Modeling variations in soil moisture and crop yield for an irrigated alfalfa field in southwestern Montana

by Daniel Bishop Harelson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Agricultural Engineering
Montana State University

Abstract:
The purpose of this study was to evaluate two computer models which can be used to predict variations in soil moisture with time and space as well as crop yield. This evaluation was performed using data from a sprinkler irrigated alfalfa field on the Montana State University Red Bluff Research Ranch. FORTRAN models named SPAW and Plantgro were selected for evaluation because they differ significantly in their random access memory requirements and because they were readily available. Both models perform a water budget for a selected number of soil layers using pan evaporation to estimate evapotranspiration. Crop yields are predicted using a linear relationship between potential yield and the ratio of actual to potential transpiration. The models were calibrated using soil moisture and yield data from 1979 while similar data from 1981 was used for testing. The results of this study indicated that the SPAW model predicted soil moisture variations somewhat more acurately than the Plantgro model. However, the Plantgro model predicted crop yield more accurately than the SPAW model. Unfortunately, the results of this study were subject to doubt because model calibrations were based on very limited data and the accuracy of some of these data was uncertain. More effective use of the available data would eliminate some doubt and provide a more reasonable basis for evaluating the models in terms of the accuracy of simulated results.

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Daniel Bishop Harelson

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

The purpose of this study was to evaluate two computer models which can be used to predict variations in soil moisture with time and space as well as crop yield. This evaluation was performed using data from a sprinkler irrigated alfalfa field on the Montana State University Red Bluff Research Ranch. FORTRAN models named SPAW and Plantgro were selected for evaluation because they differ significantly in their random access memory requirements and because they were readily available. Both models perform a water budget for a selected number of soil layers using pan evaporation to estimate evapotranspiration. Crop yields are predicted using a linear relationship between potential yield and the ratio of actual to potential transpiration. The models were calibrated using soil moisture and yield data from 1979 while similar data from 1981 was used for testing. The results of this study indicated that the SPAW model predicted soil moisture variations somewhat more acurately than the Plantgro model. However, the Plantgro model predicted crop yield more accurately than the SPAW model. Unfortunately, the results of this study were subject to doubt because model calibrations were based on very limited data and the accuracy of some of these data was uncertain. More effective use of the available data would eliminate some doubt and provide a more reasonable basis for evaluating the models in terms of the accuracy of simulated results.

CHAPTER 1

INTRODUCTION

Soil water is an important quantity in the hydrologic cycle since it is a water supply for plants, influences erosion and runoff and is percolated to groundwater reservoirs. The time and spatial distribution of soil water within the upper soil profile is the result of complex interactions between many variables related to current and past occurences of weather, crops and soil conditions. Computer models have been developed to provide methods for quantifying interactions between these variables so the time-depth distribution of soil water in an active soil profile can be predicted and related to crop yield. Two such computer models were examined in this study using data collected from an irrigated alfalfa field located on the Montana State University Red Bluff Research Ranch 35 miles west of Bozeman Montana.

Statement of Problem

The purpose of this study was to compare and evaluate two computer models which can be used to predict soil moisture and crop yield. The models which were selected for study differed significantly in their computational requirements. The accuracy of predicted soil moisture and yield values, the ease of calibration and application as well as computational requirements were used to provide a basis for comparing the models.

Stated in more specific terms, the objective of this study was to evaluate two computer models for use in predicting soil moisture and hay production from an irrigated alfalfa field.

To accomplish this objective, it was necessary to perform this study in the following stages:

1. Select models for study.
2. Analyze available data for the irrigated alfalfa field.
3. Make necessary modifications to the models so that they would be compatable with an AT&T 6300 microcomputer.
4. Calibrate the models to simulate changes in the time-depth distribution of soil moisture.
5. Test the capacity of the models to simulate changes in soil moisture.
6. Calibrate the models to simulate crop production.
7. Test the capacity of the models to predict crop production.

Literature review

A large number of computer models are available for the purpose of simulating evapotranspiration and soil water movement. A monograph published by the American Society of Agricultural Engineers (ASAE, 1982) includes a chapter outlining 75 models that could be used for this purpose or related purposes. Many of the models outlined in this publication simulate processes in addition to soil water movement and crop production. These processes include some or all of the following; flood routing, precipitation, snowmelt, infiltration, surface runoff, chemical movement and erosion yield.

A table summarizing the processes simulated and the areas where each model had been applied is included in this chapter. Following this table are abstracts and references for each of the 75 models. In addition, a second table including references for models that were under development at the time of publication is incorporated in this chapter. Another chapter which was particularly useful in this study dealt with the calibration and testing of hydrologic models. Other chapters in this monograph provide information regarding the development of approaches for modeling flood routing, precipitation, snowmelt, infiltration, surface runoff, evapotranspiration, subsurface flow, chemical movement and erosion.

The SPAW (Saxton et al., 1984) and Plantgro (Retta and Hanks, 1980) models were examined in this study because they differ in their computational requirements by an order of magnitude and they were readily available. In addition, they are frequently refered to in literature concerning computer modeling of soil moisture and crop yield. There are other computer models (Kanemasu et al., 1976; Goldstien et al. 1974) which are directly comparable to the SPAW and Plantgro models in terms of the predictions which are made. One such program is the PROSPER model developed at the Oak Ridge National Laboratory in Tennesee (Goldstien et al., 1974). This program calculates evapotranspiration using the combination equation and simulates liquid water flow using network equations. Unfortunately, documentation for this program could not be obtained while this study was in progress.

Considerable study has been devoted to the SPAW model in the past. The SPAW model has been calibrated and tested to simulate soil moisture and crop yield at study sites in western Iowa and central Missouri (Sudar et al., 1981). Corn and soybean yields were examined at these sites and the results showed that the SPAW model provided a practical and accurate approach for assessing water stress effects on crop yield. An additional study of the SPAW model tested the program for regional application to corn at 49 sites in Kansas, Missouri, Iowa and South Dakota (Saxton and Bluhm, 1982). The results of this study indicated that some local calibration of the model was required but that after a parameter set was established, crop yields could be predicted with moderate to good accuracy.

The SPAW model has also been compared with the Stockle-Campbell model (Stockle, 1983) in terms of their ability to predict winter wheat yields (Stockle and Saxton, 1984). The model comparison was based on winter wheat yields at two sites in Washington. Preliminary results of this comparison indicated that both models showed good predictive capability and might be useful for practical applications. However these results were based on calibration data only and additional work was necessary before any firm conclussions could be drawn. Additional work would involve testing the models using independent data from different years and locations.

In previous work with the Plantgro model, several variations of the model have been studied. One study tested the ability of the model to simulate corn dry matter and grain yield as well as sorghum dry matter yield (Hanks, 1974). This version of the Plantgro model differed from the one examined in this study in that the entire soil profile was represented as a single layer and evaporation was specified using a single seasonal value. Although the results of this study showed relatively good predictive capability, the model was not tested using data which were independent of the calibration year.

Another variation of the Plantgro model was studied using the modified Penman equation to evaluate evapotranspiration over the course of the growing season (Nimah and Hanks, 1973). This version differed from the one studied here in the way evapotranspiration was evaluated and in the way the movement of soil moisture was simulated. Soil moisture movement was simulated using a finite difference form of the Darcy equation for porous media flow. In addition, no attempt was made to simulate crop yield. The results of this study indicated that soil moisture movement could be simulated accurately after calibration. However, the model was not tested using data which were independent of the calibration data.

A version of the Plantgro model has also been used to simulate spring wheat grain yield (Rassmussan and Hanks, 1978). Grain yields were simulated at several sites in Utah for several years. These simulations predicted grain yield with errors of eight to thirty percent. However, the error of thirty percent was predicted for an anomolous year in terms of the length of the growing season. During this growing season, weather was warmer than normal and the planting date was significantly earlier than the planting dates of the calibration years.

The SPAW and Plantgro models have also been extended to predict soluble ion movement and the effects of salinity on yield. The SPAW model has been modified to simulate nitrate nitrogen movement and dissipation by considering additions, subtractions, storage and biological conversions represented as a time distribution (Saxton et al., 1977). In this extension of the SPAW model, the factors considered in the calculation of nitrate transport include; infiltration, soil water redistribution, percolation, plant uptake, fertilizer addition, rainfall addition, mineralization and nitrification. Although nitrate movement through diffussion was simulated, the effects of adsorption were not considered.

The Plantgro model has been extended to simulate the effects of salinity on crop yield and salt movement within the soil profile (Childs and Hanks, 1975). This extension takes into consideration effects of the irrigation amount and scheduling, irrigation water quality, initial soil salinity, crop type and uniformity of irrigation. A decreased osmotic potential was used to represent salinity effects on yield. Solute flow was modeled both in terms of bulk solution flow and solute difussion. The effects of adsorption as well as salt precipitation and dissolution were not represented.

In addition to the information described, two documents were essential to this study. These documents are the user's manuals for the SPAW (Saxton et al.,1984) and Plantgro (Retta and Hanks, 1980) models. The user's manual for the SPAW model is a publication that covers in detail every aspect of the operation of the SPAW model. The user's manual for the Plantgro model is a much smaller publication with insufficient detail. The user's manual for the Plantgro model was inadaquate because the units of measure used by the program are not clearly specified.

A paper titled "Evaluating wash tub evaporation irrigation scheduling" by Hanson (1984) provided useful information regarding previous study of the alfalfa field at the Red Bluff Ranch. In addition to discussing aspects of irrigation scheduling based on direct measurements of pan evaporation, this paper provided background information on the alfalfa field in question. This information included a summary of yield, soils and evaporation data as well as a description of the methods and materials used to plant the field.

CHAPTER 2

BACKGROUND INFORMATION

The SPAW and Plantgro models are predictive accounting procedures which produce a daily water budget for soil water within specified soil layers. These accounting procedures are governed by the major effects of weather, crops and soils. The primary purpose for developing these models was to improve predictions of infiltration, runoff, erosion and water quality. An equally important reason for developing these models was the assessment of available soil moisture throughout the growing season for agricultural crops. A number of secondary objectives can be approached through the application of these accounting procedures. These might include assesement of crop water stress effects on growth and yield, soil water influences on soluble ion distribution and the percolation of soil water for groundwater recharge. While the SPAW and Plantgro models were developed to represent a complex physical and biological system, the data requirements were restricted to those readily available through normal sources.

The diagram in Figure 1 represents the control volume considered by the SPAW and Plantgro programs to compute estimates of the soil water profile, actual evapotranspiration and deep percolation. Daily estimates of all of these quantities are made by the models to produce vertical water budgets. In the SPAW model, soil water profiles are estimated at a maximum time step of one to four hours as required to maintain computational stability. The soil profile is represented in the models by a selected number of layers and depths designed to

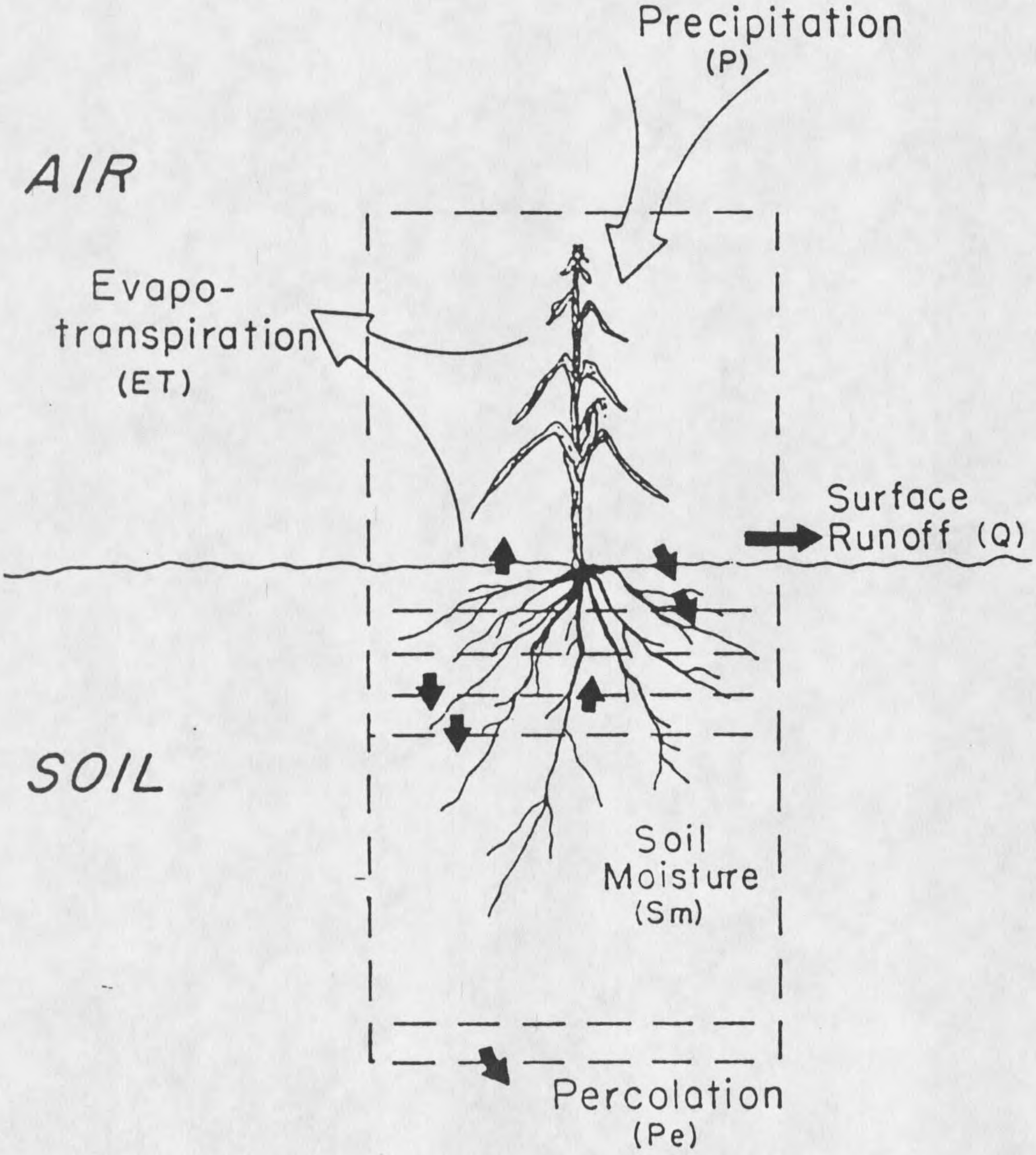

Figure 1. Control volume for the SPAW and Plantgro models.

reflect the average soil profile over the field or watershed being modeled. Each layer may be assigned a unique set of water holding characteristics and, in the case of the Spaw model, the unsaturated hydraulic conductivity of the layers can also be represented. The above ground portion of the control volume is assumed to be a uniformly distributed plant canopy.

SPAW model description

The general computational scheme used in the SPAW model is shown in Figure 2. In this computational scheme, potential evapotranspiration is determined independently and then reduced to an estimate of actual evapotranspiration. Susequent calculations divide the actual evapotranspiration into components of interception evaporation, soil water evaporation and plant transpiration. After subtracting the actual evapotranspiration from existing soil moisture by soil layers, daily infiltration is added. Then, soil water is redistributed based on a Darcian equation. A brief description of each element considered in this computational scheme follows.

Potential evapotranspiration

The potential evapotranspiration may be obtained from a variety of meteorological methods. As presented, the SPAW model estimates potential evapotranspiration from measured or estimated daily pan evaporation. The pan evaporation rates are reduced by a monthly pan coefficient to become estimates of potential evapotranspiration.

Interception

Interception of water by the crop canopy is simulated using a storage device with a maximum capacity representing potential

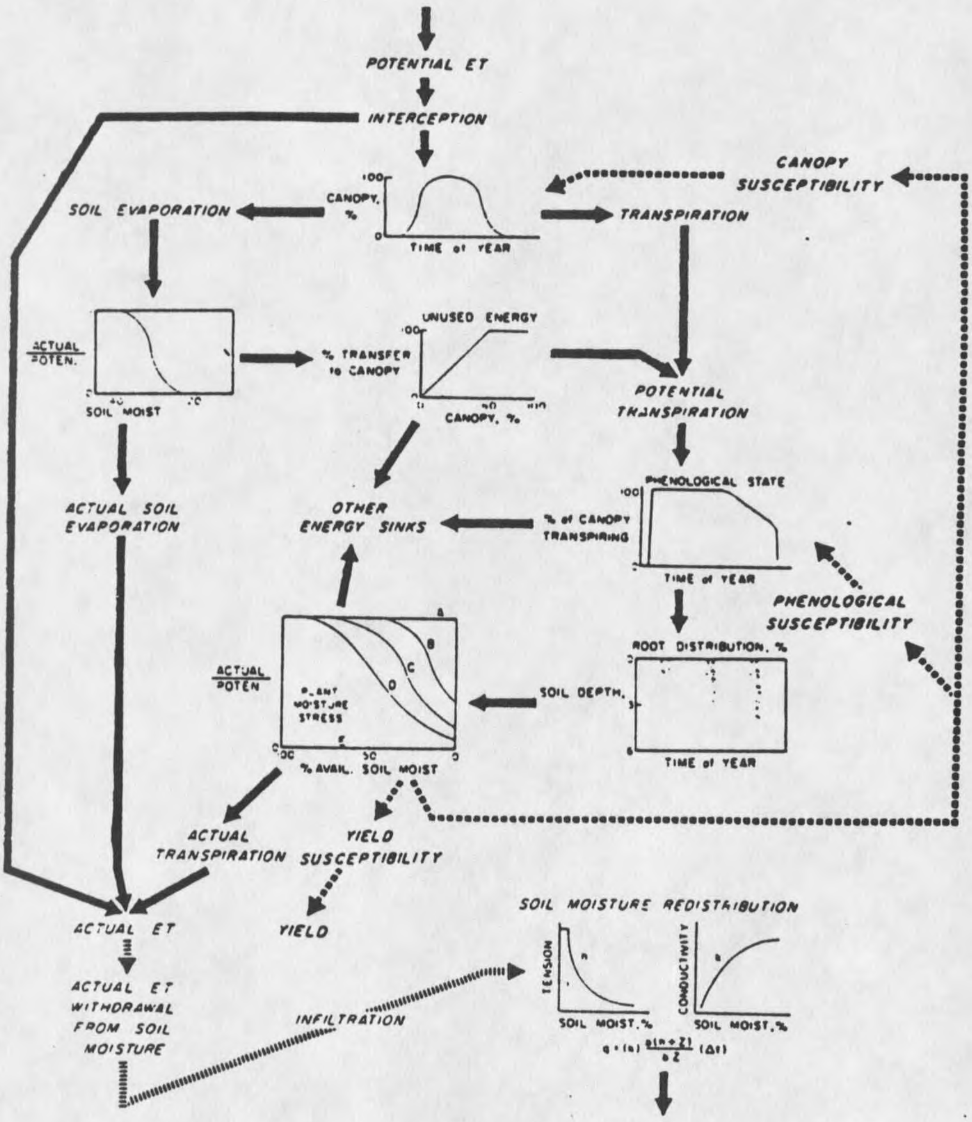

Figure 2. SPAW model computational scheme

interception. The potential evapotranspiration value is reduced by the amount of interception before transpiration and soil water evaporation are computed.

Crop canopy

Because solar radiation plays a major role in causing transpiration, the SPAW program uses crop canopy as an indicator of the proportion of the potential evapotranspiration that will be considered as transpiration from the crop canopy. Crop canopy is expressed as an annual time graph of the percentage of shaded soil. Values vary from zero for bare soils to almost 1.00 for dense canopies. Crop residues are treated as canopy cover because they provide soil shading which affects evaporation from the soil. The inability of crop residues to transpire is accounted for in the model by considering plant phenology.

For dry soil conditions with a partial canopy, there is some portion of the energy available for potential evapotranspiration which is not used for water evaporation. Unused energy heats the soil, the adjacent air and the canopy. As a result, the canopy has a second source of energy in addition to directly intercepted energy. To represent this effect, a linear relationship of canopy versus percent unused energy is incorporated into the SPAW model. When the canopy reaches sixty percent, all unused energy is captured by the canopy and it becomes part of the energy available for potential transpiration.

Plant phenology

A second annual time graph of a phenological factor is included in the SPAW model as a direct modifier of the crop canopy's ability to transpire. At times during the year when the canopy is not transpiring, the phenological factor takes on a value of zero. As the proportion of the crop canopy transpiring increases, the value of this factor approaches 1.0.

Soil water evaporation

In the SPAW program, a thin upper boundary layer is included in the soil profile incrementation. This layer has all of the functions of the other layers except plant roots are not present. In addition, water can be readily evaporated from this boundary layer and evaporation is limited only by potential evapotranspiration. Upward water movement from the second layer into the evaporative boundary layer is estimated by a Darcian equation using a small fraction of the unsaturated hydraulic conductivity for the current soil water content of the second layer. The conductivity reduction represents the fact that evaporation is by vapor flow rather than liquid flow and the effective conductivity is several magnitudes less.

Water uptake by plant roots

A simple description of a water extraction pattern with depth was programed into the SPAW model. For selected dates the percent of water to be abstracted from each soil layer is entered. Each distribution is applied to succeeding dates until a new distribution is specified to reflect root development. The entered water extraction distribution assumes that water is readily and equally available in all soil layers. Any water stress due to soil drying is considered in the crop water stress relationship.

Crop water stress

As the water supply to a plant becomes limited, physical and biological controls begin to limit the rate of transpiration. To account for this effect, several curves representing the ratio of actual to potential evapotranspiration (AT/PT) versus plant available moisture and potential evapotranspiration have been programed into the SPAW model. Several curves, shown in Figure 3, are included because a plant is more likely to attain a larger proportion of a lower potential evapotranspiration rate than it is a higher potential evapotranspiration rate. In the model, the programed curves are applied to each soil layer independently and the actual transpiration is a multiple function of the canopy, phenology and root distribution.

After estimating the daily plant actual transpiration, the SPAW program further estimates the magnitude of water stress as (1-(AT/PT)). This value is then used to calculate stress effects on canopy growth, phenologic development and yield. Stress effects on canopy and phenology are used to derive the plant status and adjustments are made to plant descriptors (canopy and phenology) for calculations on the subsequent day. These adjustments are such that prolonged water stress will severly limit plant growth or even cause plant death.

The capability to estimate how the daily crop water stress is integrated throughout the growing season to result in a final yield was also incorporated into the model. To represent the relative water stress susceptability in time and among crops, yield susceptability

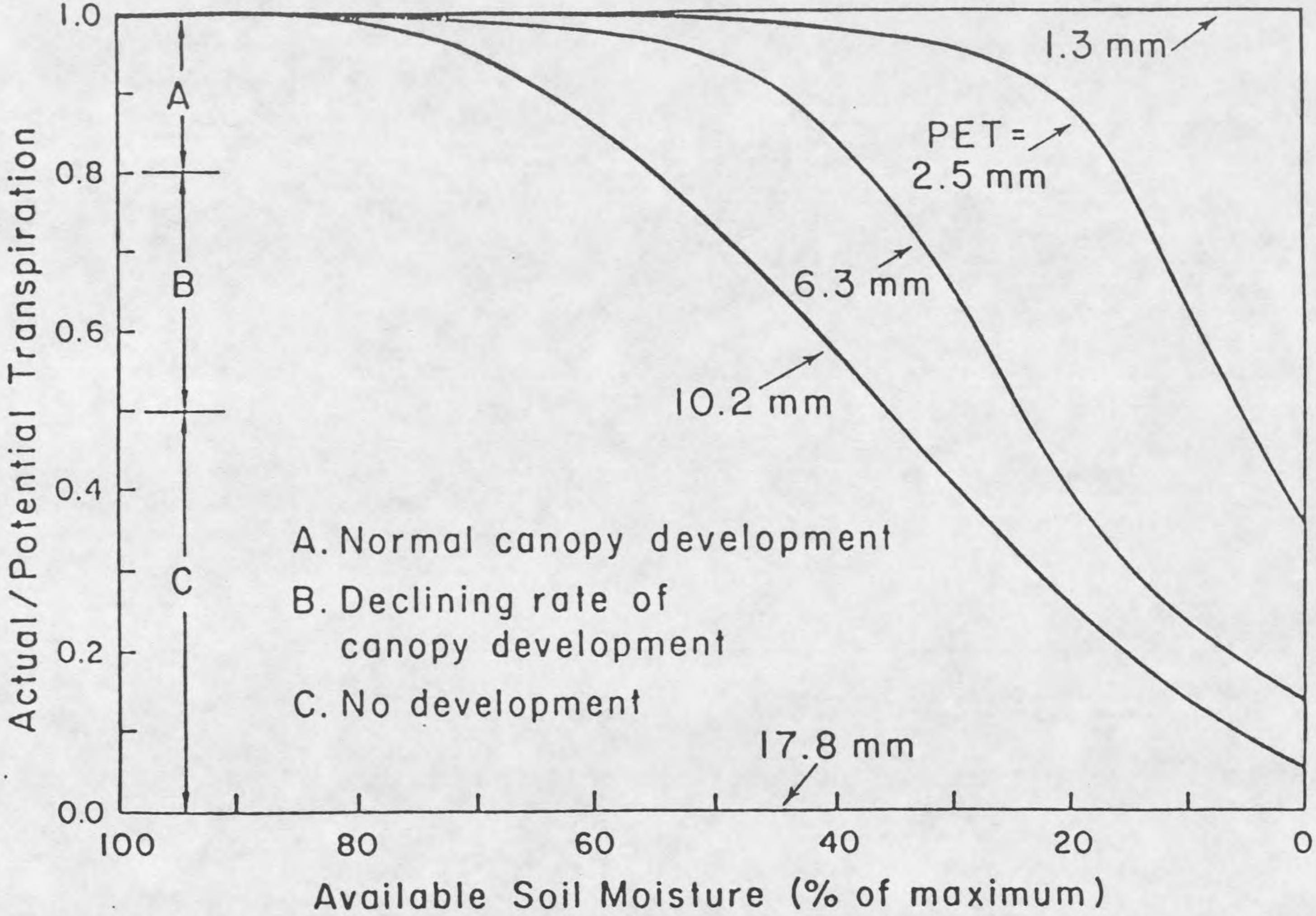

Figure 3. SPAW model moisture stress curves

relationships for particular crops must be developed and entered into the program. Yield reduction due to stress on a particular day is calculated as the product of the water stress on that day and a factor representing the susceptability of the crop to stress on the same day. The program provides relative stress indices which become meaningful only after they are correlated with observed yields from the study site or the region to derive a yield susceptability relationship.

Actual evapotranspiration

An estimate of actual evapotranspiration is obtained by adding the components of intercepted water evaporation, soil water evaporation and plant transpiration.

Infiltration

The Spaw model estimates a daily infiltration value for each day that has precipitation by one of two methods. If measured daily runoff data are available and correctly associated with a precipitation event, they are entered and infiltration is computed as precipitation minus runoff and interception. If measured data are not available, then a daily estimate of runoff is made by a modified version of the Soil Conservation Service curve number method.

The SCS curve number method estimates runoff based on a series of curves which indicate the percentage of precipitation which becomes runoff. A particular curve is selected for use based on tabulated values for various soil and crop combinations. The standard SCS method was modified in the SPAW model to utilize predicted estimates of crop canopy and soil moisture.

Daily infiltration amounts enter and move through the soil profile instantaneously in the Spaw model. Infiltrating water is added to the upper soil layers without exceeding their saturation capacity. Water is cascaded to deeper layers until adaquate storage is available for the infiltrated water. All further redistribution of water is done by the Darcian moisture redistribution routine.

Soil water redistribution

A simplified Darcian equation of water flow between soil layers was included in the SPAW program to evaluate soil water redistribution. The Darcy equation in finite difference form is:

$$q = K(\theta)\frac{(h(\theta) + \Delta Z)}{\Delta Z}(\Delta t)$$

where;

q is the estimated volumetric water flow per unit area per time step across layer boundaries ($cm^3/cm^2/hr$)

$K(\theta)$ is the mean unsaturated hydraulic conductivity of the two layers being considered. These conductivities are functions of the respective layer water contents (cm/hr).

$h(\theta)$ is the matric potential head difference between the two layers being considered as a function of their respective water contents (cm).

ΔZ is the distance between the midpoints of the layers being considered (cm).

Δt is the time increment (hr).

Many pressure and conductivity versus moisture content relationships were summarized from literature and classified by soil texture to provide a series of average relationships for estimating these when no others are available. However, there are input options to provide measured soil water characteristic data to the program or pressure and conductivity relationships can be calculated empirically by the model. Empirically calculated pressure and conductivity relationships are a function of soil texture and soil moisture. These relationships are described in a paper soon to be published in the Soil Science Society of America Journal (Saxton et al. 1986)

Summary of data requirements for the SPAW model

Weather data

Daily precipitation and irrigation amounts (cm).

Daily runoff-either observed or estimated by the model using the modified SCS curve number method.

Daily potential evapotranspiration-the model is now programed to use daily pan evaporation and monthly pan coefficients.

Crop data

Dates of planting and harvest.

Crop canopy- estimated soil shading percentage for selected dates which define a crop canopy curve.

Canopy susceptability-values to represent water stress effects on crop growth.

Crop phenology-values from 0.0 to 1.0 which describe the proportion of the canopy able to transpire on selected dates. These values and the corresponding dates describe a crop phenology curve.

Phenology susceptability-values to represent water stress effects on crop phenology.

Plant water extraction pattern-values for each soil layer for selected dates which reflect the expected water withdrawal percentage by the crop if water were readily and equally available throughout the soil profile.

Plant moisture stress curves-values describing the available soil water and evaporative demand effects on the ratio of actual to potential plant transpiration.

Yield susceptabilty-values describing the relative significance of water stress to yield throughout the crop growth period.

Soils data

Incrementation depths representing the soil profile and appropriate soil water characteristic curves for each layer. Curves can be selected from standard programed curves, user specified or calculated by the program.

Observed volumetric soil moisture values for each soil layer on each date entered. Used for initialization, or model calibration and varification.

Summary of output presented by the SPAW model

Daily and accumulated values of Potential and actual evapotranspiration, transpiration and soil water evaporation as well as precipitation, irrigation runoff and drainage.

Daily soil moisture values by soil layer.

Values for daily and accumulated crop water stress and yield reduction.

Plantgro model description

A simplified version of the flow chart for the Plantgro model is shown in Figure 4. This model operates by splitting evapotranspiration into its components of evaporation from the soil surface and transpiration from plants. Crop production is then predicted based on a linear relationship between transpiration and yield. Since evaporation from the soil surface does not contribute to plant growth, it is not included in the production relationship. Production estimation is based on an equation having the form;

Dry matter yield=P(AT/PT)

where;

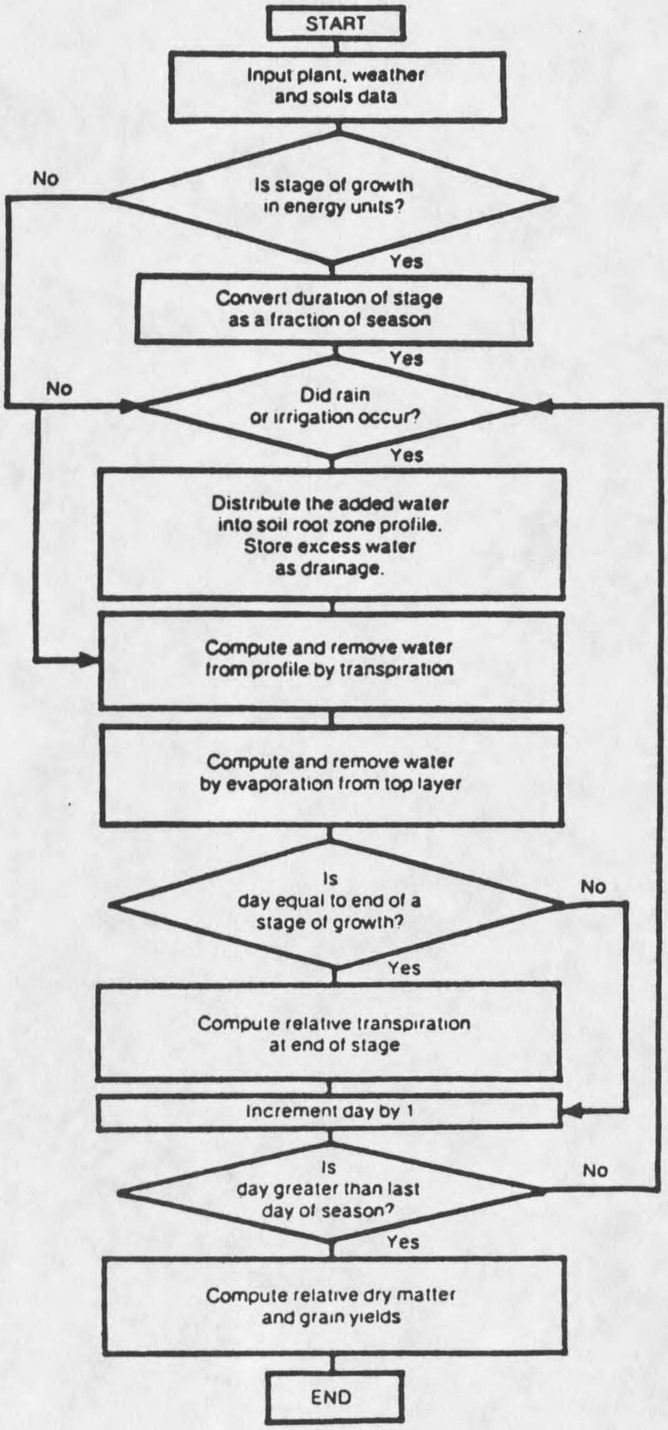

Figure 4. Plantgro model computational scheme

P is the potential dry matter yield if water is not limiting.

AT is the accumulated seasonal actual transpiration.

PT is the accumulated seasonal potential transpiration.

In addition to predicting dry matter yield, the Plantgro model also has the ability to predict grain production. Grain yield is predicted based on a relationship which accounts for the varying significance of moisture stress during different growth stages. This relationship is similar to that used to predict dry matter yield except the ratio of actual to potential transpiration is calculated for each stage of growth and raised to an appropriate power. Grain prodution is assumed to be the product of these ratios each raised to a power. Each ratio is raised to a power which represents the relative significance of moisture stress during the corresponding stage of growth.

Potential evapotranspiration is determined in the Plantgro model by multiplying observed pan evaporation by a seasonal pan coefficient. Daily values of pan evaporation or average values for several days may be supplied to the model. Potential evapotranspiration is split into its components of potential soil evaporation and potential transpiration using the following equations;

$$PT=Kt(PET)$$
$$PE=Ks(PET)=(1-Kt)(PET)$$

where;

PT is potential transpiration on a given day.
PE is potential soil evaporation on a given day.
PET is potential evapotranspiration on a given day.
Kt is the proportion of the PET that could be transpired.
Ks is the proportion of the PET that could evaporate from the soil.