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INTRODUCTION

The design of efficient agricultural water management systems is becoming more and more critical as competitive uses for our water resources increases, and as installation and operation 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, to insure a suitable environment for plant growth during the growing season, and to permit harvest in the fall. 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.

The design and operation of each component of a water management system should be dependent on soil properties. 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 multi-component water management systems should provide the capability 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 paper is to describe DRAINMOD, a water management model that was developed for soils with high water tables. The model is a computer simulation program that 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 determine hydraulic loading capacities of sites for land disposal of waste water. Climatological data are used in the model to simulate the performance of a given water management system over several years of record. In this way, optimum water management systems 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

Background

A schematic of the type of water management system considered is given in Figure 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, most of the surface water will be available for runoff. However, if sur-

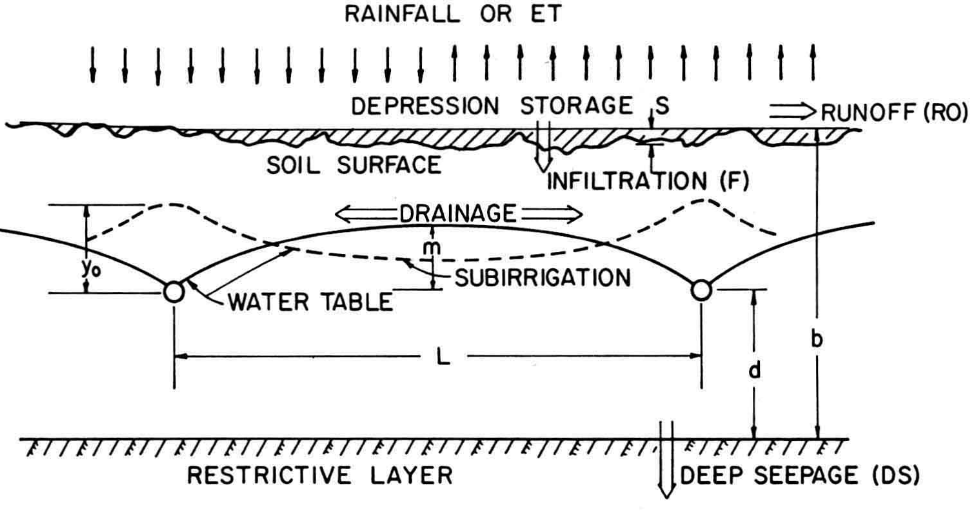

Figure 1. Schematic of water management system with subsurface drains that may be used for drainage or subirrigation.

face 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.

The rate that water is drained from the profile depends on the hydraulic conductivity of the soil, the drain depth and spacing, the effective profile depth, and the depth of water in the drains. When the water level is raised in the drainage ditches, 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 1. It was shown in a previous study (Skaggs, 1974) 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 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 for the development of a successful computer model were adopted. First, the model must be capable of describing all aspects of water movement and storage in the profile so as to characterize, with reasonable accuracy, 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 processes is not prohibitive. The movement of water in soil is a complex process and it would be an easy matter to become so involved with getting exact solutions to every possible situation that the final answer 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. 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 (Freeze, 1971). However, these methods would require prohibitive amounts of computer time for long term simulations and thus could not be used in the model. 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 data from five sites in North Carolina (Skaggs, 1978b) and from long-term experiments in Ohio (Skaggs et al., 1979).

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 (Figure 1). The water balance for a time increment of Δt may be expressed as,

$$\Delta V_a = D + ET + DS - F \tag{1}$$

where ΔV_a is the change in the air volume (cm) in the section, D is 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 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,

$$P = F + \Delta S + RO \tag{2}$$

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 1 and 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 1 is based on Δt of 1 day. Conversely, time increments of 0.1 hr. 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. Methods used to evaluate components of equations 1 and 2 are discussed below.

Model Components

Precipitation. Precipitation records are one of the major inputs to 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 of these model components than will 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 U.S.

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. Hourly data for other locations in the U.S. can be obtained from the National Weather Climatic Center at Asheville, N.C.

Infiltration

Infiltration of water at the soil surface is a complex process which has been studied extensively during the past two decades. A recent review of infiltration and methods for quantifying infiltration rates was presented by Skaggs and Khaleel (1979). Philip (1969), Hillel (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 dpeth;

plant factors such as extent of cover and depth of root zone; and rainfall factors such as intensity, duration, and time distribution.

One method for characterizing the infiltration process involves the solution of the nonlinear partial differential equation first derived by Richards (1931) for transient unsaturated flow under rainfall or ponded surface conditions. Although the Richards equation provides a rather comprehensive method of determining the effects of many interactive factors on infiltration, input and computational requirements prohibit 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, the Richards equation 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 have been proposed by Green and Ampt (1911), Horton (1939), Philip (1957) and Holtan, 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. The equation may be written as,

$$f = K_s + K_s\, M_d\, S_f/F \qquad (3)$$

where f is the infiltration rate, F is accumulative infiltration, K_s is the hydraulic conductivity of the transmission zone, M_d is the difference between final and initial volumetric water contents ($M_d = \theta_o - \theta_i$), and S_f is the effective suction at the wetting front. For a given soil with a given initial water content equation 3 may be written as,

$$f = A/F + B \qquad (4)$$

where A and B are parameters that depend on the soil properties,

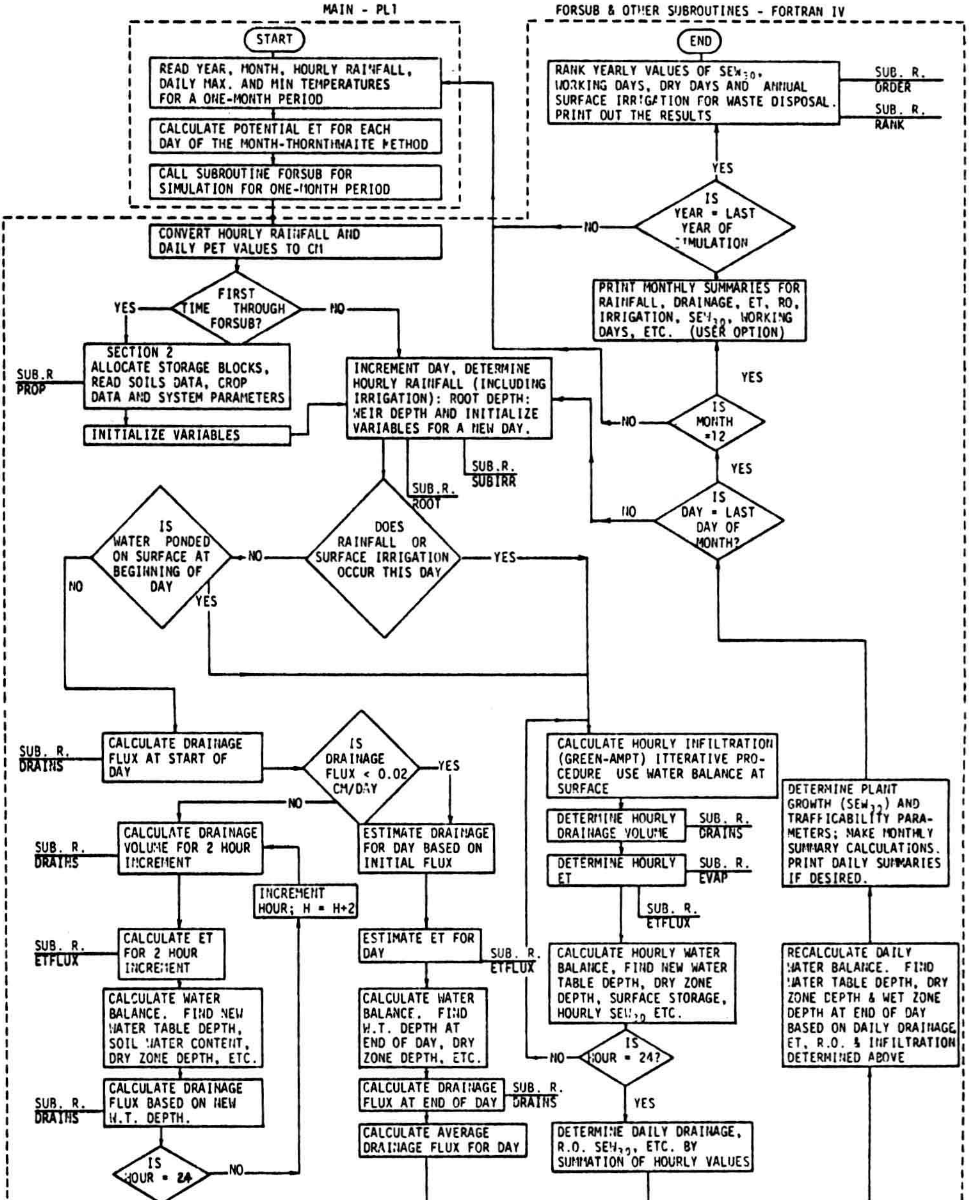

Figure 2. An abbreviated general flow chart for DRAINMOD.

initial water content and distribution, and surface conditions such as cover, crusting, etc.

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, 1969). Bouwer (1969) showed that it may also be used for nonuniform initial water contents. Resistance to air movement may 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. The equation parameters were simply modified to include effects of air movement.

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 is implicitly assumed in the Green-Ampt equation and in the parametric model proposed by Smith (1972). Smith showed that this assumption could be extended 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. Similar investigations by Reeves and Miller (1975) 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.

The model requires input for infiltration in the form of a table of A and B versus water table depth. The parameters A and B in equation 4 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. 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 interative procedure is used with equation 4 to determine the cumulative infiltration at the end of hourly time intervals. When the rainfall rate exceeds the infiltration capacity as given by equation 4, equation 2 is applied to conduct a water balance at the surface for Δt increments of 3 min. (0.05 hr). 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 4 until rainfall terminates and all water stored on the surface has infiltrated. Likewise, the same A and B values are used 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 are 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 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.

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 the present version of DRAINMOD. This equation may be written as,

$$q = \frac{8\ K\ d_e m + 4\ K\ m^2}{C\ L^2} \tag{5}$$

where q is the flux in cm/hr, m is the midpoint water table height above the drain (Figure 1), K is the equivalent lateral hydraulic conductivity, d_e is the equivalent depth from the drains to the impermeable layer, 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. 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 1 will tend to correct drainage fluxes predicted by equation 5 for convergence near the drains. Moody (1967) examined Hooghoudt's solutions and presented the following equations from which d_e can be obtained.

For $0 < d/L < 0.3$

$$d_e = \frac{d}{1 + \frac{d}{L}\{\frac{8}{\pi}\ln(\frac{d}{r}) - \alpha\}} \qquad (6)$$

in which

$$\alpha = 3.55 - \frac{1.6d}{L} + 2\left(\frac{d}{L}\right)^2 \qquad (7)$$

and for $d/L > 0.3$

$$d_e = \frac{L}{8\{\ln(\frac{L}{r}) - 1.15\}} \qquad (8)$$

in which r = drain tube radius. Usually α can be approximated as α = 3.4 with negligible error for design purposes (van Schilfgaarde, 1974).

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 (1950) 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. Their data was used by Skaggs (1978a) to define r_e for the 114-mm (4.5-in.) O.D. tubing that they used (standard 4-in. (100-mm) 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.

Use of equation 5 assumes 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 location and crops to be grown. When the flux given by equation 5 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 the 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.

The above discussion treats the soil as a homogeneous medium with saturated conductivity K. Most soils are actually layered with each layer having a different K value. Since subsurface water movement to a drain is primarily in the lateral direction, the equivalent hydraulic conductivity in the lateral direction is used in equation 5. The equivalent conductivity depends on the water table depth and is calculated in terms of the conductivities of the individual layer prior to every flux calculation.

Other methods for calculating the drain flux which considers convergence to the drains and layered profiles have been summarized by van Beers (1976). The most general is 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 graphical solution for some layered systems. The modified Hooghoudt-Ernst equation is also discussed by van Beers (1976) and could be easily employed in DRAINMOD.

Subirrigation

When subirrigation is used, water is raised in the drainage outlet so as to maintain a pressure head above the center of the drain of y_o (refer to the broken curve in Figure 1). Then the equation corresponding to equation 5 for flux is,

$$q = \frac{4K}{L^2}(2\ h_o\ m + m^2) \qquad (9)$$

where $h_o = y_o + d_e$ is the equivalent water table elevation at the drain and m is defined as $m = h_m - h_o$ with h_m being the equivalent water