SIMULATION OF IRRIGATION REQUIREMENTS FOR PARANA STATE, BRAZIL

By

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ABSTRACT

Ph.D. Agricultural Engineering

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Simulation of Irrigation Requirements for Paraná State, Brazil

A risk analysis of drought and an assessment of irrigation requirements were ascertained for a wheat (*Triticum aestivum* L.) crop in Paraná, Brazil, using 28 years of historical weather data. Two soil moisture models, The Versatile Soil Moisture Budget (VB4) and SWACROP models, were compared using data from six wheat cropping periods. The models showed good performance in predicting soil moisture contents, but SWACROP underpredicted soil evaporation and runoff, and VB4 did not separate evapotranspiration into its components. Therefore, a new soil moisture model was proposed. In the new model, a Darcy type equation was used to calculate fluxes in the soil profile, and inputs of daily rainfall and potential evapotranspiration were partitioned during the day using simple disaggregation methods. Crop growth input parameters, interacting with weather and soil inputs, were used to calculate a detailed output of the water balance components. The validation of the model showed predictions of soil water contents and evapotranspiration in close agreement with field data.

A crop yield model based on the stress day index approach was selected from an evaluation of seven crop-water production functions using wheat field data. This model was combined with the soil moisture model to assess risks of drought during the establishment and development of non-irrigated wheat crops with different planting dates. Irrigation management strategies were simulated to identify net system delivery capacities and application frequencies that promote maximum yield with minimum requirements of water. Yield reductions in non-irrigated wheat due to water stress varied between 16%, for early plantings, to 50%, for late plantings. Maximum yields with minimum applied water was obtained by the use of low intensity (5 to 10 mm) and frequent (3 to 5 days) irrigations. System delivery capacity requirements varied from 1.5 to 3.0 mm/day, according to planting dates.

RESUME

Ph.D. Génie Rural

Rogério T. de Faria

Simulation des besoins d'irrigation pour l'état de Paraná, Brésil

A partir d'une base de données météorologiques de plus de 28 ans, une analyse du risque de sécheresse et une évaluation des besoins d'irrigation d'une culture du blé dans l'état de Paraná au Brésil, furent entreprises. Dans un premier temps, deux modèles de calcul de l'humidité des sols, Versatile Soil Moisture Budget (VB4) et SWACROP, furent comparés en utilisant les données de six périodes de culture de blé. Les modèles firent une bonne prédiction du niveau d'humidité des sols, mais ne puirent s'addresser aux besoins de recherche dans le Paraná. Un nouveau modèle de calcul de l'humidité des sols qui prena en considération les avantages et limitations des deux modèles précédants fut proposé. Dans ce nouveau modèle, une équation du type Darcy fut utilisée afin de calculer les mouvements de l'eau dans le profil du sol. Les données quotidiennes de precipitation et d'évapotranspiration potentielle furent distribuées pour la durée de la journée en utilisant des méthodes simples de désagrégation. Les données de croissance des plantes en relation avec les données météorologiques et des sols, furent utilisées afin de calculer les différentes composantes de l'équation du bilan hydrique. La validation du modèle montra que les prédictions d'humidité du sol et d'évapotranspiration étaient en bon accord avec les résultats obtenus au champ. Le modèle ne requit qu'un temps de calcul assez court.

Un modèle d'estimation du rendement des cultures, basé sur le principe de l'indice de stress journalier, fut choisi et utilisé avec des données obtenues des champs de blé, afin d'évaluer sept fonctions de production eau-plante. Ce modèle fut rattaché au modèle d'humidité des sols afin d'estimer les risques de sècheresse durant l'établissement et le dévelopment du blé non-irrigué, planté à différentes dates. Des stratégies de gestion d'irrigation furent simulées, dans le but d'identifier la capacité nette necessaire du système d'irrigation et la fréquence d'application nécessaire à maximiser le rendement tout en minimisant l'apport d'eau. La réduction moyenne du rendement du blé cultivé en terres

non-irriguées causée par la sécheresse, varia entre 16% pour les récoltes hâtives, et 50% pour les récoltes tardives. L'irrigation permit de maintenir le rendement près du niveau maximal. Des irrigations de faibles intensités (5 à 10 mm) mais à des fréquences élevées (3 à 5 jours) réduisirent considérablement l'apport saisonnier d'eau requis. La capacité du système d'irrigation varia entre 1.5 et 3.0 mm/jour, selon la date du semis.

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I am grateful to Dr. Georges Dodds for proof-reading the manuscripts and translation of my abstract.

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I would like to dedicate this thesis to my parents (João and Alcinda) and my sisters and brothers for their love.

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MANUSCRIPTS AND AUTHORSHIP

The candidate has the option, **subject to the approval of the Department,** of including as part of the thesis the text, or duplicated published text, of an original paper or papers.

- Manuscript-style theses must still conform to all other requirements explained in the Guidelines Concerning Thesis Preparation.

- Additional material (procedural and design data as well as description of equipment) must be provided in sufficient detail (eg. in appendices) to allow clear and precise judgement to be made of the importance and originality of the research reported.

- The thesis must be more than a mere collection of manuscripts published or to be published. It must include a general abstract, a full introduction and literature review and a final conclusion. Connecting texts which provide logical bridges between different manuscripts are usually desirable in the interest of cohesion.

It is acceptable for thesis to include, as chapters, authentic copies of papers already published, provided these are duplicated clearly and bound as an integral part of the thesis. In such instances, connecting text are mandatory and supplementary explanatory material is always necessary.

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This thesis is of the format of a group of papers mentioned in Section 3 of Chapter I.

CHAPTER I

GENERAL INTRODUCTION

1. Introduction

The State of Paraná, in the south of Brazil (Figure 1.1), is a leading agricultural producer in the country. Paraná's total harvest is equivalent to 25% of the national yield (DERAL, 1990). In the north of the State, one of the most important economical region, the prevailing system is double cropping, where wheat is the winter crop followed by soybeans as a summer crop. On a small scale, maize and cotton are grown instead of soybeans (Vieira et al., 1990). In 1990, wheat was cultivated on a area of approximately 1.9 million hectares with a total production equivalent to 50% of the national yield (DERAL, 1990).

The soils of the northern region are predominantly Oxisols, which are characterized by a relatively high fertility, deep profile, fine texture, good drainage, lack of salinity, and a deep water table (EMBRAPA, 1984). The climate is classified as subtropical humid, with hot summer and cool winter. The area is frost-free and temperature conditions allow cropping throughout the year. The region has a good annual rainfall supply, with an annual precipitation of about 1,600 mm and potential evapotranspiration of approximately 1,300 mm. These conditions have allowed the development of an intensive agriculture without the use of irrigation.

In spite of the sufficient annual water supply, precipitation is pronouncedly variable during the seasons (Figure 1.2). Higher precipitation rates occur during November, December, and January (monthly averages above 150 mm), decreasing during June, July,

Figure 1.1. Geographical location of Paraná State, Brazil.

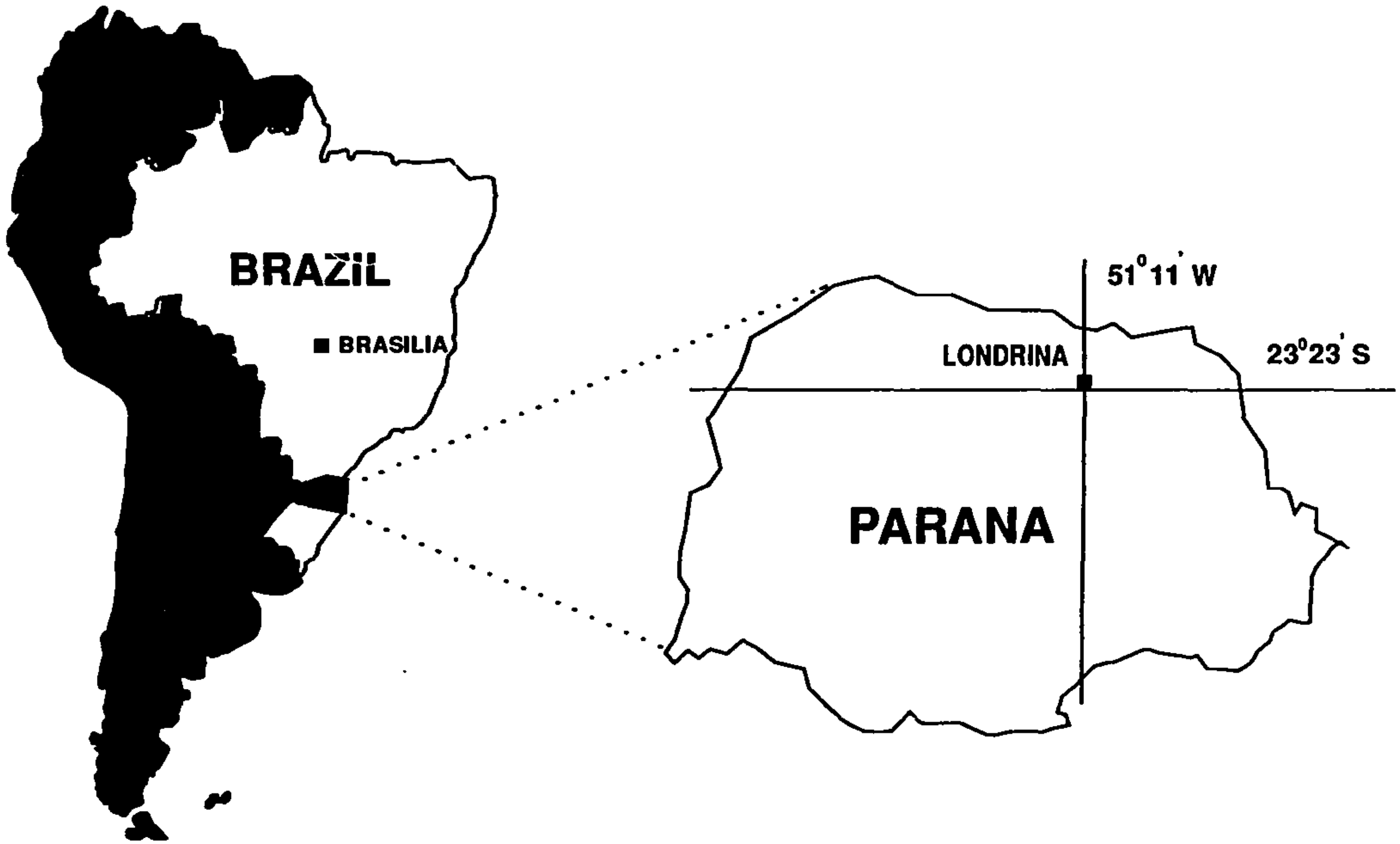
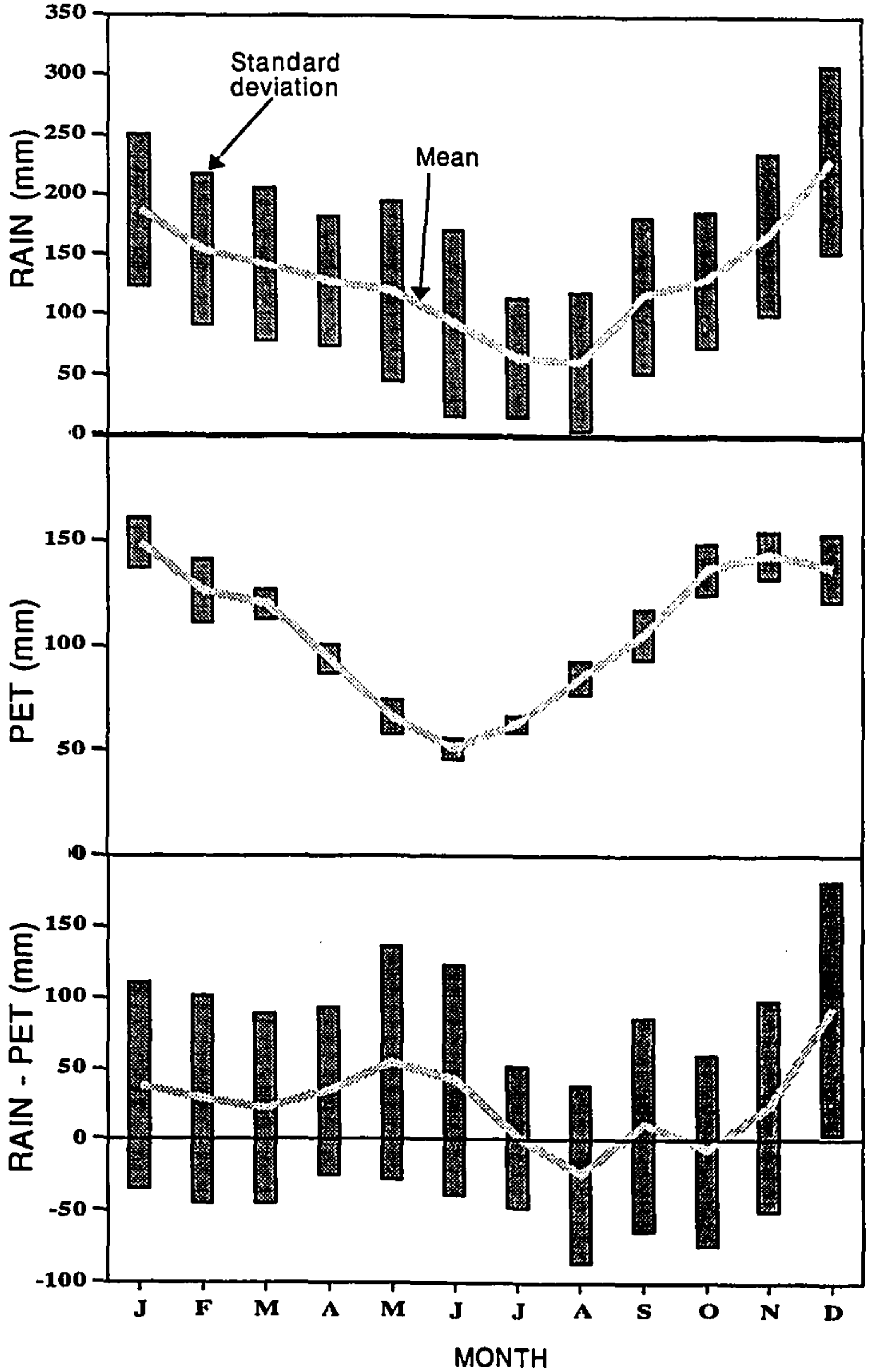

BRAZIL
BRASILIA
51°11' W
LONDRINA
23°23' S
PARANA

Figure 1.2. Monthly rainfall, potential evapotranspiration (PET), and difference between rainfall and PET for Londrina, Paraná. (Period 1978-1988).



RAIN (mm)
Standard deviation
Mean
PET (mm)
RAIN - PET (mm)
350
300
250
200
150
100
50
0
-50
-100
J
F
M
A
M
J
J
A
S
O
N
D
MONTH

and August (monthly averages below 100 mm). Potential evapotranspiration is less variable, with a maximum average (about 150 mm) recorded in January, and a minimum in June (about 50 mm). The resulting monthly average differences between rainfall and potential evapotranspiration are positive for all the months, except August. However monthly standard deviations of these differences indicate high risks of water deficit for the whole year, except December.

Periods of water deficit affect mainly wheat, which is grown from April to September. This irregular rainfall pattern, associated with degradation of soil organic matter and high soil compaction caused by the intensive cultivation, makes wheat a risky crop. Consequently, the timing of sowing wheat in Paraná is a critical management decision for farmers. Short periods without rainfall, associated with high evapotranspiration during the fall, make replanting a common practice in the region. Furthermore, wheat planting is often delayed because of the extension of the summer growing season until the end of April. As a result of the late wheat sowing, significant yield decreases occur, due to the coincidence of critical growth stages with periods of low rainfall in July and August.

In an attempt to minimize the impacts of drought on wheat yields, several experiments dealing with breeding, testing of cultivars, planting dates, and minimum tillage, have been conducted in Paraná (IAPAR, 1986). Although these techniques have shown some potential to improve yields, stabilization of the crop production using these practices is still a goal to be achieved in the long term.

Irrigation could be beneficial to increase yield and stabilize the year-to-year variation in crop production in Paraná. Supplementary irrigation is restricted to few areas in the region, despite the abundant water resources for irrigation supply. In 1989, the irrigated area was estimated at about 100,000 hectares, which represents less than 2% of the total cultivated area (8 million hectares), and only approximately 13% of the 850,000 hectares with potential for irrigation (SEAB, 1989).

The irrigated area can be expanded if economical. In addition, irrigation should not cause undesirable effects on the environment, such as soil degradation and pollution of surface and underground water. These conditions could be achieved if appropriate information for design and management of irrigation systems is available, allowing for maximum crop production with minimum water, energy and costs of irrigation systems, without increasing erosion and leaching of nutrients and pesticides. Furthermore, in order to assess the benefits of irrigation, the effects of drought on non-irrigated crop yields have to be known.

There is little information on irrigation of wheat or other crops in the region. Preliminary experiments have shown that irrigation can increase wheat yield from 30 to 70% in years of moderate to severe drought (Okuyama and Costa, 1990; Okuyama and Riede, 1990).

Estimates of climatic risk and crop water requirements may be obtained by observation or by experimentation using models. Due to the high costs and expensive time commitment involved with surveys or field trials, crop models are more appropriate to perform risk analysis of drought and to assess potential crop response to irrigation. Specific management practices may be replicated over a number of seasons, using either historical or synthetic weather data, so that the variability of performance can be measured (Harrison et al., 1989). In applying a computer model, its credibility must be established by validating it for the conditions of the study area. Usually, some calibration or adjustments of input parameters are also required. Eventually there is need for adaption on some of the processes, or even the development of a new model in order to address a specific study.

Despite a great availability of models in the literature, only two models have been used so far in Paraná. Caramori and Faria (1987), and later Caramori et al. (1991), used a simple model to evaluate risks of drought for different crops in the State. While the results were useful in identifying and comparing areas with water deficits, they did not provide accurate information to quantify crop water demands and aid in the design of irrigation systems. The other study was conducted by Gomes (1988) using a crop model (Stewart and Dwyer, 1986) to predict maize yield on different planting dates. The use of this crop model for studies of irrigation is limited, because of the simplifications of the computations of soil moisture contents and fluxes by the assumption of a soil profile with only three layers.

2. Objectives

The major objectives of this research were to:

1. Compare the performance of two soil moisture models in predicting water balance components for wheat production in the State of Paraná.

2. Adapt the most appropriate soil moisture model, or develop a new model, to address specific research needs in water management in Paraná.

3. Link different crop yield models with the soil moisture model developed to evaluate their performance in predicting wheat yield.

4. Perform a risk analysis of drought during the establishment and development of a non-irrigated wheat crop, using the model developed in item 3.

6. Establish recommendations for irrigation water management strategies for wheat.

3. Method of presentation

The above objectives were achieved and reported in Chapters II to V, in the form of four papers suitable for journal publication with the following titles:

a) A comparison of the Versatile Soil Moisture Budget and SWACROP models in Brazil.

b) Modelling soil water balance and simulation of hydrological components for a wheat crop in a subtropical climate.

c) Evaluation of crop-water production functions for wheat in Brazil.

d) Risk analysis of drought and irrigation requirements for wheat in Parana, Brazil.

A complete literature review is presented in each paper. A general conclusion is given in Chapter VI, followed by claim of original contribution to knowledge in Chapter VII, and recommendations for future research in Chapter VIII.

The author of this thesis designed, directed, and analyzed the results of all this research.

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CHAPTER II

A COMPARISON OF THE VERSATILE SOIL MOISTURE BUDGET AND SWACROP MODELS IN BRAZIL

ABSTRACT

SWACROP, a transient, one-dimensional, finite-difference soil water model, and the Versatile Soil Moisture Budget (VB4), a semiempirical model, were compared using data from six wheat (*Triticum aestivum*, L) cropping periods in Paraná, Brazil. Locally available input parameters were used in SWACROP and field calibrated coefficients were utilized in VB4, in order to assess their ability to predict soil water regimes and other hydrological variables.

Predictions of soil moisture content and water storage by the two models were comparable, and corresponded very well with field measurements. Largest deviations occurred in the top soil compartment (0-10 cm). The average absolute difference and standard error of estimate between predicted and observed soil water storage over the six cropping periods were less than 1.22 cm and 1.72 cm, respectively.

SWACROP predicted higher percolation and lower evapotranspiration and runoff than VB4, due to differences in methods of simulating soil water distribution and actual soil evaporation.

INTRODUCTION

In the State of Paraná, Southern Brazil, wheat is cultivated on approximately two million ha during winter (March-September). The Northern region of the State has a subtropical humid climate with highly variable rainfall during the year, mostly experienced during the wheat growing period. This is considered as the dry season. During this period, 75% of the 16 cm annual water deficit occurs. The peak demand for irrigation is in July and August.

Reliable estimates of soil moisture and evapotranspiration can provide basic information to improve agricultural practices such as determination of appropriate planting dates and irrigation requirements. This knowledge can contribute to increased crop productivity and water use efficiency. Furthermore, this information can be used to build crop yield models.

There have been few studies on crop water requirements for Paraná State. Caramori and Faria (1987) and Caramori et al. (1991) used a simple model to evaluate risks of drought for economic crops at different locations of the State. While these studies were useful in identifying and comparing areas with water deficits, they did not provide accurate information to quantify crop water demand and design of irrigation systems.

In the past two decades numerous soil moisture models have been developed with varying degrees of sophistication. Model choice depends on the nature of the study and availability of input data and resources (Silva and De Jong, 1986). However, physical and semi-empirical models are likely to be most appropriate for simulating the dynamic processes of water flow in the soil-plant-atmosphere system.

Physically-based models use measured input and comprehensive methods to calculate water contents and fluxes. They require minimal local calibration and give detailed and accurate output of hydrological variables. A major disadvantage of these models is their requirement for very detailed input data. This often limits model performance, especially if there are inaccuracies in inputs (De Jong, 1988). Moreover, the use of relatively small soil depth and time increments frequently leads to excessive computational time.

Semi-empirical models incorporate the major physical processes encountered in the soil-plant-atmosphere system, using a simplified biophysical approach and statistically derived coefficients obtained from field observations. These models have the advantage of requiring simple and easy-to-obtain input parameters, and have a low computational time, since a large time step is used. However, some soil moisture measurements are required for model calibration. In general, model output is readily applicable to irrigation scheduling and soil moisture studies, but is not sufficiently detailed for crop yield models. This is because transpiration is considered to be more directly related to plant water stress and the resulting yield reduction, than is the combined value of evapotranspiration given by semi-empirical models (Hanks and Rasmussen, 1982).

The Versatile Soil Moisture Budget (Baier et al., 1976; Dyer and Mack, 1984) and SWACROP (Feddes et al., 1984) are widely used models and represent semi-empirical and physical approaches, respectively. The Versatile Soil Moisture Budget performed well when compared to a semi-empirical model (SPAW model, Saxton et al., 1974) in Canada (De Jong and Zentner, 1985) and a physically-based model in Northeastern Brazil (Silva and De Jong, 1986). It was also was used to simulate irrigation requirements for different crops in Quebec (Gallichand et al., 1991). SWACROP and its early version SWATRE (Belmans et al., 1983) are used extensively in Europe (Feddes et al., 1988; Wesseling and Van den Broek, 1988) and have also been employed in North America (Prasher et al., 1986; Prasher et al., 1987; Workman and Skaggs, 1989).

The purpose of this paper is to compare the performance of the SWACROP and the Versatile Soil Moisture Budget models, in predicting water balance components for wheat production in Paraná State, Brazil. In future studies, the model with better capability to estimate soil moisture contents and evapotranspiration may be incorporated into crop growth models, in order to establish regional risks of drought, crop water requirements, and irrigation scheduling.

DESCRIPTION OF THE MODELS

SWACROP model

SWACROP (Feddes et al., 1984) combines a soil moisture model, SWATRE (Belmans et al.,1983), and a crop model, CROPR (Feddes et al., 1978). The version of SWACROP used in this study was provided by Wesseling et al. (1989).

SWACROP is based on numerical solutions of the transient, one dimensional Richard's equation with a sink term to describe soil water-root uptake:

$$\frac{\partial h}{\partial t} = \frac{1}{C(h)} \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - \frac{S(h)}{C(h)} \qquad (1)$$

where:

h is hydraulic head (cm), t is time (days), z is soil depth (cm), C(h) is specific soil moisture capacity ($\delta\theta/\delta h$ in cm^{-1}) with θ being volumetric soil water content (cm^3/cm^3), K(h) is unsaturated hydraulic conductivity (cm/day), and S(h) is volume of water taken up by roots, the sink term (cm/cm.day).

The sink term, S, represents actual transpiration and is a function of h, as described by Feddes et al. (1978):

$$S = \alpha(h)\, S_{max} \tag{2}$$

where S_{max} is the maximum possible extraction by roots and may assume a homogeneous distribution with depth:

$$S_{max} = \frac{PT}{z} \tag{3}$$

or a decreasing function of depth:

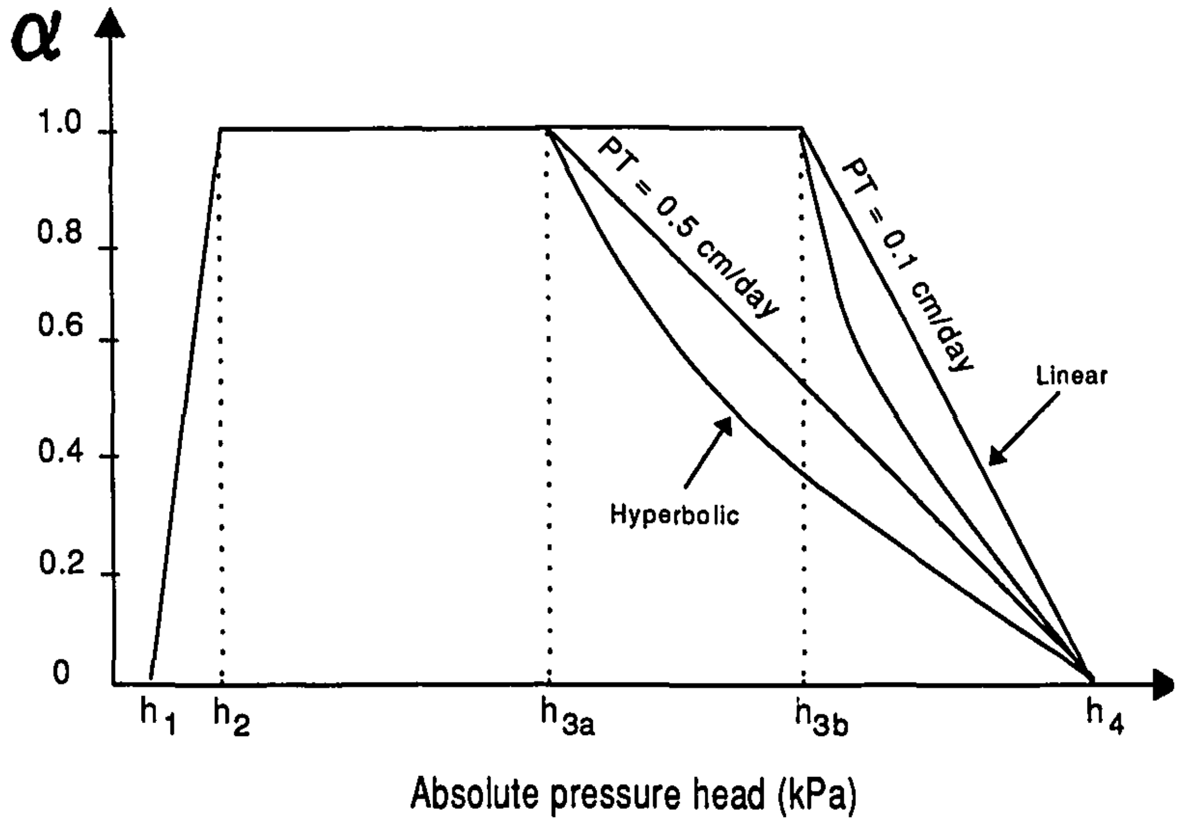
$$S_{max} = a - \frac{b}{z} \tag{4}$$

where PT is potential transpiration, z is rooting depth, and a and b are empirical parameters.

The parameter $\alpha(h)$ is a prescribed function which represents root soil-water extraction characteristics of each crop. As illustrated in Figure 2.1, the function $\alpha(h)$ increases from 0 to 1 in the interval of pressure heads between which the roots start to extract water and reach optimum extraction (h_1 to h_2); remains constant in the interval in which roots have optimal water extraction (h_2-h_3); and finally decreases linearly or hyperbolically to 0 at a pressure head equivalent to wilting point (h_3-h_4). The value of h_3 is variable and dependent on atmospheric demand. It is interpolated in the range from h_{3a} to h_{3b}, as potential transpiration varies from a higher to a lower rate (Figure 2.1).

The soil system can be divided into as many as five layers of differing physical properties, and up to 40 compartments, either equally or unequally spaced. Daily rainfall,

Figure 2.1. General shape of the dimensionless sink term α as a function of soil pressure head.



α
1.0
0.8
0.6
0.4
0.2
0
PT = 0.5 cm/day
PT = 0.1 cm/day
Linear
Hyperbolic
h 1
h 2
h 3a
h 3b
h 4
Absolute pressure head (kPa)

potential soil evaporation, and potential transpiration are the boundary conditions at the soil surface. Potential transpiration and soil evaporation can be given directly as input to SWACROP when available, or can be calculated from a combination of evapotranspiration equations, such as those of Penman, Priestely-Taylor, and Monteith-Rijtema (Jensen et al., 1990).

Boundary conditions at the bottom of the soil profile may either be in the saturated or unsaturated zone. They can be either given as daily input or calculated. For unsaturated soil profiles there are three choices : a) zero flux, b) free drainage (flux equal to hydraulic conductivity), and c) flux calculated as a function of prescribed pressure head at the bottom of the profile. In case of saturated flow at the bottom, the groundwater level can be given as input. The groundwater level, however, can also be calculated when the flux from or toward the saturated zone is known. The flux can either be given as daily input or be computed for each time step. Two possibilities of flux computations are included in the program: from a flux-groundwater level relationship which must be known, or from a combination of fluxes from/to ditches (subirrigation/drainage) and from/to deep aquifers (seepage/deep percolation).

SWACROP requires a detailed input of soil hydraulic properties and seasonal crop growth characteristics. Soil water retention data and the unsaturated hydraulic conductivity function must be input for each soil layer. Rooting depth, soil cover, and leaf area vary with time and are also model inputs.

Potential transpiration (PT) is calculated as the difference between potential evapotranspiration (PET) and potential soil evaporation (PE). Potential soil evaporation is given by the following Beer's law relationship (Belmans et al., 1983):

$$PE = e^{(-0.6\,LAI)}\ PET \tag{5}$$

where LAI is the leaf area index (cm^2/cm^2) and -0.6 is an attenuation coefficient for solar radiation in the canopy.

Actual soil evaporation (AE) is evaluated according to Black et al. (1969) as:

$$AE = \lambda\,(t+1)^{0.5} - \lambda\,t^{0.5} \tag{6}$$

where λ and t are, respectively, empirical soil dependent factor and time (days) after the start of a dry period. Dry periods end when an arbitrary depth of precipitation occurs.

Daily rainfall is considered to be uniformly distributed over a 24 hour period and the potential flux through the soil surface is calculated by the equation:

$$q = PE_r - (P - E_{itc}) \tag{7}$$

where q is the flux of water, PE_r is reduced potential soil evaporation, P is precipitation, and E_{itc} is intercepted rainfall by the canopy, all in cm/day. PE_r is estimated as the minimum value of potential and actual soil evaporation and E_{itc} is evaluated as a function of depth of precipitation and percentage of soil covered by the crop or soil cover (S_c), according to Belmans et al. (1983). For precipitation less than 2 cm/day, E_{itc} is calculated by:

$$E_{itc} = 0.169\,S_c P^{[0.516-0.179\,(P-0.0593)]} \tag{8}$$

and for precipitation greater than 2 cm/day:

$$E_{itc} = 0.19\,S_c \tag{9}$$

In the case of positive flux at the soil surface (evaporation), actual evaporation rate is taken as the minimum of q in Equation 7 and the flux governed by Darcy's equation q_1, from the upper compartment to the soil surface, at which the pressure head h_0 is assumed to be in equilibrium with the surrounding atmosphere. In the case of negative flux (infiltration), the actual infiltration rate is also governed by the Darcian flux q_1 from the soil surface ($h_0 = 0$) to the upper compartment. It is the minimum of q and q_1.

The model gives a detailed output of the water balance of the soil profile, including daily calculations of water content and pressure head, infiltration, percolation, runoff, irrigation, canopy interception, potential and actual transpiration, soil evaporation, and root water extraction in each compartment of the soil profile.

The Versatile Soil Moisture Budget model

The Versatile Soil Moisture Budget-version four (VB4) (Boisvert et al., 1992a,b) is an improvement of the previous versions described by Baier and Robertson (1966) and Dyer and Mack (1984). The model calculates components of the water balance on a daily basis including actual evapotranspiration, percolation, runoff, surface ponding, and soil moisture contents for different depths of the soil profile. VB4 uses measured input parameters, such as daily rainfall, potential evapotranspiration, soil water characteristics (saturation, field capacity, and permanent wilting point moisture contents), and dates of phenological stages. Other inputs consist of empirical coefficients of drainage, runoff, and soil water extraction characteristics by the roots.

The soil profile is divided into several compartments. Upward flux is represented by the extraction of water from each compartment of the profile by actual evapotranspiration, according to the following equation:

$$AET = \sum_{j=1}^{n} K_{ij}\ Z_j\ PET \tag{10}$$

where:

AET - daily actual evapotranspiration (cm/day),

n - number of soil compartments,

K_{ij} - rooting coefficient accounting for root activity in the j^{th} compartment during the phenological stage i (dimensionless),

Z_j - empirical function representing different types of soil dryness curves (dimensionless),

PET - daily potential evapotranspiration (cm/day).

The rooting coefficient (K_{ij}) represents the characteristics of water extraction by the crops. It is linearly interpolated from one phenological stage to another for each compartment of the profile, in order to simulate changes in rooting depth and density during the growing season. These coefficients can be obtained from calibration by comparing measured soil moisture contents under a specific crop and site with computed values. Optimization subroutines based on an iterative process are used to determine the set of coefficients K_{ij} that produce the least square deviation between measured and predicted soil moisture contents. Rooting coefficients can also be obtained from the literature (Dyer and Dwyer, 1982; Dyer and Mack, 1984). Gallichand et al. (1991) defined the coefficient K_{ij} as equal to the crop coefficient(K_c) of Doorenbos and Pruitt (1977). In order to represent root activity for each soil depth, Gallichand et al. (1991) divided the rooting depth into four root layers of equal thickness. To each of these layers they assigned a value corresponding to 40, 30, 20, and 10% of K_c. These root layer crop coefficients were then adjusted to fit the soil layering pattern defined in their experiment.

The function Z is related to the unsaturated hydraulic conductivity and the ability of the crop to extract water from each compartment. It can be expressed as the ratio of actual to potential daily evapotranspiration (AET/PET) which is a function of the soil moisture status in each soil compartment. This function is reflected by the ratio of actual to potential available water (S_j/C_j), derived from the soil dryness curve (Figure 2.2). For this curve, Z is equal to 1 from soil saturation to a specific S_j/C_j value (R). At this point, evapotranspiration changes from potential to actual and the curve may assume either linear, concave, or convex shapes. Equation 11 defines Z as a function of the remaining available water (Sj/Cj) (Dyer and Baier, 1979):

$$Z_j = \frac{X^{hmn}}{R}\left[\frac{X^m}{R}\,\frac{n}{X} + \frac{(R-X)^n}{R}\,\frac{m}{R}\right] \tag{11}$$

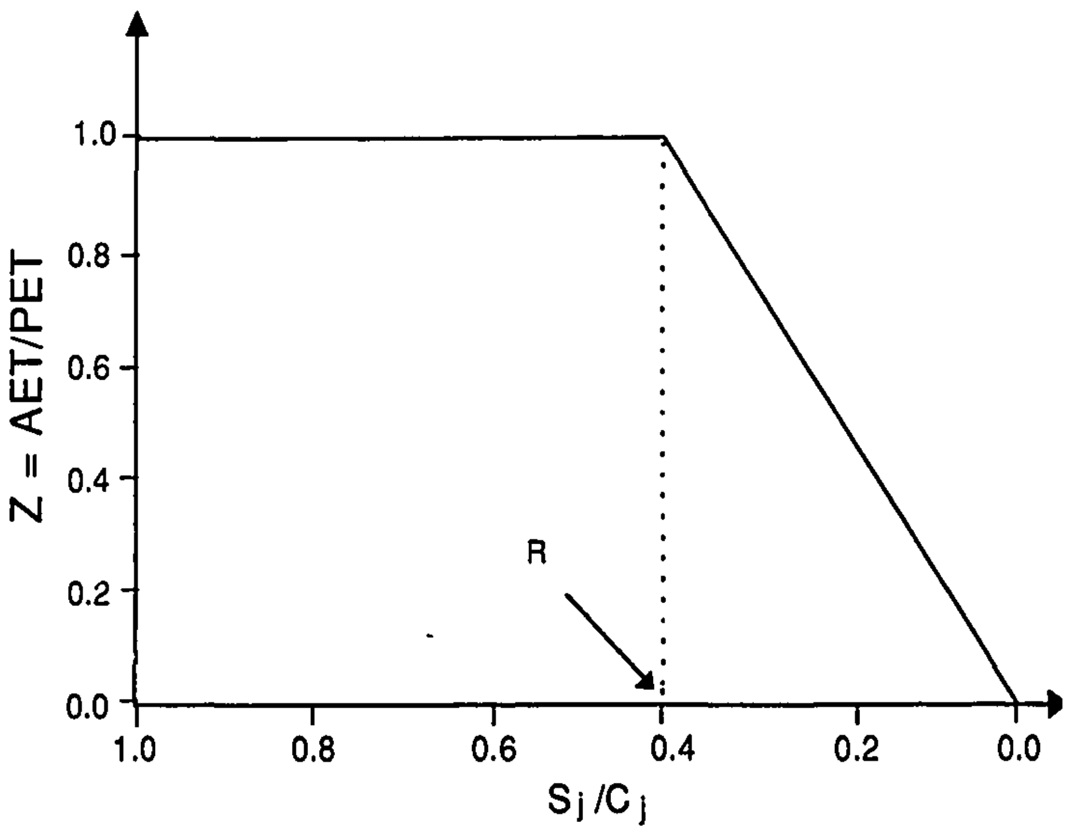
where

$X = S_j/C_j$ and $X \leq R \leq 1$.

The empirical coefficients h, m, and n vary from 0 to 1 and govern the shape of the curve in the of R to zero available water. The coefficients R, m, n, and h can be obtained from the literature (Dyer and Mack, 1984; Boisvert and Dyer, 1987), or by calibration procedures similar to those described for root coefficients.

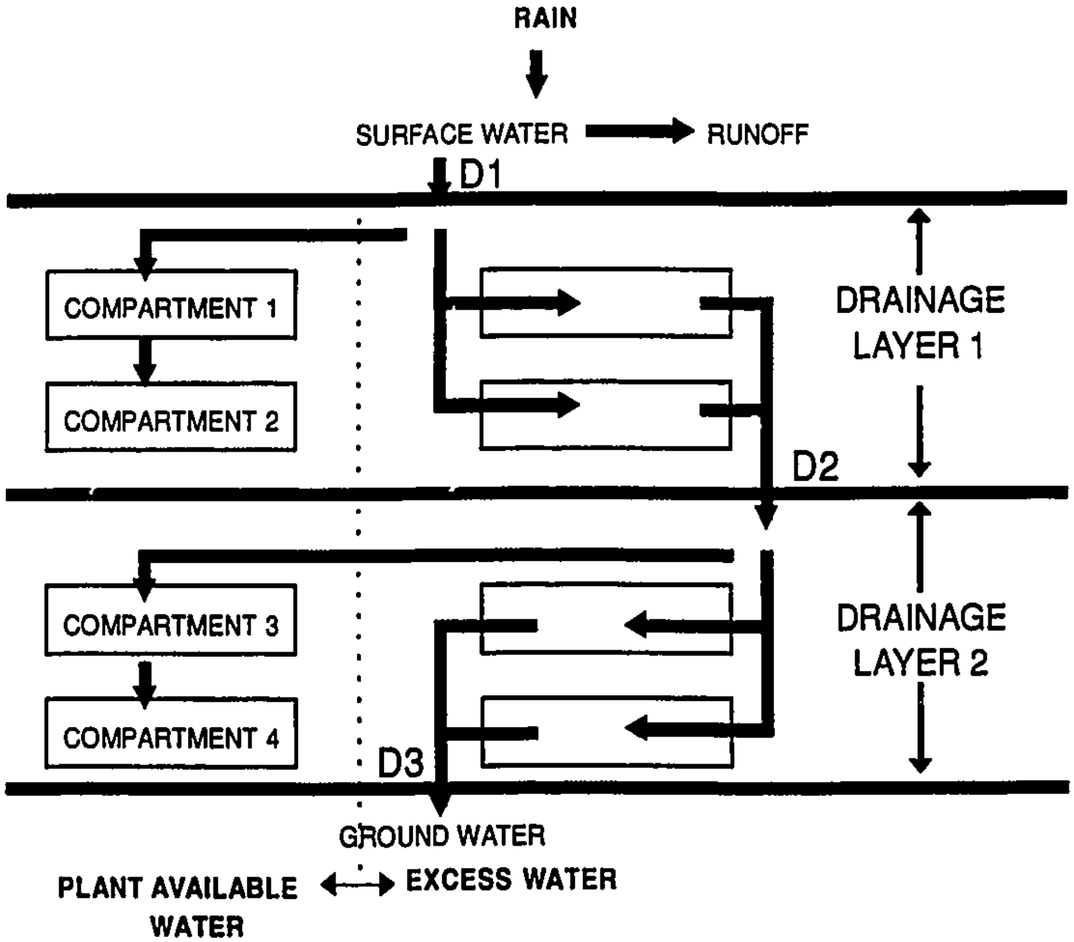
Infiltration and drainage are described by a simple two zone budget, as illustrated in Figure 2.3 (Dyer and Mack, 1984). The soil profile is divided into two drainage layers, containing one or more compartments. The thickness of the first drainage layer is empirically defined as the depth of a wetting front caused by the daily average precipitation. VB4 does not account for any water redistribution in the profile when soil

Figure 2.2. Dimensionless factor Z as a function of remaining fraction of soil available water (S_j/C_j).



1.0
0.8
0.6
0.4
0.2
0.0
Z = AET/PET
R
1.0
0.8
0.6
0.4
0.2
0.0
Sj /Cj

Figure 2.3. Schematic representation of the drainage submodel in VB4.



RAIN
SURFACE WATER
RUNOFF
D1
COMPARTMENT 1
COMPARTMENT 2
DRAINAGE LAYER 1
D2
COMPARTMENT 3
COMPARTMENT 4
DRAINAGE LAYER 2
D3
GROUND WATER
PLANT AVAILABLE WATER
EXCESS WATER

moisture content is below field capacity. Only the excess water (water content above field capacity) is allowed to drain from upper to lower compartments. The excess water from precipitation added to the compartments of the first drainage layer is delayed for one day before draining to the second layer. Three coefficients control the maximum depth which can be drained through three points of the profile (Figure 2.3):

a) the depth of water which can infiltrate from the surface to the first drainage layer (D_1),

b) the depth which can enter into the second drainage layer(D_2), and

c) the depth which percolates to the deep groundwater (D_3).

An additional coefficient D_4 describes the drainage rate of excess water from the first to the second drainage layer. D_4 defines a fraction of the excess water in drainage layer 1 that can drain into drainage layer 2 during each day. This ensures that a certain amount of excess water persists in the first drainage layer until the next day.

Ponded water at the soil surface is produced either when precipitation exceeds the limit fixed for the drainage coefficient D_1 or when the storage capacity of the compartments included in the first drainage layer is exceeded.

Ponding and excess water in the first soil compartment are allowed to evaporate at zero resistance (Ev). In this case, daily evapotranspiration is increased by adding Ev to the value of actual evapotranspiration (AET) calculated in Equation 10. Ponded water is evaporated first using the available energy from the difference between potential evapotranspiration (PET) and AET calculated in Equation 10. When the depth of ponding is less than the available energy, it is totally evaporated and the remaining amount of energy is then used to extract excess water from the top compartment.

Runoff (RUN) in cm/day is found by the following equation:

$$RUN = POND * COEF * \frac{ES_1}{EC_1} \tag{12}$$

where COEF is an empirical coefficient (varies from 0 to 1), ES_1 is actual and EC_1 is maximum excess water in the first compartment.

The number of soil compartments in the first drainage layer and the coefficients of drainage (D_1, D_2, D_3) and runoff (COEF) are also obtained from calibration by comparing observed and predicted soil moisture contents using the optimization subroutines in VB4. This is similar to the procedure described for calibration of rooting coefficients and parameters of the soil dryness curve.

METHODS

Field Measurements

The models were tested against field data collected at the Experimental Station of the Instituto Agronômico do Paraná (IAPAR) in Londrina (Latitude 23°23'S and Longitude 51°11'W).

Wheat cultivar IAPAR 9 (Tapejara) was sown at a density of 500 plants/m^2 in 20 m x 20 m (0.04 ha) plots replicated four times. The experiments were conducted in the same field for three years (1986-88), with two cropping periods per year (Table 2.1). Chemical analysis, at the beginning of each growing season, were used to determine fertilizer requirement. The crop was maintained free of diseases, pests, and weeds.

The growing season was divided into five phenological stages defined as: emergence to tillering (Stage I), tillering to jointing (Stage II), jointing to heading (Stage III), heading to soft dough (Stage IV), and soft dough to maturity (Stage V). The dates of

Table 2.1. Wheat crop sequence.

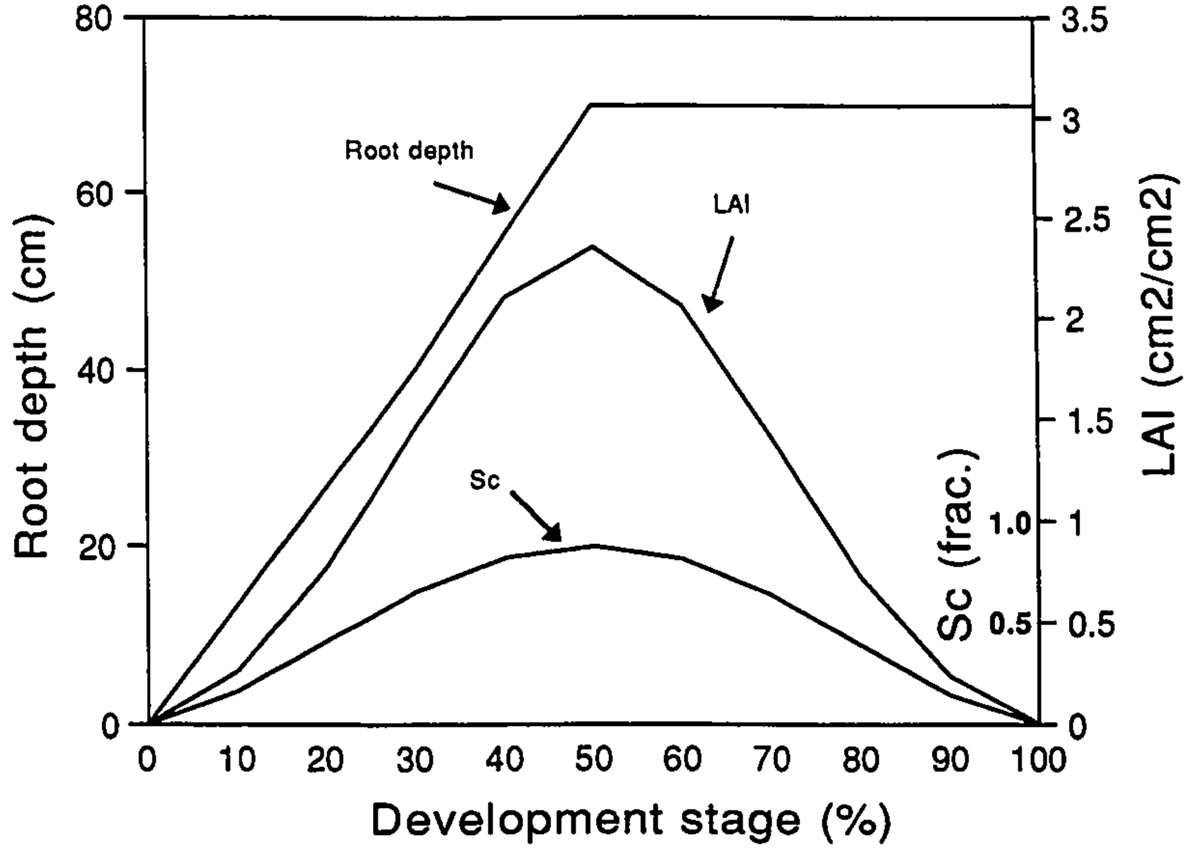
Year	Cropping period	Emergence	Harvest
1986	1	April 26	August 12
	2	June 6	September 8
1987	1	April 14	August 7
	2	May 19	September 10
1988	1	April 12	July 30
	2	May 13	September 10

occurrence of phenological stages were recorded and averaged during crop development. During each growing period, rooting depth was measured on a monthly basis, and leaf area index and soil cover on a weekly basis. The average values of these parameters for the experimental period are presented in Figure 2.4.

The soil was a Typic Haplorthox, characterized by a deep profile, fine texture, good drainage, and absent or deep water table. Soil water retention curves were obtained from field data. Three replicates of undisturbed 100 cm^3 soil samples from four depths (10, 30, 50, and 70 cm) were obtained in a pit close to the experimental area. Water contents were measured at various levels of soil water potential using pressure plate equipment (Soil Moisture Inc), according to Richards (1954). The water potential versus soil moisture data for each depth of the profile were fitted according to Equation 13 (Van Genuchten and Nielsen, 1985):

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[(1 + \alpha h)^n]^m} \tag{13}$$

Figure 2.4. Leaf area index (LAI), soil cover (Sc), and root depth, according to development stage of wheat.



Root depth
LAI
Sc
Root depth (cm)
LAI (cm2/cm2)
Sc (frac.)
Development stage (%)
0
20
40
60
80
0
0.5
1
1.5
2
2.5
3
3.5
0.5
1.0
0
10
20
30
40
50
60
70
80
90
100

where θ is water content (cm^3/cm^3), h is soil water potential (kPa), θ_s and θ_r are respectively saturated and residual values of soil water content (cm^3/cm^3), and α, m, and n are regression parameters (dimensionless).

Unsaturated hydraulic conductivity was determined in the field using the instantaneous profile method (Hillel et al., 1972). A 5 m x 5 m bare soil plot was saturated and covered with plastic to avoid evaporation. Three sets of tensiometers at depths of 10, 30, 50, 70, and 90 cm and three neutron probe access tubes were placed at the center of the plot to measure soil water potential and moisture contents, respectively. Daily measurements at the different depths, to determine downward flux as a function of soil water potential gradient with depth for each range of soil moisture content, were taken for one month. The following equation was used to fit unsaturated hydraulic conductivity (K) in cm/day as a function of soil moisture content (θ) in cm^3/cm^3:

$$K = a\ e^{(b\theta)} \tag{14}$$

where a and b are regression parameters (dimensionless).

The values of the parameters described in Equations 13 and 14 are given in Table 2.2, according to soil depth.

Soil moisture contents were measured every 3 to 4 days during the six cropping periods, gravimetrically for 0-10 cm depth and by a neutron probe for: 10-40 cm, 40-70 cm, 70-100 cm, and 100-130 cm depths. Corresponding measurements of soil moisture were also taken in two bare soil plots, adjacent to the experimental field.

Observed actual evapotranspiration was obtained by the water balance method during a period without precipitation, assuming negligible drainage. Observed values of

Table 2.2. Parameters of the soil water retention (cm^3/cm^3) and hydraulic conductivity (cm/day) equations for Londrina, according to soil depth.

Soil depth (cm)	Parameter						
	θ_r	θ_s	α	n	m	a	b
0-10	0.178	0.474	0.38	1.968	0.200	4.44×10^{-12}	62.79
10-40	0.277	0.447	0.33	4.158	0.100	6.77×10^{-14}	75.62
40-130	0.266	0.451	0.27	1.301	0.432	6.03×10^{-13}	70.90

actual transpiration and actual soil evaporation were obtained using the estimates of actual soil evaporation from the bare soil experiment and the simultaneous wheat experiment (Cooper et al., 1983). In this method, drainage is assumed to be negligible during a period without precipitation. In the wheat field, the variation in soil water storage with time was assumed to be equal to actual evapotranspiration, which can be written as:

$$AET_c = AT_c + AE_c \tag{15}$$

where AET_c is actual evapotranspiration, AT_c is actual transpiration, and AE_c is actual soil evaporation observed for the cropped area in cm/day. The value of AE_c was estimated from the following equation:

$$AE_c = e^{(-0.6\,LAI)}\, AE_b \tag{16}$$

where AE_b are observed values of actual soil evaporation, estimated by the water balance from the bare soil experiment.

Since AET_c is known from the water balance, observed actual transpiration for the wheat area (AT_c) was estimated using Equation 15.

Inputs to the models

SWACROP was executed using daily precipitation and Penman potential evapotranspiration (Penman, 1948) obtained from the IAPAR Weather Station located close to the experiments. The geometric characteristics of the soil profile, soil evaporation parameters (Equation 6), and values of soil water potential used to define the sink term function $\alpha(h)$ in SWACROP are given in Table 2.3. Homogeneous distribution with depth was used to describe the sink term. The anaerobic point at 1 kPa , as assumed for h_1, corresponded to approximately 4% of air filling porosity for the upper layer (0-10 cm) and 2.5% for the next two lower layers (10-40 cm and 40-130 cm). The limiting points of water extraction h_{3a} and h_{3b} were established for transpiration rates of 0.1 cm/day and 0.5 cm/day, respectively. The values of soil water potential at h_{3a} and h_{3b} in Table 2.3 corresponded to 50% and 20% of the remaining available water, respectively, and are in agreement with Doorenbos and Kassam (1979).

Free drainage at the bottom (flux equal to hydraulic conductivity of bottom compartment) was assumed as a boundary condition. The parameters given in Table 2.2 were used as input to SWACROP to calculate soil water retention and unsaturated hydraulic conductivity for layers 1 to 3 (0-10, 10-40, and 40-130 cm). The variations of soil cover, leaf area index, and rooting depth with crop development were supplied to the model using the data given in Figure 2.4. Actual evapotranspiration was calculated by summation of actual transpiration and actual soil evaporation.

VB4 was run using local daily precipitation data and Penman potential evapotranspiration estimates. The soil profile was divided into five compartments of unequal size, as shown in Table 2.4. The model used inputs of soil moisture content at

Table 2.3. SWACROP input parameters.

Parameter	Value
Depth of the soil profile (cm)	130
Nodal spacing (cm)	5
Total number of soil compartments	26
Number of soil layers	3
Number of compartments per layer:	
first layer	2
second layer	6
third layer	18
Water pressure head of the sink term parameter (kPa):	
h_1	1
h_2	10
h_{3a}	50
h_{3b}	100
h_4	1500
Soil evaporation dependent parameter λ	0.35
Minimum depth of rainfall to end dry period (cm)	1.0

saturation, field capacity, and permanent wilting point for each compartment of the profile. These inputs were obtained from the soil retention curve determined for the experimental site (Equation 13 and Table 2.2) by setting soil water potential at 0, 10, and 1,500 kPa. The soil moisture contents used as input in VB4 are given in Table 2.4. The dates of crop stages observed during each growing season were also supplied as input to VB4. The remaining input parameters of VB4, corresponding to root coefficients K_{ij}, parameters m, n, h, and R of the function Z (Equation 11), number of compartments in the first drainage layer, and drainage and runoff coefficients, were obtained by calibration.

Table 2.4. VB4 soil inputs.

Depth (cm)	Soil moisture content (cm^3/cm^3)		
	Saturation	Field capacity	Permanent wilting point
0-10	0.47	0.34	0.20
40-70	0.45	0.37	0.29
70-130	0.45	0.36	0.27

SWACROP and VB4 started simulations with initial soil water content distribution equal to the one measured in the field at the beginning of each cropping period.

RESULTS AND DISCUSSION

Calibration of the Versatile Soil Moisture Budget

A set containing 420 observations of soil moisture content in five depths of the profile (0-10, 10-40, 40-70, 70-100, and 100-130 cm), measured during three cropping periods (first and second growing seasons in 1986 and first growing season in 1987), was used in the process of calibration. The three last growing seasons were used as an independent data set for validation of VB4. Drainage and runoff coefficients were calibrated first, using as input 2, 3, or 4 compartments in the first drainage layer and values of root coefficients K_{ij} and parameters of the function Z given by Dyer and Mack (1984). The set of parameters which gave the least square deviation between observed and predicted values of soil moisture was selected as input and the calibration of K_{ij} and Z coefficients was then performed.

The calibrated values of the root coefficients K_{ij} and coefficients R of the function Z for each soil depth and phenological stage are presented in Table 2.5.

A linear shape for the Z function (m=1, n=0, and h=0) was selected to represent the decrease of the evapotranspiration ratio (AET/PET) as a function of available water (Figure 2.2). A value of R equal to 0.4 in Table 2.5 indicates that AET/PET is unity between 100 and 40% available water for each soil compartment. Further depletion causes the ratio AET/PET to decrease linearly to zero, at which point the soil compartment reaches the permanent wilting point (Figure 2.2). This value of R fits the recommendation given by Doorenbos and Kassam (1979) for calculation of the readily available water for wheat.

The calibrated coefficients K_{ij} for each soil depth and stage in Table 2.5 suggest a higher potential for water extraction in the first compartment (0-10 cm) during the early stages of the growing season (Stages I to III). For the last two crop stages, the values of K_{ij} were more uniformly distributed along the soil profile. Non zero values of K_{ij} were calibrated for compartments below the root zone, indicating some water extraction without the presence of roots. This was necessary in simulating water extraction by upward flux in soil compartments below the root zone since VB4 does not include mechanisms to simulate capillary rise below the rooting system. Therefore, the coefficient K_{ij} expresses not

Table 2.5. Calibrated R and K_{ij} coefficients for wheat.

Soil depth (cm)	R	K_{ij}				
		Phenological stages				
		I	II	III	IV	V
0-10	0.40	0.92	0.75	0.47	0.30	0.30
10-40	0.40	0.08	0.15	0.22	0.30	0.30
40-70	0.40	0.00	0.10	0.21	0.20	0.20
70-100	0.40	0.00	0.00	0.05	0.15	0.15
100-130	0.40	0.00	0.00	0.05	0.05	0.05

only root activity for water extraction, as originally defined, but also the fraction of water extracted by soil evaporation from different compartments of the profile. This agrees with the procedure adopted by Gallichand et al. (1991). They added 20 cm to the maximum rooting depth in order to simulate capillary flow.

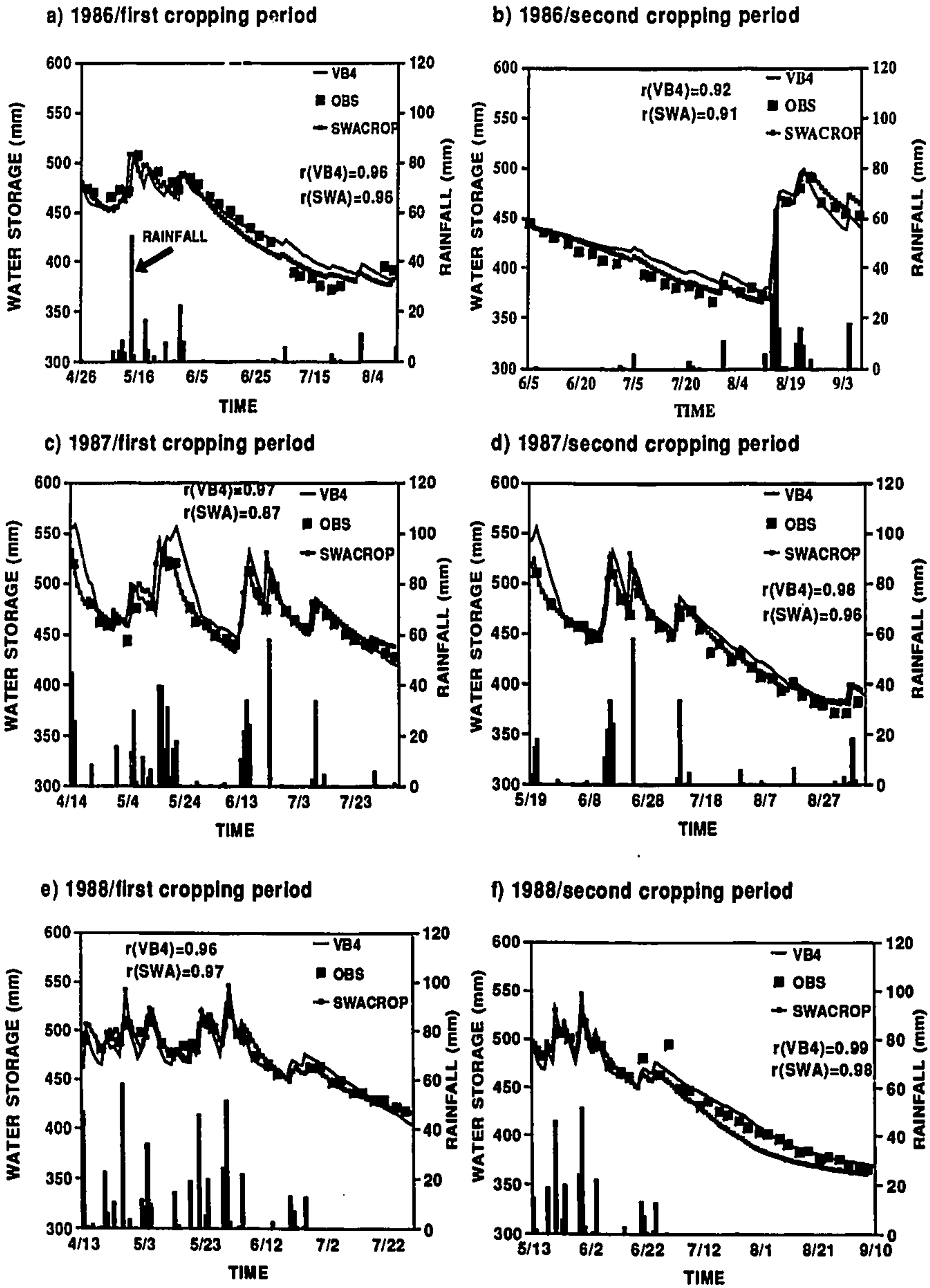
VB4 was calibrated with three soil compartments in the first drainage layer (0-10, 10-40, and 40-70 cm) and with two compartments in the second drainage layer (70-100 and 100-130 cm). The runoff coefficient was taken as 0.8, i.e. 80% of excess surface water (precipitation minus infiltration) becomes surface runoff and 20% goes into depressional storage or ponding. The drainage coefficients D_1, D_2, and D_3 were calibrated as 3.7, 1.5, and 0.8 cm/day, respectively, and the value for drainage rate (coefficient D_4) was 0.5. These values express the internal drainage of the soil and are in accordance with the characteristic of high infiltration of the study area.

Comparison of computer simulations with field data

a) Soil moisture and water storage

The observed and calculated water storage in the soil profile (0-130 cm), with respective correlation coefficients (r) and rainfall during the six growing seasons, are presented in Figure 2.5. Observed and calculated soil water storage by VB4 was in close agreement for both, dependent data used for calibration (Figures 2.5a, b, and c) and independent data used for verification of the model (Figures 5d, e, and f). Very good estimates were also given by SWACROP for the whole experimental period. The predictions of the two models followed the trend of the observed data during wet and dry periods in each year of experimentation, demonstrated by correlation coefficients

Figure 2.5. Predicted and observed soil water storage (0-130 cm) and rainfall during six wheat crops.

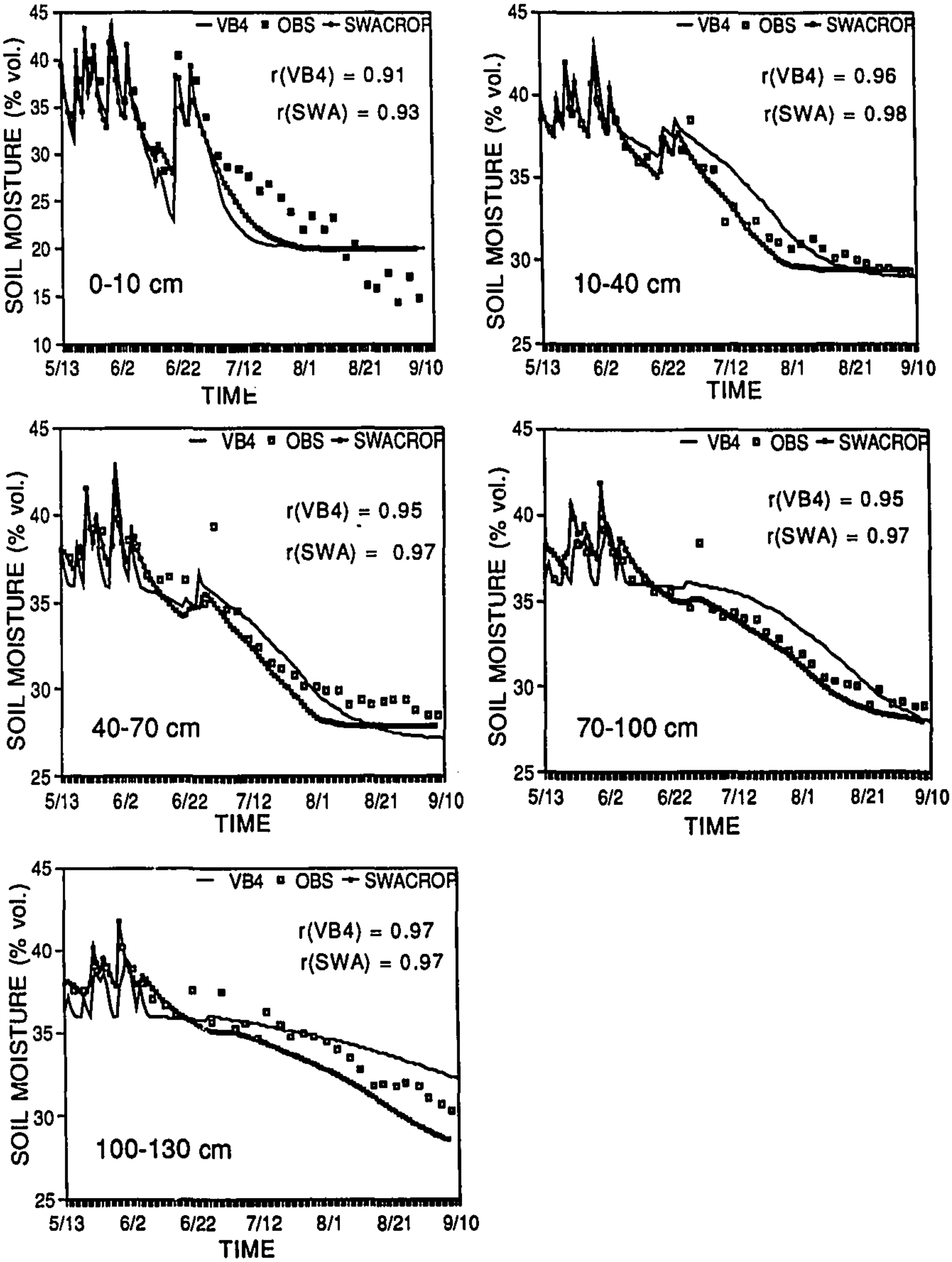

a) 1986/first cropping period
b) 1986/second cropping period
c) 1987/first cropping period
d) 1987/second cropping period
e) 1988/first cropping period
f) 1988/second cropping period
WATER STORAGE (mm)
RAINFALL (mm)
TIME
VB4
OBS
SWACROP
RAINFALL
r(VB4)=0.96
r(SWA)=0.96
r(VB4)=0.92
r(SWA)=0.91
r(VB4)=0.97
r(SWA)=0.87
r(VB4)=0.98
r(SWA)=0.96
r(VB4)=0.96
r(SWA)=0.97
r(VB4)=0.99
r(SWA)=0.98
4/26
5/16
6/5
6/25
7/15
8/4
6/20
7/5
7/20
8/19
9/3
4/14
5/4
5/24
6/13
7/3
7/23
5/19
6/8
6/28
7/18
8/7
8/27
4/13
5/3
5/23
6/12
7/2
7/22
5/13
6/2
6/22
7/12
8/1
8/21
9/10

(significant at the 0.01 level) exceeding 0.87.

The predicted soil moisture contents given by SWACROP and VB4, and the measured values for the five soil depths during the second cropping period in 1988 are shown in Figure 2.6. The models presented similar estimates, and the correspondence between measured and predicted soil moisture contents in both models was good. The correlation coefficients (r), significant at the 0.01 level, reflect the accuracy of the models in predicting soil moisture distribution along the profile. Figure 2.6 also shows that SWACROP had a higher depletion of soil moisture in the lower compartments (70-100 and 100-130 cm), compared to VB4, during the drying period from the middle to the end of the growing season. This can be attributed to the effects of upward or downward flux carrying water from these compartments, to the upper depths or across the lower boundary, respectively, for the estimates by SWACROP. Similar results were obtained in Brazil, when comparing a previous version of VB4 was compared with the physically-based model of Silva and De Jong (1986). In that case, poor simulations of the changes in water content at depths below the root zone resulted for The Versatile Soil Moisture Budget, because no upward flux was simulated.

Average absolute difference and standard error of estimate (Steel and Torrie, 1980) between predicted and observed water storage in 130 cm depth of the soil profile were used to quantify deviations of predictions by the two models from observed values. The results are given in Tables 2.6, according to soil depth and cropping periods. Paired t-tests between deviations of VB4 and SWACROP showed no significant differences at the 0.01 level. Similar deviations were observed for VB4 during the periods of calibration and verification of the model. The average absolute difference varied from 0.57 to 1.06 cm for SWACROP

Figure 2.6. Predicted and observed soil moisture under the second wheat crop in 1988, according to soil depth.



VB4 OBS SWACROP
r(VB4) = 0.91
r(SWA) = 0.93
0-10 cm
SOIL MOISTURE (% vol.)
TIME
VB4 OBS SWACROP
r(VB4) = 0.96
r(SWA) = 0.98
10-40 cm
SOIL MOISTURE (% vol.)
TIME
VB4 OBS SWACROP
r(VB4) = 0.95
r(SWA) = 0.97
40-70 cm
SOIL MOISTURE (% vol.)
TIME
VB4 OBS SWACROP
r(VB4) = 0.95
r(SWA) = 0.97
70-100 cm
SOIL MOISTURE (% vol.)
TIME
VB4 OBS SWACROP
r(VB4) = 0.97
r(SWA) = 0.97
100-130 cm
SOIL MOISTURE (% vol.)
TIME
5/13 6/2 6/22 7/12 8/1 8/21 9/10

Table 2.6. Average absolute difference and standard error of estimate in cm, between observed and predicted water storage in the soil profile (0-130 cm),during six cropping periods.

Year/Cropping period	Average absolute difference		Standard error of estimate	
	VB4	SWACROP	VB4	SWACROP
1986/1*	1.08	1.06	1.30	1.23
1986/2*	1.22	0.72	1.37	0.82
1987/1*	0.63	0.99	0.85	1.72
1987/2	0.84	0.62	1.01	1.22
1988/1	0.87	0.57	1.02	0.87
1988/2	0.64	1.05	0.84	1.31

* Cropping periods used for calibration of VB4.

and from 0.63 to 1.22 cm for VB4. SWACROP had standard error of estimate varying from 0.82 to 1.72 cm and VB4, from 0.84 to 1.37 cm. These results indicate that both models performed with very good accuracy, since the maximum average absolute difference (1.22 cm for VB4) represented less than 2.7% of the soil water storage at field capacity (45.6 cm) and less than 3.5% at permanent wilting point (35 cm). Similarly, the maximum standard error of estimate (1.72 cm for SWACROP) was less than 3.8% of the soil water storage at field capacity and 4.9% at permanent wilting point. These deviations were slightly lower than that reported by De Jong (1988), using the Versatile Soil Moisture Budget in the Canadian Prairies. In that study, the average absolute difference in soil water content in a 120 cm soil profile varied from 1.0 to 1.7 cm.

The values of average absolute difference and standard error of estimate for comparison of predicted and measured soil moisture contents, given by SWACROP and VB4, are shown in Tables 2.7 and 2.8. Again, very similar deviations were calculated by

Table 2.7. Average absolute difference in % volume for comparison of observed and predicted soil moisture by VB4 and SWACROP, according to depth and cropping period.

Soil depth (cm)	Model	Year/Cropping period					
		1986/1*	1986/2*	1987/1*	1987/2	1988/1	1988/2
0-10	VB4	2.82	3.03	2.19	2.52	2.42	3.40
	SWACROP	3.62	3.15	3.12	2.78	2.53	2.58
10-40	VB4	1.79	0.98	0.86	1.90	0.91	0.99
	SWACROP	2.13	1.15	0.93	1.52	1.08	0.78
40-70	VB4	1.08	0.90	0.98	1.75	0.97	1.43
	SWACROP	1.30	1.05	0.94	1.80	0.98	1.00
70-100	VB4	0.70	1.29	0.82	0.96	0.85	0.99
	SWACROP	0.71	1.22	0.71	1.08	0.75	0.82
100-130	VB4	1.10	1.16	0.80	1.96	0.72	0.89
	SWACROP	0.64	0.98	0.92	2.40	0.85	1.11

* Cropping periods used for validation of VB4.

both models and the values indicate good predictions over depths and years. However, smaller deviations were observed at the four lower depths, resulting in average absolute differences and standard errors of estimate of less than 2.4 and 2.63%, respectively, for both models. For the top soil compartment, VB4 showed average absolute difference varying from 2.19 and 3.40%, and SWACROP from 2.53 and 3.62%. VB4 had standard error of estimate ranging from 2.19 to 3.08%, and SWACROP from 2.85 to 5.15%. Larger deviations at the top layer were expected since the rapid process of extraction and recharge in this layer resulted in large deviations of soil moisture. The models were unable to accurately simulate these surface soil processes. Further, the errors associated with measurements, caused by soil variability, can also be responsible for the differences in the results. In the study of De Jong (1988) using The Versatile Soil Moisture Budget in

Table 2.8. Standard error of estimate in % volume for comparison of observed and predicted soil moisture by VB4 and SWACROP, according to soil depth and cropping period.

Soil depth (cm)	Model	Year/Cropping period					
		1986/1*	1986/2*	1987/1*	1987/2	1988/1	1988/2
0-10	VB4	2.82	3.08	2.19	2.52	2.89	3.23
	SWACROP	5.15	4.42	4.78	3.82	2.85	3.00
10-40	VB4	1.79	0.98	0.86	1.90	1.28	0.87
	SWACROP	2.48	1.32	1.42	2.06	1.22	0.99
40-70	VB4	1.08	1.03	0.98	1.75	1.21	1.55
	SWACROP	1.64	1.25	1.45	2.20	1.25	1.29
70-100	VB4	0.70	1.33	0.82	0.96	0.77	1.08
	SWACROP	0.92	1.44	1.21	1.41	0.95	1.07
100-130	VB4	1.10	1.20	0.80	1.96	1.01	1.11
	SWACROP	0.84	1.22	1.46	2.63	1.03	1.30

* Cropping periods used for calibration of VB4.

Canada, the average absolute difference between predicted and measured soil-water profile distribution were of a same order of magnitude (less than 4%) as the values obtained in this study. He attributed the deviations to the use of inappropriate values for the crop coefficients (K_{ij}).

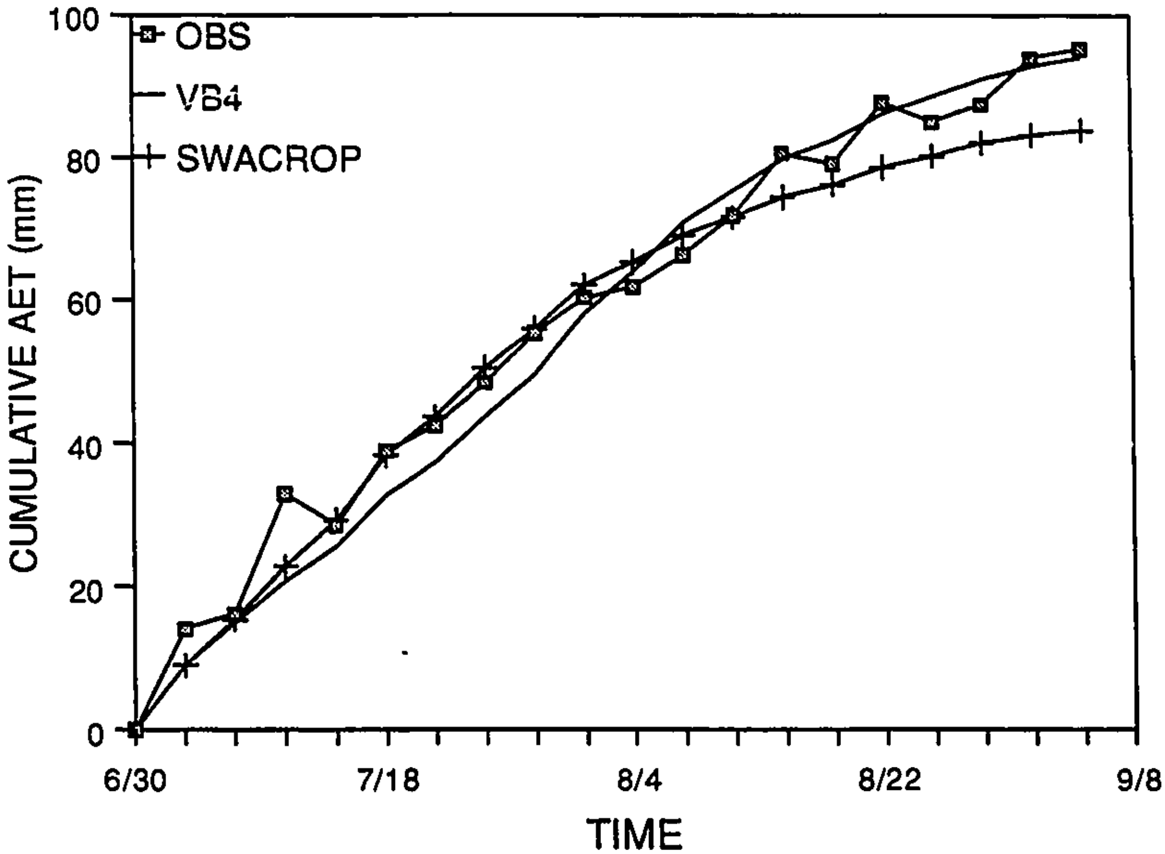
b) Components of evapotranspiration, runoff and percolation

A 67 day rainless period in 1988 (June 30 to September 5) was chosen to compare predicted evapotranspiration and its components with observed data. This period included more than half of the phenological stages of the wheat crop sown at the second cropping period in 1988, which developed from jointing to maturity.

The results of observed and predicted values of actual evapotranspiration by VB4 and SWACROP, given in Figure 2.7, show better prediction by SWACROP during the first part of the drying period, and an underestimation during the second half of the period. The inverse was found for VB4, i.e. good estimates were obtained during the second half of the drying cycle and lower values at the beginning. Underestimated AET by VB4 during the beginning of the drying period occurred because the soil surface layers were dry and the model did not account for upward flux from the moister deep layers to the drier layers within the root zone. As the rooting system became deeper with crop development, AET increased due to a higher root water uptake from the lower soil compartments.

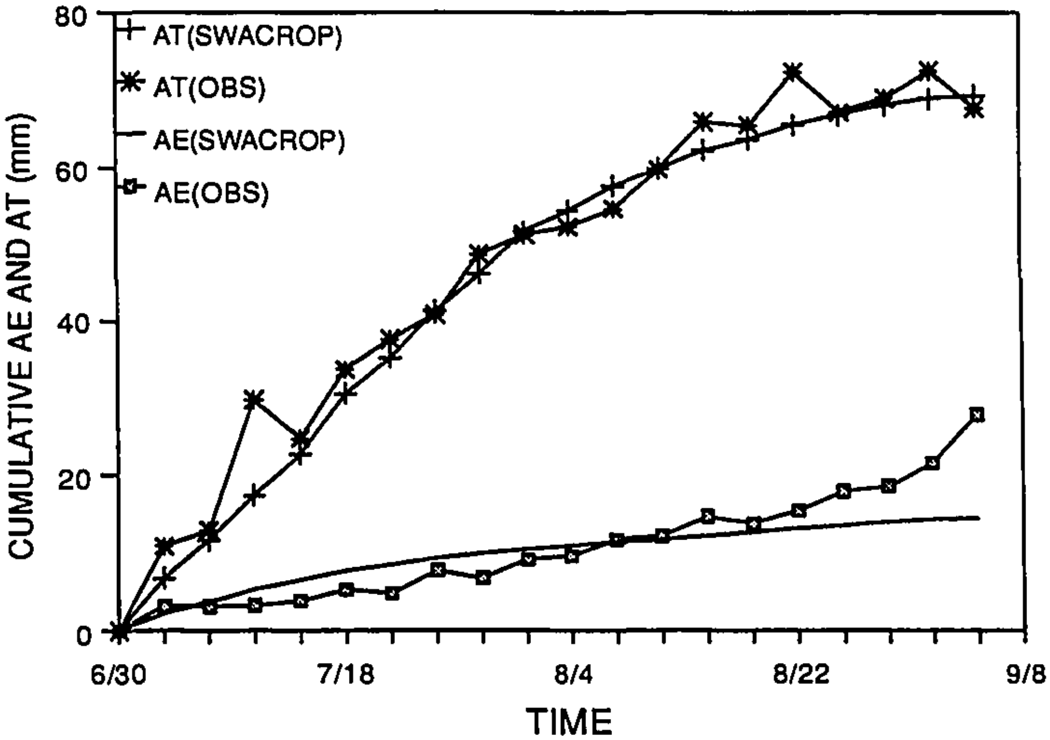
The discrepancies between observed and predicted AET by SWACROP can be explained by the estimates of cumulative actual transpiration and soil evaporation in Figure 2.8. SWACROP predicted actual transpiration very close to observed data for the whole interval, but estimated higher soil evaporation at the beginning, and underestimated during the second half of the drying period. The increase in observed soil evaporation from the middle to the end of the growing season (Figure 2.8), was due to increases in potential evapotranspiration, because of the higher insolation during August and September. Therefore, Equation 6 used in SWACROP was not appropriate to accurately simulate soil evaporation under this condition of variable atmospheric demand. In fact, Gill and Prihar (1983) showed that the soil dependent parameter λ is related to potential evapotranspiration. They found a linear increase in λ as evaporative demand increased, indicating that this coefficient may assume different values during the year according to variations in potential evapotranspiration. Some researchers have suggested models using soil evaporation as a function of potential evapotranspiration, rather than time (Reddy, 1983; Boesten and Stroosnijder, 1986; Brisson and Perrier, 1991). Since actual transpiration was properly

Figure 2.7. Cumulative actual evapotranspiration (AET) observed and predicted by VB4 and SWACROP during a rainless period in 1988.



OBS
VB4
SWACROP
CUMULATIVE AET (mm)
0
20
40
60
80
100
6/30
7/18
8/4
8/22
9/8
TIME

Figure 2.8. Cumulative actual soil evaporation (AE) and transpiration (AT) observed and predicted by VB4 and SWACROP during a rainless period in 1988.



AT(SWACROP)
AT(OBS)
AE(SWACROP)
AE(OBS)
CUMULATIVE AE AND AT (mm)
80
60
40
20
0
6/30
7/18
8/4
8/22
9/8
TIME

estimated by SWACROP, the underprediction of actual evapotranspiration during the last part of the rainless period was due to lower estimates of actual soil evaporation.

Observed actual evapotranspiration and its components were not measured or estimated for the remainder of the experimental period. Predictions of both models were compared in order to evaluate their agreement.

Cumulative values of rainfall and potential evapotranspiration, observed during the six growing seasons, and estimated hydrologic components by both models are given in Tables 2.9 and 2.10. Rainfall was quite variable during the years of study (Table 2.9). The first cropping period in 1986 and 1987 can be considered as dry and wet seasons, respectively. The cumulative hydrologic components for these two cropping periods are shown in Figures 2.9 and 2.10 and the drainage rates and rainfall for the wet season in Figure 2.11.

SWACROP predicted zero runoff during the six cropping periods, as shown in Table 2.9. VB4 predicted 0.7 cm for the driest year (first cropping period in 1986) and 4.2 cm for the wettest year (first cropping period in 1987). These amounts represented 4 and 8% of the depth of rain during the respective growing seasons. Since SWACROP uses daily values of rainfall uniformly distributed over the day, this procedure resulted in low rainfall intensities which completely infiltrated. However, it is more common to observe rainfall in shorter periods in Paraná, eg. 1 to 5 hours. Higher rainfall intensities occur, thus producing significant amounts of runoff. High infiltration predicted by SWACROP was also reported by Workman and Skaggs (1989). They suggested inclusion of a capability to consider varying rainfall rates in SWACROP. Despite the approximations used by VB4 to calculate runoff, its results seem to be more realistic than the zero values calculated by SWACROP.

Table 2.9. Rainfall, predicted percolation at the bottom of the soil profile (0-130 cm), intercepted rainfall, and runoff in cm, during six wheat crops.

Year/ Cropping period	Rainfall	Percolation		Intercepted rainfall	Runoff	
		VB4	SWACROP	SWACROP	VB4	SWACROP
1986/1*	16.2	6.1	9.7	1.0	0.7	0.0
1986/2*	19.3	3.1	3.7	1.1	0.4	0.0
1987/1*	52.0	28.5	40.3	2.4	4.2	0.0
1987/2	26.7	17.0	23.5	1.2	1.2	0.0
1988/1	46.1	25.4	30.7	2.2	3.7	0.0
1988/2	24.3	15.2	19.7	0.8	1.9	0.0

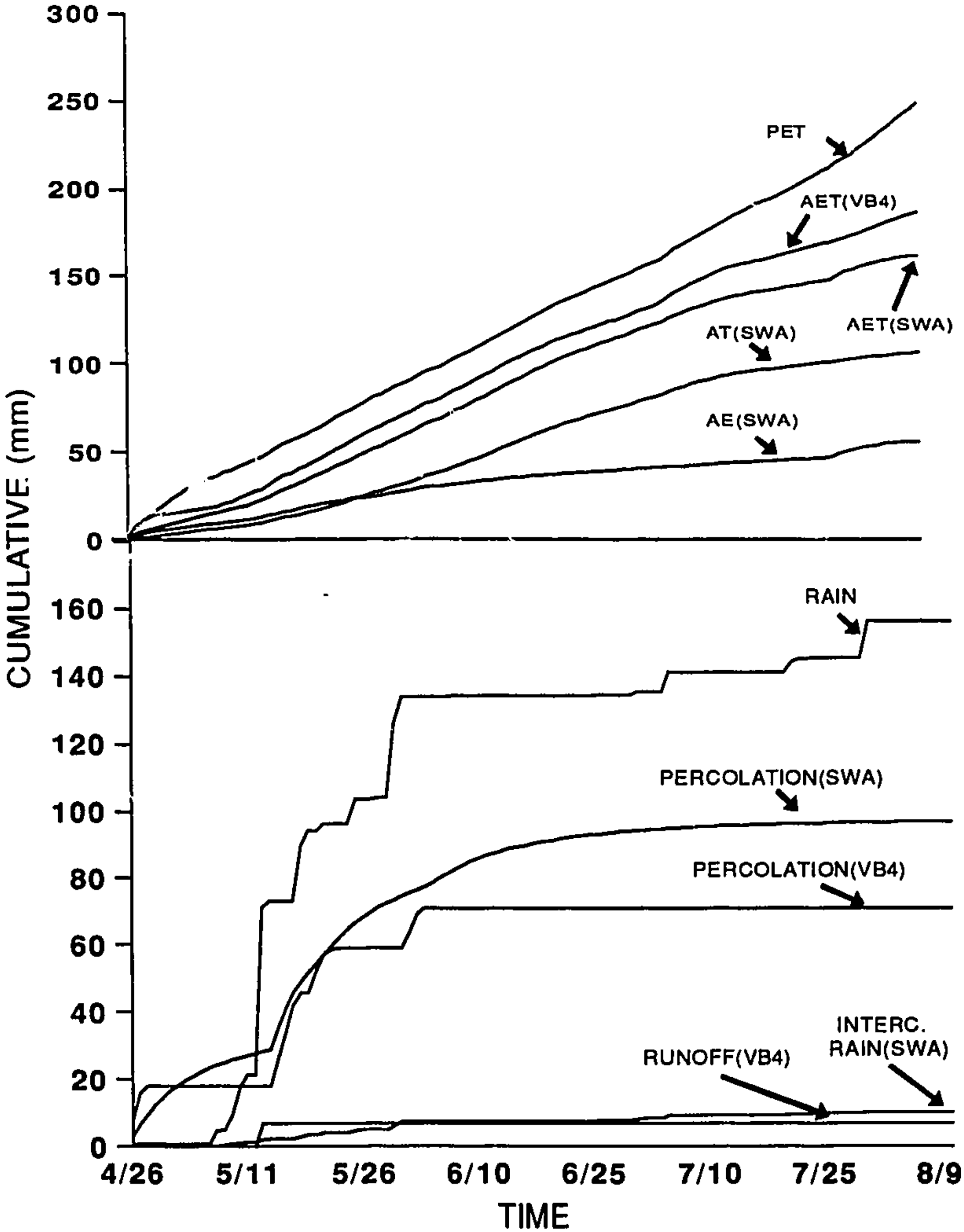
* Cropping periods used for calibration of VB4.

Table 2.10. Potential (PET) and actual (AET) evapotranspiration, actual transpiration (AT), and soil evaporation (AE) in cm, during six wheat crops.

Year/ Cropping period	PET	VB4	SWACROP		
		AET	AET	AT	AE
1986/1*	25.2	19.2	16.3	10.7	5.6
1986/2*	23.3	16.3	12.8	7.7	5.1
1987/1*	26.2	25.3	19.2	11.7	7.5
1987/2	27.9	21.3	17.9	11.8	6.1
1988/1	23.7	22.7	18.0	10.6	7.4
1988/2	31.5	18.6	16.6	10.9	5.7

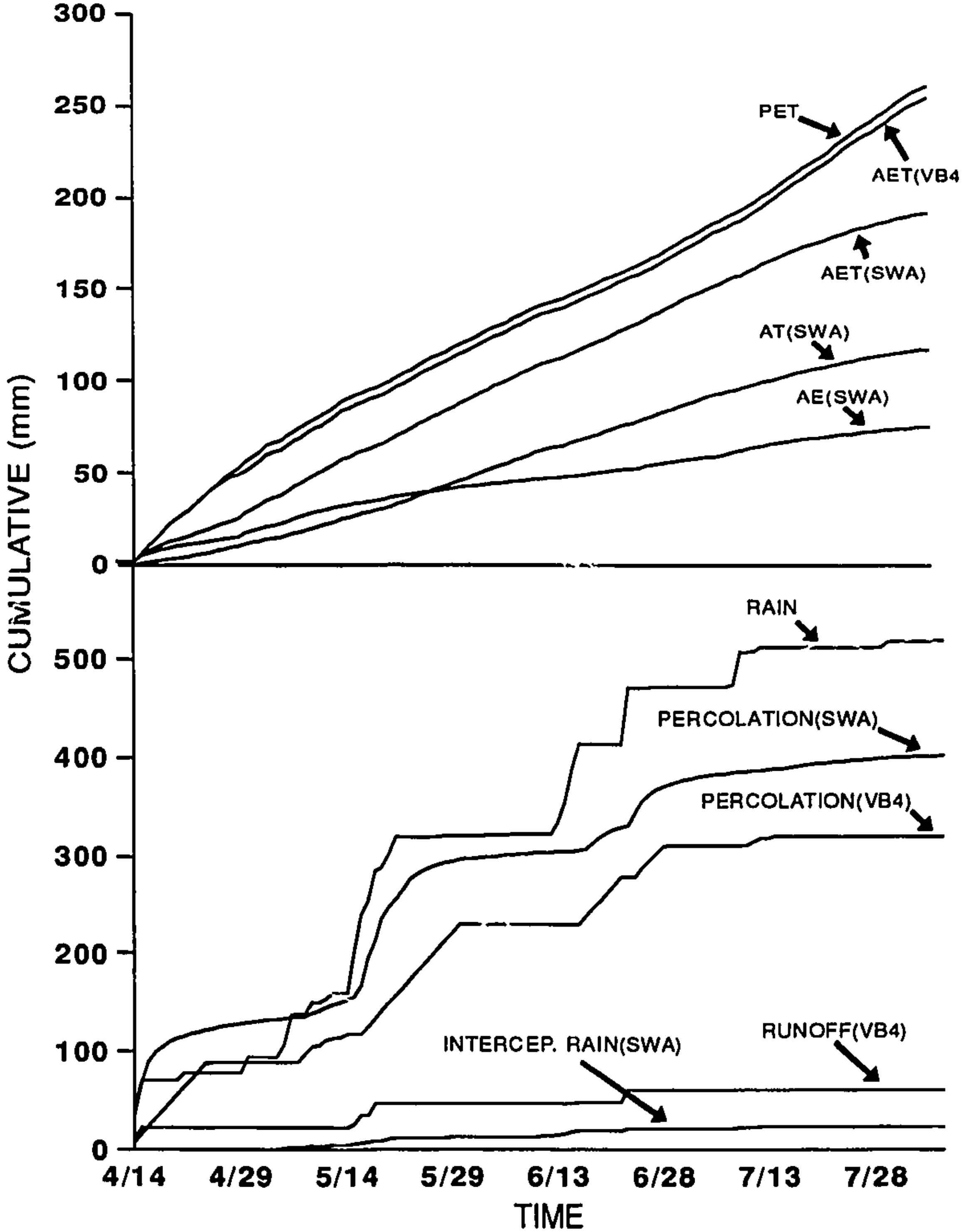
* Cropping periods used for calibration of VB4.

Figure 2.9. Cumulative rainfall, potential evapotranspiration (PET), and components of the water balance predicted by VB4 and SWACROP (SWA), during the first cropping period in 1986.



CUMULATIVE (mm)
300
250
200
150
100
50
0
PET
AET(VB4)
AET(SWA)
AT(SWA)
AE(SWA)
160
140
120
100
80
60
40
20
0
RAIN
PERCOLATION(SWA)
PERCOLATION(VB4)
RUNOFF(VB4)
INTERC.
RAIN(SWA)
4/26
5/11
5/26
6/10
6/25
7/10
7/25
8/9
TIME

Figure 2.10. Cumulative rainfall, potential evapotranspiration (PET), and components of the water balance predicted by VB4 and SWACROP (SWA), during the first cropping period in 1987.



300
250
200
150
100
50
0
500
400
300
200
100
0
CUMULATIVE (mm)
PET
AET(VB4)
AET(SWA)
AT(SWA)
AE(SWA)
RAIN
PERCOLATION(SWA)
PERCOLATION(VB4)
INTERCEP. RAIN(SWA)
RUNOFF(VB4)
4/14
4/29
5/14
5/29
6/13
6/28
7/13
7/28
TIME

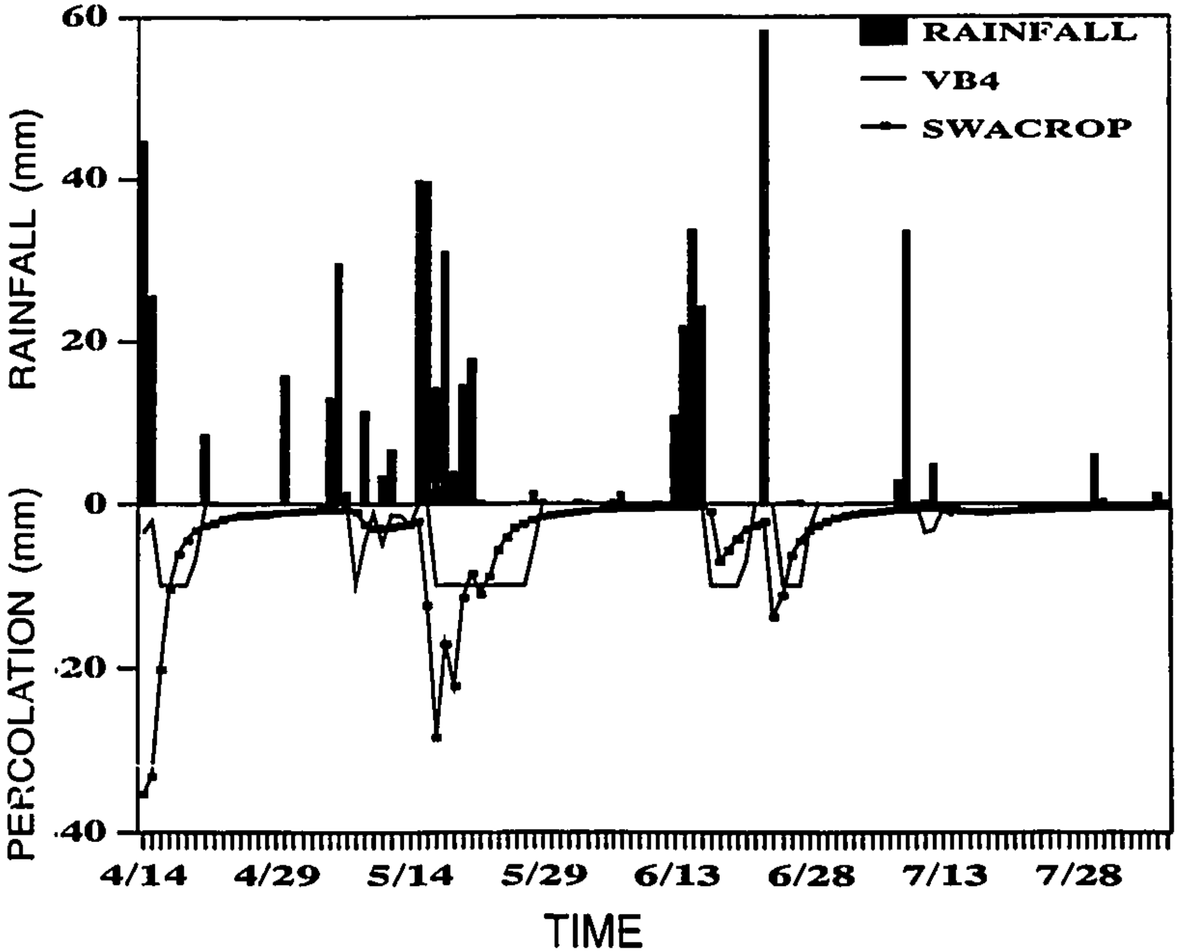
Furthermore, the values of runoff estimated by VB4 agreed well with the estimates given by its earlier version in a previous study in Northeastern Brazil (Silva and De Jong, 1986), in which 4 and 6 cm runoff were predicted for corn and beans, respectively.

The higher depth of infiltration calculated by SWACROP was minimized by the intercepted rainfall (Table 2.9, and Figures 2.9 and 2.10), which was not computed by VB4. These amounts varie from 3 to 6% of the total rainfall, during the different cropping periods.

VB4 predicted higher actual evapotranspiration than SWACROP during all six years of experimentation (Table 2.10). During the driest cropping period (first cropping period in 1986) both models predicted less actual evapotranspiration than potential, and small differences between the predictions were observed (15%), as shown in Figure 2.9 and Table 2.10. During the wettest growing season (first cropping period in 1987), VB4 calculated actual evapotranspiration very close to the potential, while SWACROP predicted 24% less evapotranspiration than VB4 (Figure 2.10 and Table 2.10). The high depth and frequency of precipitation during this growing season maintained soil moisture at high levels. Therefore, SWACROP predicted actual transpiration equal to the potential. The lower values of actual evapotranspiration calculated by the model resulted from decreases in soil evaporation during rainless periods in 1987, when actual soil evaporation decreased as a function of the square root of the time after the drying period had started (Equation 6). For the same period, VB4 predicted higher values because the soil water storage during the rainless periods was not very often below the value equivalent to R (Figure 2.2), thus actual evapotranspiration was equal to the potential most of the time.

The models predicted high amounts of percolation during five of the six growing

Figure 2.11. Predicted percolation rates and rainfall during the first cropping period in 1987.



60
40
20
0
-20
-40
RAINFALL (mm)
PERCOLATION (mm)
RAINFALL
VB4
SWACROP
4/14
4/29
5/14
5/29
6/13
6/28
7/13
7/28
TIME

seasons (Table 2.9). This is explained by the fact that all the cropping periods, except the first and the second cropping periods in 1986, started with soil moisture close to field capacity and precipitation occurred most of the time at the beginning of the season (Figure 2.5), resulting in more percolation. This is a common situation in Paraná since the rainy season extends from October to March, and the dry season from June to September. Percolation depths predicted by SWACROP were 19 to 60% higher than the values predicted by VB4, and represented 19 to 88% of the total precipitation during the corresponding growing seasons, compared to 16 to 55% given by VB4 (Table 2.9). The higher amounts of percolation computed by SWACROP, as compared to VB4, may be attributed to three factors: a) higher infiltration due to underprediction of runoff, b) lower water extraction from the soil profile by evapotranspiration caused by decreases in soil evaporation during rainless periods, and c) different conceptualization of water distribution in the soil profile. The variations of cumulative percolation with time in Figures 2.9, 2.10, and 2.11 illustrate the effects of the different methods used in VB4 and SWACROP to account for water movement through the boundary at 130 cm. During wet periods (when the soil moisture was above field capacity), VB4 calculated a maximum percolation rate of 1.0 cm/day (equivalent to the value calibrated for the drainage coefficient D_3 of the second drainage layer), while SWACROP gave higher values since the flux is assumed to be equal to the hydraulic conductivity at the bottom of the profile. During dry periods (when the soil moisture was below field capacity), VB4 did not predict any deep drainage, whereas SWACROP predicted unsaturated flux. These results agree with the findings of De Jong (1988) in a study comparing models under a wheat crop in Western Canada over 12 years of recorded climatic data. In that study, due to the low precipitation during the experimental period, The Versatile Soil Moisture Budget did not predicted any water movement across the lower boundary at 120 cm, while the other model (SPAW model, Saxton et al., 1974) predicted an average annual drainage of 0.6 cm, because it calculated unsaturated flow by a Darcy type equation.

SUMMARY AND CONCLUSIONS

The performance of the SWACROP and the Versatile Soil Moisture Budget (VB4) models in predicting soil water regimes and evapotranspiration were compared with field data under six wheat cropping periods in Paraná, Brazil.

Locally available input parameters in SWACROP and calibrated coefficients in VB4 resulted in comparable predictions of soil moisture content and water storage. Models' estimates were in good agreement with field measurements. The average absolute difference and standard error of estimate, used to quantify deviations between predicted and observed water storage over the six cropping periods, were less than 2.7 and 3.8%, respectively, of the depth of water stored in 130 cm of the soil profile at field capacity.

Differences in methods of simulating soil water distribution and soil evaporation by the models caused SWACROP to predict higher percolation and lower evapotranspiration and runoff, as compared to VB4.

SWACROP gave a more detailed description of water regime and evapotranspiration, but required more input parameters and longer computational time than VB4. Furthermore, only one year at a time could be simulated by SWACROP because of the way inputs were entered into the model. VB4 was able to simulate any climatological record length. Since both models predicted similar soil moisture contents and soil water storage, VB4 is preferable in processing long record climatic data when these parameters are required, or in situations where good computational facilities are unavailable. If detailed information on water movement in the root zone and capillary rise is required, SWACROP should be chosen.

Empirical parameters used in VB4 are easily calibrated by optimization subroutines. While this feature makes VB4 advantageous if input parameters are not available or accurate, it requires soil water measurements for calibration. If accurate input parameters are available, SWACROP can be used without the high cost involved in field experiments. This was the case in the present study. While three to five cropping periods were necessary to calibrate VB4, only locally available soil, plant, and climatic parameters were required for SWACROP to give good predictions due to its more elaborate mathematical approach.

SWACROP can be improved by including hourly rainfall intensities as input, instead of daily data. Also the soil evaporation method in SWACROP needs to be improved in order to account for variations in evaporative demand during the growing season.

Improvements in VB4 by providing means to partition actual evapotranspiration into transpiration and soil evaporation would give more realistic predictions of the hydrologic components. Furthermore, this procedure would make it possible to couple VB4 with crop yield models in order to predict crop response to irrigation using long term climatic data.

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PREFACE TO CHAPTER III

Because of the limitations of the models tested in Chapter II, a new soil moisture model was developed in order to address the specific research needs in water management in Paraná State. The development of this model is described in Chapter III, followed by its validation using the same data set as in the previous Chapter.

CHAPTER III

MODELLING SOIL WATER BALANCE AND SIMULATION OF HYDROLOGICAL COMPONENTS FOR A WHEAT CROP IN A SUBTROPICAL CLIMATE

ABSTRACT

A computer model to estimate components of the water balance for a cropped, layered soil profile without the influence of water table is described. Inputs of daily precipitation (P) and Penman potential evapotranspiration (PET) are partitioned during the day using simple disaggregation methods. Crop growth input parameters (leaf area index and rooting depth) together with weather (P and PET) and soil (soil water retention and unsaturated hydraulic conductivity curves) inputs are used to calculate a detailed output including the partition of evapotranspiration into soil evaporation, transpiration, and evaporation from water intercepted by the crop canopy. The model also calculates fluxes, pressure head, and soil moisture at different depths of the profile and runoff and ponding at the soil surface.

The model was validated for a subtropical humid region in Paraná State, Brazil, under six wheat cropping periods. Predictions of soil water contents and evapotranspiration were in close agreement with field data. The estimates of the other hydrological components seemed to represent quite reasonably the field scale water regime of a wheat crop in the study area. The model requires a short computation time and is appropriate for long term simulations.

INTRODUCTION

Under the subtropical climatic conditions of Paraná State, Brazil (22-26° S; 48-54° W), roughly two-thirds of the 1,200 to 1,900 mm annual precipitation falls in the summer, from October to March. Dry spells of 10 days to 1 month are a common feature in the course of the growing seasons, mostly for wheat, which is cultivated on about 2 million hectares during the winter (March to September). This, in conjunction with degradation of organic matter and soil physical characteristics, makes the crops very susceptible to drought. Because of this irregular precipitation pattern, considerable yield decline occurs due to water stress during critical stages of crop development. Furthermore, unsatisfactory soil water content during sowing results in low plant population or delay in planting.

Supplementary irrigation is still incipient in the State, despite a great potential. Information on soil water availability and the relationships between crop production and crop water use during the growing seasons is needed to assess risks of drought, crop water requirements, and irrigation scheduling. This knowledge can be used to improve water use efficiencies and increase returns to the producer. Also, it can be useful for farmers and government as a planning tool for development of investment strategies in the area.

Temporal variations of the water content in the soil-plant-atmosphere system are rather complex. Mathematical models have been devised and used to simulate the intricate dynamic process of water movement in this system, by accommodating interactions of the many variables such as weather, crops, soil, and agricultural management. Although a great number of models with varying degrees of sophistication are available, the choice of model depends on the nature of the problem. Adaptation of an existing model or even development of a new model may be necessary in order to address a specific study.

Performance of the SWACROP (Wesseling et al.,1989) and the Versatile Soil Moisture Budget (VB4) (Boisvert et al., 1992) models was compared under wheat in Paraná, as described in Chapter II. Estimates of soil moisture contents were in good agreement with field measurements. However, the models presented some limitations for subsequent applications to studies involving long-term crop yield simulations and irrigation management in the region. SWACROP underestimated runoff and soil evaporation, because it assumed constant rainfall rates over the day and the soil evaporation method did not account for variations in evaporative demand during the growing season. Furthermore, SWACROP required a long computation time because of the iterative procedure used to solve Richard's equation for several compartments of the soil profile using relatively small time increments. Besides that, only one year at a time could be simulated by SWACROP due to the way inputs are entered into the model. On the other hand, VB4 had a much shorter computation time and was able to simulate long term climatological data. However, unlike SWACROP, it did not separate evapotranspiration into transpiration and soil evaporation, and as such it was unable to accommodate crop yield models. Furthermore, VB4 required soil water measurements for calibration, which are very costly and time consuming. Although SWACROP demanded much more detailed inputs, this was preferable to field calibration, since SWACROP inputs are generally standard field experimentation measurements, and are usually available locally or can be extrapolated from data found in the literature

Considering the advantages and limitations of SWACROP and VB4, a new soil moisture model is proposed in order to address the specific research needs in crop water management in Paraná. This paper describes the development of such a model and its validation using wheat field data collected over three years.

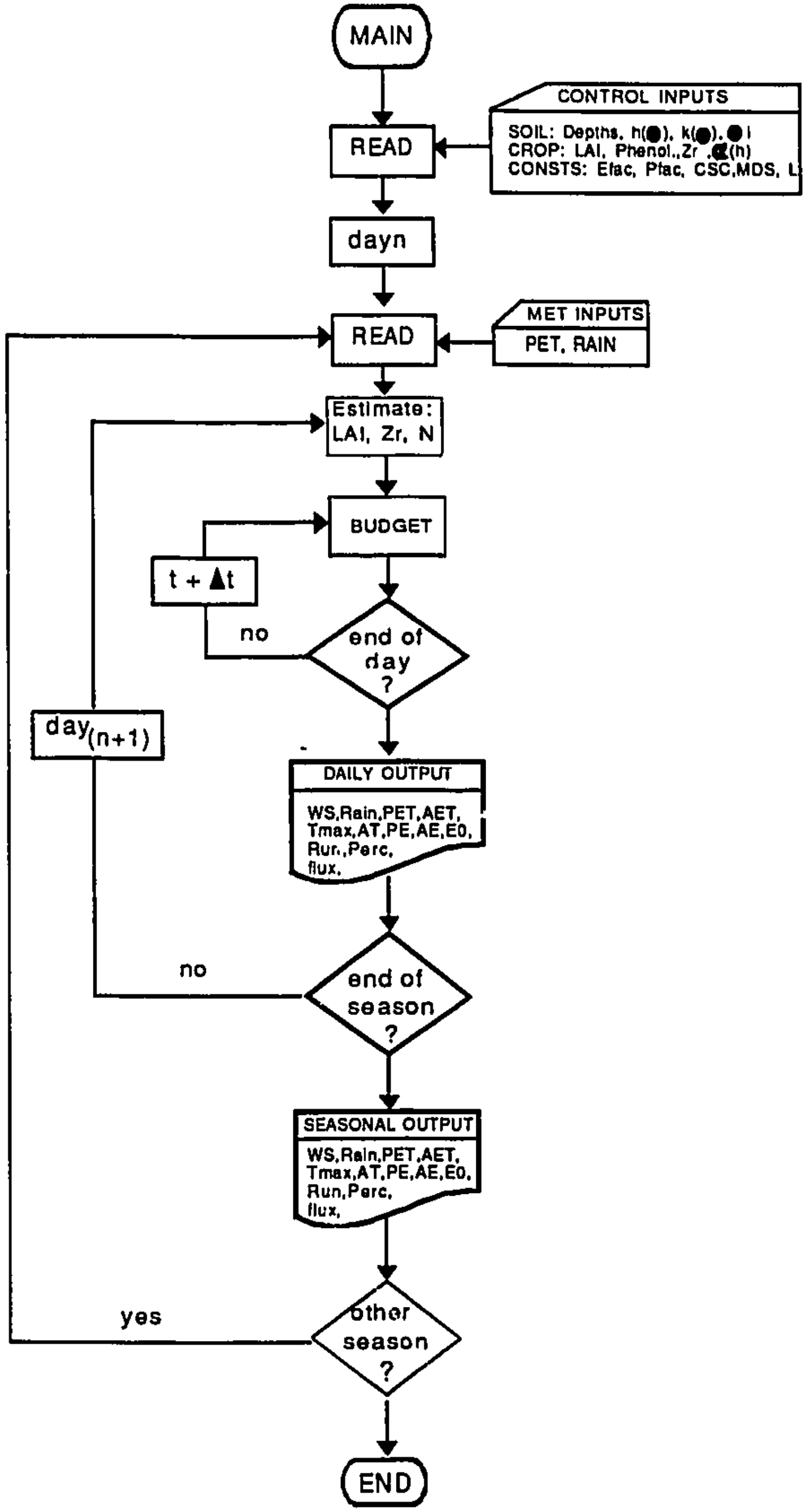
METHODS

Model description

The general model structure and information flow among subroutines are shown in Figure 3.1. The model reads a control input file containing specifications of the input parameters. These parameters can be divided into soil parameters, crop coefficients, and model constants. As soil parameters, the model requires a discretization of the soil profile with specifications of depths at the bottom of each soil compartment and the soil water retention and unsaturated hydraulic conductivity curves. The soil moisture content profile at the beginning of the simulation has also to be specified. Crop parameters include start and end dates for the growing season, leaf area index and rooting depth throughout the growing period, and a set of coefficients used to define a sink term function, which is related to the characteristics of water extraction by the roots. The model constants include precipitation factors (used to simulate hourly rainfall data from daily rainfall data), maximum depressional storage, soil evaporation parameters, canopy storage coefficient, and the latitude of the site.

At each day in a growing season, the model reads climatic parameters (daily rainfall and potential evapotranspiration) in a meteorological input file, initializes variables, estimates daylight period, and interpolates leaf area index and rooting depth to perform the water balance of the soil profile using a variable time step. For each time step, it calculates soil moisture content, pressure head, fluxes, soil water depletion by transpiration and evaporation for each depth, soil water storage in the soil profile, potential and actual

Figure 3.1. General model structure.


MAIN
READ
CONTROL INPUTS
SOIL: Depths, h(●), k(●), ●i
CROP: LAI, Phenol.,Zr ,●(h)
CONSTS: Efac, Pfac, CSC,MDS, L
dayn
READ
MET INPUTS
PET, RAIN
Estimate:
LAI, Zr, N
BUDGET
t + ▲t
no
end of day ?
day(n+1)
DAILY OUTPUT
WS,Rain,PET,AET,
Tmax,AT,PE,AE,E0,
Run,Perc,
flux,
no
end of season ?
SEASONAL OUTPUT
WS,Rain,PET,AET,
Tmax,AT,PE,AE,E0,
Run,Perc,
flux,
yes
other season ?
END

evapotranspiration and its components, runoff, percolation, and ponding. Output includes the cumulative values of these parameters over each day in a growing period and the accumulated daily values at the end of the season. The model can simulate several growing seasons for one or more crops at the same site, or at different sites. This is accomplished by concatenating several sets of control input parameters of different growing seasons in a unique control file, provided that corresponding climatic data is available in the same sequence in the meteorological input file.

The major processes accounted for by the model in the calculation of the water balance of the soil profile are as follows. Precipitation can be intercepted by the plant canopy or fall directly on the soil surface. Part of the intercepted water can drip to the soil and the remaining amount is budgeted between evaporation and canopy storage during the day with precipitation. Water that reaches the soil surface can infiltrate, leave the system as runoff, evaporate, or remain on the soil surface as ponded water. The soil profile is recharged by infiltration or capillary rise and the soil water is distributed through the several compartments of the profile. Soil water storage is depleted by transpiration, evaporation, or drainage out of the soil profile.

The soil profile can be divided into as many as 20 compartments with the thickness of each compartment specified by the user. A boundary layer at the bottom of the soil profile with the same hydraulic characteristics and thickness as the compartment above is assumed .

In a day with precipitation, the model sets the period of the day in which rainfall occurs and estimates hourly precipitation rates. A rainy period is assumed to extend for 6 hours (h = 1 to h = 6) and starts randomly at any hour of the day. Hourly precipitation rates are simulated from partition of daily precipitation (P^{24}) using a synthetic hyetograph for storms of 6 hours duration, similar to the curve presented in Figure 3.2a. The average precipitation rate (P^h) for each hour interval is found by the product of P^{24} in a given day and a precipitation factor (P_{fac}). This factor is a model input defined for each hour of the rainy period. It is obtained by the difference between values of the ratio of accumulated rainfall (P^t) to total (P^{24}) of two subsequent one hour time intervals. The values of P_{fac} derived from the rainfall distribution in Figure 3.2a are given in Figure 3.2b. With small modifications in the program codes, the model can also use hourly rainfall data as input, when available at a specific location of interest.

Precipitation rate is assumed to be constant during one time step and the depth of precipitation within a time increment (P) is estimated by integrating P^h over the interval.

Precipitation is intercepted by the crop canopy assuming an analogy to solar radiation interception. The intercepted rainfall during one time increment (PI) in mm is given by:

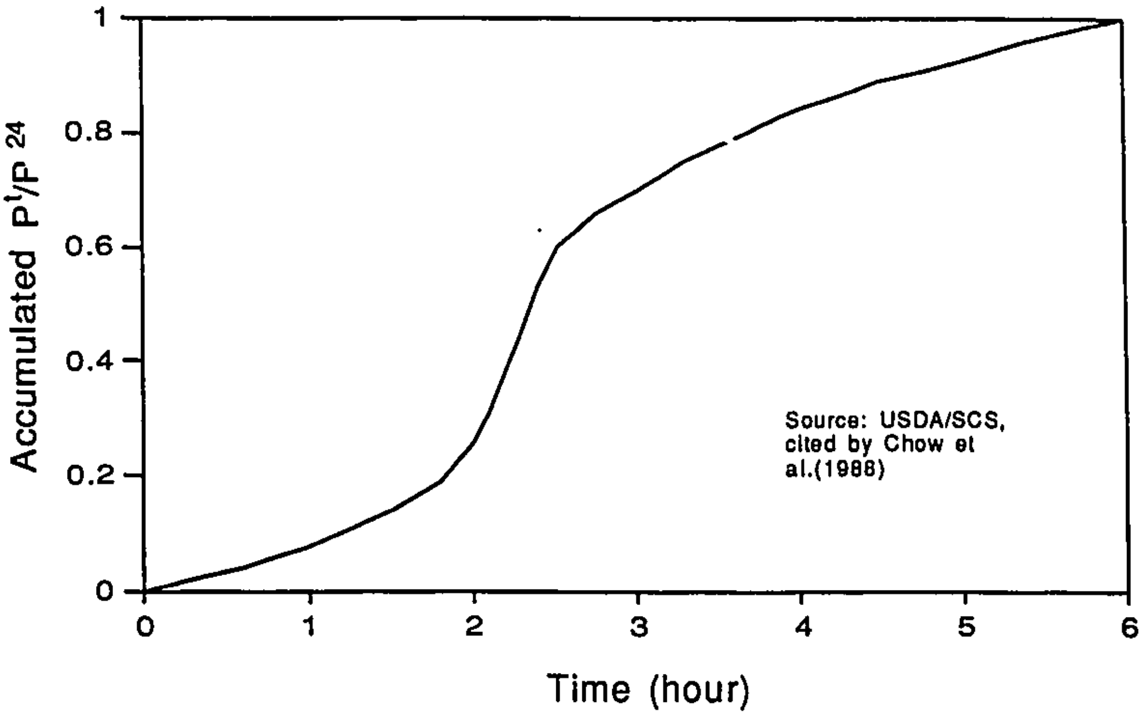
$$PI = [1 - e^{(-0.6LAI)}]\ P \qquad (1)$$

where P is depth of precipitation in mm during one time step and LAI is leaf area index in cm^2/cm^2.

During a rainy period, the water intercepted by the leaves can reside on the canopy or drip to the ground if the amount exceeds the storage capacity of the canopy. A maximum canopy storage capacity for water interception (CS_{max}) is defined assuming constant crop leaf wetness characteristics during the growing season, and a linear relationship between CS_{max} and LAI. Consequently, for each day of the growing season CS_{max} is calculated by

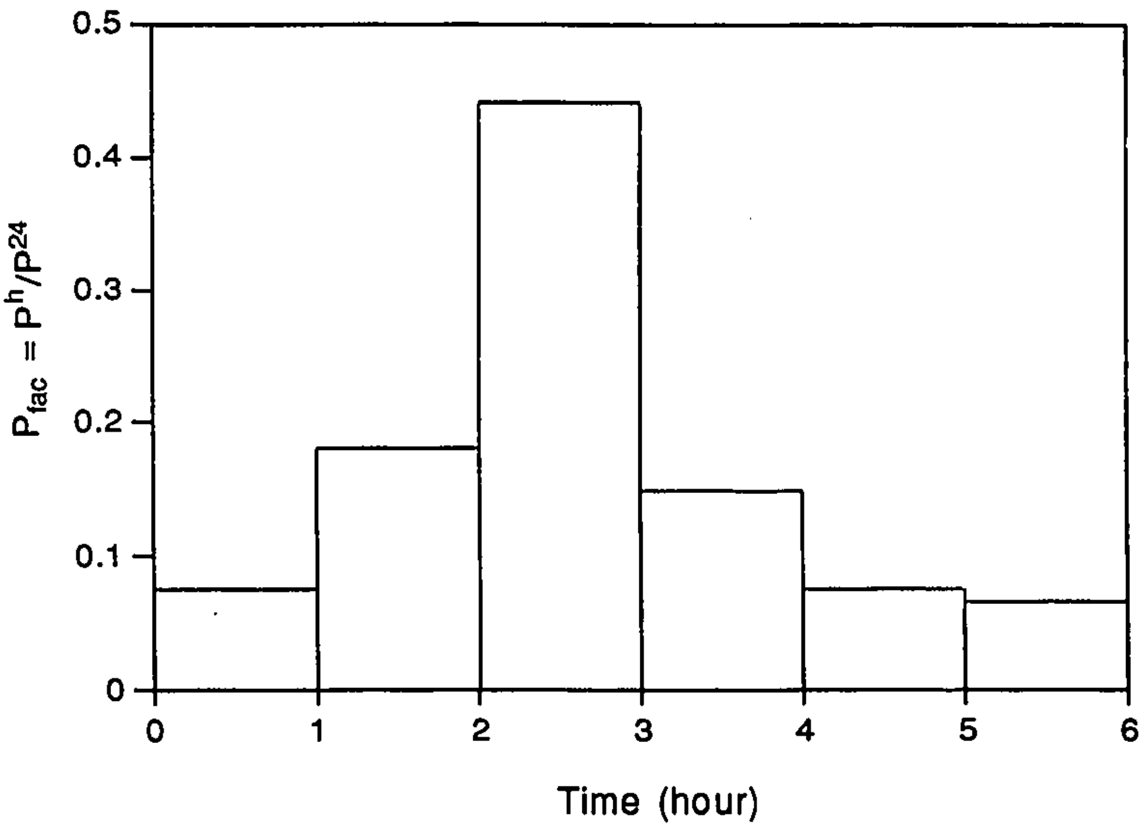
Figure 3.2. Rainfall distribution of a 6-hour synthetic hyetograph. a) Ratio accumulated rainfall to total (P^t/P^{24}) and b) Precipitation factor (P_{fac}).

a)



Accumulated P^t/P^24
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
Time (hour)
Source: USDA/SCS, cited by Chow et al.(1988)

b)



P_fac = P^h/P^24
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
Time (hour)

the product of LAI at that specific day and a constant, the canopy storage coefficient (CSC). The CSC is a model input and can be derived by many crop interception research techniques. If at least one paired value of CS_{max} and LAI is known during the growing season, their relationship can be established by assuming CS_{max} equal to zero when LAI is zero (Figure 3.3). Therefore, CSC is the function's slope estimated by the ratio CS_{max} to LAI.

Instantaneous potential evapotranspiration (PET') at any time of the day is calculated assuming a sine wave variation of daily Penman potential evapotranspiration (PET^{24}) during daylength (N) in hours, expressed as (Jackson et al., 1983):

$$PET' = PET_{max} \sin\left[\frac{\pi t}{N}\right] \tag{2}$$

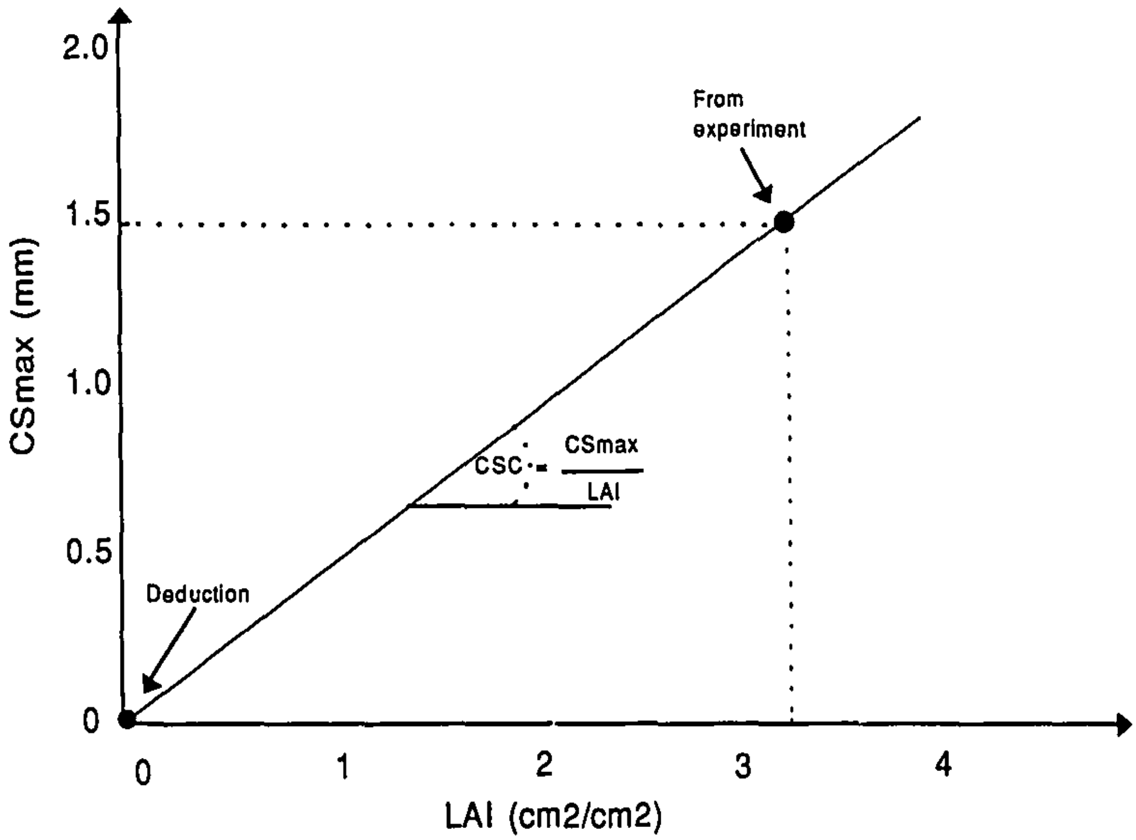
where t is hours from sunshine (hours) and PET_{max} is the maximum evapotranspiration rate (mm) occurring at t = N/2.

Daylength in hours is calculated as a function of latitude (L) in degrees and Julian day (D), according to Jackson et al. (1983):

$$N = a + b \sin^2\left[\pi \frac{|c - D| + 10}{365}\right] \tag{3}$$

where c is a constant equal to zero for the Northern hemisphere and 180 for the Southern hemisphere, parameter a is the length of the daylight period (hours) for the shortest day of the year, and term b is the amount that must be added to a to obtain the daylight period of the longest day of the year (hours). The coefficients a and b are given by the following equations:

Figure 3.3. Relationships between CS_{max} and LAI and determination of CSC.



2.0
1.5
1.0
0.5
0
CSmax (mm)
From
experiment
CSC = CSmax / LAI
Deduction
0
1
2
3
4
LAI (cm2/cm2)

$$a = 12 - (5.69*10^{-2}L) - (2.02*10^{-4}L^2) + (8.25*10^{-6}L^3) - (3.15*10^{-7}L^4) \tag{4}$$

and

$$b = 0.123L - (3.10*10^{-4}L^2) + (8.00*10^{-7}L^3) + (4.99*10^{-7}L^4) \tag{5}$$

The term PET_{max} in Equation 2 is calculated by integration of PET' over daylight period as follows:

$$PET^{24} = \int_0^N PET'dt = PET_{max}\left[\frac{2N}{\pi}\right] \tag{6}$$

or

$$PET_{max} = PET^{24}\left[\frac{\pi}{2N}\right] \tag{7}$$

The depth of potential evapotranspiration during one time step PET in mm is estimated as:

$$PET = PET^{24}\,\frac{\cos\left[\frac{\pi\,(t+\Delta t)}{N}\right]-\cos\left[\frac{(\pi\,t)}{N}\right]}{2} \tag{8}$$

Potential evapotranspiration is set equal to zero at night and during precipitation events. Therefore, in a rainy day, PET is partitioned outside of the precipitation interval. In this case, the equivalent depth of potential evapotranspiration integrated over the rainy period (PET^{h1-h6}) is divided by the time of the remaining diurnal period without precipitation, and then the result is added to PET calculated by Equation 8 for the intervals of the daylight period without rain.

Soil evaporation is modeled by separating it into two stages (Bond and Willis, 1970): stage 1, in which actual soil evaporation rate (AE) is equal to the potential rate (PE); and stage 2, in which the soil surface has become dry and AE is a rapidly decreasing portion of PE. Potential soil evaporation during one time increment (PE) is given by a Beer's law relationship of the form:

$$PE = e^{(-0.6 LAI)}\, PET \tag{9}$$

where PE and PET are given in mm and LAI in cm^2/cm^2.

Actual soil evaporation (AE) is calculated by a method adapted from Boesten and Stroosnijder (1986), in which AE is dependent on PE. The method is graphically represented in Figure 3.4 and analytically described as:

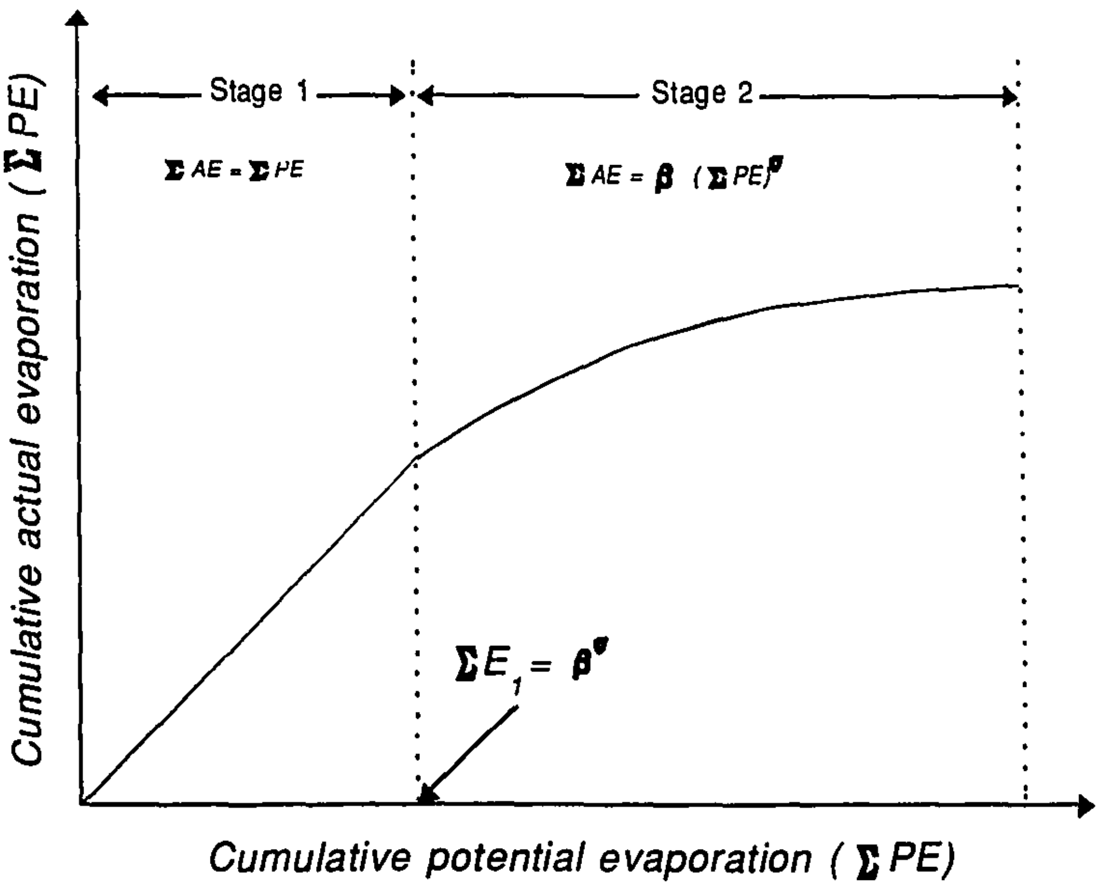
$$\begin{aligned} \Sigma AE &= \Sigma PE && \text{for } \Sigma PE < \beta^{\sigma} \\ \Sigma AE &= \Sigma PE && \text{for } \Sigma PE = \Sigma E_1 = \beta^{\sigma} \\ \Sigma AE &= \beta (\Sigma PE)^{\delta} && \text{for } \Sigma PE > \beta^{\sigma} \end{aligned} \tag{10}$$

where ΣE_1 (mm) is the value of cumulative soil evaporation at the transition of stage 1 to stage 2, ß and δ are the evaporation characteristic soil parameters to be determined experimentally and σ is equal to $(1-\delta)^{-1}$. In the original model, Boesten and Stroosnijder (1986) assumed $\delta = \sigma^{-1} = ½$, and only ß was determined experimentally. In this case the equation contains only one parameter, ß, which determines both ΣE_1 and the slope of the Σ AE versus $(\Sigma PE)^{½}$ relationship in stage 2.

According to the soil evaporation submodel, AE is equal to PE in stage 1 and is determined by the PE dependent function in stage 2. However, in a sequence of drying and wetting events soil evaporation is calculated according to the following procedure.

In a day without precipitation, Σ PE is increased by PE and ΣAE is estimated from the updated value of Σ PE for each time step using Equation 10. In this case, AE is given

Figure 3.4. Soil evaporation submodel.


Stage 1
Stage 2
$\Sigma AE = \Sigma PE$
$\Sigma AE = \beta\ (\Sigma PE)^{\theta}$
$\Sigma E_1 = \beta^{\theta}$
Cumulative actual evaporation (ΣPE)
Cumulative potential evaporation (ΣPE)

by the difference between the updated Σ AE and the value of Σ AE calculated for the previous time interval.

On a rainy day, the calculation follows the method described above for the interval antecedent to the precipitation period. During the rainfall period, AE is set to zero and infiltration gradually decreases soil water deficit by decreasing Σ AE. For the subsequent time steps in that day, the model assumes that the soil surface is at field capacity and thus AE is set equal to PE up to the point at which either all the water from the last rainfall event has been evaporated or the daylight period has been ended. During this interval, Σ AE is increased by the value of PE in each time step. At the end of this interval Σ PE is calculated from Σ AE using Equation 10, and a new drying or wetting cycle can start.

A certain amount of sensible heat is assumed to be transferred from between rows to the crop canopy when soil surface layers become dry and then potential soil evaporation can not be met. This can increase transpiration if soil available water is still sufficient to supply the crop evaporative demand (Tanner, 1957; Hanks et al., 1971; Saxton et al., 1974; Ritchie, 1983; Ehlers, 1991). The process is accounted for by the amount of unusable energy (U_n) in the process of soil evaporation and is estimated as the difference between potential and actual soil evaporation. This energy is assumed to be totally transferred (T equal to 1, where T is a coefficient of energy transfer) to the plant canopy when leaf area index (LAI) is higher than 1.5 and by a fraction of U_n (T = 0.67 * LAI) for sparser canopies. Saxton et al. (1974) used a similar relationship to describe this process, but transference of sensible heat was calculated as a function of soil cover. In Paraná, a wheat crop with LAI equal to 1.5 has a correspondent value for soil cover of about 60%, which was the threshold value established by Saxton et al. (1974) for the total transference of sensible heat to the plant canopy to occur.

Potential transpiration (PT) is equal to the difference between PET and PE, added to the part equivalent to unusable energy transferred to the plant canopy (U_n * T). The amount of water stored in the canopy from intercepted rainfall is evaporated first (EI) at the potential rate, using a portion of the available energy for potential transpiration.

Potential transpiration reduced by EI (PT_r) is then input into Equation 11 to calculate crop potential transpiration during each time step (Tmax). A linear decreasing root extraction pattern with depth z (mm), up to zero at the bottom of the root zone, is assumed to estimate the amount of water depleted from each compartment of the soil profile ($Tmax_j$) (Prasad, 1988), such that:

$$Tmax = \int_0^{z_r} (Tmax_j)\, dz = PT_r \int_0^{z_r} (a - bz)\, dz \tag{11}$$

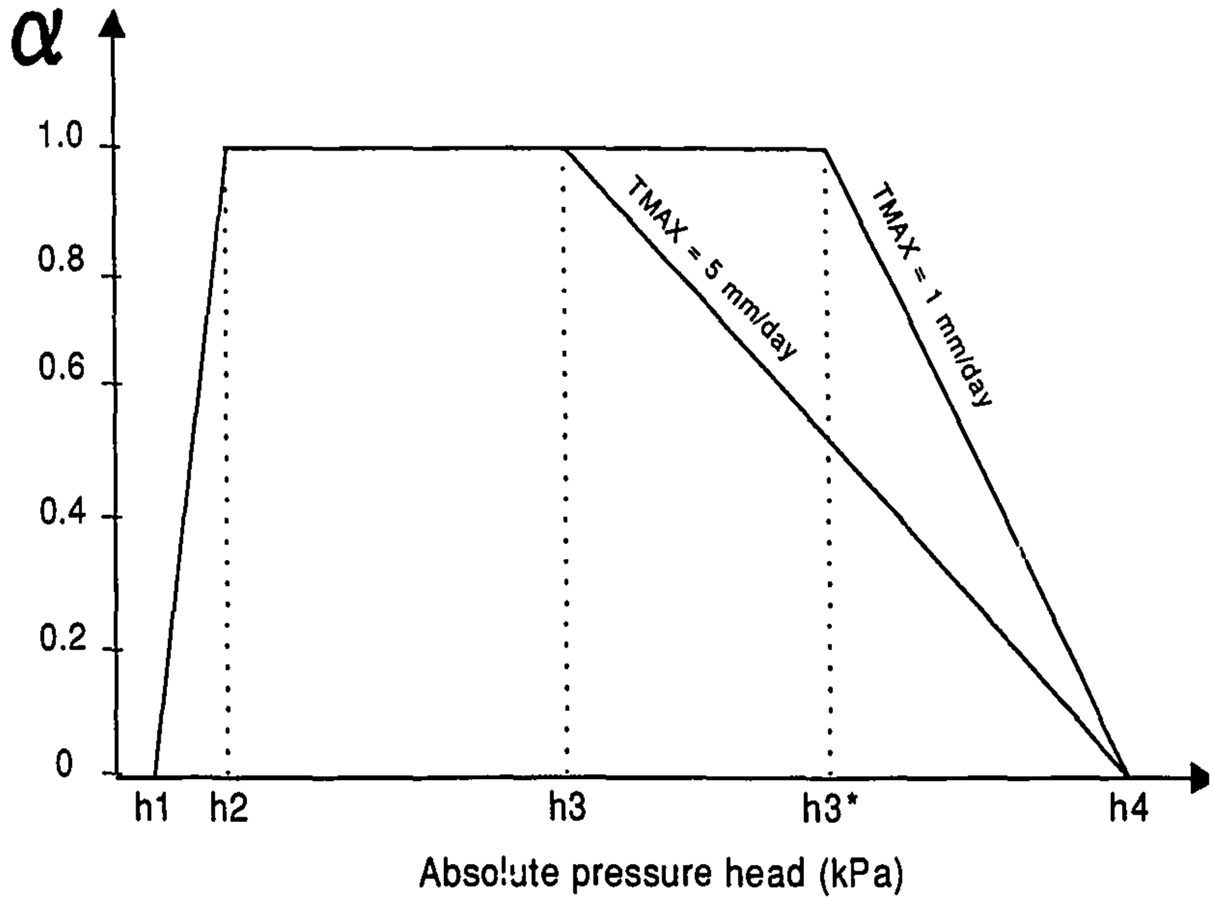
where $a = 2/z_r$ and $b = 2/(z_r)^2$, z_r being the maximum rooting depth for each day of the growing season (cm). Since the coefficients a and b depend on rooting depth, they vary from day to day through the cropping season.

Actual transpiration (AT) during one time step is obtained by the integration of actual transpiration in each soil compartment (AT_j) over the root zone:

$$AT = \int_0^{z_r} (AT_j)\, dz = \int_0^{z_r} \left[\alpha(h)_j\ Tmax_j\right] dz \tag{12}$$

The parameter α(h), or sink term function, is a prescribed function of pressure head (h) which represents root water extraction characteristics of the crop (Feddes et al, 1978). As shown in Figure 3.5, this function is equal to zero below h1 (oxygen deficiency) and above

Figure 3.5. Representation of the dimensionless parameter α as a function of pressure head.



α
1.0
0.8
0.6
0.4
0.2
0
TMAX = 5 mm/day
TMAX = 1 mm/day
h1
h2
h3
h3*
h4
Absolute pressure head (kPa)

h4 (permanent wilting point). It remains constant at 1 between h2 and h3, which represents conditions for optimum water extraction. Finally, $\alpha(h)$ assumes a linear variation in the intervals h1-h2 and h3-h4. The value of h3 depends on crop potential transpiration. It is interpolated between h3 and h3* when Tmax varies from a higher to a lower value.

For each time step, actual evapotranspiration (AET) is the sum of EI, AT, and AE. AET represents the energy used to deplete water from different storage positions in the system, according to each component. Therefore, EI is used to evaporate water stored on the canopy by intercepted precipitation, as already described. The extraction of water by actual transpiration is calculated directly by Equation 12, since it is applied for each compartment of the soil profile. Finally, the energy available for soil evaporation (Equation 10) is used first to evaporate ponded water, when it exists. The remaining or the total energy (when no ponding occurs), is then used to extract water from the top soil compartment.

Actual transpiration and soil evaporation are subject to the constraint that the soil water storage in each compartment must be above a threshold level. This threshold level is set as the value equivalent to the permanent wilting point for each depth.

Infiltration and redistribution of water through the soil profile is described by the following Darcy's equation form:

$$q_j = -\left[\frac{(k_{j+1}-k_j)}{2}\right]\left[\frac{(h_{j+1}-h_j)}{\Delta Zm_j} - 1\right]\Delta t \qquad (13)$$

where q_j is the depth of flux at the top of the j^{th} soil compartment (mm) during the time step Δt (days), k_j is unsaturated hydraulic conductivity (mm/day), h_j is pressure head (mm), and ΔZm_j (mm) is the difference between midpoint depths of two subsequent soil compartments.

The values of h_j and k_j are assumed to be constant during one time step. They are estimated from the soil water retention and unsaturated hydraulic conductivity curves using the updated value of soil moisture content at each depth, after depletion of water by transpiration and soil evaporation. In the case of infiltration, the actual flux is either the potential flux calculated from Equation 13, assuming saturated conditions at soil surface ($h_j = h_0 = 0$), or the application rate (precipitation minus interception), whichever is limiting.

The boundary layer at the bottom of the soil profile is assumed to have the same hydraulic characteristics and thickness as the layer above. It is assumed to have free drainage at the bottom and exchanges water with the layer above, according to the Darcian calculation. However, this does not allow for upward flux. Consequently, the water content in this layer decreases up to the permanent wilting point, in case of a long drying period, or increases up to saturation, during or shortly after precipitation events.

Surface ponding is depleted using part or the total energy available for actual soil evaporation, as described previously. After evaporation, the ponded water is increased by the depth of precipitation reduced by canopy interception and constitutes the potential amount for infiltration. After infiltration, the remaining amount of water that exceeds a value to be specified as the maximum depressional storage is considered runoff.

The change in water storage in each soil compartment (ΔW_j) in mm during one time step (Δt) is estimated by:

$$\Delta W_j = (qn_j - AT_j - AE_j)\Delta t \tag{14}$$

where qn_j is the net flux given by the difference between the flux at the bottom (q_{j+1}) and the top (q_j) of each compartment.

The model uses a variable time step, similarly to the approach described by Belmans et al. (1983), such as:

$$\Delta t^{(i+1)} = \frac{\Delta\theta_{max}}{\left(\frac{\Delta\theta}{\Delta t}\right)^{i}_{max}} \tag{15}$$

The denominator of Equation 15 is defined as:

$$\left(\frac{\Delta\theta}{\Delta t}\right)^{i}_{max} = \underset{j=1,..,K}{MAX} \left[\frac{\left(\frac{AET}{\Delta z}\right)^{i} + \left|\left(\frac{\Delta q}{\Delta z}\right)^{i}\right|}{\Delta t^{i}}\right] \tag{16}$$

where Δt is time step in days; i is an index of time; j is compartment number; $\Delta\theta_{max}$ is an assumed value for maximum change of soil moisture content (cm^3/cm^3) allowed within one time step (ranging from 0.002 to 0.03); $(\Delta\theta/\Delta t)^{i}_{max}$ is the maximum amount of soil moisture content change among the various compartments of the soil profile during the previous time step (cm^3/cm^3/day); AET_j (mm/day), Δq_j (mm/day), and Δz_j (mm) are actual evapotranspiration, flux, and thickness at the j^{th} soil compartment, respectively.

According to Equations 15 and 16, time step is calculated from the flow conditions prevailing during the preceding time increment. Therefore, time step is longer for periods in which soil moisture is high and shorter when it is low. In the case of transition between dry and rainy periods or when precipitation rate increases during a rain event, $\Delta t^{(i+1)}$ is reduced to Δt_c, in order to preserve the criteria established for $\Delta\theta_{max}$. This occurs when the depth of precipitation during the time increment Δt^{i+1} exceeds a value given by P_{max}, which is calculated by the product of $\Delta\theta_{max}$ and the thickness of the top soil compartment (Δz_1). The corrected time step Δt_c is estimated by:

$$\Delta t_c^{(i+1)} = \left[\frac{1}{(P^{(i+1)})^2 + 1} + 1 \right] \Delta t^{(i+1)} \tag{17}$$

where P^{i+1} is the depth of precipitation (mm) during the increment Δt^{i+1}. Time step has a maximum of 0.167 days (4 hours) and a minimum calculated by:

$$\Delta t_{min} = \frac{P_{max}}{24\, P_{exp}} \tag{18}$$

where Δt_{min} is the minimum time step (days) and P_{exp} in is maximum precipitation rate (mm/h) expected for the region in a certain return period.

Experimental description and model inputs

Data from experiments conducted at the Experimental Station of the Instituto Agronômico do Paraná (IAPAR) in Londrina, PR, Brazil (23°23'S and 51°11'W), were used as inputs to test the model. A more detailed description of the experimental procedures was given in Chapter II.

Spring wheat was grown during six growing seasons, at two cropping periods per year, from 1986 to 1988. Soil moisture measurements were made by the gravimetric method for the depth 0-10 cm and with a neutron probe at the depths of 10-40, 40-70, 70-100, and 100-130 cm at 3 to 4 day intervals throughout the growing seasons. Corresponding measurements were made in two bare soil plots, adjacent to the experimental field.

The dates of emergence and harvesting at each growing season were supplied to the model using the data presented in Figure 3.6. Figure 3.7 shows the inputs of crop grown, including the average values of leaf area index and rooting depth determined during the experimental period.

The soil was classified as an Oxisol (Typic Haplorthox). This soil was extensively described by Sidiras et al. (1981) and Faria and Caramori (1985). Oxisols represent 15% of the agricultural area of the State, occur in undulating topography, and are characterized by clay content of 40 to 60%, deep profile, high infiltration, absent or deep water table, and low organic matter content (less then 3%).

The soil physical parameters used as input to the model were obtained from field data following the procedures described in Chapter II. Soil water retention curves were described by a Van Genuchten type equation (Van Genuchten and Nielsen, 1985), such that:

$$\theta = \theta_r + \frac{(\theta_s + \theta_r)}{[(1 + \alpha h)^n]^m} \tag{19}$$

where θ is water content (cm^3/cm^3), h is soil water potential (kPa), θ_s and θ_r are respectively saturated and residual values of soil water content (cm^3/cm^3), and α, m, and n are regression parameters (dimensionless).

Unsaturated hydraulic conductivity (K) in mm/day as a function of soil moisture content (θ) in cm^3/cm^3 was fitted by the following equation:

$$K = a\ e^{(b\theta)} \tag{20}$$

where a and b are regression parameters (dimensionless).

The coefficients of Equations 19 and 20 are given in Table 3.1. These inputs were used by the model to describe the hydraulic properties of a soil profile with geometric characteristics presented in Table 3.2. An extra 10 cm thick soil compartment with the same

Figure 3.6. Wheat crop growing seasons during 1986 to 1988.

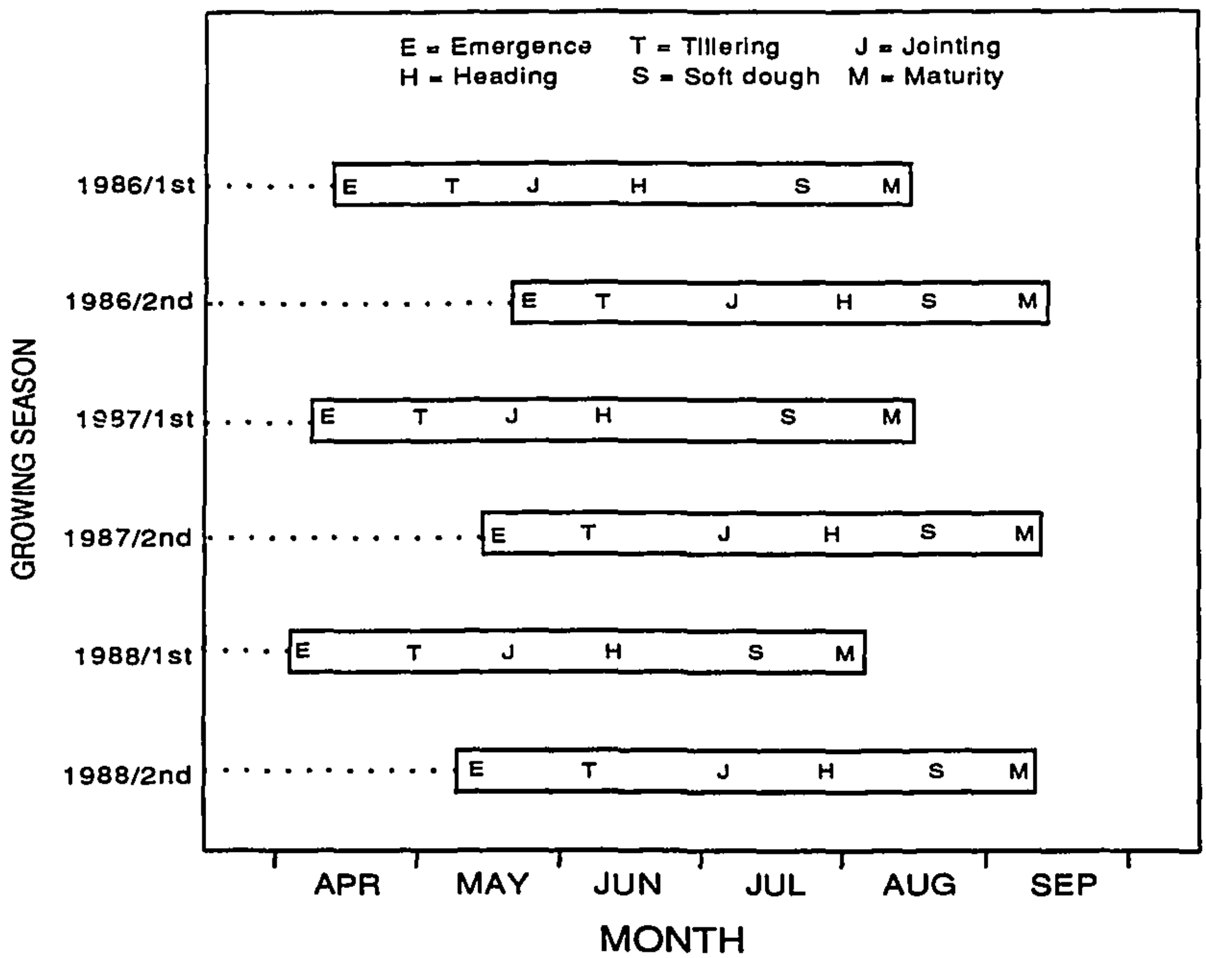
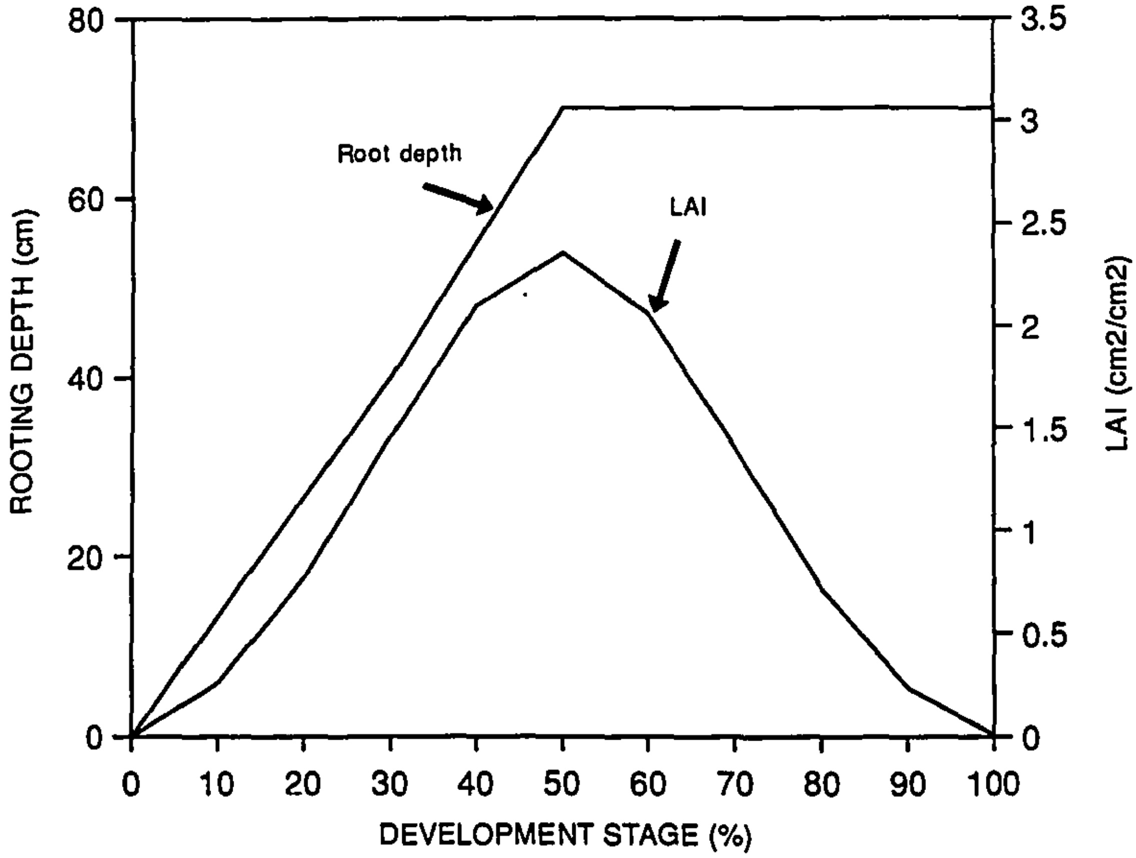

E = Emergence
T = Tillering
J = Jointing
H = Heading
S = Soft dough
M = Maturity
GROWING SEASON
1986/1st
1986/2nd
1987/1st
1987/2nd
1988/1st
1988/2nd
E T J H S M
APR
MAY
JUN
JUL
AUG
SEP
MONTH

Figure 3.7. Rooting depth and leaf area index (LAI) according to wheat development.



Root depth
LAI
ROOTING DEPTH (cm)
LAI (cm2/cm2)
DEVELOPMENT STAGE (%)
0
20
40
60
80
0.5
1
1.5
2
2.5
3
3.5
10
30
50
70
90
100

hydraulic characteristics of the layer above was introduced at the bottom of the soil profile to characterize the base boundary layer.

The inputs to describe the sink term function are also given in Table 3.2. These values are the same as the ones used in SWACROP (Chapter II), except for h2, which assumed a lower value. According to Vieira et al. (1990) oxygen deficiency in Oxisols can occur only during long rainy periods with high precipitation or in conditions of high levels of soil compaction, which were not the conditions of the soil in the experimental field.

Specific data of canopy rainfall interception for wheat were not found in the literature. Armstrong and Mitchell (1987) studied rainfall interception under different canopies, including corn and soybeans. Their results showed maximum thickness of water intercepted by the leaves varying from 0.08 to 0.38 mm. According to Norman and Campbell (1983), a corn canopy with LAI equal to 4 can store about 1 mm of water on the leaves and a small amount in the leaf-stem junction. Based on this information a canopy

Table 3.1. Parameters of the soil water retention (cm^3/cm^3) and hydraulic conductivity (mm/day) equations used as input.

Soil depth (cm)	Parameter						
	θ_r	θ_s	α	n	m	a	b
0-10	0.178	0.474	0.038	1.968	0.200	4.44×10^{-12}	62.79
10-40	0.277	0.447	0.033	4.158	0.100	6.77×10^{-14}	75.62
40-130	0.266	0.451	0.027	1.301	0.432	6.03×10^{-13}	70.90

Table 3.2. Soil and sink term input parameters.

Parameter	Value
Geometrical characteristics of the profile:	
Depth of the profile (cm)	130
Number of compartments	13
Thickness of the compartments (cm)	10
Pressure head of the sink term function (kPa):	
h1	1.0
h2	2.5
h3	50.0
h3*	100.0
h4	1500.0

storage coefficient equal to 0.3 was taken as a reasonable assumption for wheat.

A maximum depressional storage of 1 mm was used for input to the model in the calculations of runoff and ponding. Since data on rainfall distribution were not available for the region, the inputs of precipitation factors used for dissagregation of daily rainfall into hourly rainfall were taken from the curve presented in Figure 3.2b.

Minimum time steps were calculated by Equation 18 as 4.0×10^{-4} days (0.58 min), assuming a maximum precipitation rate expected for the region (P_{exp}) in a return period of 10 years equal to 52.4 mm/h (Faria and Wagner, 1990) and a maximum change of soil moisture content ($\Delta\theta_{max}$), within a time increment equal, to 0.05 cm^3/cm^3. Maximum time step was established by the model as 1.67 10^{-1} days (4 hours).

The soil evaporation parameters were the only calibrated inputs. The coefficients ß and δ were obtained by linear regression of observed cumulative actual soil evaporation from the bare soil plots (ΣAE_b) and potential Penman evapotranspiration (ΣPET) data during a period without precipitation, after log transformation of Equation 10. ΣAE_b was estimated by the water balance method assuming drainage to be negligible. The results of the calibration will be reported in the next section.

The weather inputs, including daily rainfall and Penman potential evapotranspiration, were taken from the nearby IAPAR Weather Station. The model started simulations with initial soil moisture content distribution equal to the one measured in the field at the beginning of each growing period. Cumulative actual and potential soil evaporation (Equation 10) were set to zero at crop emergence, assuming soil moisture contents for the upper compartments to be near field capacity.

The model's performance was evaluated against measured soil moisture contents, water storage, and evapotranspiration. Observed data of evapotranspiration (AET), transpiration (AT) and soil evaporation (AE) for wheat were obtained in the same manner as reported in Chapter II. Observed AET (mm/day) was estimated by the water balance method from the wheat plots, during a period without precipitation assuming drainage to be negligible. Evaporation from the bare soil plots, AEb (mm/day), was used to calculate AE (mm/day) from the cropped area (Cooper et al., 1983):

$$AE = e^{(-0.6LAI)} AE_b \tag{21}$$

Finally, observed wheat AT (mm/day) was estimated as the difference between AET and AE.

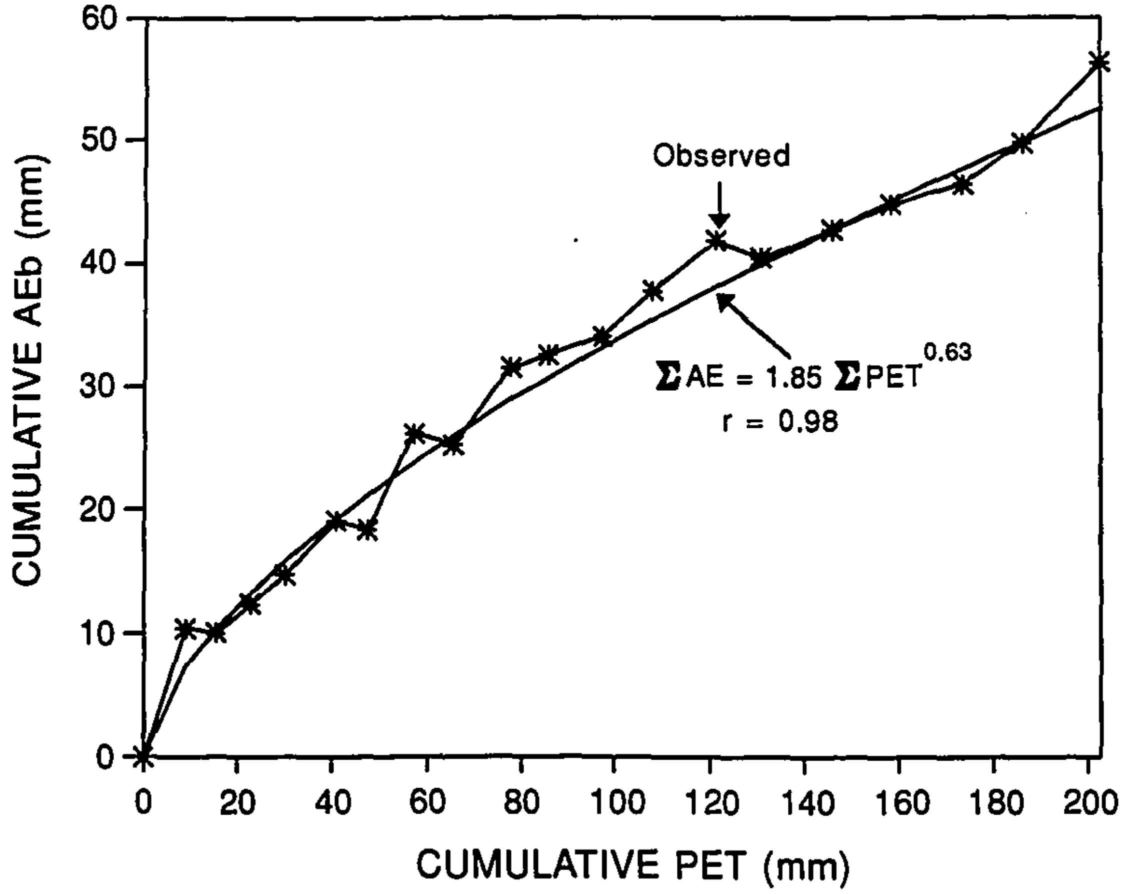
RESULTS AND DISCUSSION

The calibrated soil evaporation parameters (Equation 10) are given in Figure 3.8.

The calibration was performed during a 67 day rainless period in 1988 (June 30 to September 5). The value obtained for ß (1.85) was very similar to the one calibrated by Boesten and Stroosnijder (1986) for a loamy sand soil in The Netherlands. However, the cumulative actual evaporation curve did not follow a square root relationship of cumulative potential evapotranspiration, as assumed by these authors. The best fit of experimental data ($r = 0.98$) was obtained for δ equal to 0.63. This resulted in a value for the transition between evaporation stages 1 and 2 (Σ E1) equal to 5.27 mm, which was of a same order of magnitude as the values obtained in several field studies of soil evaporation reported in the literature (Ritchie, 1972; Al-Khafaf et al., 1978; Boesten and Stroosnijder, 1986).

The parameters ß and δ, along with the other inputs reported in the previous section, were entered into the model to test its performance over the six wheat cropping periods. Simulated and measured soil moisture contents at three depths within the root zone during two cropping periods are shown in Figures 3.9 and 3.10. The agreement between model predictions and measurements was generally good either in wet (Figure 3.9) or dry years (Figure 3.10), reflected by correlation coefficients (r) ranging from 0.94 to 0.98. Small deviations between model estimates and field data were also observed for the remaining experimental period and depths, as quantified by the average absolute difference and standard error of estimated (Table 3.3 and 3.4). Larger differences occurred in the top soil compartment, with average absolute difference varying between 1.52 to 2.94% and standard error of estimate between 2.10 to 3.75%. The results for the lower depths showed values of average absolute difference ranging between 0.37 to 2.82% and standard error of estimate between 0.58 to 3.25%. These differences were similar to those reported in Chapter II, when the same observed data set was used to test VB4 and SWACROP. In that

Figure 3.8. Calibration of the parameters β and δ using observed data from the bare soil plots during July 1988.



60
50
40
30
20
10
0
CUMULATIVE AEb (mm)
0
20
40
60
80
100
120
140
160
180
200
CUMULATIVE PET (mm)
Observed
$\Sigma AE = 1.85\ \Sigma PET^{0.63}$
r = 0.98

Figure 3.9. Predicted and observed soil moisture at three depths of the soil profile during the first wheat crop in 1987.

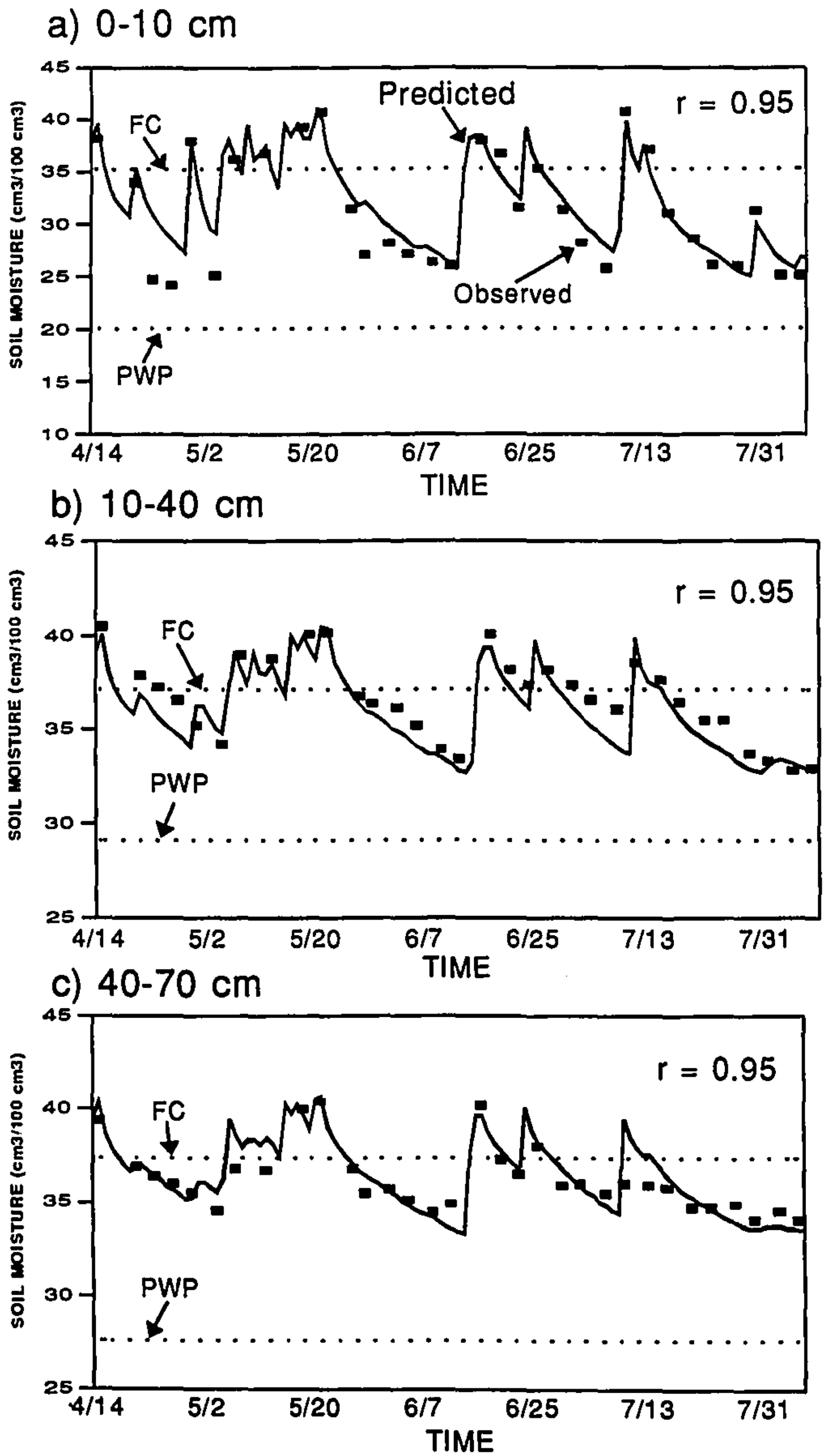

a) 0-10 cm
Predicted
r = 0.95
FC
Observed
PWP
SOIL MOISTURE (cm3/100 cm3)
45
40
35
30
25
20
15
10
4/14
5/2
5/20
6/7
6/25
7/13
7/31
TIME
b) 10-40 cm
r = 0.95
FC
PWP
SOIL MOISTURE (cm3/100 cm3)
45
40
35
30
25
4/14
5/2
5/20
6/7
6/25
7/13
7/31
TIME
c) 40-70 cm
r = 0.95
FC
PWP
SOIL MOISTURE (cm3/100 cm3)
45
40
35
30
25
4/14
5/2
5/20
6/7
6/25
7/13
7/31
TIME

Figure 3.10. Predicted and observed soil moisture at three depths of the soil profile during the second wheat crop in 1988.

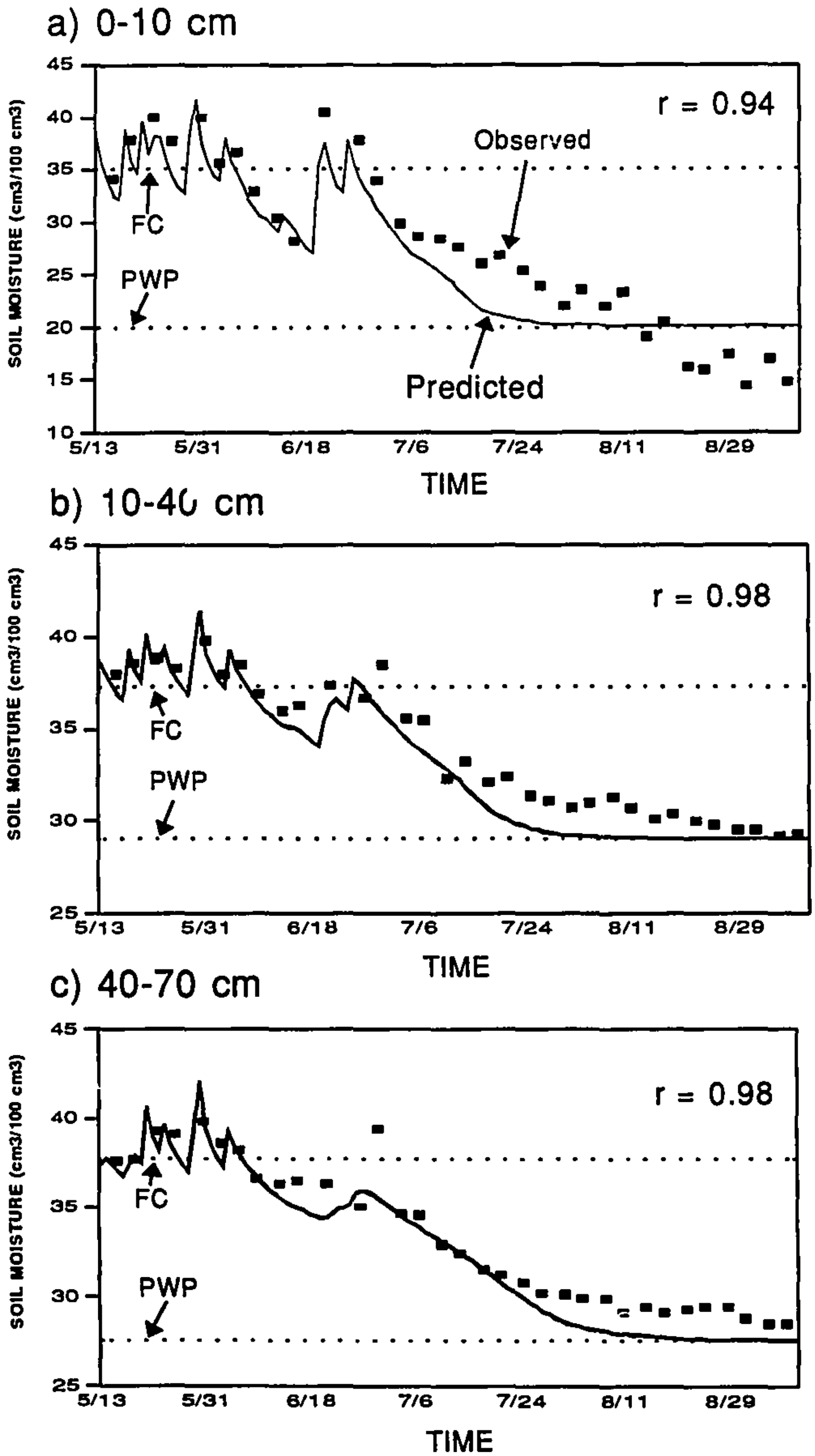

a) 0-10 cm
r = 0.94
Observed
FC
PWP
Predicted
SOIL MOISTURE (cm3/100 cm3)
45
40
35
30
25
20
15
10
5/13
5/31
6/18
7/6
7/24
8/11
8/29
TIME
b) 10-40 cm
r = 0.98
FC
PWP
SOIL MOISTURE (cm3/100 cm3)
45
40
35
30
25
5/13
5/31
6/18
7/6
7/24
8/11
8/29
TIME
c) 40-70 cm
r = 0.98
FC
PWP
SOIL MOISTURE (cm3/100 cm3)
45
40
35
30
25
5/13
5/31
6/18
7/6
7/24
8/11
8/29
TIME

Table 3.3. Average absolute difference in % volume for comparison of observed and estimated soil moisture contents in different soil depths and cropping periods.

Year/ Cropping period	Soil depth (cm) 0-10	10-40	40-70	70-100	100-130
1986/1st	2.70	2.82	1.04	0.85	1.33
1986/2nd	2.94	2.11	0.78	1.13	1.02
1987/1st	1.52	0.66	0.58	0.37	1.33
1987/2nd	2.61	1.19	1.95	1.58	1.85
1988/1st	2.63	1.93	0.64	0.71	0.88
1988/2nd	2.85	1.10	1.05	0.53	0.62

Table 3.4. Standard error of estimate for comparison of observed and predicted soil moisture contents in % volume in different soil depths and cropping periods.

Year/ Cropping period	Soil depth (cm) 0-10	10-40	40-70	70-100	100-130
1986/1st	3.16	3.25	1.17	1.06	1.69
1986/2nd	3.75	2.39	1.14	1.36	1.20
1987/1st	2.10	0.79	0.71	0.58	1.46
1987/2nd	3.09	1.51	2.13	1.66	2.11
1988/1st	2.91	2.03	0.84	0.92	1.09
1988/2nd	3.19	1.28	1.31	0.72	0.73

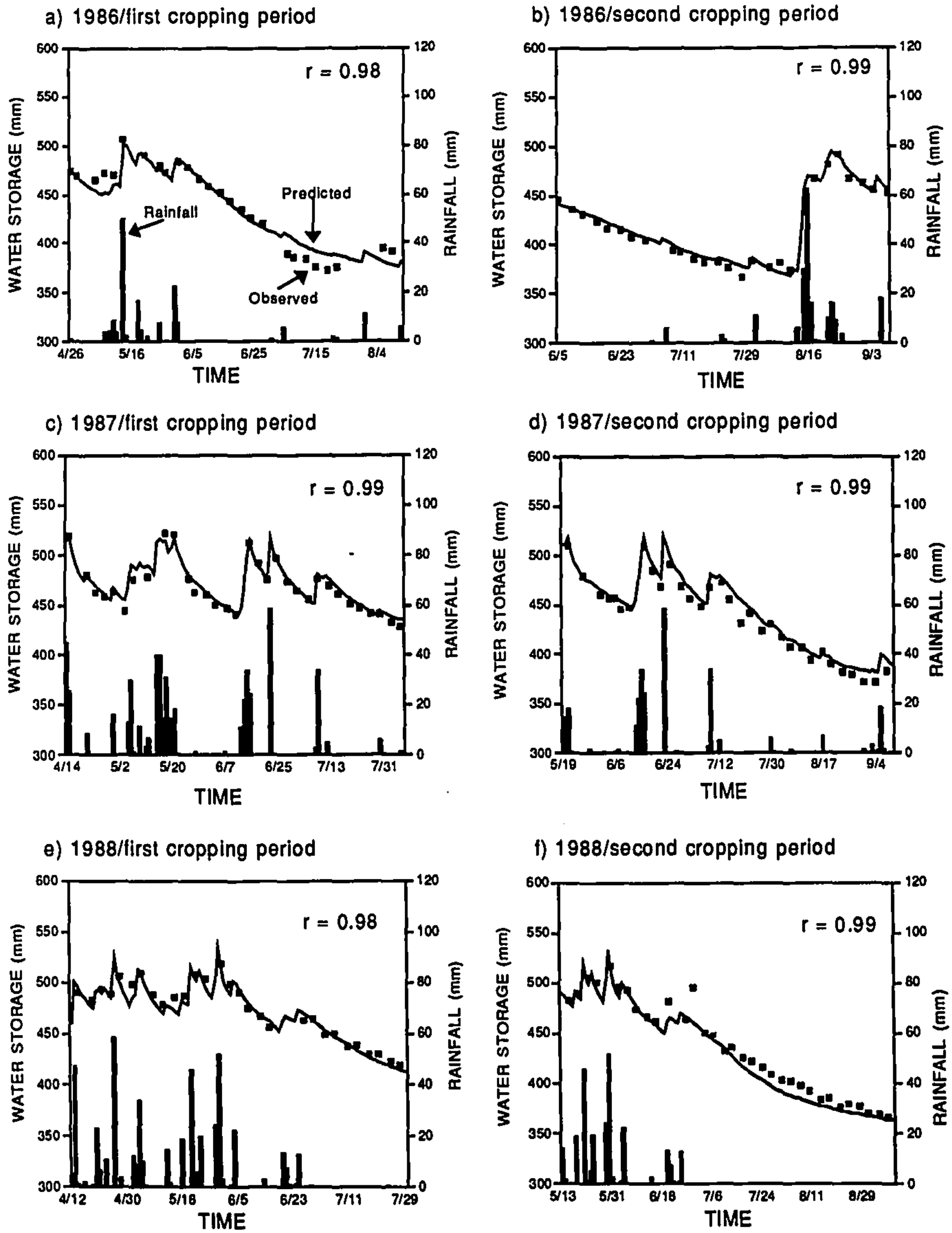
study, the larger deviations for the layers near the surface boundary were attributed to the inability of the models to simulate the rapid changes in soil water caused by the processes of infiltration and evapotranspiration. Errors associated with field measurements due to soil variability were also cited as possible causes of the discrepancies.

Predicted and measured soil water storage in 130 cm of the soil profile during the six cropping periods are presented in Figure 3.11. The correspondence between estimates and measurements for individual growing seasons was excellent ($r \geq 0.98$). The deviations, quantified by the average absolute difference and standard error of estimate (Table 3.5), varied between 4.0 to 10.1 mm and 4.8 to 11.0 mm, respectively. These results indicate a very good accuracy of the model, since the maximum values of average absolute difference and standard error of estimate represented, respectively, only 2.2% and 2.4% of the soil water storage at field capacity (456 mm) and about 2.9% and 3.1% of the soil water storage at permanent wilting point (350 mm). This performance is comparable to the ones given by SWACROP and VB4 when tested for the same conditions (Chapter II).

A full test of the model against observed values of evapotranspiration over the whole experimental period was not possible, because of the uncertainties in the estimates of field data using the water balance method. The period from June 30 to September 5 in 1988 was the only interval in which evapotranspiration from the wheat plots could be estimated without interference of drainage. Therefore, the verification of the model capability in predicting evapotranspiration was performed only for the second cropping period in 1988. This period extended for more than half of the growing season, including the phenological stages from jointing to maturity.

Predicted and observed cumulative actual evapotranspiration (AET), transpiration

Figure 3.11. Predicted and observed soil water storage (0-130 cm) and rainfall during six wheat cropping periods.



a) 1986/first cropping period
r = 0.98
Predicted
Rainfall
Observed
b) 1986/second cropping period
r = 0.99
c) 1987/first cropping period
r = 0.99
d) 1987/second cropping period
r = 0.99
e) 1988/first cropping period
r = 0.98
f) 1988/second cropping period
r = 0.99
WATER STORAGE (mm)
RAINFALL (mm)
TIME

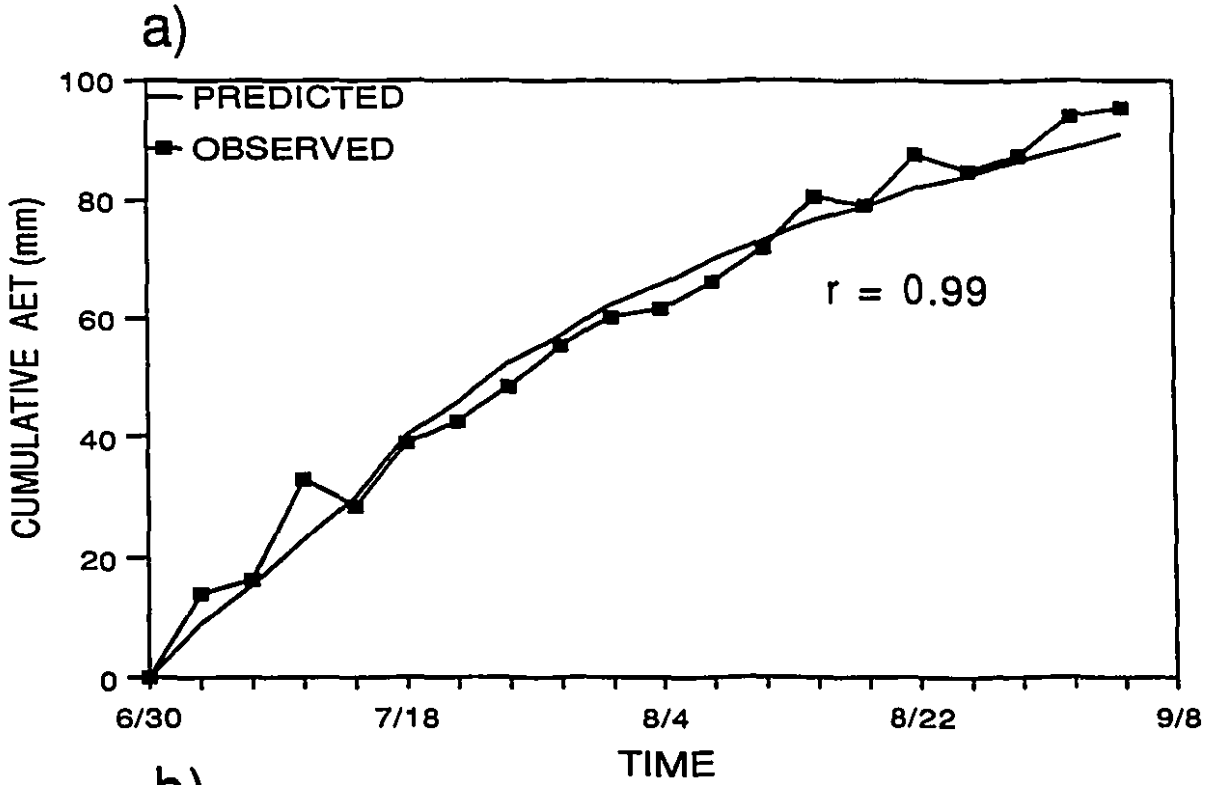
Table 3.5. Average absolute difference (AAD) and standard error of estimate (SEE) in mm for comparison of observed and predicted water storage in the soil profile (0-130 cm) during different cropping periods.

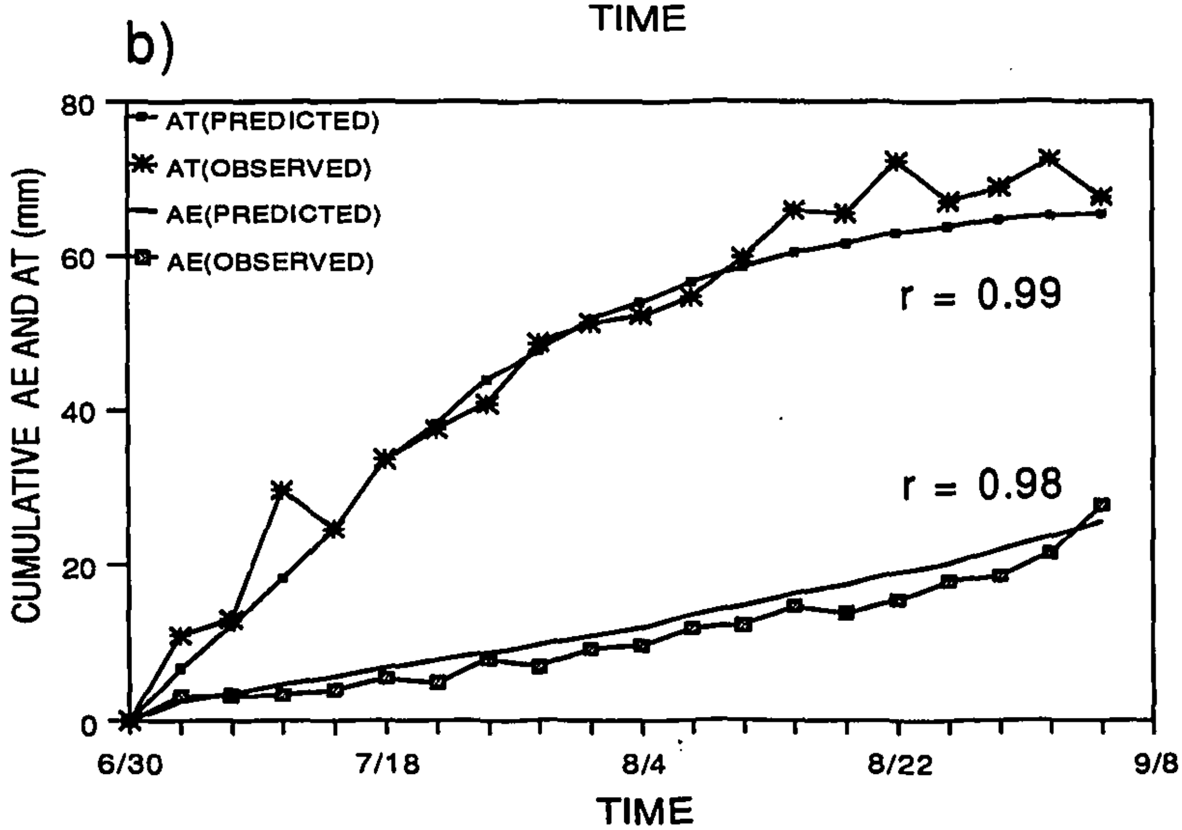
Year/ Cropping period	AAD	SEE
1986/1st	10.1	11.0
1986/2nd	4.0	4.8
1987/1st	4.3	5.5
1987/2nd	7.0	8.5
1988/1st	5.7	6.7
1988/2nd	7.8	10.2

(AT), and soil evaporation (AE) curves during the second wheat cropping period in 1988 are plotted against time in Figure 3.12. Figure 3.12a shows that the model provided a very good representation of the field observed AET ($r = 0.99$). Also the partition of AET into AT and AE (Figure 3.12b) was well simulated ($r \geq 0.98$), with predicted curves following closely the observed trend over time. However, simulated AE was slightly higher than observed values during the majority of the period and the model slightly underestimated AT and AET toward the end of the dryness period.

The differences in cumulative AE remained almost constant (about 2 to 4 mm) from the second week after the dry period started until the end of the season (Figure 3.12b). This indicates that inaccurate determinations (overprediction) occurred only at a short interval during the early part of the drying cycle. These differences could be attributed to factors not accounted for by the model, since partition of evapotranspiration is a complex process. This could be also caused by imprecision in the estimation of observed evapotranspiration and its components by the water balance method, due to errors involved in soil moisture

Figure 3.12. Comparison between observed and predicted evapotranspiration and components during the second wheat cropping period in 1988. a) Cumulative actual evapotranspiration (AET), and b) cumulative actual transpiration (AT) and soil evaporation (AE).


a)
100
80
60
40
20
0
PREDICTED
OBSERVED
CUMULATIVE AET (mm)
r = 0.99
6/30
7/18
8/4
8/22
9/8
TIME


b)
80
60
40
20
0
AT(PREDICTED)
AT(OBSERVED)
AE(PREDICTED)
AE(OBSERVED)
CUMULATIVE AE AND AT (mm)
r = 0.99
r = 0.98
6/30
7/18
8/4
8/22
9/8
TIME

measurements. Further, the simplifications involved in the estimation of soil evaporation for the wheat crop from bare soil plots by the Cooper method could also have produced a less accurate estimate of the partition of evapotranspiration.

The lower prediction of AT (Figure 3.12b), and consequently AET (Figure 3.12a), could be explained by the fact that, in the simulation, the soil moisture in the upper compartments reached levels close to the permanent wilting point during the later part of the drying period (Figure 3.10), and thus low amounts of water were calculated as extracted by the plants. On the other hand, soil moisture decreased to values lower than the permanent wilting point in the first compartment in the experimental plots after the second week in August (Figure 3.10). This increased cumulative observed AT and AET (Figures 3.12a and 3.12b).

Despite small discrepancies, the present model gave a better representation of evapotranspiration and its components than SWACROP or VB4, when these models were tested using the same field data (Chapter II).

Since the model was able to reproduce the trend of field evapotranspiration data with a reasonable precision over more than half of an independent growing season, it is possible to consider it appropriate to estimate evapotranspiration and components over any wheat growing period in this location.

Predicted seasonal evapotranspiration and the other hydrological components of the water balance during the six wheat cropping periods are summarized in Table 3.6. The values obtained for these parameters reflect reasonably the effects of variable evaporative demand (ETP) and depth of precipitation at different times of the several growing seasons. They also give a valuable indication of the water regime pattern for wheat grown in Paraná.

Table 3.6. Hydrological components of the water balance (mm) during six wheat cropping periods.

Year/ Cropping period	Rain	PET	Change in water storage	Evapotranspiration and components				Percolation	Runoff
				AET	AT	AE	EI		
1986/1st	162	252	-99	184	100	78	6	75	2
1986/2nd	193	233	12	152	76	69	7	20	9
1987/1st	520	262	-69	216	102	102	12	360	13
1987/2nd	267	279	-134	203	117	80	6	192	6
1988/1st	461	237	-49	202	92	99	11	287	21
1988/2nd	243	315	-120	181	99	78	4	168	14

According to Table 3.6, the initial soil water storage was depleted to supply crop water demand and percolation during all the growing seasons, except for the crop grown during the second period in 1986. Actual evapotranspiration was quite variable during the growing seasons. AET estimates ranged from 152 mm in a dry year (second cropping period in 1986) to 216 mm in the wettest year (first cropping period in 1987). Soil evaporation (AE) accounted for 39 to 49% of the water returned to the atmosphere via evapotranspiration (AET), while transpiration (AT) varied from 46 to 58% and intercepted evaporation (EI) from 2.2 to 5.6% of the seasonal AET. For the same situation, the estimates of seasonal AT with SWACROP (Chapter II) were very similar to the sum of AT and EI obtained in the present study. In that simulation SWACROP calculated AT without accounting for the effects of intercepted rainfall.

The estimated cumulative percolation ranged from 360 mm in the first growing season in 1987 to 20 mm in second cropping period in 1986 (Table 3.6). These results are in accordance with the amount of rainfall which occurred during the growing seasons, which varied from 162 to 520 mm, and the characteristics of high internal drainage of the soil profile.

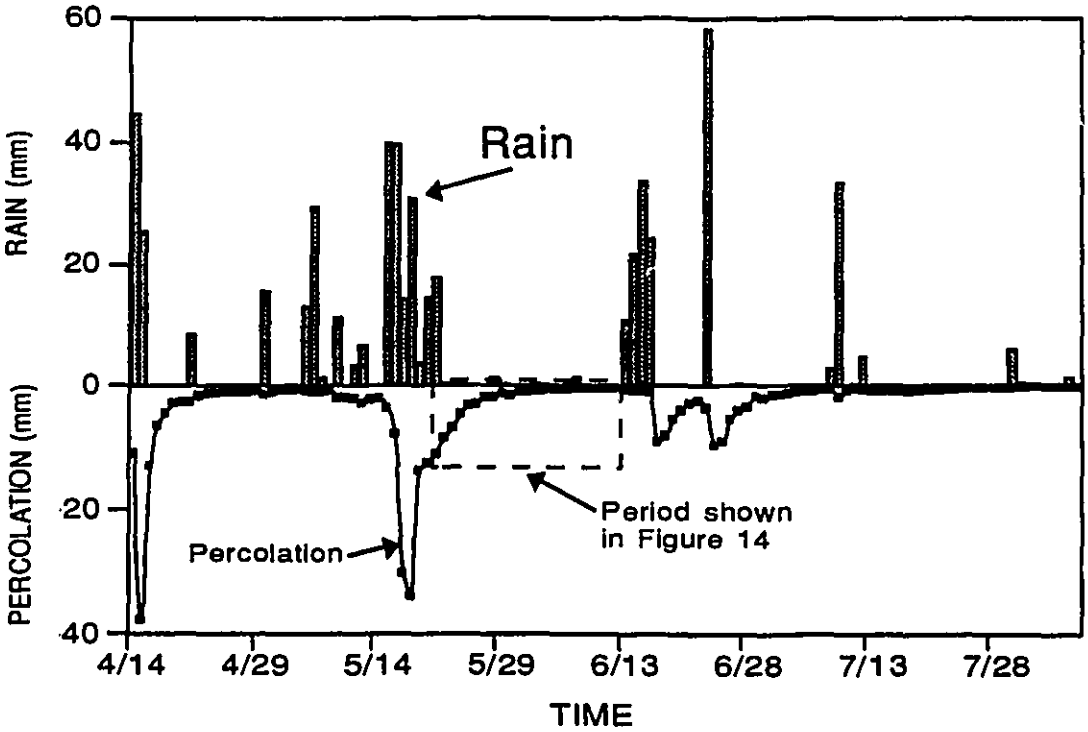
Estimated runoff represented only a small portion of the total precipitation during the growing seasons, as shown in Table 3.6. Considering the high infiltration and the soil conservation practices adopted in the study area, these results can also be considered a reasonable representation of reality.

In order to illustrate how the model simulates the variations of fluxes through the lower boundary of the soil profile with time, percolation rate over the wettest growing season (first cropping period in 1987) is presented in Figure 3.13. Changes in percolation rates were highly influenced by the different precipitation depths which occurred during the period.

Similarly, the variations of fluxes with soil depth and time are shown in Figure 3.14 for the first growing season in 1987. High rates of descending fluxes (negative values) occurred immediately after the end of the wet period (May 21 and 22), followed by lower rates in the subsequent days, due to decreases in unsaturated hydraulic conductivities and gradients in the several soil compartments. The positive values at the soil surface during the whole drying period represent the flux water extracted from the top soil compartment by evapotranspiration. Toward the end of the drying cycle, the model calculated positive fluxes for the upper soil compartments. This represents the water flow from the lower depths to the top (capillary rise) as soil moisture was depleted from the upper soil compartments by evapotranspiration.

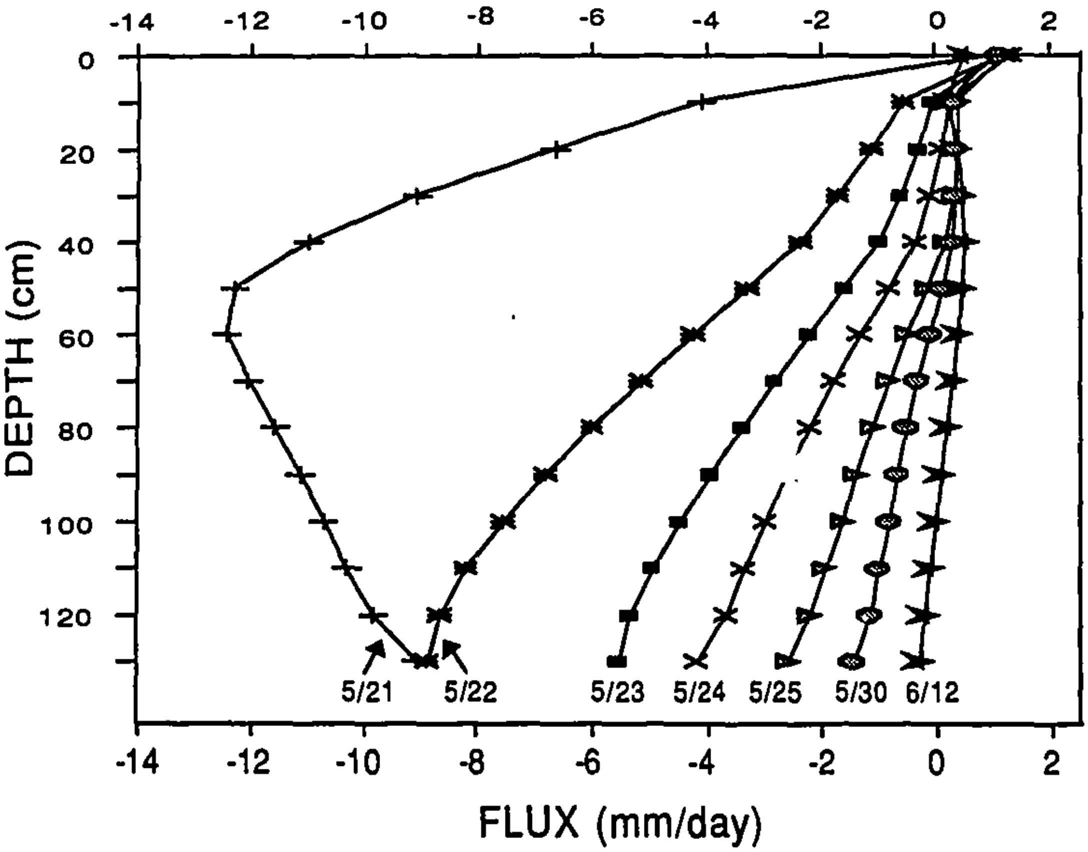
Predicted seasonal water taken up by roots for two growing periods (second period in 1986 and first in 1988) is given in Figure 3.15. These growing seasons had a similar

Figure 3.13. Percolation and rainfall rates during the first cropping period in 1987.



60
40
20
0
20
40
RAIN (mm)
PERCOLATION (mm)
Rain
Percolation
Period shown
in Figure 14
4/14
4/29
5/14
5/29
6/13
6/28
7/13
7/28
TIME

Figure 3.14. Fluxes according to depth at selected dates during a drying period in the 1987/1st growing season.



DEPTH (cm)
FLUX (mm/day)
5/21
5/22
5/23
5/24
5/25
5/30
6/12

seasonal evaporative demand (ETP about 235 mm), but different seasonal precipitation depths (193 mm in 1986 and 461 mm in 1988). Water extraction decreased linearly with depth for both crops and seasonal transpiration was higher for 1988. The lower precipitation during the growing season in 1986 caused soil water deficits and thus lower extraction of water by the roots occurred, mostly for the shallower layers. Despite the empiricism involved in the description of the root water extraction process, the model was sensitive to soil water availability and the estimates seemed to be quite reasonable.

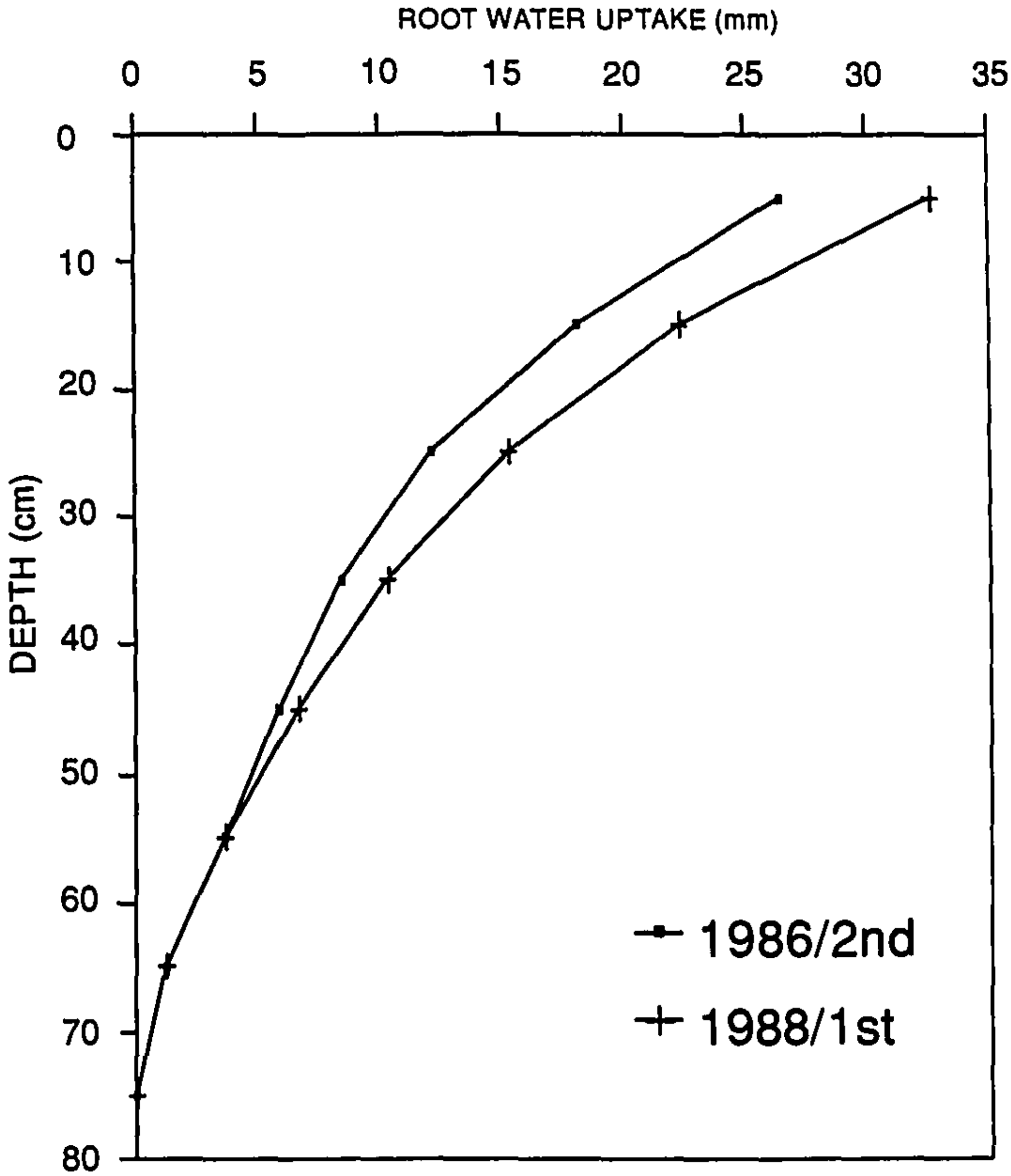
The model took about 20 seconds on a PC 80386 33MHZ microcomputer to simulate a growing season of about 110 days in a soil profile with 13 soil compartments, as defined in the present study. This was about 10 times less than the time taken by SWACROP to simulate the same period. Although fast computers are becoming more accessible nowadays, a shorter computation time is generally advantageous, when processing long term record data under several condition of crops and sites, or when the water balance in a soil profile is part of a more global process.

SUMMARY AND CONCLUSIONS

A model for simulating the components of the water balance for a cropped layered profile was described. Locally available parameters of soil, weather, and crop development were used as input. Only the coefficients used to describe soil evaporation were calibrated using field data. The model estimates were compared with field data of soil moisture contents and evapotranspiration collected in Londrina, Paraná, Brazil.

Soil moisture at different depths and water storage in the 130 cm of the soil profile were simulated with a great accuracy by the model, during six wheat growing periods. The

Figure 3.15. Seasonal root water uptake from the root zone during the 1986/2nd and 1988/1st cropping periods.



ROOT WATER UPTAKE (mm)
0
5
10
15
20
25
30
35
0
10
20
30
40
50
60
70
80
DEPTH (cm)
1986/2nd
1988/1st

deviations quantified by the average absolute difference and standard error of estimate were less than 2.2 and 2.4%, respectively, of the total water stored in 130 cm of the soil profile at field capacity. The model provided very good estimates of the field evapotranspiration data ($r = 0.99$). The partition of evapotranspiration into transpiration and soil evaporation was also in good agreement with observed data ($r \geq 0.98$). Although not compared with observed data, the estimates of the other hydrological components of the water balance seemed to represent reasonably well the water regime of a wheat crop on a field scale in Paraná.

Compared to the performance of other models tested previously for the same data set (VB4 and SWACROP; Chapter II), the present model gave a similar accuracy for prediction of soil moisture contents and water storage, but better estimates of evapotranspiration and its components. It has the potential to be more widely applied to different environmental conditions than models like VB4, because only a few input parameters require calibration (β and δ in Equation 10), while the others are measured inputs. Since a high computation efficiency was achieved with a good predictive accuracy, the model is appropriate for uses in studies involving long term simulations. The ability to partition evapotranspiration into its components permits the coupling of the present model with crop yield models to be used in further applications in studies of regional risks of drought, crop water requirements, and irrigation scheduling, such as are required in Paraná State.

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PREFACE TO CHAPTER IV

In Chapter IV, different crop yield models are combined with the model described in Chapter III. Their capability to predict wheat yield are evaluated using field data.

CHAPTER IV

EVALUATION OF CROP-WATER PRODUCTION FUNCTIONS FOR WHEAT IN BRAZIL

ABSTRACT

The performance of seven linear crop-water production functions was evaluated for wheat in Paraná State, Brazil. The functions were classified as seasonal and growth stage functions, according to the form of water stress indices used in the models. A soil moisture model, previously validated for the area, was used to obtain the inputs of transpiration, evaporation of intercepted rain on the canopy, and soil pressure head, required to calculate the water stress indices used in the crop models. For each model, the regression parameters for the relationship between crop yield and water stress index were obtained by linear regression using data from field experiments conducted over three years.

Three seasonal and two growth stage functions showed statistically acceptable results and similar performance for predicting wheat yield. Because wheat growth and yield are sensitive to water stress at specific stages, the growth stage functions were considered more appropriate for use in further studies on assessments of drought risk and crop irrigation strategies for the region.

INTRODUCTION

Optimization of water use by agricultural crops, defined as the highest level of crop yield obtainable from a limited source of water, is of great importance in decision making for resource development and management in Paraná State, Southern Brazil. Farmers, irrigation project managers, and policy makers can maximize profits, estimate water requirements, and decide on resource allocations to expand irrigated area when this information is locally available.

Plant growth simulation models coupled with climatic data can predict yield under variable environmental conditions, and different crop and soil management practices, with reasonable accuracy at a relatively low cost. Where crop water supply is the major limiting factor, this approach is a valuable tool in risk assessment for drought and irrigation requirements.

Crop growth models developed in the past 20 years were reviewed by Jones and Ritchie (1990) and Ritchie (1991). Recently, emphasis has been placed on the development and use of process-oriented crop simulation models. In general, these mechanistic models include simulations of the duration of crop growth, biomass growth rate, and partition of assimilates to economic yield as a function of weather, soil, and production management. Such models seem to be appropriate for practical use in Paraná as diagnostic and problem solving tools. However, due to the use of some rational empiricism to provide simple analysis of more complex biophysical processes, these models usually require some field calibration. The calibration procedure requires a detailed field data set, including phenological and biomass parameters for each specific cultivar at environmentally different locations, in order to estimate the genetic coefficients used as inputs in the simulations of growth and development of the chosen cultivar (Uehara and Tsuji, 1991). Since such detailed information on wheat growth is not available in Paraná, the use of mechanistic crop growth models is not possible at present.

Many researchers (Hanks and Rasmussen, 1982; Sudar et al.,1981; Hanks, 1974; Feddes et al., 1984, Walker, 1989; Evans et al., 1988) have shown that simple models incorporating rainfall, irrigation, evapotranspiration, and simple soil and crop characteristics can adequately characterize the response of crops to water supply. These models, also called crop-water production functions, usually ignore or assume favourable conditions for factors other than water applied or used by the plants, such as soil conditions, fertilizers, pest control, etc. This simplified approach can, in principle, provide guidelines for crop water management and rational design of irrigation systems in situations where soil water availability is the major constraint.

The objective of this paper is to combine different crop production functions with a soil moisture model (Chapter III) to evaluate their performance in predicting wheat yield in Paraná State. The most appropriate combination will be selected for application in future studies on irrigation requirements and risks of drought in the region.

CROP-WATER PRODUCTION FUNCTIONS

Several studies (Slabber et al, 1979; Singh et al, 1987; Ehlers, 1991)revealed a close relationship between yield and transpiration, since production and photosynthesis are closely related, and photosynthesis and transpiration are also associated via the diffusional resistances of water and CO_2. Based on this principle, many evapotranspiration or transpiration-yield functions using different indices to quantify crop water deficit have been proposed and used with relative success for predicting cereal crop yields. Detailed reviews on the relationship between crop production and evapotranspiration, or irrigation, are given by Doorenbos and Kassam (1979), Slabbers et al. (1979), Vaux and Pruitt (1983), Hanks (1983), Howell (1990) and Howell et al. (1990).

The models considered in this analysis were previously developed by different workers. From several models, we have chosen the additive linear crop production functions because of their simplicity and also because of the mounting evidence showing a linear relationship between yield and crop water use (Stewart et al., 1977; Doorenbos and Kassam, 1969; Howell, 1990). Originally, most of these functions related yield with evapotranspiration, rather than with transpiration. In addition, they did not consider evaporation of water stored on the canopy from intercepted precipitation or irrigation affecting yield. In this paper, those functions are modified to describe grain yield as a function of the combined values of evaporation of intercepted rain by leaves and transpiration (TI), in mm, according to:

$$TI = T + I \tag{1}$$

where T is transpiration and I is evaporation of rain water intercepted on the canopy, both in mm.

Since soil evaporation does not directly affect crop yield, the advantage of using a yield-transpiration relationship, instead of a yield-evapotranspiration relationship, is that the resulting yield function is not influenced by year to year variation of soil evaporation as given by the combined values of evaporation and transpiration in evapotranspiration. The inclusion of intercepted evaporation is justified because, during times of leaf wetness, a low vapor deficit of the air occurs near the leaves. Thus stomata may be open, allowing CO_2 assimilation (Tenhunen et al., 1982). This assumption was also adopted by Ehlers (1991) and De Jong and Kabat (1991).

In a crop production function, water input can be either seasonal or on a critical growth period basis. The corresponding functions are named seasonal functions and growth stage functions, respectively (Rajput and Singh, 1986). The seasonal and growth stage functions included in this analysis are described as follows.

Seasonal functions

De Wit (1958) showed by a comprehensive analysis that the following relation holds for regions with a long bright sunshine duration:

$$Y = a_1 + m\frac{TI}{PET^*} \tag{2}$$

where Y is grain yield (kg/ha), TI is the addition of seasonal transpiration (T) plus evaporation of rain intercepted on the canopy (I), (mm), PET^* is mean seasonal evapotranspiration (mm/day), a_1 is the function's Y-intercept (kg/ha), and m is a crop specific parameter (kg/ha/day).

Arkley (1963) devised a function similar to the one described above, but using seasonal mean relative humidity of the air (RH^*, in fraction) to normalize TI, such that:

$$Y = a_2 + A\frac{TI}{(1 - RH^*)} \tag{3}$$

where a_2 is Y-intercept of the function (kg/ha) and A is a crop specific constant (kg/ha/mm/day).

Bierhuizen and Slatyer (1965) substituted De Wit's PET* with the mean seasonal vapor saturation of the air (Δe^*) and expressed yield as a function of transpiration as:

$$Y = a_3 + k\frac{TI}{\Delta e^*} \tag{4}$$

in which a_3 is Y-intercept of the function (kg/ha) and k is a crop dependent parameter in kg/ha/mm/day-kPa, when Δe^* is given in kPa

Stewart et al.(1977) proposed a seasonal crop production function (Stewart's model S1) in which the effect of water stress on crop yield is described by a relationship between relative yield decrease ($1 - Y/Y_m$) and seasonal relative transpiration deficit ($1 - TI/TI_m$), such as:

$$1 - \frac{Y}{Y_m} = \beta_o(1 - \frac{TI}{TI_m}) \tag{5}$$

where β_o is a yield reduction factor due to water deficit (dimensionless) and Y_m is the yield (kg/ha) that is obtained when soil water is not limiting, and then when crop seasonal transpiration is equal to the potential (TI_m).

Growth stage functions

Stewart et al.(1977) proposed a second formulation of their model (Stewart's model S2) to incorporate variable responses to water stress occurring in different growth stages in an additive manner. This model may be described as:

$$1 - \frac{Y}{Y_m} = S \frac{\sum_{i=1}^{N} [\beta_i \, (TI_m - TI)_i]}{TI_m} \tag{6}$$

in which transpiration deficit (TI_m - TI) is accumulated during the growth stages (i) and weighted by crop sensitivity factors (ß) defined for each stage. These values are added over the growing season and divided by the seasonal TI_m. The slope of the function (S) is a yield reduction factor due to the combined stresses (dimensionless) and N is the number of stages in a growing season.

Hiler and Clark (1971) developed the stress day index (SDI) concept, defined as:

$$1 - \frac{Y}{Y_m} = b \; SDI \tag{7}$$

where b is a reduction yield factor due to SDI.

SDI is determined from a stress day (SD) factor and a crop susceptibility factor (CS) defined on a daily basis or accumulated over the growth stages, according to Equation 8:

$$SDI = \sum_{i=1}^{N} CS_i \; SD_i \tag{8}$$

where i is the growth stage number in a total of N stages. In this analysis, SDI is considered only on a daily basis.

Hiler and Clark (1971) defined CS as an indication of the plant's sensitivity to a water deficit at different growing stages. CS can be determined experimentally as the fractional reduction in yield resulting from a maximum water deficit imposed during a given crop growth stage such as:

$$CS_i = 1 - \frac{Y_i}{Y_m} \tag{9}$$

where Y_m is the crop yield from a control treatment kept without water stress throughout the growing season, and Y_i is the yield in the treatment that was subjected to water deficit only during the i^{th} growth stage. Daily CS values can be estimated by interpolation of CS values determined for the different stages.

SD is a measure of the degree and duration of plant water stress. There are several methods for characterization of stress day. SD as a function of relative transpiration deficit (SD(T)) is defined as (Hiler and Clark, 1971):

$$SD(T) = 1 - \frac{TI}{TI_m} \tag{10}$$

We propose here an index for computation of daily SD based on the soil water potential in the root zone (SD(h)), such that:

$$SD(h) = \sum_{j=1}^{M} (h - h_c)_j \tag{11}$$

where h is pressure head and h_c is a threshold value of pressure head (kPa) corresponding to the lower limit of readily available water in the j^{th} soil compartment of a total of M compartments within the root zone. Negative terms inside the summation are neglected, such that the index accounts for values of pressure head that exceed the critical value. The index defined above is similar to the SEW_{30} index defined by Sieben (Wesseling, 1974) and used by Skaggs and associates (Skaggs et al., 1982; Hardjoamidjojo and Skaggs, 1982; Evans et al., 1988) to quantify stress caused by excessive water conditions in areas with high water table.

EXPERIMENTAL APPROACH

The parameters in the crop production functions were calibrated using field data from experiments conducted at the Experimental Station of the Instituto Agronômico do Paraná-IAPAR in Londrina, Paraná, Brazil (Latitude 23°23'S and Longitude 51°11'W). Spring wheat 'IAPAR 9' was grown in 20 m x 20 m plots, replicated four times, during six growing seasons with two cropping periods per year, from 1986 to 1988. Further details about experimental procedures were given in Chapter II.

The several crop production functions were coupled to a soil moisture model previously validated for the area. A complete description of this model was given in Chapter III. Climatic data from the IAPAR Weather Station were used to calculate daily potential evapotranspiration by the method of Penman (PET). Daily mean saturation deficit of the air (Δe) was estimated from relative humidity (RH) and air temperature. The parameters PET, RH, and Δe were averaged over the growing season to obtain PET^*, RH^*, and Δe^*, as required by the models, shown in Equations 2, 3, and 4. Crop and soil parameters (leaf area index, rooting depth, soil water retention, and unsaturated hydraulic conductivity) obtained from the experiments, together with daily rainfall and Penman potential evapotranspiration, were used as inputs in the soil moisture model to calculate transpiration (T), potential crop transpiration (T_m), evaporation of intercepted rain (I), and pressure head (h) at different depths. The value of h_c in Equation 11 was assumed to be equal to 50 kPa, according to the recommendations of Doorenbos and Kassam (1979), and constant through the rooting zone. These parameters were used as inputs in the several crop production functions.

For the growth stage functions, the crop sensitivity factors ß and CS (Equations 6 and 8, respectively) were taken from a wheat experiment conducted by Frizzoni and Olitta (1990) in São Paulo, Brazil. They used a genetically similar wheat cultivar in a region with comparable soil and climatic conditions. In that experiment the values of ß were evaluated as: 0.04 for emergence to tillering, 0.10 for tillering to jointing, 0.38 for jointing to heading, 0.49 for heading to soft dough, and 0.11 for soft dough to maturity. For each day of the growing season, CS was estimated by interpolation of ß.

To obtain the regression parameters, grain yield data were regressed to the indices in each model. For the models Stewart S_1, Stewart S_2, and SDI, the equations were solved for Y before performing the regression analysis.

RESULTS AND DISCUSSION

The cropping period for each growing season, together with grain yield, seasonal rainfall, potential evapotranspiration, transpiration and transpiration ratio are given in Table 4.1. Wheat yield ranged from 1020 kg/ha in the second growing season in 1986, to 2590 kg/ha in the first season in 1988. Rainfall and potential evapotranspiration also varied considerably from season to season. During the first growing season in 1987, seasonal rainfall was 520 mm, while only 162 mm occurred during the first cropping period in 1986. Potential evapotranspiration ranged from 233 mm for the second growing season in 1986 to 315 mm during the second season in 1988. These variable weather conditions resulted in a wide range of soil water contents during the growing seasons. Since crop consumptive use was dependent on soil water supply and atmospheric demand, wide ranges of seasonal transpiration and transpiration ratios occurred during the experimental period. Actual transpiration plus evaporation of intercepted rain (TI) varied from 83 mm for the second

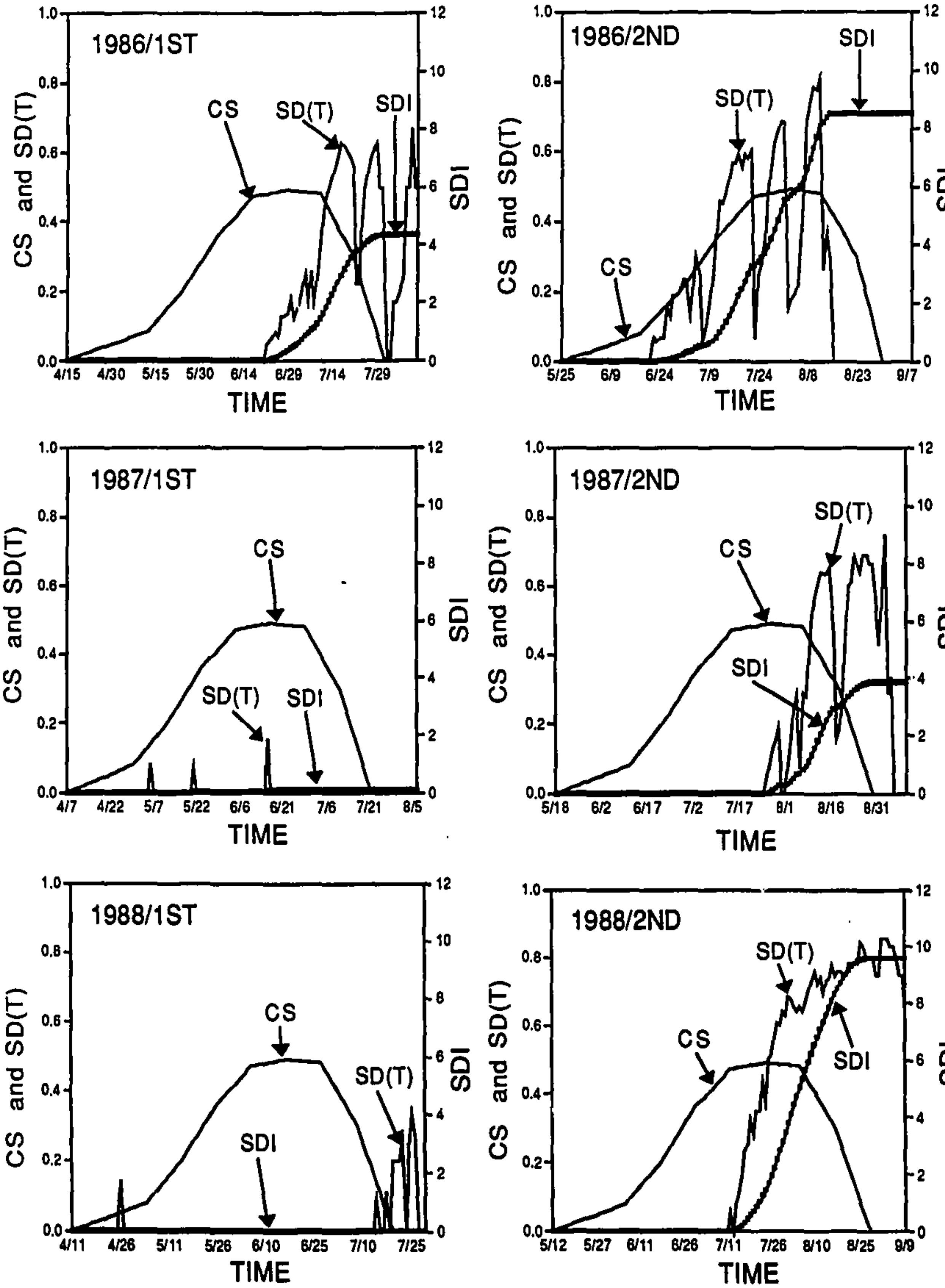
Table 4.1. Cropping period, grain yield, rainfall, potential evapotranspiration (PET), actual transpiration plus evaporation of intercepted rain on the canopy (TI), potential transpiration plus evaporation of intercepted rain on the canopy (TI_m), and transpiration ratio (TR = TI/TI_m) during six wheat growing seasons.

Growing season	Cropping period	Yield (kg/ha)	Rainfall	PET	TI	TI_m	TR
			(mm)				
1986/1st	April-26 to August-12	1128	162	252	106	125	0.85
1986/2nd	June-06 to September-08	1020	193	233	83	128	0.65
1987/1st	April-14 to August-07	2362	520	262	174	174	1.00
1987/2nd	May-19 to September-10	1856	267	279	123	143	0.86
1988/1st	April-12 to July-30	2590	461	237	103	104	0.99
1988/2nd	May-13 to September-10	1405	243	315	103	166	0.62

cropping period in 1986 to 123 mm for the second period in 1987. Transpiration ratios were minimal for the second season in 1988 (0.62) and maximum for the first growing seasons in 1987 (1.00) and 1988 (0.99).

Water deficit during the development of the crop in each growing season is represented in Figure 4.1 by the estimates of SD(T), calculated as the relative transpiration deficit (1- TI/TIm), and the accumulated values of SDI. No deficit was computed during the first growing seasons in 1987 and 1988 because of the high precipitation. For the remaining cropping periods, precipitation events occurred mostly during the early season. Consequently, SD(T) was zero until mid-season, followed by an increase toward the end of the season, except for the second cropping period in 1986. During this growing season

Figure 4.1. Crop susceptibility (CS), stress day (SD(T)), and stress day index during six wheat cropping periods. First and second seasons in each year are indicated by 1ST and 2ND, respectively.


1986/1ST
CS
SD(T)
SDI
CS and SD(T)
SDI
TIME
4/15 4/30 5/15 5/30 6/14 6/29 7/14 7/29
1986/2ND
SDI
SD(T)
CS
CS and SD(T)
SDI
TIME
5/25 6/9 6/24 7/9 7/24 8/8 8/23 9/7
1987/1ST
CS
SD(T)
SDI
CS and SD(T)
SDI
TIME
4/7 4/22 5/7 5/22 6/6 6/21 7/6 7/21 8/5
1987/2ND
SD(T)
CS
SDI
CS and SD(T)
SDI
TIME
5/18 6/2 6/17 7/2 7/17 8/1 8/16 8/31
1988/1ST
CS
SD(T)
SDI
CS and SD(T)
SDI
TIME
4/11 4/26 5/11 5/26 6/10 6/25 7/10 7/25
1988/2ND
SD(T)
CS
SDI
CS and SD(T)
SDI
TIME
5/12 5/27 6/11 6/26 7/11 7/26 8/10 8/25 9/9

a considerable water deficit occurred during the mid-season, which was coincident with high values of crop susceptibility factor (CS). This resulted in the second highest SDI value (9.0) among the six cropping periods. The highest accumulated SDI was calculated for the second season in 1988 (9.6), due to a long period without precipitation and high evaporative demand in July and August. For the remaining cropping periods, SDI was estimated as 4.4 for the first season in 1986 and 3.95 for the second season in 1987.

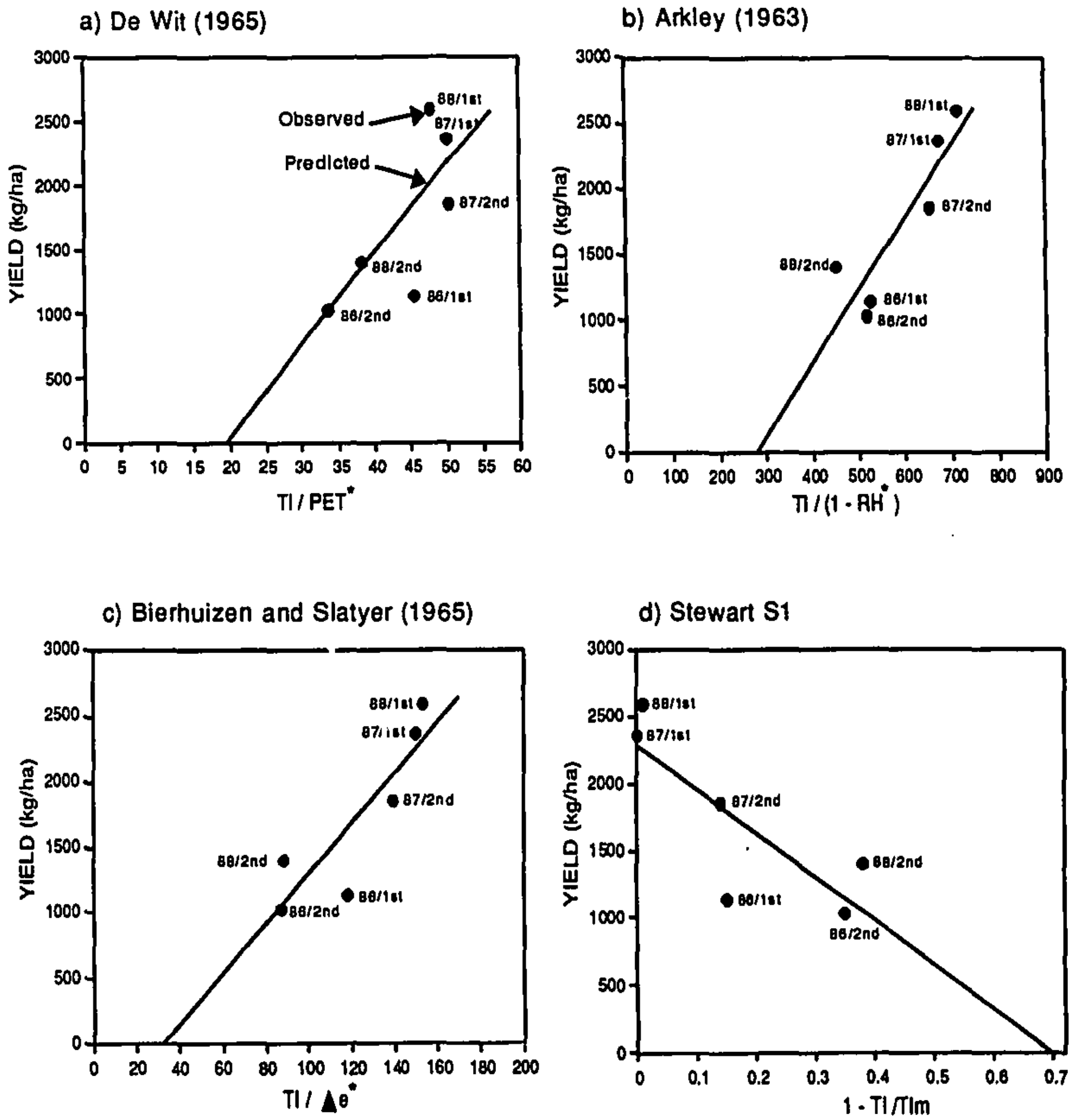
Seasonal functions

Plotting of observed yield and regression lines for the seasonal functions are presented in Figure 4.2. The regression parameters, correlation coefficient, and standard error of estimate (SEE) for each seasonal model are given in Table 4.2.

Figure 4.2a shows that PET^*, as given by the model of De Wit (1958), was not a good normalizer for year to year variations in TI. This relationship resulted in the lowest correlation coefficient (0.73, not statistically significant at the 0.05 level), and the highest deviation from observed values (SEE = 406 kg/ha), as compared to the other models (Table 4.2).

Less scatter of data around the regression line was found when TI was normalized by either $(1\text{-}RH^*)$ or Δe^* (Figure 4.2b and 4.2c, respectively). Therefore, yield estimates given by the models of Arkley (1963) and Bierhuizen and Slatyer (1965) were in close agreement with observed data ($r \geq 0.88$, statistically significant at the 0.05 level). Standard errors of estimate were as low as 271 and 289 kg/ha, respectively (Table 4.2). The values of Y-intercepts for these models, similarly to the De Wit (1958) model, were negative and significantly different from zero ($p \leq 0.05$ level). This can be considered realistic, since

Figure 4.2. Observed and predicted wheat yield by the seasonal functions.



a) De Wit (1965)
Observed
Predicted
88/1st
87/1st
87/2nd
88/2nd
86/1st
86/2nd
YIELD (kg/ha)
TI / PET*
b) Arkley (1963)
88/1st
87/1st
87/2nd
88/2nd
86/1st
86/2nd
YIELD (kg/ha)
TI / (1 - RH*)
c) Bierhuizen and Slatyer (1965)
88/1st
87/1st
87/2nd
88/2nd
86/1st
86/2nd
YIELD (kg/ha)
TI / ▲e*
d) Stewart S1
88/1st
87/1st
87/2nd
88/2nd
86/1st
86/2nd
YIELD (kg/ha)
1 - TI /TIm

Table 4.2. Regression coefficients INTERCEPT, SLOPE, and crop potential yield (Y_m), correlation coefficient (r), and standard error of estimate (SEE) for the seasonal functions.

Function	Y_m	INTERCEPT	SLOPE	r	SEE
De Wit (1985)	-	-1350	69.6	0.73 ns	406
Arkley (1963)	-	-1548	5.56	0.89 *	271
Bierhuizen and Slatyer (1965)	-	-614	19.1	0.88 *	289
Stewart S1	2291	-	1.43	0.82 *	344

ns - Statistically not significant by the t-test at $p \leq 0.05$.
* - Statistically significant by the t-test at $p \leq 0.05$.

functions passing through the origin are more appropriate to describe dry matter yield relationships, rather than economic yield relationships. Good performances for the Bierhuizen and Slatier (1965) model were also found by Rijtema and Enrodi (1970), Tanner and Sinclair (1983) and Ehlers (1991). Tanner and Sinclair (1983) assumed this relationship to be universally applicable for different climatic regions and explained its physical meaning, in a review of the early work of Bierhuizen and Slatyer (1965), by taking yield (Y) as photosynthetic rate and describing Y/T ratio (water use efficiency) in the form of diffusion equations.

The Stewart S1 model (Figure 4.2d) presented a lower accuracy, as given by standard error of estimate equal to 344 kg/ha, but the relationship was still statistically significant (r = 0.82; $p \leq 0.05$). The value of the function's slope coefficient (β_o) is within the range of values obtained for wheat by Rajput and Singh (1986) in several locations in India. The Y_m value obtained for the Stewart S1 model was about 400 kg/ha lower than the maximum observed yield (2590 kg/ha).

Growth stage functions

The comparison of observed and predicted yield by the growth stage functions are presented in Figure 4.3 and regression parameters and correlation coefficients are given in Table 4.3, along with the values of standard error of estimate.

Similarly to the seasonal Stewart S1 model, the results obtained for the Stewart S2 model were rather poor, as shown by a high scatter of data around the regression line (Figure 4.3a). This resulted in a non-significant correlation coefficient ($r=0.79$; $p \leq 0.05$) and a low accuracy of estimates (SEE = 368 kg/ha) (Table 4.3).

The results of the linear regression for the models based on the stress day index method (SD(T) and SD(h)) showed that the independent variables were closely related to yield, as given by statistically significant ($p \leq 0.05$) correlation coefficients (Table 4.3) and relatively low deviations of estimates from observed data (Table 4.3, Figure 4.3b and 4.3c). The function using the proposed stress index estimated by the soil water potential (SD(h)) gave a slightly better performance ($r = 0.89$ and SEE = 275 kg/ha) than the function with stress index calculated by relative transpiration deficit (SD(T)) ($r = 0.85$ and SEE = 314 kg/ha). These performances were comparable to ones obtained for the seasonal Arkley

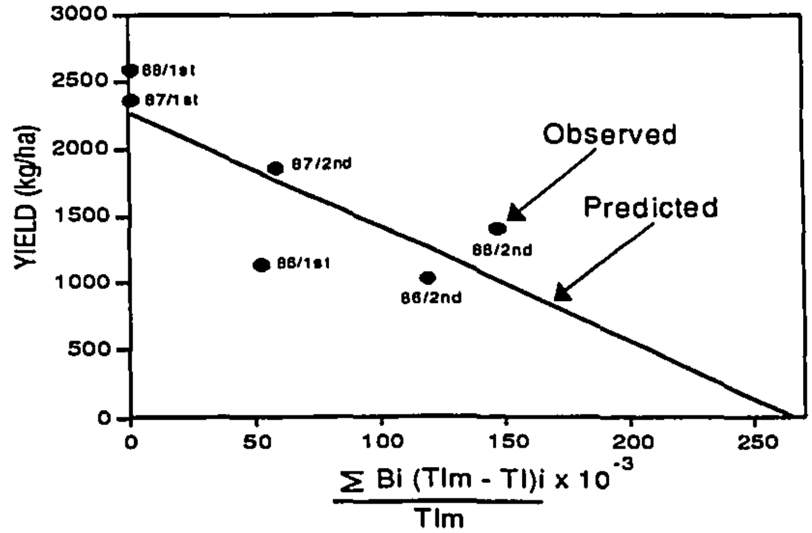
Table 4.3. Regression coefficients SLOPE and crop potential yield (Y_m), correlation coefficient (r), and standard error of estimate (SEE) for the growth stage functions.

Function	Y_m	SLOPE	r	SEE
Stewart S2	2266	3.77	0.79 ns	368
SDI(T)	2337	5.76×10^{-2}	0.85 *	314
SDI(h)	2331	8.61×10^{-3}	0.89 *	275

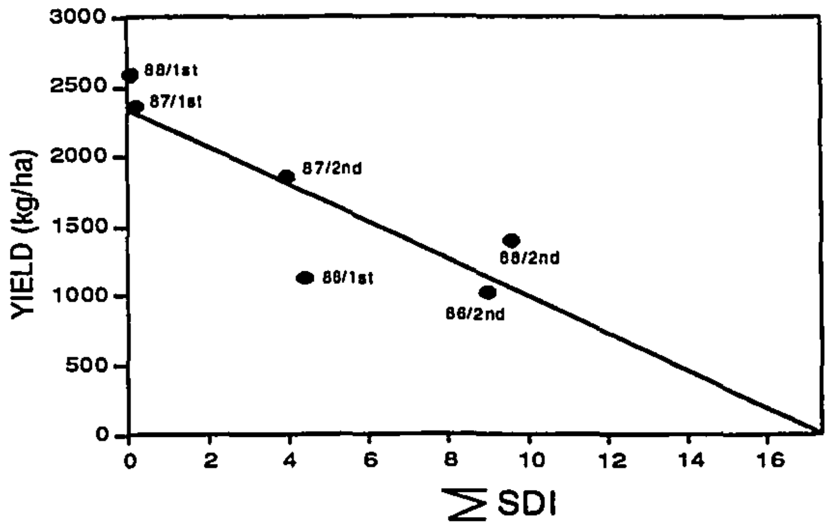
ns - Statistically not significant by the t-test at $p \leq 0.05$.
* - Statistically significant by the t-test at $p \leq 0.05$.

Figure 4.3. Observed and predicted wheat yield by the growth stage functions .

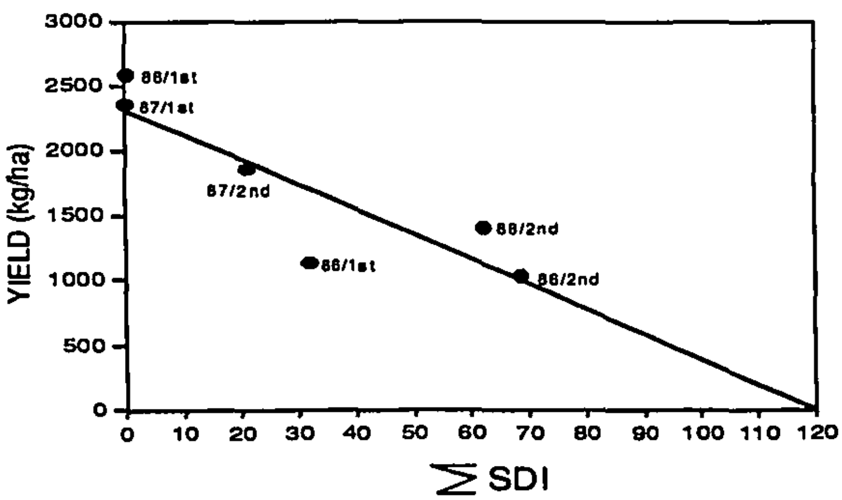
a) Stewart S2



b) SDI(T)



c) SDI(h)



(1963) and Bierhuizen and Slatyer (1965) models (Table 4.2). The estimated Y_m values for these two growth stage functions (2331 and 2337 kg/ha) were closer to the maximum observed yield than the Y_m estimated for the Stewart S1 and Stewart S2 models (2291 and 2266 kg/ha, respectively). These results agree with those of other researchers who successfully used the stress day index method as an indicator of drought and wet stresses for water table management (Skaggs et al., 1982; Hardjoamidjojo and Skaggs, 1982; Evans et al., 1988), as an irrigation scheduling tool (Hiler and Howell, 1983), or linked to soil moisture models for yield prediction of maize and soybeans (Sudar et al., 1981), and wheat (De Jong and Zentner, 1985).

Figures 4.2 and 4.3 show that the observed yield for the first growing season in 1986 had a consistently higher deviation from the predictive curves for all the functions, except for the Arkley (1963) model. Figure 4.1 shows a similar pattern for the SD(T) and SDI curves for this growing season and the second crop season in 1987, but yield in 1986/1st growing period was about 600 kg/ha lower than the one in 1987/2nd growing season. This can be attributed to other environmental factors not accounted for by the models, such as the individual or combined effects of temperature with water stress at different stages of crop growth.

SUMMARY AND CONCLUSIONS

The performance of seven linear crop production functions developed previously by different workers was evaluated for wheat in Paraná State, Brazil. The functions were classified as seasonal and growth stage functions, according to the form of water stress indices used in the models. A previously described soil moisture model was used to obtain transpiration, intercepted evaporation, and soil water pressure head. These parameters were used as inputs in the calculation of the several indexes for water stress, as defined by the different crop production functions. Another index to reflect crop susceptibility to water stress during the developmental stages (CS) was an additional input for the growth stage functions. Inputs of CS were obtained from the literature. The regression parameters for the relationship between crop yield and index of water stress for each model were obtained by linear regression using three years of data obtained from field experiments.

For the conditions prevailing during the experimental period, three seasonal and two growth stage functions showed statistically acceptable results and similar performance in predicting wheat yield. The seasonal functions were simpler to use than the growth stage functions because they did not require crop susceptibility coefficients as input. However, these kinds of functions can effectively be used only when sensitivity of crop growth periods to water stress is not of practical significance or when irrigation is scheduled to avoid considerable deficit during the development of the crop (Stewart et al., 1977). In general, this is not the situation in agricultural areas. Several reports show that sensitivity of wheat to water stress differs significantly among growth stages (Singh et al., 1987; Rajput and Singh, 1986; Mongensen et al., 1985). Furthermore, it usually may not be practical or economical to adjust irrigation schedules in order to maintain soil moisture conditions within the optimal range. Therefore, the growth stage functions, such as the ones based on the stress index approach, should be more successful than the seasonal models in applying simulation methods on studies of crop water management. While input data are not available to allow use of more elaborate models, these simple models can be used to provide guidelines for assessments of drought risks or crop irrigation strategies for Paraná State.

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PREFACE TO CHAPTER V

Chapter V describes the application of the combined soil moisture - crop production model in a study of irrigation requirements and risk analysis of drought for wheat in Paraná.

CHAPTER V

RISK ANALYSIS OF DROUGHT AND IRRIGATION REQUIREMENTS FOR WHEAT IN PARANA, BRAZIL.

ABSTRACT

A computer model was used to simulate crop yield over a long term period (1961-1988), in order to assess risks of drought for different planting dates of a non-irrigated wheat crop (*Triticum aestivum*, L.) in Paraná State, Brazil. Similarly, different irrigation management strategies were simulated to identify net system delivery capacities and application frequencies that promote maximum yield with minimum requirements of water.

Non-irrigated wheat crops showed average yield reductions of between 16%, for early planting, and 50%, for late planting, due to water stress at planting and during crop development. Irrigation minimized the year-to-year variation in crop production and maintained yields close to the maximum level. Maximum yields with minimum applied water was obtained by the use of low intensity (5 to 10 mm) and frequent (3 to 5 days) irrigations. The required net system delivery capacity varied from 1.5 to 3.0 mm/day, according to planting dates.

INTRODUCTION

The timing of sowing of wheat in Paraná State, Brazil, is a critical management decision for farmers. Short periods without rainfall, associated with high evapotranspiration during the fall, make replanting a common practice in the region. Field observations and experimental trials indicate that early sowing increases the probability of high yield due to higher rainfall during critical stages of development (IAPAR, 1990). However, opportunities for sowing early (early April) are limited because the growing seasons of the summer crops (soybeans and maize) are often extended until the end of April. Consequently wheat sowing is frequently delayed up to mid-May. This increases the risks of exposing the crop to low rainfall in July and August, and, consequently, to lower crop yield due to water stress during sensitive growth stages.

Irrigation is restricted to a few areas in the State. It can be expanded if economical. High profitability of irrigated lands can be achieved with appropriate design and management of irrigation systems in order to obtain maximum production with minimum inputs of water, energy, and labor. In order to assess the benefits of irrigation, the effects of drought on non-irrigated crop yields have to be known. There is little information on irrigation of wheat in the region. Preliminary experiments have shown that irrigation can increase yield from 30 to 70% (Okuyama and Costa, 1990; Okuyama and Riede, 1990).

Risk analysis of drought and crop response to irrigation usually require data obtained over a long period in order to avoid the influence of specific years and to represent variability in the form of probability density functions. Crop models play a vital role in the evaluation of such problems. According to Harrison et al. (1989), specific management may be replicated over a number of seasons, using either historical or synthetic weather data, so that the variability of performance can be measured. Furthermore, crop models can be used to pre-test technology packages, hence reducing the time and the cost of field trials.

There are many studies on the use of crop simulation models to estimate the effects of constraints on crop yield (Egli and Bruening, 1992; Muchow et al., 1991; Stockle et al., 1992). However, risk of crop establishment constrained by water stress was addressed in only one case (Carberry and Abrecht, 1991). There are also several reports using simulations to assess appropriate management (Bernardo et al., 1988; Rogers and Elliot, 1989; Stockle and James, 1989) and design of irrigation systems (Heermann et al., 1974; English and Nuss, 1982; von Bernuth et al., 1984; Howell et al., 1989). The management objective criteria used to determine improved strategies or design varies widely. Boggess et al. (1983) classified them into three categories: a) maximization of unconstrained yield, b) maximization of unconstrained profit, and c) alternative maximization or minimization objectives subject to various constraints. Heermann et al. (1974) and von Bernuth et al. (1984) used the third objective criteria to recommend sprinkler delivery capacities and irrigation cycle intervals for corn in Colorado and Nebraska, respectively. They selected system capacities which prevented soil moisture depletion, or yield decrease, from exceeding specific levels. The design irrigation delivery capacity, defined as the total continuous flow rate at which water should be supplied to the crop, was determined using simulation modelling, rather than peak evapotranspiration requirements. The advantage was that the simulation method allowed for depletion of available water during high atmospheric demand. Since soil water supplied part of the crop evaporative demand, this decreased the amount to be applied by irrigation. Therefore, the designed system delivery capacity was lower than that determined by the peak evapotranspiration method.

Water supply capacity is a major constraint for the design of irrigation systems in situations where the optimum amount of irrigation water is constrained by water supply rate (Howell et al., 1989). In conditions where irrigation water is available upon demand, system delivery capacity is constrained by the costs involved with equipments and energy (English at al., 1992). In spite of abundant water resources for irrigation supply, both situations may occur in Paraná.

The irrigation interval has a primary implication on the eventual yield decrease caused by water deficit during periods between irrigation. The choice of irrigation interval when using systems with intensive labor costs, such as portable sprinkler systems, is also determined by the number of applications per season. Less frequent cycles may reduce labor costs for some types of application systems. However, if the intervals are very long, it becomes necessary to apply larger quantities of water with attendant losses from percolation and runoff (English et al., 1992), increasing the potential for leaching nutrients and pesticides from the soil profile. Furthermore, a complicating factor when using long irrigation intervals in humid areas like Paraná is the occurrence of rainfall that recharges the whole area to the same level of soil moisture. For the next cycle, irrigation must begin earlier than the critical moisture level be reached, to allow complete coverage of the total area during the irrigation cycle without stress in the latter areas to be irrigated (Camp et al., 1992). On the other hand, highly mechanized systems (center pivot) have much more flexibility for application intervals. However, evaporation and wind drift tend to reduce application efficiency due to the low amounts applied per irrigation (Martin et al., 1992). In addition, very short irrigation intervals (1 to 3 days) might increase chances for higher incidence of crop diseases, as a result of soil and canopy surfaces being almost continuously wet.

The objectives of this study were to:

a) evaluate risks of drought during the establishment and development of a non-irrigated wheat crop in Paraná.

b) develop recommendations for irrigation management of wheat, in particular, determine net system delivery capacity requirements and appropriate irrigation intervals, in order to maximize yield and minimize system capacity and seasonal irrigation requirements.

MATERIALS AND METHODS

Wheat growth was simulated for 28 years of historical climatic data (1961 to 1988) from the INMET Weather Station in Londrina, Paraná, Brazil. A previously validated soil moisture model was used to estimate hydrological components of the water balance throughout the growing seasons. Details of the model were given Chapter III. In short, daily rainfall and potential evapotranspiration were partitioned during the day using simple procedures and a Darcy type equation was used to estimate soil water distribution. The model accounted for partition of evapotranspiration into transpiration, soil evaporation, and evaporation of intercepted water on the canopy. Soil water extraction by roots was described by a sink term (Belmans et al., 1983) and soil evaporation was calculated as a function of evaporative demand during the growing season (Boesten and Stroosnijder, 1986). The model also considered the transference of sensible heat from between rows to the crop canopy in the calculation of evapotranspiration. The weather data required for the model included daily rainfall and the weather parameters used to calculate daily potential evapotranspiration (PET). PET was calculated by a modified Penman equation (Caramori and Faria, 1987), in which the aerodynamic term was estimated by a linear equation dependent on the Piche evaporimeter, since wind speed was not available for the whole recorded period. Soil (soil retention and hydraulic conductivity curves) and crop growth parameters (leaf area index and rooting depth) inputs were the same as the data used for the validation of the model (Chapter II). The growing seasons were simulated for a duration of 120 days, based on the average duration of six cropping periods determined in the previous field experiments. Emergence was assumed to occur five days after planting, if soil water was not limiting, or five days after water input made soil water no longer limiting.

The soil moisture model was linked to a locally calibrated crop-production function (Chapter IV) to estimate wheat yield as a function of crop stress day index (Hiler and Clark, 1971). The normalized form of this function with the calibrated parameters is given by:

$$\frac{Y}{Y_m} = 1.00 - 5.76x10^{-2}\ SDI \tag{1}$$

where

$$SDI = \sum_{i=1}^{n} CS_i SD_i \tag{2}$$

and

$$SD = 1 - \frac{TI}{TI_m} \tag{3}$$

in which Y is crop grain yield , Y_m is the yield attained by a crop under no soil water stress (both in kg/ha), CS is a crop yield susceptibility factor for water stress (dimensionless), i is the day and n is the total days in a growing season, TI (mm/day) is the combined value of transpiration plus evaporation of water stored on the canopy from interception of rain or irrigation, and TI_m (mm/day) is the same as TI but with soil water not limiting transpiration. The values of CS were obtained from Frizzone and Olitta (1990), similar to the procedure used in the calibration of the model (Chapter IV).

A non-irrigated crop was simulated for the following planting dates: April 1, April 11, April 21, May 1, and May 11. A criterion for crop emergence was established based on the conclusions of an earlier experiment conducted in the region by Faria and Caramori (1985). In that study, 30 mm of irrigation was required to promote wheat emergence when soil water content was at the permanent wilting point. Simulation of the same conditions by the computer model resulted in a value of soil moisture content for the top 0-10 cm layer equivalent to 31.5% by volume, which corresponded to 90% of the remaining soil available water for this layer. Therefore, emergence was assumed to occur if soil moisture at the 0-10 cm depth was above this value. In the analysis for risk of planting, two management decisions were considered: a) sowing is done at specific dates, regardless of soil moisture conditions, and b) planting is delayed until appropriate conditions of soil moisture occurs. For the latter case, if the criterion for emergence was not met by May 16, the crop did not grow and yield was considered as zero. The assumption of May 16 as the latest date for planting was based on the fact that temperatures after mid-September are excessively high and not convenient for wheat cultivation.

Due to the long computational time required to process the 28 years of historical data, an irrigated wheat crop was simulated only for the following planting dates: April 1, April 21, and May 11. The linked soil moisture-crop production model was expanded to include sprinkler irrigation. Irrigation water was assumed to be applied at a constant rate equal to 6 mm/h. Each application started at the beginning of a daylight period with duration given by the ratio between application depth and application rate.

If soil moisture at the top 10 cm depth was lower than 90% available water at the sowing date, irrigation was applied in order to replenish soil moisture in the 0-30 cm depth up to the field capacity. Irrigation timing during the growing season was accomplished following the method described by Hiler and Howell (1983). Irrigation was triggered when the daily SDI (Equation 2) reached a predetermined value SDI_c, which was calculated by:

$$\left(SDI_c\right)_i = \frac{SDI_o}{CS_i} \tag{4}$$

where SDI_o is the average seasonal SDI using a prefixed value for SD (SD_c), according to Equation 5:

$$SDI_o = \frac{\sum_{i=1}^{n} CS_i SD_c}{n} \tag{5}$$

SD_c was assumed to be equal to 0.01, i.e. SD was critical when TI was decreased by 1% of the value of TI_m. Using the values of CS from Frizzone and Olitta (1990) in Equation 5 and considering only the non zero CS periods, SDI_o was estimated as 0.0026. The resulting relative yield at the critical level, which is given by Equation 1 using SDI_o instead of SDI, was close to one. Since CS varied with time, SD_c was maximum for non-critical stages and minimum for critical stages. Consequently, more frequent irrigations were required during sensitive periods and less frequent for less susceptible stages.

Different irrigation depths were obtained by simulating four system delivery capacities and six irrigation intervals (Table 5.1). These application depths included the water that reached soil and crop surfaces, since the model considered evaporation from intercepted water by the canopy as part of the process of transpiration and accounted for it in the calculation of crop yield (Equation 1). The irrigation intervals in Table 5.1 are related to the operational characteristics of the system. They were given by the minimum interval that a system was planned to return to the starting position after completing irrigation in the whole area. The depths of application in Table 5.1 were given by different combinations of system delivery capacities and irrigation cycles. For example, a 2 mm/day system delivery capacity, operated to complete a cycle in one day, would apply 2 mm, while the same system with a 5-day cycle would apply 10 mm. However, the actual time for water application was determined according to the method of Hiler and Howell (1983), as discussed above. Therefore, if SDI_c was not reached at the interval established by a given cycle, irrigation was not applied. On the other hand, if irrigation was required in a shorter interval than an established irrigation cycle, water was not applied and some water

Table 5.1. Irrigation depths (mm) resulting from different system delivery capacities and irrigation intervals used in the simulations.

Delivery capacity (mm/day)	Irrigation interval (days)					
	1	2	3	5	10	15
1.0	1.0	2.0	3.0	5.0	10.0	15.0
1.5	1.5	3.0	4.5	7.5	15.0	22.5
2.0	2.0	4.0	6.0	10.0	20.0	30.0
3.0	3.0	6.0	9.0	15.0	30.0	45.0

deficit occurred. The irrigation depths in Table 5.1 were limited by the capacity of the soil to store water in the root zone at a maximum value equal to the field capacity. Therefore, application depths were limited during the early season, when the root system was shallow. Irrigation was fully applied, when the rooting system was deeper and available soil water depletion was higher than the specified depths.

The simulations started two months before sowing under bare soil conditions with 50% available water, in order to estimate soil moisture contents at different depths of the profile at planting. The computer model included subroutines to sort output data, to generate probability density functions of the main parameters. The probability, P, for a given parameter to be equalled, but not exceeded, was given by:

$$P = \frac{N_i}{N} \tag{6}$$

where N_i is parameter ranking number in an ascending order and N is the total number of years analyzed.

RESULTS AND DISCUSSION

1. Non-irrigated crop simulation

Mean growing season PET varied from 294 to 308 mm for the five different cropping periods during the 28 simulated years, with a relatively low variability within each season, as given by standard deviations ranging from 18 to 23 mm (Table 5.2). Mean seasonal rainfall was higher for the season starting in April 1 (370 mm) and decreased linearly as planting was delayed until May 11 (310 mm). Rainfall standard deviation was almost constant for the different cropping periods, varying from 139 to 144 mm (Table 5.2).

Table 5.2. Mean and standard deviation (STD) rainfall and potential evapotranspiration (PET) for Londrina (1961-88), according to planting dates.

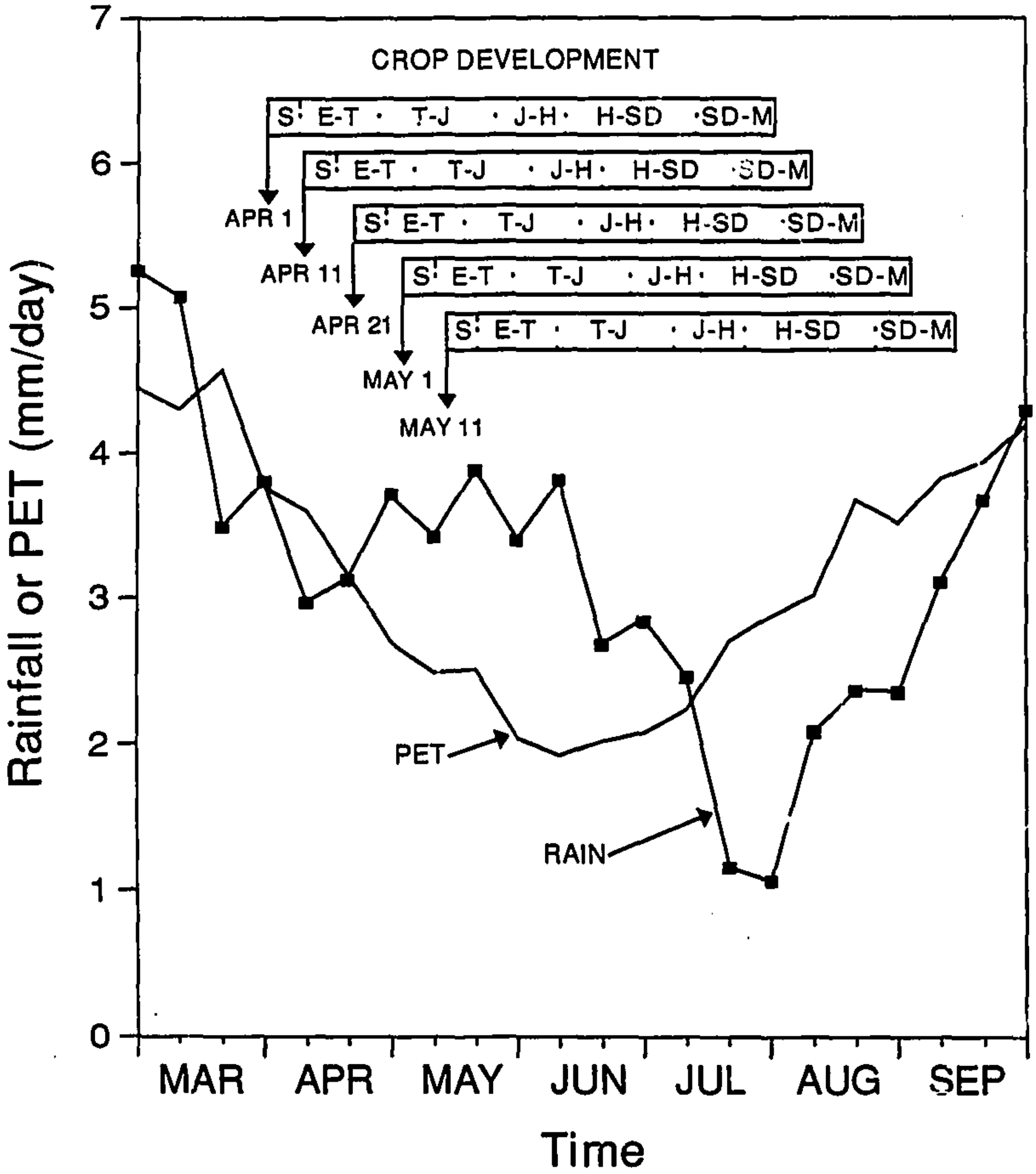
Planting date	Rainfall (mm)		PET	
	Mean	STD	Mean	STD
April 1	370	143	308	18
April 11	344	139	305	19
April 21	338	137	294	21
May 1	323	136	303	21
May 11	310	144	308	23

This level of variability in rainfall reveals a relatively high risk of water deficit during the years of crop growth, independent of the planting date.

The distribution of mean rainfall and potential evapotranspiration (PET) through the growing seasons are shown in Figure 5.1. PET decreased from about 4.5 mm/day in April to a minimum of 1.9 mm/day in June, and then increased again to about 4 mm/day in mid-September. Except for short periods during the sowing in mid-April, rainfall exceeded PET from the beginning of the season until June 10. The remaining period was characterized by rainfall averages lower than PET with the maximum water deficit occurring during the end of July and beginning of August. Thus, there is more chance for a wheat crop to be exposed to these periods of water deficit in a later planting than in a earlier planting. Therefore, while wheat sown in April 1 has only the stage Soft dough-maturity coinciding with periods of PET exceeding rainfall, the cropping period starting in May 11 has the chance of experiencing a water deficit from the stage of Jointing-heading until crop maturity.

The cumulative probability for crop establishment is presented in Table 5.3 for the

Figure 5.1. Mean rainfall and potential evapotranspiration during the growing seasons of wheat in Londrina (1961-1988). The stages of crop development are: S = Sowing-emergence; E-T = Emergence-tillering; T-J = Tillering-Jointing; J-H = Jointing-heading; H-SD = Heading-soft dough; and SD-M = Soft dough-maturity.



CROP DEVELOPMENT
S E-T T-J J-H H-SD SD-M
APR 1
APR 11
APR 21
MAY 1
MAY 11
PET
RAIN
Rainfall or PET (mm/day)
0
1
2
3
4
5
6
7
MAR
APR
MAY
JUN
JUL
AUG
SEP
Time

different planting dates. The situation where a risk is taken by scheduling sowing at specific dates, regardless of the soil moisture conditions, is represented by the second and third columns in Table 5.3. When the crop was simulated with sowing on April 1, April 11, and April 21, germination is expected to start at the same day in about 30% of the years, in which soil moisture content at the 0-10 cm layer was higher than 90% available water at the day of planting. Slightly higher chances of meeting the criterion for crop emergence at the same day of sowing would occur for planting on May 1 (46%) and May 11 (39%). If five days were assumed to be the maximum period that non-germinated seeds can stay in the soil after sowing without considerable decreases of their germination potential, opportunities for successful crop establishment would be about 70% for sowing on April 1, May 1, and May 11. Lower chances of achieving conditions for emergence in periods less than or equal to five days after sowing would occur for plantings on April 11 (56%) and April 21 (46%). These results are in agreement with the rainfall distribution through the sowing season, in which some periods of water deficit occurred during mid-April and there was satisfactory water supply for the remaining period of sowing (Figure

Table 5.3. Cumulative probability for meeting the criterion for crop emergence (90% soil available water in the 0-10 cm layer) in different times after sowing.

Planting date	Time after sowing		
	1 day	5 days	End of the sowing season (May 16)
April 1	0.29	0.71	0.93
April 11	0.32	0.56	0.89
April 21	0.29	0.46	0.86
May 1	0.46	0.68	0.82
May 11	0.39	0.68	0.68

5.1).

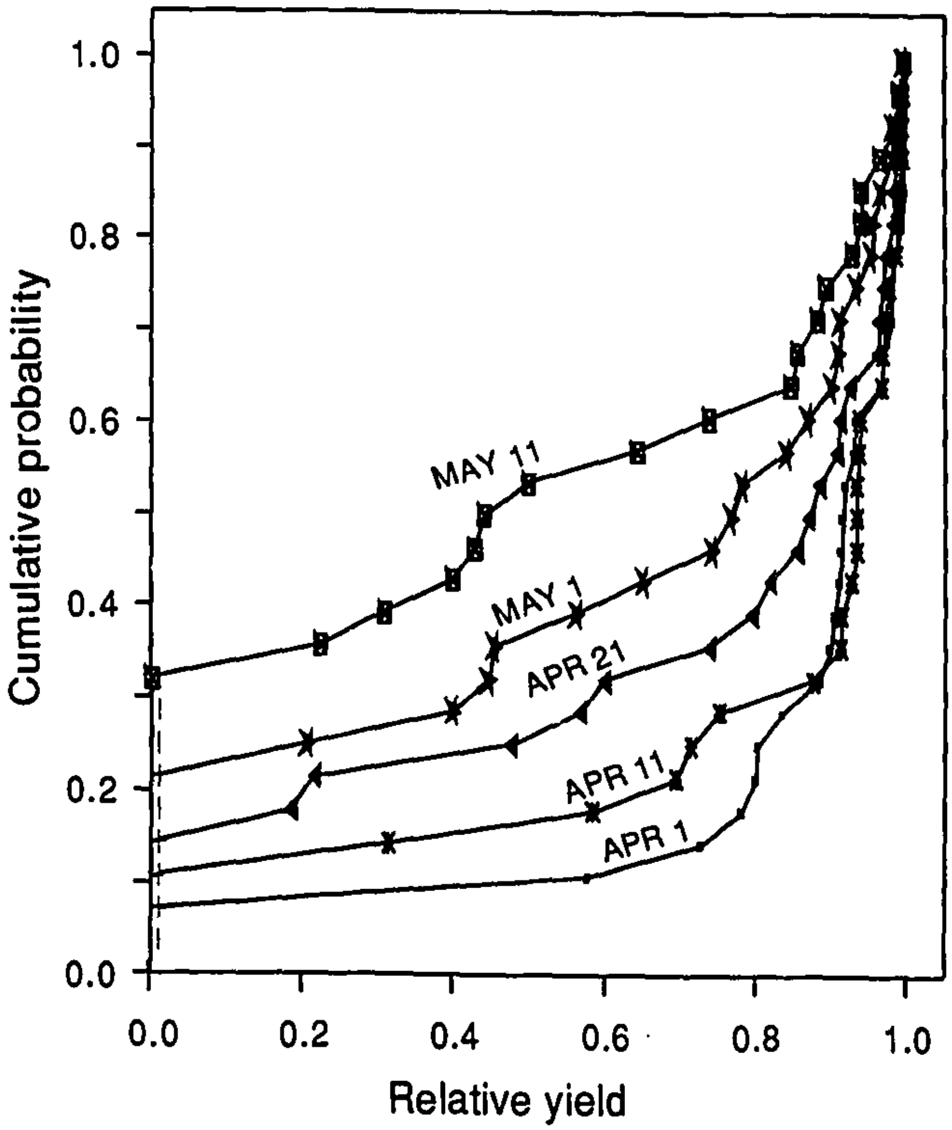
In practice, the risk of planting at specific times, without taking into account soil moisture conditions, such as considered in the previous analysis, is not taken. Usually farmers delay sowing until precipitation refills soil water to a level sufficient to promote crop emergence. An additional constraint in Paraná is that wheat can be sown only after the harvesting of the summer crops. The last column in Table 5.3 shows the opportunities for successful crop establishment when wheat planting is delayed because the area is still occupied by the summer crops. When the area is ready for planting on April 1, there are 45 days (until May 16) for appropriate soil moisture conditions to occur and the crop can be sown. On the other hand, when planting is possible only after May 11 the criterion for germination has to be met in only five days. According to Table 5.3, the number of years without soil water conditions for emergence increased from early to late sowing. Therefore, for planting after April 1, appropriate soil water conditions on at least one day until May 16 did not occur in two of 28 years of simulation. Similarly, the criterion for crop emergence was not met during the sowing period between April 11 and May 16 in three years of 28 years. For the remaining growing seasons with sowing starting after April 21, May 1, and May 11, the number of years that crop establishment was not achieved because of water deficit increased to four, five, and nine, respectively. In practice, the risk for not planting in some years may be higher than the results presented above. Usually, at least a light tillage to control weeds and seedbed preparation is required before planting. As this operation is done just after rainfall, it makes the soil drier. This can lead to inappropriate crop stand and the consequent need for replanting. The analysis of such a scenario would require detailed experimental data dealing with the effects of tillage on soil drying and is beyond the scope of this research.

The mean and standard deviation of relative yields, according to the planting dates, for the non-irrigated crop over the 28 year long term simulation are presented in Table 5.4. These values included the zero yield means during the years in which crop establishment was not accomplished due to unsuitable soil water conditions, as discussed above. Mean relative yield declined steadily from 0.84 to 0.50 as the sowing season was delayed from April 1 to May 11. In addition, there was an increasing yield instability over the years for the later plantings compared to earlier plantings, as given by standard deviations varying from 0.25 (April 1) to 0.40 (May 11). The probability distributions for relative yield for the different planting dates show the same trend (Figure 5.2). This representation is useful to determine the chances to attain a certain yield level. Therefore, the chances for 50% yield decrease to occur is about 10, 15, 28, 35, and 54% for the planting dates from April 1 through May 11, respectively. Similarly, relative yields less than or equal to 0.8 (20% yield decrease) is expected in about 30% of the years if crop is planted on April 1 and April 11, and in 40, 55, and 62% of the years for planting on April 21, May 1, and May 11, respectively. If the risks for sowing were not considered and the crops assumed to

Table 5.4. Mean and standard deviation relative wheat yield for different planting dates under non-irrigated conditions.

Planting date	Relative yield	Standard deviation
April 1	0.84	0.25
April 11	0.80	0.31
April 21	0.69	0.36
May 1	0.61	0.38
May 11	0.50	0.40

Figure 5.2. Cumulative probability distribution for relative yield of the non-irrigated wheat crops, according to three selected planting dates.


Cumulative probability
1.0
0.8
0.6
0.4
0.2
0.0
MAY 11
MAY 1
APR 21
APR 11
APR 1
0.0
0.2
0.4
0.6
0.8
1.0
Relative yield

germinate at the specific days established for each planting date, the mean relative yield reductions due to water deficit during the crop development would be 13, 14, 17, 24, and 28% for the April 1 through the May 11 planting dates, respectively. These results confirm the findings reported in previous field experiments (IAPAR, 1990), in which there were advantages for early planting.

2. Irrigated crop simulation

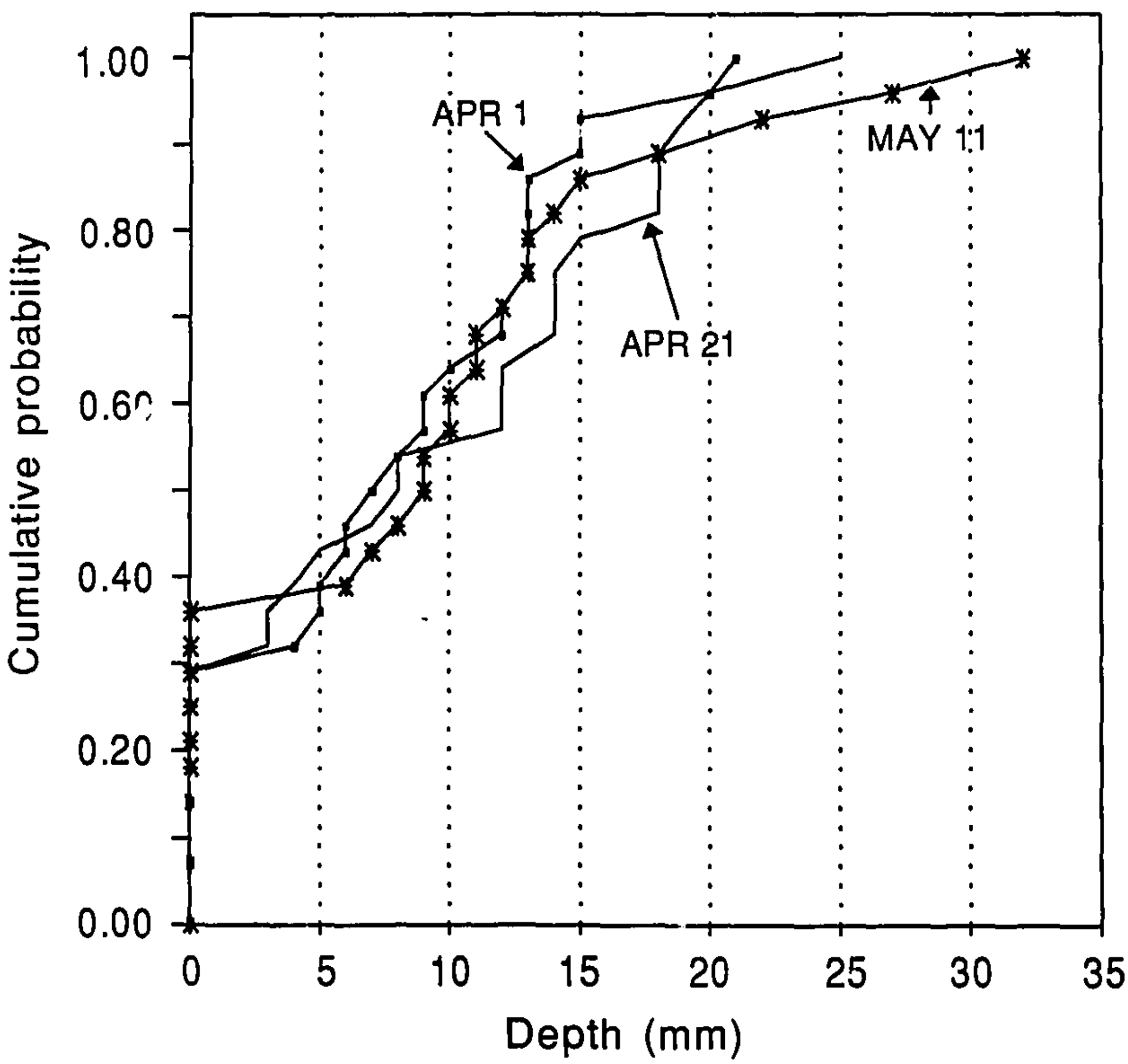
2.1. Irrigation needs for crop establishment

The probability distributions for the required depths of irrigation to replenish soil water storage up to field capacity in the 0-30 cm depth at sowing are presented in Figure 5.3, according to the different planting dates. Irrigation was not needed in about 30 to 40% of the years, because the 0-10 cm soil layer was above 90% available water and seeds were assumed to germinate. However, the required application depths to promote crop emergence in the driest year in ten years (P = 90%) were 15 mm for planting on April 1, 17 mm for April 21, and 20 mm for May 11.

2.2. Irrigation needs during crop development

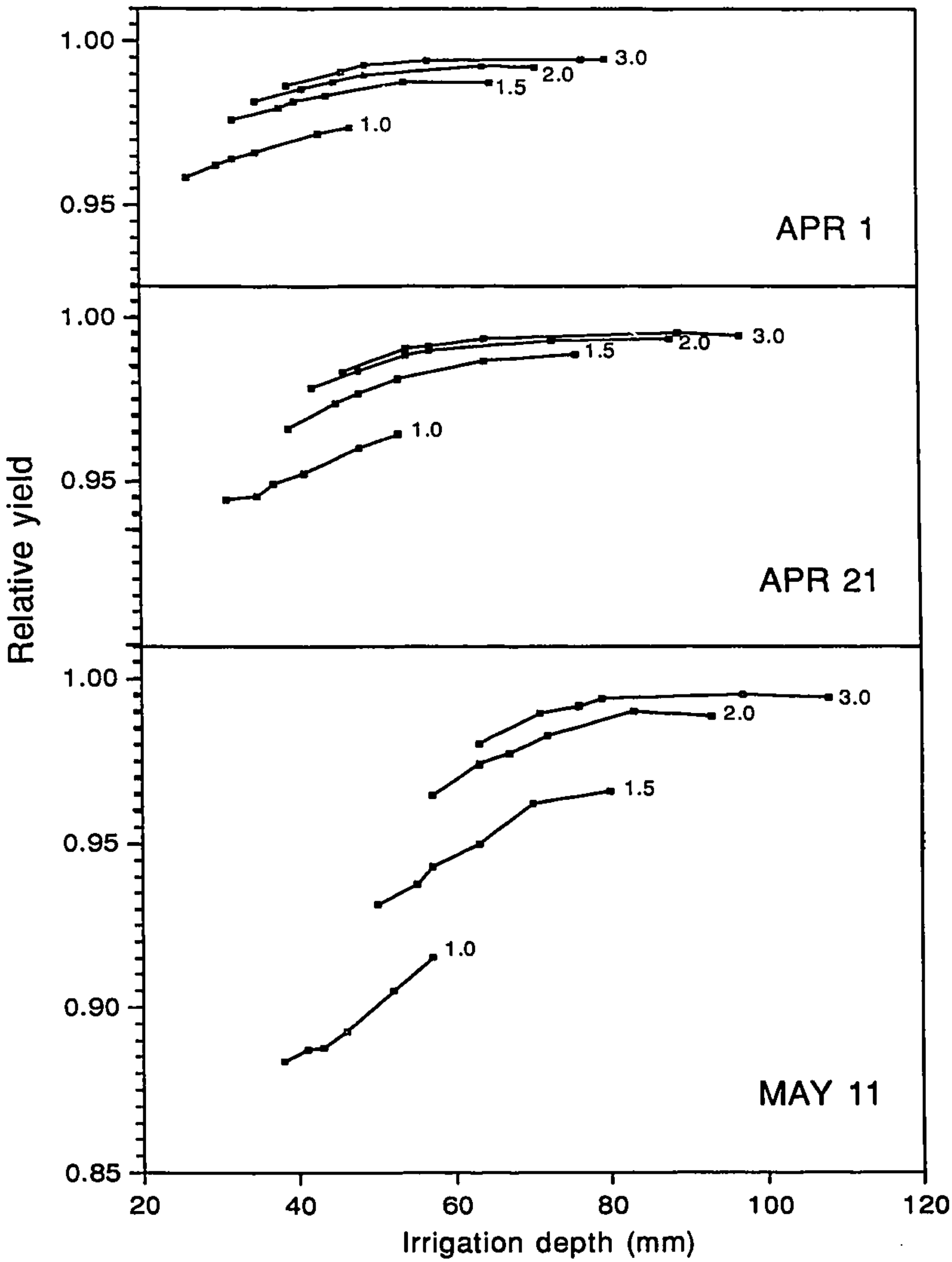
The following analysis simulates the use of the different management strategies in order to assess irrigation requirements during crop development. The results of the 2016 combinations among four system delivery capacities, six irrigation intervals, three planting dates, and 28 years of historical climatic data are summarized in Figures 5.4 and 5.5 by the mean and 90% probability level relative yield as a function of seasonal irrigation depth, respectively. Relative yield and required seasonal applied water were affected by planting

Figure 5.3. Cumulative probability distribution for depth of irrigation at different planting dates.



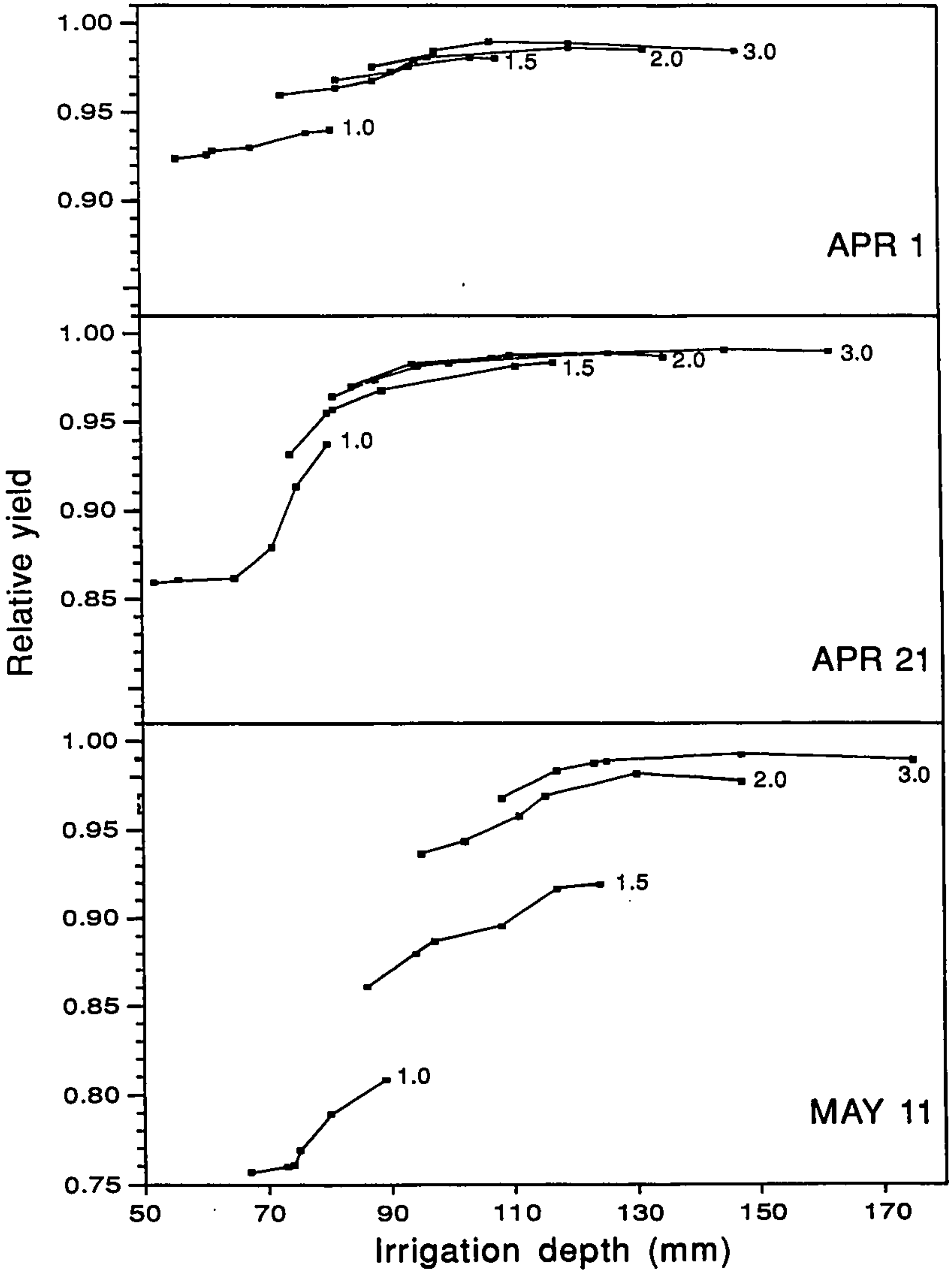
1.00
0.80
0.60
0.40
0.20
0.00
Cumulative probability
0
5
10
15
20
25
30
35
Depth (mm)
APR 1
APR 21
MAY 11

Figure 5.4. Mean wheat relative yield as a function of seasonal irrigation depth for different combinations of system delivery capacity and irrigation interval, according to planting date. Delivery capacity is represented by numbers following curves (mm/day) and irrigation intervals (1, 2, 3, 5, 10, and 15 days) by dot markers on the curves, always increasing from left to the right.



1.00
0.95
3.0
2.0
1.5
1.0
APR 1
1.00
0.95
3.0
2.0
1.5
1.0
APR 21
1.00
0.95
0.90
0.85
3.0
2.0
1.5
1.0
MAY 11
Relative yield
20
40
60
80
100
120
Irrigation depth (mm)

Figure 5.5. Expected wheat relative yield at the 90% probability level as a function of seasonal irrigation depth for different combinations of system delivery capacity and irrigation interval, according to planting date. Delivery capacity is represented by numbers following curves (mm/day) and irrigation intervals (1, 2, 3, 5, 10, and 15 days) by dot markers on the curves, always increasing from left to the right.



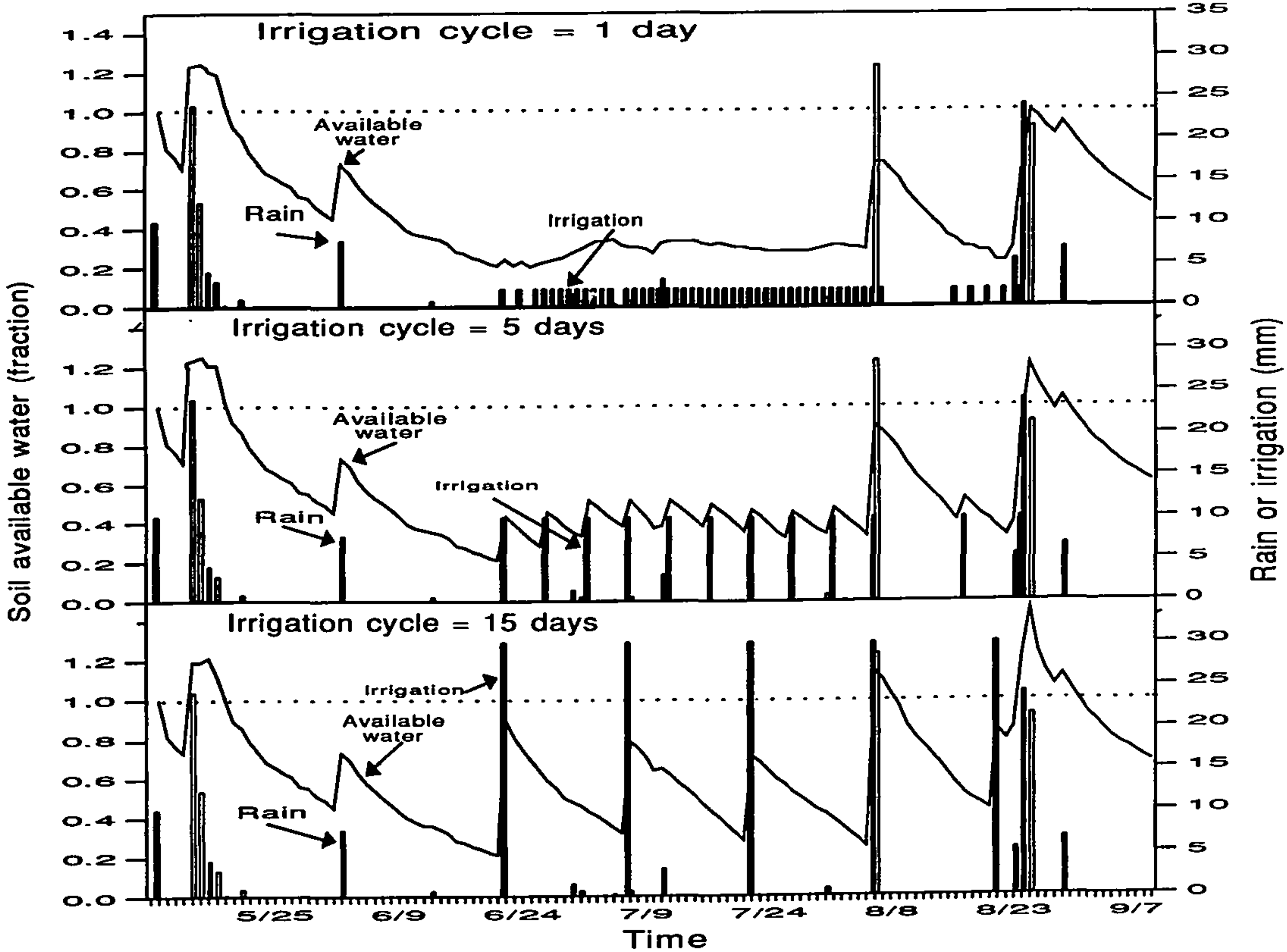
Relative yield
Irrigation depth (mm)
APR 1
APR 21
MAY 11
1.0
1.5
2.0
3.0
1.00
0.95
0.90
0.85
0.80
0.75
50
70
90
110
130
150
170

dates and irrigation strategies. A wider range of variation in relative yield was simulated for the crop sown on May 11, compared with earlier plantings, because of the higher probability of periods with deficit in precipitation in July and August to coincide with critical stages of crop development (Figure 5.1). Consequently, the required application depths and system delivery capacities increased from early to late planting, as indicated by the horizontal displacement of the curves along the x axis.

Seasonal irrigation depth and corresponding crop yields were a result of the capability of the different strategies in supplying crop water needs at specific times during the growing season. The analysis of the data in Figures 5.4 and 5.5 allows the following conclusions: a) different levels of relative yield were calculated for the same amount of seasonal application depth, b) the total water applied during the growing season increased with decreases in irrigation interval for a given system capacity, and c) systems with higher delivery capacities required a shorter irrigation interval to reach a certain seasonal irrigation depth. This can be exemplified by the response curves in Figure 5.5. For the growing season with planting on May 11, a total depth about 110 mm resulted from the simulation of a system with delivery capacity of 1.5 mm/day, operated to apply 15 mm per irrigation with minimum interval of ten days. A similar seasonal depth would be expected if 10 mm per irrigation were applied with maximum frequency of five days using a 2.0 mm/day system capacity. Similarly, about 110 mm could have been obtained with two day irrigation cycle using a 3.0 mm/day system capacity. The simulated relative yields would be 0.91 for the first strategy, 0.96 for the second and 0.98 for the third. The higher yield reduction for the low delivery capacity and long irrigation cycle strategy occurred not only due to the long periods between irrigations, since production levels closer to the maximum relative yield are expected for systems with greater water supply (ie. 2.0 and 3.0 mm/day) irrigating at long intervals (10 to 15 days), in spite of greater seasonal water. This effect was the result of a combination between irrigation interval and system delivery capacity which was deficient to supply crop water demand. The 15 mm applied in each irrigation were not enough to refill soil available water to a level sufficient to maintain transpiration at the potential rates during critical stages of development. Thus, some water stress occurred during the periods between irrigations, and yield was lower.

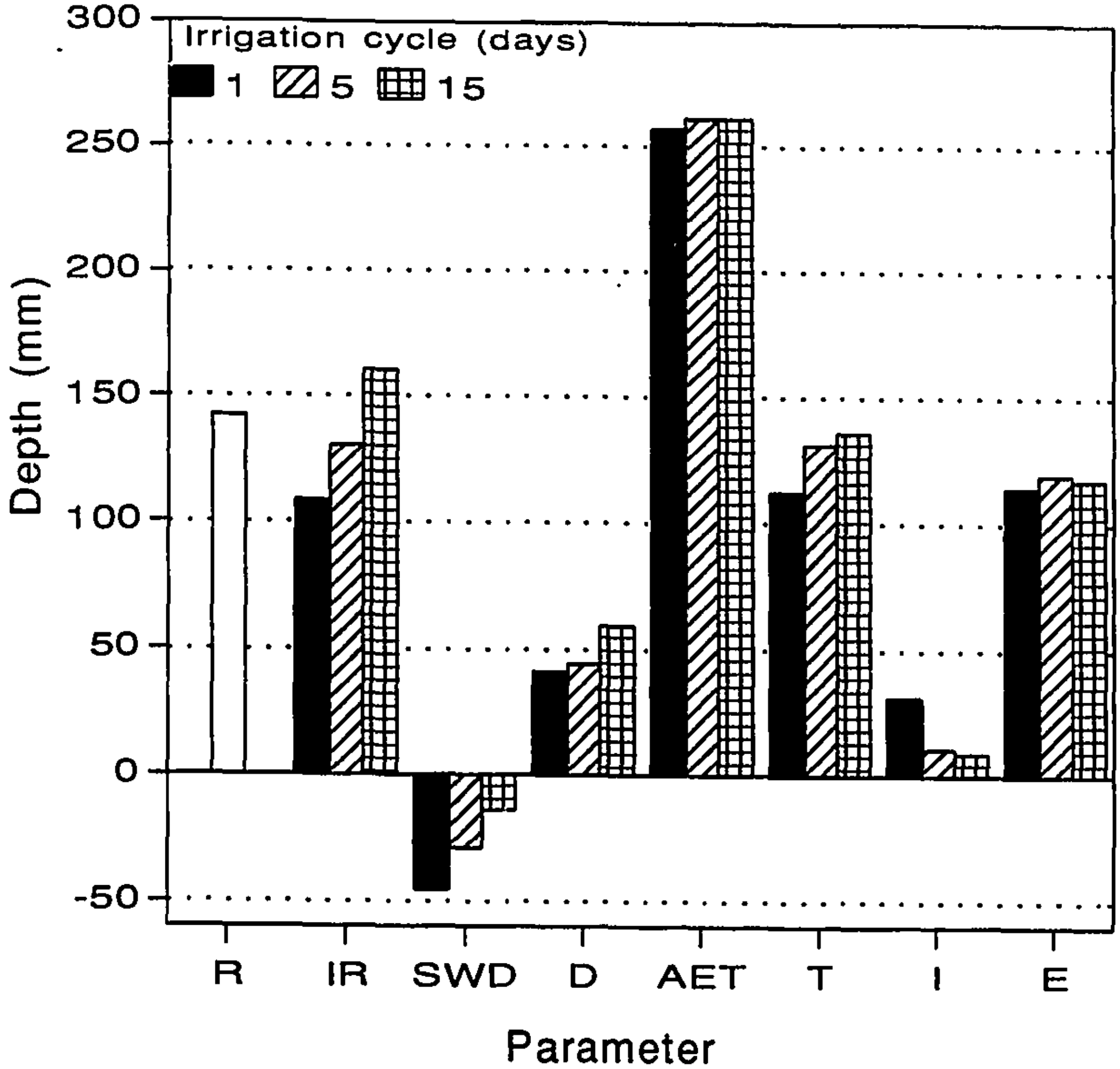
The total rainfall during the season with planting date on May 11, 1984 closely approximated that of the long term 90% probability for the 28 year period (the driest year in ten years). The simulation during this period was chosen to demonstrate the effects of the different irrigation intervals on yield and the hydrological components of the water balance. Irrigation depths and their distribution through the growing season for a 2.0 mm/day system delivery capacity in three different irrigation intervals are given in Figure 5.6, together with the respective values of soil available water in the root zone and rainfall. The corresponding accumulated growing season values of the several parameters of the water balance are given in Figure 5.7. The seasons started with the 0-30 cm soil layer at field capacity because of irrigation at planting (Figure 5.6). Early season rainfall allowed irrigations to be delayed for about 40 days. During the following rainless period, the more frequent and low intensity irrigations, as given by the strategy with irrigation cycle of one day, caused little changes in soil available water, which was maintained at levels between 20 and 30% (Figure 5.6). These relatively low values were caused by higher canopy interception of irrigation water (Figure 5.7). In contrast, the less frequent and heavier applications (irrigation cycle of 15 days) caused soil water to oscillate in a

Figure 5.6. Remaining soil available water, rainfall, and irrigation during a wheat crop with planting in May 11, 1984, irrigated at different intervals with a system of 2.0 mm/day delivery capacity.



Irrigation cycle = 1 day
Available water
Rain
Irrigation
Irrigation cycle = 5 days
Available water
Rain
Irrigation
Irrigation cycle = 15 days
Irrigation
Available water
Rain
Soil available water (fraction)
Rain or irrigation (mm)
Time
5/25
6/9
6/24
7/9
7/24
8/8
8/23
9/7
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
5
10
15
20
25
30
35

Figure 5.7. Rainfall (R), irrigation (R), soil water depletion (SWD), drainage (D), evapotranspiration (AET), transpiration (T), intercepted evaporation (I), and soil evaporation (E) during a wheat crop with planting in May 11, 1984, irrigated at different intervals with a 2.0 mm/day system capacity.



Irrigation cycle (days)
1
5
15
300
250
200
150
100
50
0
-50
Depth (mm)
R
IR
SWD
D
AET
T
I
E
Parameter

wider range during the irrigated period. The minimum values of soil available water fluctuated between 20 and 30 % at the times that irrigation was applied. Maximum values varying between 70 to 90% occurred after irrigations. For the simulation with intermediary frequency (5 days), soil available water was slightly higher, increasing from about 20% at beginning of the irrigation season to values fluctuating between 40 and 50% during the remaining irrigation period. As a result of the different management strategies, the values of seasonal irrigation depth increased by 50% as irrigation interval was increased from one to 15 days (Figure 5.7). For such differences in application depth, relative yield was only 2% higher in the 15 day cycle strategy. The differences in application depths can be explained by the fact that a more efficient use of the rain water occurred when irrigation was applied more frequently. Therefore, heavier (or less frequent) applications replenished a higher fraction of soil available water and reduced the chances of storing rainfall in periods after irrigation. This was evident during the precipitations following irrigations on August 6 and 23 (Figure 5.6). Consequently, there was more chance for percolation and runoff to occur. In this simulation, runoff was not affected due to the high infiltrability of the soil. However, drainage increased significantly as irrigation depth increased (Figure 5.7). Another reason for the increase in seasonal irrigation demand in low frequent applications was the higher soil water content at the end of the season, due to the heavier applications during late season (Figures 5.6). The soil was wetter at harvesting, but this water was unusable for the crop. This is given in Figure 5.7 by the values of soil water depletion for each simulated strategy.

Figure 5.7 also indicates that little changes in evapotranspiration and soil evaporation resulted from the different application intervals. However, actual transpiration

(T) increased and evaporation from intercepted water by the canopy (I) decreased as irrigation cycle varied from one to 15 days. The variations in T were a consequence of the partition of the energy available for potential transpiration into T and I, as simulated by the model, rather than significant effects of water stress. Since the summation between T and I was almost constant for the different simulations, and the model used this value to calculate relative yield (TI in Equation 1), crop yield was not significantly affected by the irrigation intervals. Despite the lower levels of soil available water in the simulation with irrigations at daily frequency (Figure 5.6), this result seems to be realistic since the leaf wetness uses part of the energy available for transpiration and maintains a low vapor deficit of the air near the leaves, thus sustaining turgor and photosynthetic activity (Tenhunen et al., 1982).

The small effect of irrigation interval on soil evaporation, as shown in Figure 5.7, disagrees with the results of several reports in the literature (Kundun et al., 1982; Howell et al., 1989; Stockle et al., 1989). In those studies, soil evaporation increased with frequent irrigation. The reasons for the discrepancies can be explained by method used for timing irrigations in this simulation (Equations 4 and 5). Unlike those experiments, soil evaporation losses were minimized by decreasing irrigation frequency when crop cover was incomplete in the earlier and later stages, and fully irrigating during periods of almost complete ground cover.

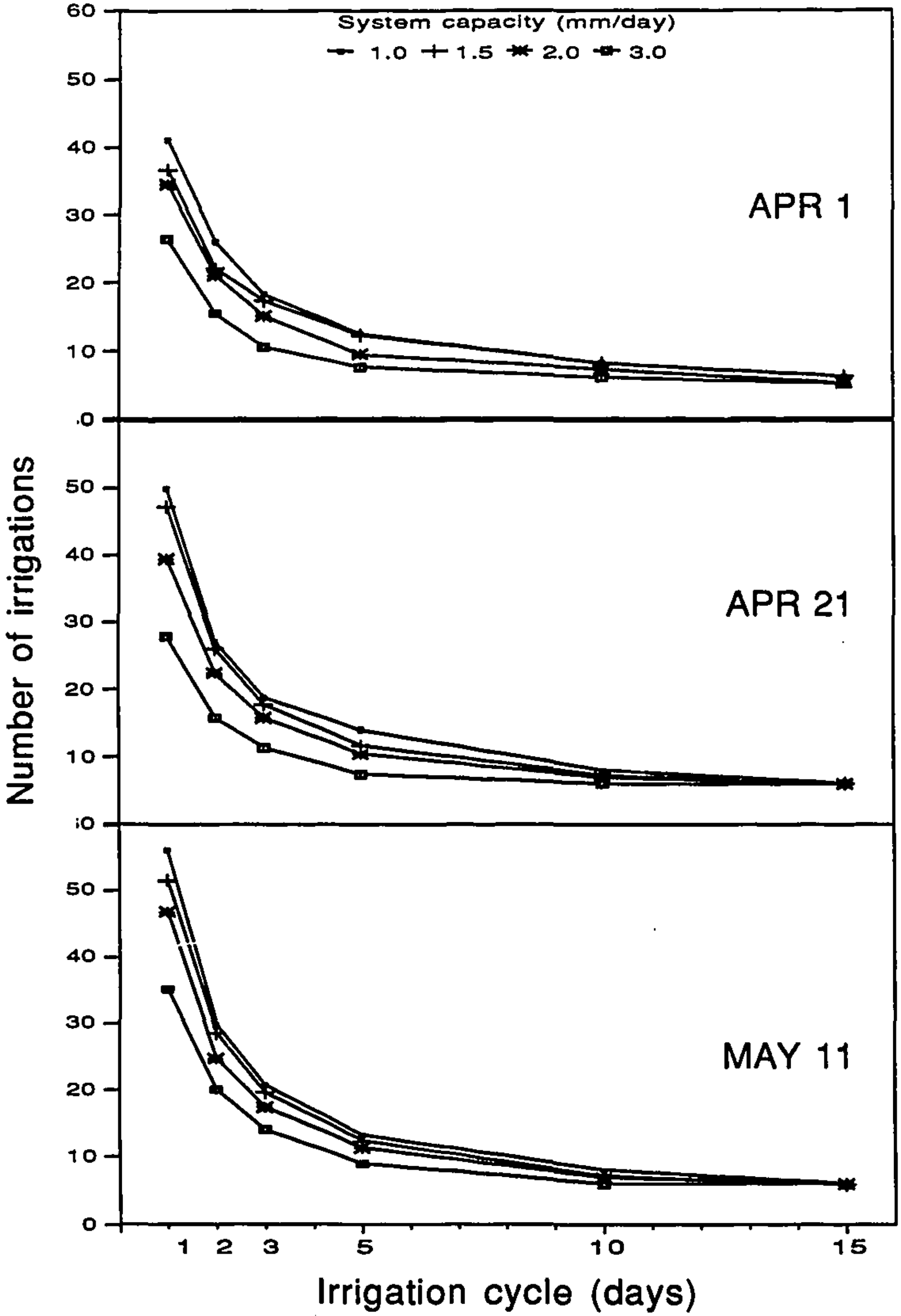
The number of irrigations per crop season is another important variable in designing capacities and operational characteristics of a system, due to the labor costs involved with irrigation. The number of irrigations per growing season as a function of frequency of application for the driest year in ten years (P=90%) is shown in Figure 5.8, according to the different planting dates and system capacities. The number of applications were almost constant for irrigation cycles of 10 and 15 days. At these intervals, there was not a significant effect of the system delivery capacity and planting dates on number of applications. However, the required number of irrigations per crop season increased significantly as irrigation cycle decreased from 10 to one day. In addition, systems with low delivery capacity demanded more applications than high capacity systems and a slightly higher number of applications was required for later planting dates in more frequent irrigation cycles.

2.3. Design system delivery capacities and operational recommendations of irrigation systems

The delivery capacity of an irrigation system required to assure crop establishment depends on the time available for planting. In order to minimize system delivery capacity requirements, sowing could be done in steps, splitting the area into small plots where irrigation would be applied in each plot until the required depth is reached. If the driest year in ten years (P = 90%) was taken as an acceptable risk, a center pivot with an application capacity of 1.0 mm/day would take a rotation cycle of 15 to 20 days to apply the required depth (Figure 5.3). Plantings following the irrigation cycle would be required during this whole period. This seems to be impractical at the farm level. Taking ten days as a more reasonable period for sowing the whole irrigated area, the minimum system delivery capacities would be 1.5 mm/day for the April 1 planting date, 1.7 mm/day for the May 21, and 2.0 mm/day for the May 11.

The data given in Figures 5.4 and 5.5 provide information for designing net system

Figure 5.8. Expected seasonal number of irrigations at the 90% probability level, according to irrigation cycle, system delivery capacity, and planting date.



System capacity (mm/day)
1.0 1.5 2.0 3.0
APR 1
APR 21
MAY 11
Number of irrigations
Irrigation cycle (days)
0
10
20
30
40
50
60
1 2 3 5 10 15

delivery capacities in order to supply irrigation water demand during the development of the crop. Assuming a maximum relative yield decrease equal to 5% in the driest year in ten years (P = 90%) as a design criterion, the required seasonal application depths were estimated as 70 to 90 mm for the planting date in April 1, 80 to 90 mm for April 21, and 100 to 120 mm for May 11 (Figure 5.5). The correspondent minimum system delivery capacity requirements were 1.5 to 2.0 mm/day for the early and mid-planting dates, and 2.0 to 3.0 mm/day for the late planting date. This would assure mean relative yields higher than 0.97, independent of planting date (Figure 5.4). The relative yield standard deviations for the simulations using these strategies were less than 0.03, which indicates a very low variability during the long term period. Comparing these results with those for the non-irrigated crop (Table 5.4), one can conclude that irrigation minimized the year to year variation in crop production and allowed increases in mean relative yield of 13, 30, and 47% for the seasons with planting on April 1, April 21, and May 11, respectively.

The design system delivery capacities estimated above must be increased to account for water losses and system downtime. Howell et al. (1989) assumed an application efficiency of 80% and allowed 5% for downtime in design of sprinkler systems for the American Southern Great Plains. Using the same information, net system delivery capacities should be increased by 30% to supply the total crop water requirements.

According to the results shown in the previous analysis, yield was not significantly affected by irrigation intervals when system delivery capacity was not limiting. This allows more operational flexibility for the management of irrigated areas and more choice for selection of system types. However, water and energy could be significantly reduced with low intensity and frequent irrigations. This indicates advantages for mechanized systems like center pivot and travellers, in which the higher number of applications does not significantly increase costs. For such systems, irrigation amounts ranging from 5 to 10 mm, applied at minimum intervals between 3 to 5 days, should efficiently meet crop water requirements in most of the years. For conventional irrigation systems, the ideal management will balance water losses and labor costs. Nevertheless, applications of 15 to 20 mm at an irrigation interval of about ten days seems to be a reasonable practice.

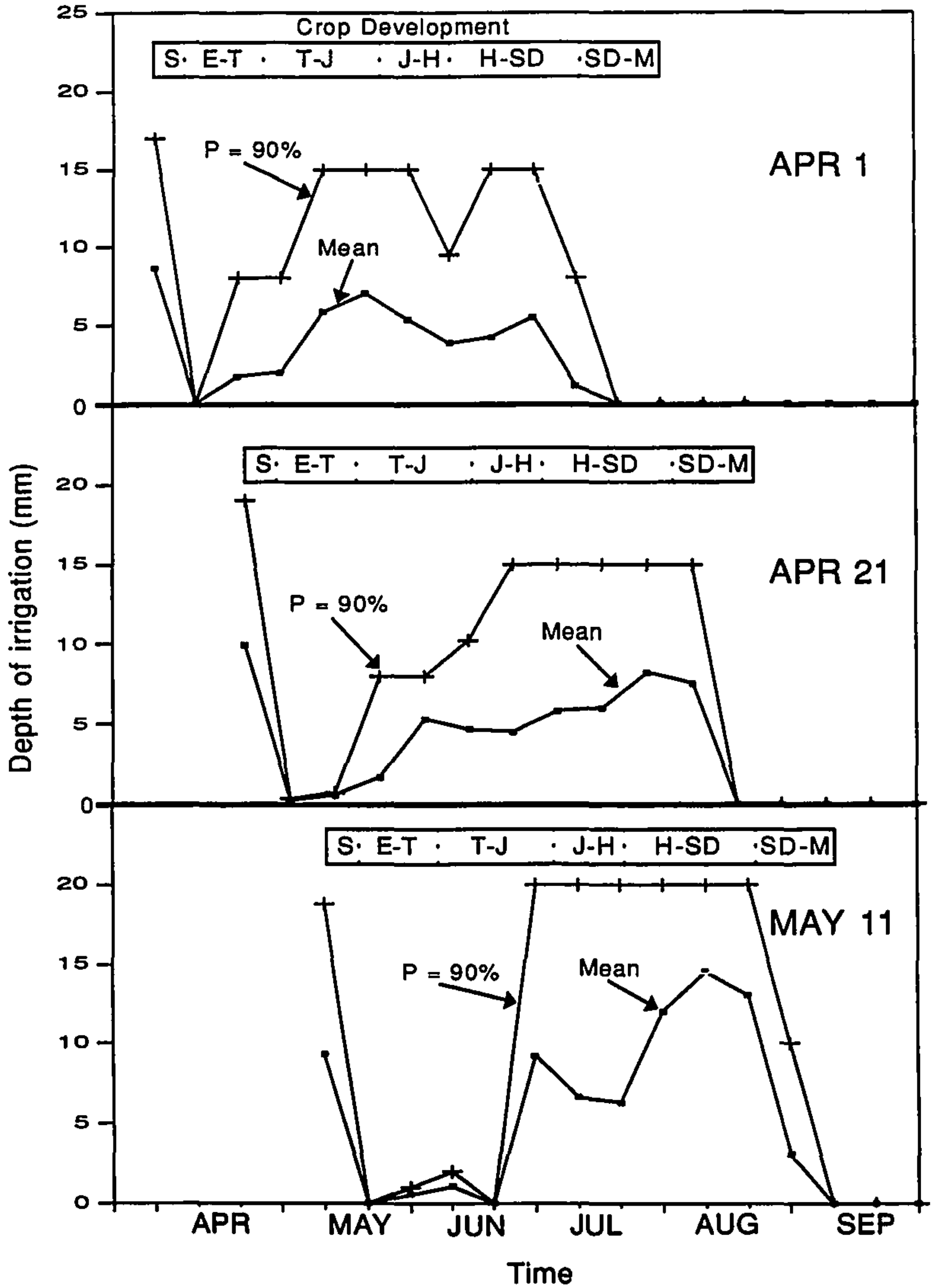
Using the strategies determined to be optimal for each planting date, the mean and expected 90% probability level irrigation depths for 10 day periods during the crop development are given in Figure 5.9. This information is useful to plan water storage or predict stream flow shortage during the growing season. Data show that the first irrigation after planting can be delayed longer for later planting dates, as a result of higher rainfall and lower evaporative demand during the time of crop establishment. Also, the periods of peak in irrigation demand varied with planting date, as a consequence of the development of the crop coinciding with different weather conditions.

SUMMARY AND CONCLUSIONS

The results of a long term simulation (1961 to 1988) revealed that, on average, yield of a non-irrigated wheat crop in Paraná can be reduced from 16 to 50% due to water stress during planting and crop development. The risks for crop reduction increased gradually as planting was delayed from the beginning of April until mid-May. Furthermore, a relatively high variability in yield occurred over the years.

Irrigation can stabilize yield and maintain crop production near the potential. However, the adoption of appropriate strategies is critical to achieve maximum yield levels

Figure 5.9. Mean and 90% probability level (P=90%) depth of irrigation for 10 day periods during the development of wheat seasons with different planting dates. System delivery capacity is 1.5 mm/day for plantings in April and 2.0 mm/day for planting in May. Irrigation cycle is five days for all the simulations. The stages of crop development are: S = Sowing-emergence; E-T = Emergence-tillering; T-J = Tillering-Jointing; J-H = Jointing-heading; H-SD = Heading-soft dough; and SD-M = Soft dough-maturity.



Crop Development
S· E-T · T-J · J-H · H-SD ·SD-M
P = 90%
Mean
APR 1
S· E-T · T-J · J-H · H-SD ·SD-M
P = 90%
Mean
APR 21
S· E-T · T-J · J-H · H-SD ·SD-M
P = 90%
Mean
MAY 11
Depth of irrigation (mm)
APR
MAY
JUN
JUL
AUG
SEP
Time
25
20
15
10
5
0

with minimum applied water. Low intensity (5 to 10 mm) and frequent (3 to 5 days) irrigations increased soil capacity for storing rainfall and allowed higher depletion of soil water by the crop, thus minimizing irrigation needs. Requirements of net system delivery capacity to supply crop water needs in nine of ten years (P = 90%) varied from 1.5 to 2.0 mm/day for plantings in April and 2.0 to 3.0 mm/day for plantings in May. For the same probability, irrigation demand at planting increased from 15 to 20 mm as planting date was delayed from April 1 to May 11.

The kind of method used for timing irrigations minimized losses from soil evaporation by decreasing applications during early and later stages, when soil cover was incomplete, and fully irrigating during critical stages.

The decision of whether irrigation of wheat is economical in Paraná would depend on a further analysis balancing the costs involved with inputs and the benefits gained with irrigation. With the information provided by this simulation model and some additional data to describe particular characteristics of the irrigated area, this can be easily accomplished.

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CHAPTER VI

GENERAL CONCLUSIONS

As a result of this research, the following conclusions can be drawn:

1. SWACROP and VB4 showed a good performance in predicting soil water contents at different depths of the soil profile. Deviations from observed values, given by the mean absolute difference and standard error of estimate, were less than 2.5 and 3.8%, respectively, of the depth of water stored in 130 cm of the soil profile, at field capacity.

2. SWACROP provided a complete output of water balance components, but required a lengthy computation time, which was considered inappropriate for long term simulation. Furthermore, it underestimated runoff and soil evaporation due to inaccuracies in the methods used to simulate these processes.

3. VB4 was appropriate for long term simulations, but required calibration and did not separate evapotranspiration into transpiration and soil evaporation. Thus it was considered inappropriate to be linked with crop yield models.

4. The new soil moisture model, using simplified but realistic methods to simulate the soil-plant-atmosphere processes, was able to predict soil

moisture contents with a similar accuracy to SWACROP and VB4. However it provided better estimates of evapotranspiration and its components. The relatively short computational time and the ability to consider several years of data, and different conditions of crop types and agro-ecologic conditions, make the model advantageous for performing long term simulation.

5. Among seven crop-water production functions, the ones based on the stress day index approach were considered the most appropriate to be linked to the new soil moisture model, in order to predict wheat yields in Paraná.

6. Drought during sowing and development of non-irrigated wheat crops caused high variability in crop production over the years. Average yield reductions due to water stress varied between 16 and 50%. The risks for crop yield reduction increased gradually as planting was delayed from the beginning of April to mid-May.

7. Irrigation stabilized yield and maintained crop production near the maximum level. Maximum yields with minimum applied water was obtained using irrigation amounts of 5 to 10 mm, applied at minimum intervals of between 3 to 5 days.

CHAPTER VII

CONTRIBUTIONS TO KNOWLEDGE

This research provides the following contributions to the knowledge:

1. This thesis represents the first major research in soil water balance and irrigation modelling in Paraná. It contributes significantly to new information for tropical and subtropical regions, since there was little data on crop water management for these areas.

2. The development of the soil moisture-crop production model constitutes an original contribution. This model includes the following features:

   a) An improvement over the model of Saxton et al. (1974), who used a Darcy type equation for calculation of unsaturated soil flux (soil moisture below 90% of the saturation content). The model developed in this research used that method to calculate soil water distribution for both, saturated and unsaturated conditions.

   b) Although procedures for daily rainfall disaggregation into hourly rainfall are available in some models (Skaggs and Konya, 1988), they differ from the method used in this research.

   c) Saxton et al. (1974) used a function dependent on soil cover to estimate transference of sensible heat from between rows to crop canopy. The model developed in this thesis uses a different approach. Transference of sensible heat is dependent on leaf area index.

d) This is the first comprehensive soil moisture model to include the method of Boesten and Stroosnijder (1986) for calculation of soil evaporation. It is an improvement over models like SWACROP (Belmans et al., 1983), and has particular implications for accurate estimation of evapotranspiration of developing canopies, where transpiration is not always the dominant vapor flux stream.

e) Two crop-water production functions based on the stress day index approach were tested and validated for wheat yield predictions in Paraná. One of these functions included a proposed new index for computation of crop water stress based on soil water potential in the root zone.

f) This model is a useful tool for deriving soil-water-balance and irrigation design parameters. The simplified but realistic methods used to simulate the different processes, associated with a relatively short computation time requirements and the capability of processing sequentially different crop types and agro-ecologic conditions over several years of data, make it advantageous over other models with similar characteristics, when long term simulation is required.

3. Wheat yield is significantly decreased by water stress during crop establishment and development in Paraná. Irrigation can stabilize wheat yields and increase production by 13 to 47%.

4. Water application can be optimized by the use of low intensity (5 to 10 mm) and frequent (3 to 5 days) irrigations.

5 Irrigation systems should be designed to deliver 1.5 to 3.0 mm/day.

CHAPTER VIII

SUGGESTION FOR FUTURE RESEARCH

1. There is potential for refining some of the methods of calculation in the model developed in this research. This includes:

   a) Improvements of the method of partition of daily rainfall, in order to disaggregate the discrete daily rainfall process into a continuous process of wet periods (showers) and dry periods within a day, similar to the study of Econopouly et al. (1990).

   b) Calibration of the parameters of the soil evaporation function for other soils and verify conditions for transferability.

   c) Improvements of the crop submodel in order to include other factors affecting yield, while maintaining its simplicity and low input requirements.

2. This model could be expanded to include subroutines to account for water table and then be applied on studies of drainage.

3. This model could be modified to include movement of pesticides and nutrients to be applied in studies of groundwater contamination.

4. A study should be initiated to verify the feasibility of applying this model on real time basis, using remote sensed measurements of rainfall and

evapotranspiration, for evaluation of crop water availability in a regional scale.

5. Economic analysis using the results reported in this thesis might be useful to assess feasibility of expanding irrigation for wheat in Paraná.

6. The model developed in this thesis could be applied for other crops and sites in Paraná, or in Brazil, on studies of water balance and irrigation. Important crops for consideration are rice, beans, soybeans, and corn.

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