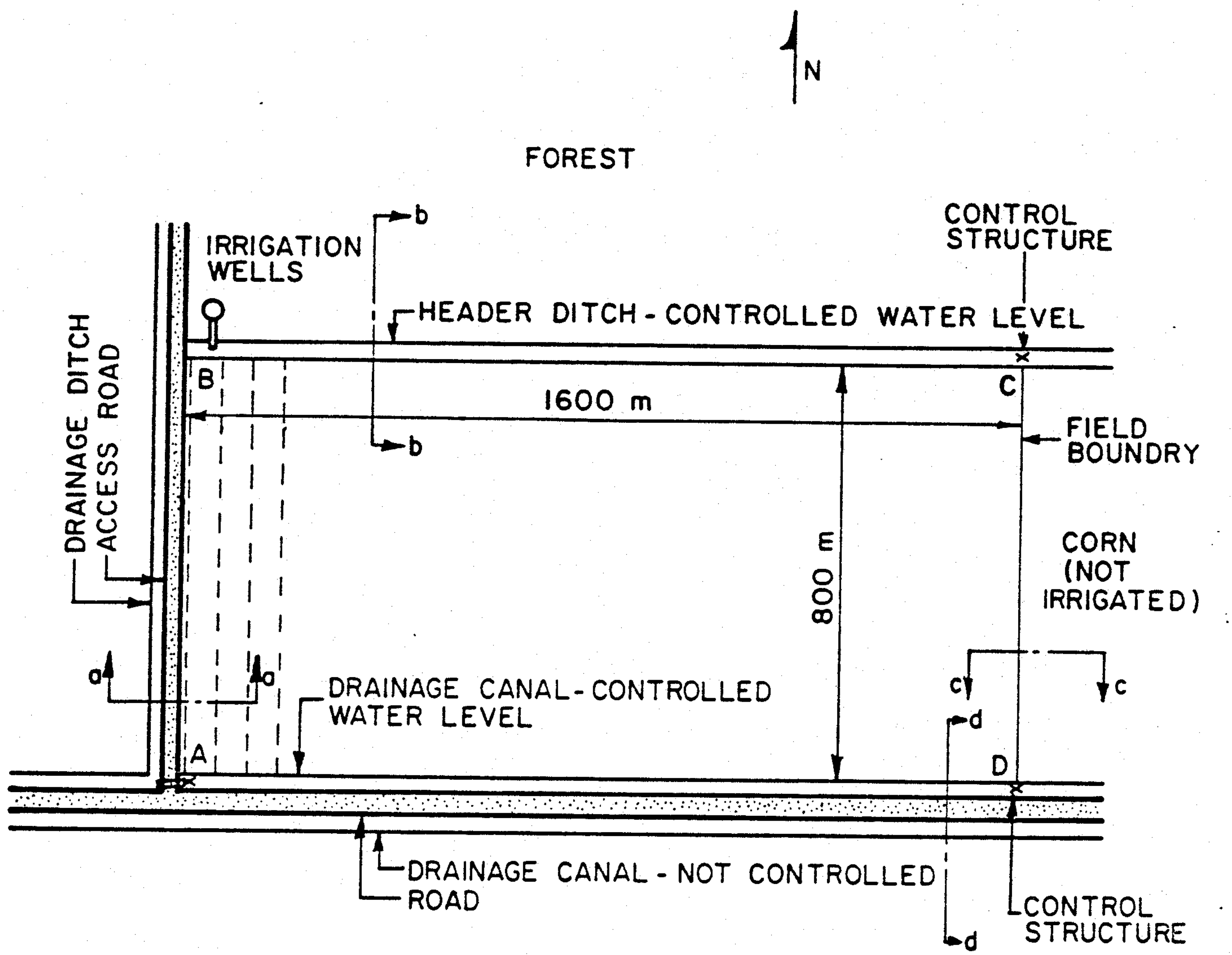

Figure 9-5. Schematic of a 128 ha (307 acre) subirrigation system showing boundary conditions for calculating lateral seepage losses.

Boundary A-B

Along Boundary A-B, water moves from the field under a 5 m wide uncompacted field access road to a drainage ditch on the other side (Figure 9-6a). A drain tube is located immediately adjacent to the road in order to maintain good water table control right up to the field boundary. The seepage rate under the road can be calculated using Equation 9-5 as,

$$q_{A-B} = \frac{2.0 \text{ m/day}}{2 \times 5 \text{ m}} (1.5^2 - 0.6^2)\text{m}^2 = 0.378 \frac{\text{m}^3}{\text{day m}}$$

$$Q_{A-B} = q\ \ell = 0.378 \text{ m}^3\text{/m day} \times 800 \text{ m} = 302 \text{ m}^3\text{/day}$$

Converted to more familiar units, the seepage rate may be written as,

$$Q_{A-B} = 302 \text{ m}^3\text{/day} \times \frac{1 \text{ day}}{24 \text{ hr}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times (3.28 \frac{\text{ft}}{\text{m}})^3 \times \frac{7.5 \text{ gal}}{\text{ft}^3}$$

$$Q_{A-B} = 55 \text{ gal/min}$$

This rather high seepage loss can be reduced by moving the first lateral away from the edge of the field, say by one-half of the drain spacing (Figure 9-6b). Then, substituting S = 10 + 5 = 15 m in Equation 9-6 gives,

$$Q_{A-B} = \frac{2.0 \text{ m/day} \times 800 \text{ m}}{2 \times 15 \text{ m}} (1.5^2 - 0.6^2) = 100 \text{ m}^3\text{/day}$$

or

$$Q_{A-B} = 18 \text{ gal/min}$$

This would be the seepage rate when ET = e = 0. Seepage losses are most critical during periods of high consumptive use (high ET by crop) because it is at this period that the highest supply rate will be required. The seepage rate for a design ET value of e = 0.6 cm/day can be calculated from Equation 9-10 as,

$$q_{A-B} = \frac{2.0 \text{ m/day } (1.5^2 - 0.6^2)\text{m}^2 + .006 \text{ m/day} \times 15^2 \text{ m}^2}{2 \times 15 \text{ m}}$$

$$q_{A-B} = 0.171 \text{ m}^3\text{/m day}$$

$$Q_{A-B} = q\ \ell = 0.171 \text{ m}^3\text{/m day} \times 800 \text{ m} = 137 \text{ m}^3\text{/day}$$

or

$$Q = 25 \text{ gal/min}$$

However, it should be noted that this is the flowrate from the first lateral toward the access road and the adjacent drainage ditch. Part of the water supplies the ET demand between the lateral and the ditch and should not be counted as seepage loss. The rate of water used in the 10 m strip between the first lateral and the access road is,

$$Q_e = 0.006 \text{ m/day} \times 10 \text{ m} \times 800 \text{ m}$$

$$= 48 \text{ m}^3\text{/day}$$

then

$$Q_{A-B} = 137 \text{ m}^3\text{/day} - 48 = 89 \text{ m}^3\text{/day} = 16 \text{ gal/min}$$

This includes water lost by seepage to the drainage ditch plus water lost by ET from the road surface (at an assumed rate of 0.6 cm/day) where grass, weeds, etc., are growing. Note that the same result would have been obtained by evaluating the quantity h dh/dx from Equation (9-9) at x = 10 m, rather than at x = 0. Then, Equation 9-10 would have been replaced by,

$$q = - e\,x + \frac{K}{2S}\left(h_1^2 - h_2^2 + \frac{e}{K}\,S^2\right) \tag{9-19}$$

and

$$q_{A-B} = -.006 \times 10 + \frac{2.0}{2 \times 15}\left(1.5^2 - .6^2 + \frac{.006}{2} \times 15^2\right)$$

$$q_{A-B} = 0.111 \text{ m}^3\text{/day m}$$

$$Q_{A-B} = 0.111 \times 800 = 88.8 \text{ m}^3\text{/day} = 16 \text{ gal/min}$$

which is the same as determined above.

It is interesting that seepage losses for e = 0 are greater than for e = 0.6 cm/day. The reason for this is that ET within the field lowers the water table elevation at the field edge and thus the hydraulic gradient and seepage rates are reduced. Losses can be further reduced by moving the first lateral further away from the field boundary. This may mean sacrificing the quality of water table control near the edge of the field, but should be considered if seepage losses are excessive.

Boundary B-C

Seepage losses along the North Boundary, B-C, are in response to gradients caused by water table drawdown due to ET, as shown schematically in Figure 9-7. The relationship between maximum upward flux and water table depth (Figure 5-6) indicate that, for the Lumbee soil, an ET rate of 0.6 cm/day can be sustained with a water table depth below the root zone of 50 cm and a rate of 0.2 cm/day at a depth of 60 cm. Assuming an effective

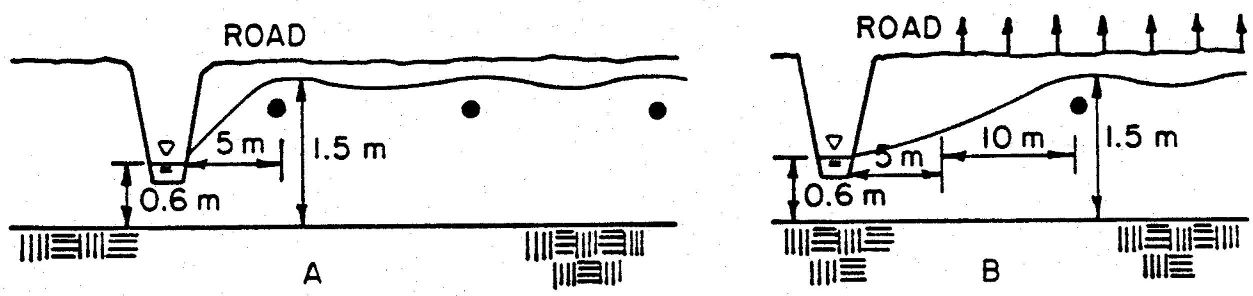

Figure 9-6. Seepage along Boundary A-B: (a) the first drain tube is located immediately adjacent to the field access road 5 m from the drainage ditch, and (b) the drain tube is located 10 m back from the road.

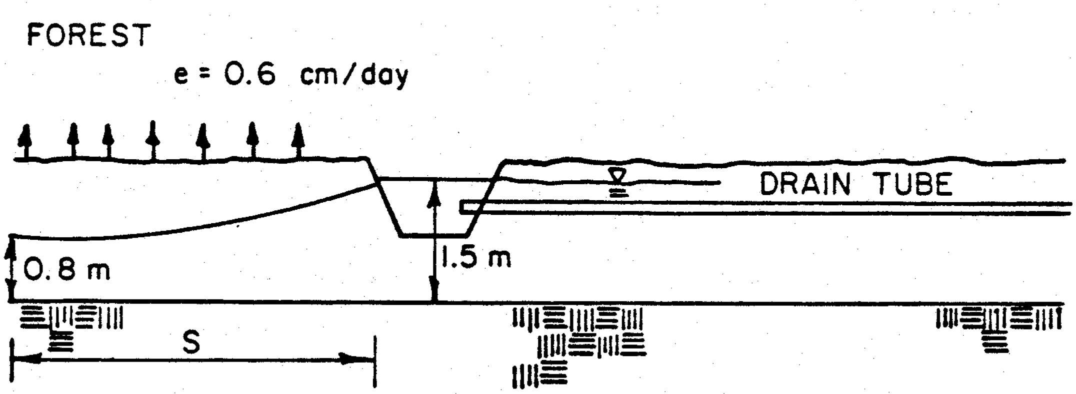

Figure 9-7. Schematic of water table position along the North Boundary (Section B-B).

rooting depth of 60 cm (2 ft) and taking a conservative estimate of 60 cm for the water table depth below the root zone, gives a total water table depth of 1. 2 m and $h_2 = 2.0 - 1.2 = 0.8$ m. Then, the seepage rate can be determined from Equation 9-16 as,

$$q_{B-C} = \sqrt{(1.5^2 - 0.8^2)\ 2.0 \times 0.006}\ m^3/m\ day$$

$$= 0.139\ m^3/m\ day$$

and

$$Q_{B-C} = 1,600\ q_{B-C} = 222\ m^3/day = \underline{41\ gal/min}$$

Seepage along B-C increases with the square root of e in contrast to Boundary A-B where seepage losses decrease with increasing e. It is also interesting to note that a 25 percent increase in h_2 to 1.0 m still gives a seepage rate of 36 gal/min, a reduction of only 12 percent.

Boundary C-D

As in the previous case, seepage losses along BC are caused by a lower water table in the adjacent nonirrigated field which was drawn down by ET (Figure 9-8). By assuming an effective maximum root depth for corn of 30 cm and a water table depth below the root zone of 60 cm ($y = 0.60 + 0.30 = 0.90$ so $h_2 = 2. - 0.90 = 1.1$) for a steady ET rate of $e = 0.6$ cm/day, the seepage rate from the last drain tube toward the boundary C-D is (Equation 9-16),

$$q = \sqrt{(1.5^2 - 1.1^2)\ 2.0 \times 0.006} = 0.112\ m^3/m\ day$$

However, part of this seepage supplies the ET demand for the region between the last tube and the field boundary and should not be considered as seepage loss. If the last drain tube is located 10 m from the edge of the field, the portion of the above seepage used by ET within the irrigated field is, $q_e = 0.006$ m/day x 10 m = 0.06 m^3/m day. Therefore,

$$q_{C-D} = 0.112 - 0.06 = 0.052\ m^3/m\ day$$

and

$$Q_{C-D} = 0.052\ m^3/m\ day \times 800\ m = 41\ m^3/day = \underline{7.5\ gal/min}$$

An alternative means of calculating this loss is to first determine S for which $h = h_2 = 1.1$ m from Equation (9-14).

$$S = \sqrt{(1.5^2 - 1.1^2)\ 2.0/.006} = 18.6\ m$$

And, then determine q_{C-D} from Equation (9-19) with x = 10 m,

$$q_{C-D} = .052\ m^3/m\ day$$

which is the same value obtained above.

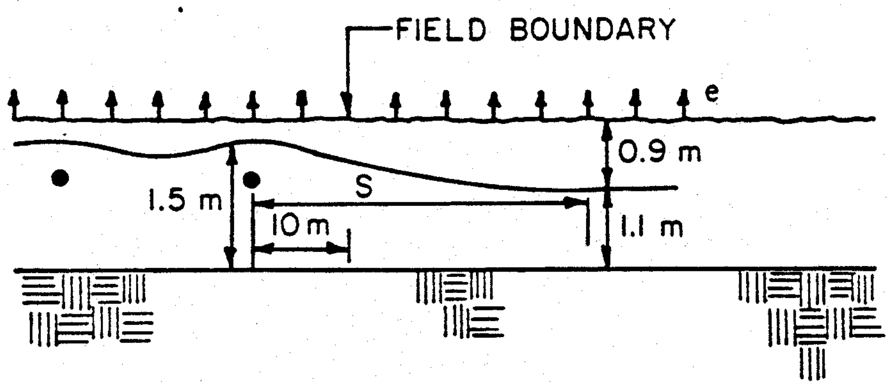

Figure 9-8. Schematic of water table and seepage along the East Boundary (Section C-C).

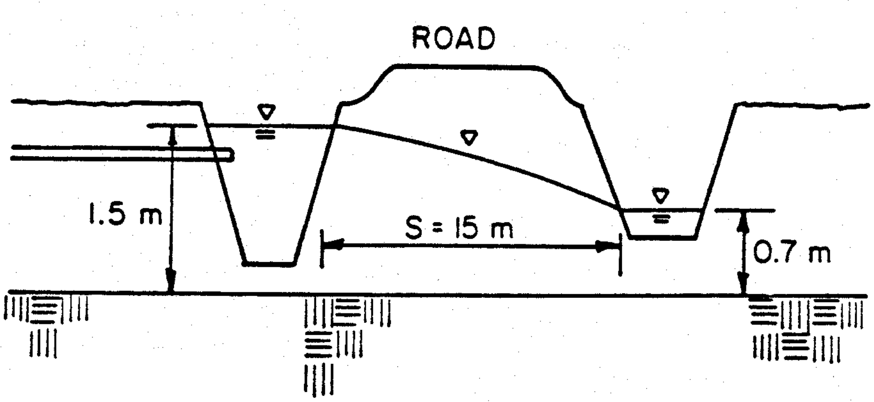

Figure 9-9. Seepage under the road along Boundary A-D. (Section D-D).

Boundary A-D

Seepage under the road along Boundary A-D (Figure 9-9) can be estimated using Equation 9-6 with K for the compacted road fill of 0.5 m/day.

$$Q_{A-D} = \frac{0.5 \text{ m/day} \times 1,600 \text{ m}}{2 \times 15 \text{ m}} (1.5^2 - 0.7^2) \text{ m}^2$$

$$Q_{A-D} = 47 \text{ m}^3\text{/day} = 8.5 \text{ gal/min}$$

Deep Seepage

Deep borings and hydraulic conductivity tests using the piezometer method indicate the thickness of the restricting layer is 20 m with an effective vertical hydraulic conductivity of K_v = 0.01 cm/hr. Measurements in observation wells, cased to the depth of the ground water aquifer (22 m deep), show a nearly constant hydraulic head of h_2 = 20.5 m (refer to Figure 9-4). Then, assuming an average h_2 = 21.3 m, the vertical seepage rate can be calculated from Equation (9-17) as,

$$q_V = 0.01 \text{ cm/hr} \frac{21.3 \text{ m} - 20.5 \text{ m}}{20 \text{ m}}$$

$$q_V = 0.0004 \text{ cm/hr} = 0.000096 \text{ m/day}$$

Then, for the entire field with dimensions of 800 m x 1,600 m, the vertical seepage rate is,

$$Q_V = q_V A = .000096 \times 800 \times 1,600 = 123 \text{ m}^3\text{/day} = 22 \text{ gal/min}$$

Total Seepage Losses

Based on the previous calculations, the total seepage losses are:

$$Q_T = Q_{A-B} + Q_{B-C} + Q_{C-D} + Q_{A-D} + Q_V$$

$$Q_T = 89 + 222 + 41 + 47 + 123 = 522 \text{ m}^3\text{/day}$$

or

$$Q_T = 95 \text{ gal/min}$$

This amount of water will have to be supplied in addition to the irrigation water necessary to satisfy ET demand during the operation of the subsurface irrigation system. The calculations are based on a peak ET rate of 0.6 cm/day. Therefore, the capacity required to satisfy ET during periods of dry weather when the total demand must be satisfied by the subirrigation system is,

$$Q_{ET} = 0.6 \text{ cm/day} \times \frac{1 \text{ m}}{100 \text{ cm}} \times 800 \text{ m} \times 1{,}600 \text{ m}$$

$$Q_{ET} = 7{,}680 \text{ m}^3\text{/day or } \underline{1{,}400 \text{ gpm}}$$

Thus, the seepage loss expressed as a percentage of the total capacity is:

$$\text{Percentage loss} = 522/8{,}200 \times 100 = \underline{6.4 \text{ percent}}$$

which is quite reasonable, compared to conventional methods of irrigation.

Natural Resources Conservation Service
Wetland Science Institute

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