Ecological Modelling, 57 (1991) 11–25
Elsevier Science Publishers B.V., Amsterdam

A simple modelling of crop water balance for agrometeorological applications

Jean-Paul Lhomme [1]
CATIE, 7170 Turrialba, Costa Rica

and Nader Katerji
INRA, Station de Bioclimatologie, 78850 Thiverval-Grignon, France
(Accepted 30 January 1991)

ABSTRACT

Lhomme, J.-P. and Katerji, N., 1991. A simple modelling of crop water balance for agrometeorological applications. *Ecol. Modelling*, 57: 11–25.

A simple agrometeorological model of crop water balance is presented. It aims at the best estimate possible of the water balance components with the simplest formulation and the minimum set of input data. The model works with a time step of one day and uses rainfall and the calculated evapotranspiration as the climatic inputs. Some soil and crop characteristics, such as the maximum available moisture and crop coefficients are required as input parameters. The model is tested using experimental data obtained on wheat and lucerne crops in the Paris region. The sensitivity of the model is discussed and some possible applications to rainfed crop management are presented.

1. INTRODUCTION

Crop water balance simulation models are numerous and diverse. They can be classified into two groups: on the one hand, mechanistic models based on the physical equations governing soil water diffusion, on the other hand, simpler and more empirical models, generally called agrometeorological models because they work with standard meteorological data. The first (e.g., Belmans et al., 1983; Rowse et al., 1983) are intended to describe with precision water diffusion processes within the soil on a time scale generally

[1] Permanent address: ORSTOM, 213 Rue La Fayette, 75010 Paris, France.

lower than one day. They involve the solution of the soil water flow equations by numerical methods. The soil is divided into a number of parallel layers and a precise description of the soil characteristics for each layer is required. These models constitute the tools to be used in research. The second type is based on budgeting techniques and requires a few input data, which are easily obtainable from agrometeorological networks (e.g. Baier and Robertson, 1966; Fitzpatrick and Nix, 1969; Franquin and Forest, 1977; Reddy, 1983; Lhomme and Eldin, 1985). The base of time is one day or a period of several days (periods of 5 days or 10 days). The soil is considered as a reservoir (or a series of reservoirs) which fills up or drains as a function of the water supply (rainfall, irrigation) and water loss (evapotranspiration). These models can be used as well on a regional scale for agroclimatological analysis, as on a field scale to monitor the soil water budget and to schedule irrigation.

The agrometeorological models generally consist of a set of submodels, each simulating one term in the water balance equation: soil available moisture, runoff, drainage and evapotranspiration. They differ in the way each submodel works. They are usually based on the notion of maximum available moisture, defined as the difference expressed in millimeters between the amount of water stored at field capacity (−33 kPa) and at wilting point (−1500 kPa) in the zone of the soil occupied by the roots (Hillel, 1982). The maximum available moisture accounts for the fact that only the water stored between wilting point and field capacity is effectively available for plants, since below the wilting point water is too strongly linked with the solid matrix to be extracted by the roots and above the field capacity water is not retained by the solid matrix and is lost by drainage. Since, in the field, the wilting point is often passed beyond in the surface layers and never reached in the deep layers, some authors (Choisnel, 1985) prefer defining the maximum available moisture as the difference between the vertical moisture profile at field capacity and the one corresponding to the maximum drying of the soil as observed, for instance, at the end of a dry season. The soil can be considered as a single reservoir (Forest, 1984; Lhomme and Eldin, 1985), a double reservoir (Reddy, 1983; Choisnel, 1985) or several reservoirs in series (Baier and Robertson, 1986). Runoff is either not taken into account (Choisnel, 1985; Lhomme and Eldin, 1985), or estimated by means of empirical functions (Baier and Robertson, 1966; Forest, 1984). Drainage from the root zone is always calculated as the excess water of the last layer when its water content exceeds its field capacity.

The way the evapotranspiration rate is estimated differs greatly between the different models. All the models generally use, as a starting point, the concept of potential evapotranspiration or climatic demand, but different formulations are used to relate actual to potential evapotranspiration via the moisture status of the soil. Baier and Robertson (1966) make use of a linear relationship between the available soil moisture and the actual evapotranspiration, weighted by coefficients that account for the root characteristics, the soil dryness curves and the effects of varying potential evapotranspiration. In the model of Reddy (1983), actual evapotranspiration is computed as a function of time after wetting of the soil, giving preference to the top layers of the soil wetted by rain. Calder et al. (1983) assessed for grassland the performance of various formulations of potential evapotranspiration and different functions relating actual to potential evapotranspiration. Forest (1984) adapts his submodel of actual evaporation from the model experimentally derived by Eagleman (1971). The submodel of Choisnel (1985) is based on a resistance formulation of actual evapotranspiration and an empirical relationship between canopy resistance and available soil water.

This paper deals with an agrometeorological model which has already been partially presented in previous French language papers (Lhomme and Eldin, 1985; Lhomme, 1986). This model is well adapted to the water balance of annual crops because it accounts for variation in crop coefficients and maximum available moisture as a function of the phenological stages. It intends to reconcile generality and precision, with the simplest formulation and the minimum set of input data. There are three objectives of this paper: (a) to describe the model, (b) to test the model against the field data obtained on winter wheat and lucerne in the Paris region, analysing its sensitivity to the main parameters of the problem and (c) to show some examples of the practical use that can be made of such a model in agrometeorology for rainfed crop management.

2. DESCRIPTION OF THE MODEL

2.1. Soil available moisture

For a given soil the maximum available moisture, denoted by MAM, varies as a function of the root depth, that is as a function of the phenological stage of the crop. In the case of annual crops the MAM varies between a minimum value MAM_n, at the time of the emergence of the crop (some days after the sowing date), and a maximum value MAM_x corresponding to the maximum root depth. The minimum value MAM_n corresponds approximately to the MAM of the surface layer (about 20–30 cm), in which water is directly evaporated at the soil surface. The maximum value MAM_x is supposed to be reached when the crop begins to cover the soil surface completely.

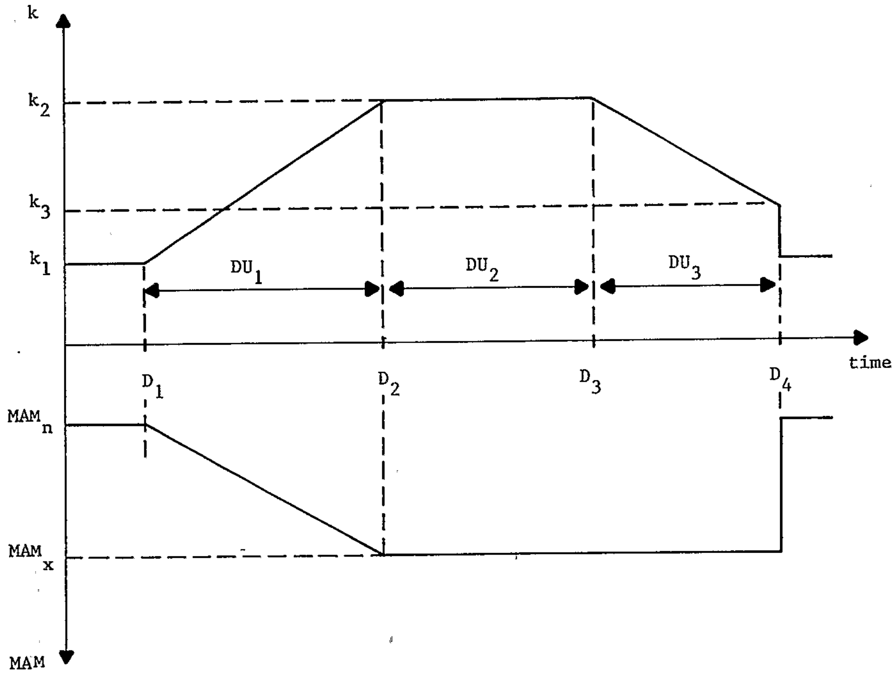

Fig. 1. Variation in crop coefficient (k) and maximum available moisture (MAM) over the different phenological stages of an annual crop, (initial stage DU_1, reproductive stage DU_2 and maturing stage DU_3).

If the variation in the rooting depth is not known (which is the most frequent case), it is always possible to choose a linear variation law as a function of the day number D between the emergence date D_1 and the date D_2 corresponding to a complete covering of the soil surface by the foliage (initial stage of duration DU_1). The maximum value MAM_x is conserved until the harvesting date D_4 (Fig. 1). This simple type of modelling can be mathematically formulated in the following way:

$$\text{if} \quad D \in]D_1, D_2] \qquad MAM(D) = MAM_n + (MAM_x - MAM_n)(D - D_1)/DU_1 \quad (1)$$

$$\text{if} \quad D \in]D_2, D_4] \qquad MAM(D) = MAM_x \quad (2)$$

$$\text{if} \quad D \in]D_4, D_1] \qquad MAM(D) = MAM_n \quad (3)$$

In the case of perennial crops, as a first approximation, the value of MAM is supposed not to vary and to be always equal to a maximum value MAM_x.

Available moisture denoted by AM is defined as the amount of water stored in the soil and available to the plants at a given time, that is the amount of water stored between the wilting point and the actual point at which the water is. The available moisture is thus always less than the maximum available moisture.

The variation in the amount of available moisture is governed by the water balance equation applied to the part of the soil occupied by the roots. This equation accounts for the water inputs and outputs and is written on a daily basis as:

$$\mathrm{AM}(D) - \mathrm{AM}(D-1) = \sum \mathrm{WS}(D) - \sum \mathrm{WL}(D) + \delta\mathrm{MAM}(D) \tag{4}$$

where $\Sigma\mathrm{WS}(D)$ is the total amount of water supplied to the soil during day D, $\Sigma\mathrm{WL}(D)$ is the total amount of water lost by the soil during the same day, $\mathrm{AM}(D-1)$ is the state of the reserve at the end of day $D-1$, $\mathrm{AM}(D)$ is the state of the reserve at the end of day D and $\delta\mathrm{MAM}(D) = \mathrm{MAM}(D) - \mathrm{MAM}(D-1)$ is the supply of water owing to root penetration, which changes the maximum moisture available. If the roots grow, we may suppose there is enough water for subjacent soil layers to be close to field capacity.

2.2. *Water supply: effective rainfall*

The water supplied to the soil reservoir come essentially from precipitation (PR) or irrigation (IR). However, they are not entirely effective since a part is lost as runoff (RO) and deep drainage (DR):

$$\sum \mathrm{WS} = (\mathrm{PR} + \mathrm{IR}) - (\mathrm{RO} + \mathrm{DR}) \tag{5}$$

It is difficult to estimate the surface runoff because it is very dependent on the pedo-climatic conditions: it depends on the ground slope, rainfall intensity, soil type and cropping practices. As a first approximation we can use the following simple model, which considers that runoff is proportional to the amount of rain when exceeding a given value P_0 (Forest, 1984):

$$\text{if} \quad \mathrm{PR}(D) > P_0 \qquad \mathrm{RO}(D) = \beta[\mathrm{PR}(D) - P_0] \tag{6}$$

$$\text{if} \quad \mathrm{PR}(D) \leqslant P_0 \qquad \mathrm{RO}(D) = 0 \tag{7}$$

The coefficient β and P_0 are two parameters which are functions of the ground slope and cropping practices (for a cropped soil with a slope lower than 3% Forest (1984) suggests: $P_0 = 25$ mm and $\beta = 0.15$).

For each day we shall define a retention capacity, denoted by $\mathrm{RC}(D)$, as the difference between the MAM and the available moisture of the previous day:

$$\mathrm{RC}(D) = \mathrm{MAM}(D) - \mathrm{AM}(D-1) \tag{8}$$

Any amount of rainfall that enters the soil on day D first recharges the soil, and then percolates, if the amount of water is greater than the retention capacity (Fitzpatrick and Nix, 1969). In this case deep percolation will correspond to the surplus of the reservoir. Thus we shall write:

$$\text{if} \quad \mathrm{PR}(D) \leqslant \mathrm{RC}(D) \qquad \mathrm{DR}(D) = 0 \tag{9}$$

$$\text{if} \quad \mathrm{PR}(D) > \mathrm{RC}(D) \qquad \mathrm{DR}(D) = \mathrm{PR}(D) - \mathrm{RC}(D) \tag{10}$$

2.3. Water loss: evapotranspiration

The water loss in equation (4) corresponds essentially to the actual evapotranspiration rate ET. ET is derived from the maximum evapotranspiration $\mathrm{ET_m}$, itself derived from climatic evapotranspiration $\mathrm{ET_c}$ (e.g., from Penman's formula), which is a climatic input to the model. $\mathrm{ET_m}$ varies as a function of the extent to which the soil surface is covered by vegetation (the leaf area index) and its physiological activity. The actual evapotranspiration rate varies with respect to $\mathrm{ET_m}$ as a function of the amount of water stored in the soil.

To describe the variation of $\mathrm{ET_m}$ as a function of the phenological stage, one uses the crop coefficients (Jensen, 1968; Franquin and Forest, 1977). The crop coefficients, denoted by k, relate the $\mathrm{ET_m}$ of a given crop, at a given phenological stage, to a climatic evapotranspiration chosen as reference: $\mathrm{ET_m} = k\,\mathrm{ET_c}$. The values of k are experimentally derived and can be found in numerous publications, such as Doorenbos and Pruitt, 1975. When the values of k are known only for particular phenological stages of annual crops, intermediate values can be linearly interpolated as a function of the day number.

For instance, if only three values are known: the initial value k_1, the value corresponding to the reproductive stage k_2 and the final value k_3 (Fig. 1), and if $\mathrm{DU_1}$, $\mathrm{DU_2}$ and $\mathrm{DU_3}$ are the durations of each stage, we shall write:

$$\text{if } D \in [D_1, D_2] \quad \mathrm{ET_m}(D)/\mathrm{ET_c}(D) = k_1 + (k_2 - k_1)(D - D_1)/\mathrm{DU_1} \tag{11}$$

$$\text{if } D \in]D_2, D_3] \quad \mathrm{ET_m}(D)/\mathrm{ET_c}(D) = k_2 \tag{12}$$

$$\text{if } D \in]D_3, D_4] \quad \mathrm{ET_m}(D)/\mathrm{ET_c}(D) = k_2 + (k_3 - k_2)(D - D_3)/\mathrm{DU_3} \tag{13}$$

For a perennial crop that is cut several times during the same year, like lucerne, the same model can be used between two succesive harvests.

The actual evapotranspiration can be calculated using the classical concepts of soil water availability to plants (Hillel, 1982). The available soil moisture (MAM) is divided into two parts: readily available moisture (RAM)

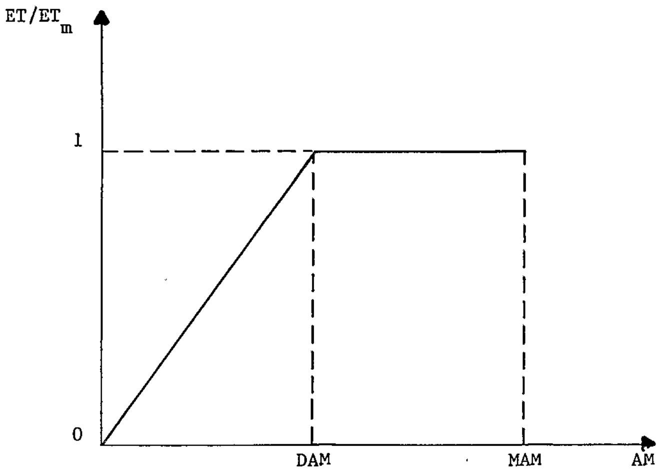

Fig. 2. Variation in the ratio of actual evapotranspiration to maximum evapotranspiration as a function of available soil moisture.

and the complement, which is decreasingly available (DAM): MAM = RAM + DAM. The critical point, somewhere between the field capacity and the wilting point, which constitutes a regulation threshold, varies as a function of the characteristics of the soil and of the root system. The DAM is commonly taken as a percentage α of the MAM: $\mathrm{DAM}/\mathrm{MAM} = \alpha$, where α has no precise value but generally lies between a third and a half.

As a first approximation we can admit that the ratio $\mathrm{ET}/\mathrm{ET}_m$ increases from zero to one as a linear function of available moisture, when it varies from zero to the value DAM, and that this ratio is equal to one when the available moisture fluctuates between DAM and MAM (Fig. 2). Then, we shall write:

$$\text{if} \quad \mathrm{AM}(D-1) \geqslant \mathrm{DAM}(D-1) \qquad \mathrm{ET}(D) = \mathrm{ET}_m(D) \tag{14}$$

$$\text{if} \quad \mathrm{AM}(D-1) < \mathrm{DAM}(D-1) \qquad \mathrm{ET}(D) = \mathrm{ET}_m(D)\mathrm{AM}(D-1)/\mathrm{DAM}(D-1) \tag{15}$$

Equation (4), which describes the water balance on a daily basis, can be rewritten as:

$$\mathrm{AM}(D) - \mathrm{AM}(D-1) = \mathrm{PR}(D) - \mathrm{ET}(D) - \mathrm{RO}(D) - \mathrm{DR}(D) + \delta\mathrm{MAM}(D) \tag{16}$$

which constitutes a recurrent relation that allows one to calculate the successive values of the available moisture. The available reserve at the beginning of the recurrent process is an input to the model. Unless we have a particular means to determine this, it is always possible to put $\mathrm{AM}(0) = 0$

at the end of the dry season in tropical or Mediterranean regions, and, in temperate regions, AM(0) = MAM at the end of winter. In a general way we shall put: AM(0) = τMAM(0), where τ will be an input parameter.

3. MODEL PERFORMANCE

3.1. Experimental validation

The model was tested using experimental data obtained on two crops, one annual, a winter wheat (*Triticum aestivum*) in 1975, and an other perennial, a lucerne (*Medicago sativa*) in 1978, both grown in the deep silt soil of the Paris region (Katerji et al., 1984). The variation in the water stock was measured using a neutron probe and actual evapotranspiration was measured by a BEARN system, based upon the Bowen ratio method (Perrier et al., 1975). The measurements took place from 20 May to 26 August for the wheat crop, and from 5 April to 13 September for the lucerne crop.

The model was run disregarding runoff and using the rainfall data of the nearby meteorological station. The reference evapotranspiration values ET_c were calculated daily according to Penman's method, from temperature, humidity, sunshine and windspeed data. However, for the practical use of the model, it is generally acceptable to use monthly normal values of ET_c converted to daily values, instead of the real values corresponding to each day, since climatic evapotranspiration is subject to more minor variations than rainfall (Frere and Popov, 1979; Radulovich, 1987). The crop coefficients were taken from FAO documents (Doorenbos and Pruitt, 1975), and adapted to suit the submodel described in Section 2.3 and Fig. 1. The values retained are $k_1 = 0.3$, $k_2 = 1.1$, $k_3 = 0.1$ for the wheat crop ad $k_1 = 0.5$, $k_2 = 1.1$ for the lucerne crop. The coefficient α, which defines the reduced amount of moisture, was arbitrarily set equal to a half for wheat. For the lucerne crop we retained the value of a third, which slightly improves the fit of the ET simulated values to those measured by the BEARN system. The root system of wheat is about 1 m deep and is more superficial than the lucerne one, which is about 1.6 m deep but possibly deeper (the lucerne crop was sown in 1977, one year before the experiment). The MAM values retained were determined after successive trials aimed at obtaining the best fit. For the wheat crop, the maximum available reserve MAM was considered to vary between a minimum value $MAM_n = 25$ mm and a maximum value $MAM_x = 80$ mm. For the lucerne crop, the MAM was considered as constant during the three cycles of the experiment (corresponding to three harvests), and was set equal to 200 mm. On the first day

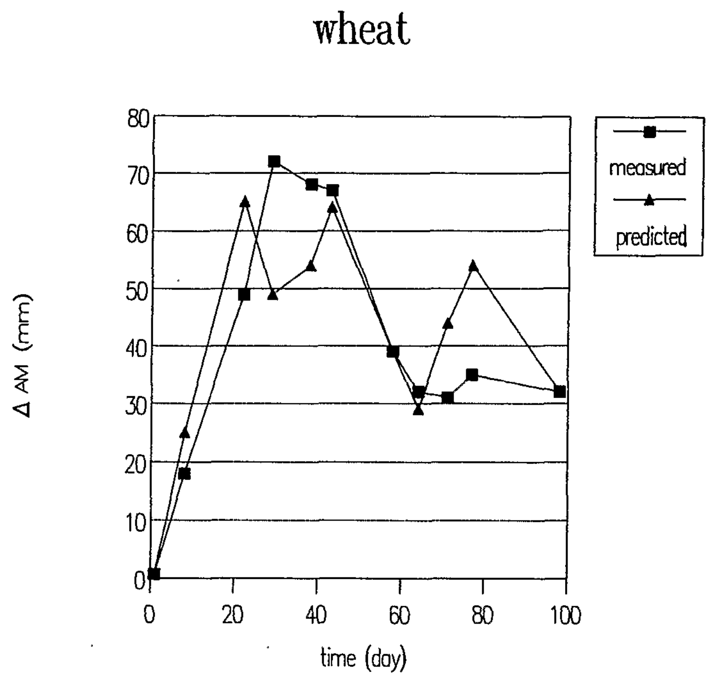

Fig. 3. Winter wheat: variation as a function of time in the available soil moisture $\Delta\text{AM} = \text{AM}(D) - \text{AM}(0)$ from an initial date (20 May, 1975).

of the simulation process the soil was assumed to be at field capacity ($\tau = 1$).

Figures 3 to 6 show the variations in the total water content in the upper layer of the soil, which is 0–170 cm deep, beginning on an initial date, as measured by the neutron probe and as predicted by the model. They also show the variations in cumulative actual evapotranspiration as measured by the BEARN system and as predicted by the model. The agreement between the model and the experimental data is fairly good though the model seems to underestimate systematically the evapotranspiration rate. This deviation between the model predictions and the experimental results could be explained by the phenomenon of capillary rise. In the deep silt soils of the Paris region, with an important amount of ground water, capillary rise may occur frequently during a dry period. This mechanism allows the plants to be supplied with water from the soil layers beneath the root depth. If the flow of rising water between the lower and upper layers is permanent it has no effect upon the soil water content but only upon the evapotranspiration rate.

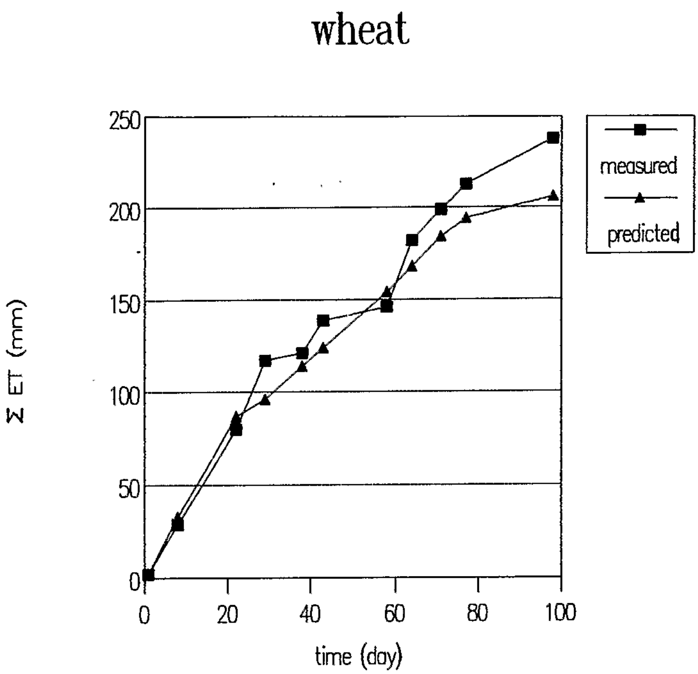

Fig. 4. Winter wheat: variation as a function of time in the cumulative actual evapotranspiration Σ ET from an initial date (20 May 1975).

3.2. Sensitivity of the model

The sensitivity of the model to its main parameters was assessed using the following method. Three parameters were selected because of their importance: the maximum available moisture MAM (equations (1) to (3)), the crop coefficients k_1, k_2 and k_3 (equations (11) to (13)), and the coefficient α defining the reduced amount of available moisture in the actual evapotranspiration linear submodel. The parameters defining runoff were not assessed because the corresponding submodels can differ greatly.

For both crops, wheat and lucerne, the values of the parameters used in section 3.1 to test the model against the experimental data were taken as references. A 20% deviation around these values was considered and the effect upon the simulation process was evaluated on two outputs, the available moisture (AM) and the actual evapotranspiration (ET). If A_0 is the value of reference of parameter A, $A_0 + 20\%$ and $A_0 - 20\%$ are tested. If $x_{0,i}$ and x_i, respectively, represent the value of the output (AM or ET), for each day of the simulation, using either the value of the reference (A_0) of

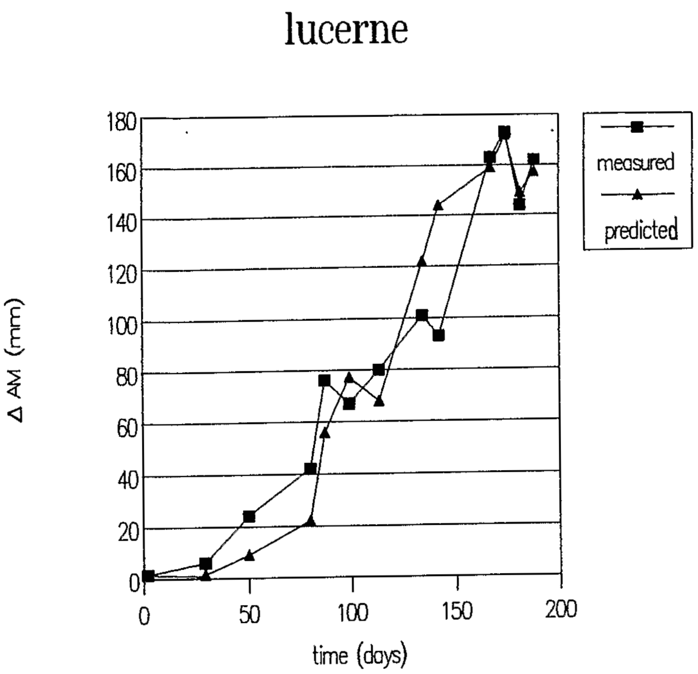

Fig. 5. Lucerne: variation as a function of time in the available soil moisture ΔAM = AM(D) − AM(0) from an initial date (5 April 1978).

the parameter or its modified value ($A \pm 20\%$), the following statistic is calculated:

$$\sigma = \left[\frac{1}{n} \sum_{i=1}^{n} \left(\frac{x_i - x_{0i}}{x_{0i}} \right)^2 \right]^{1/2} \quad (17)$$

σ represents the mean quadratic deviation percentage and is used as a sensitivity indicator.

Tables 1 and 2 give the values of σ for wheat and lucerne crops, respectively. From these tables it appears clearly that the least sensitive parameter is the coefficient α of the ET submodel, then the maximal available moisture MAM, and the most sensitive parameters are the crop coefficients. A 20% variation in MAM and α generates a mean deviation percentage lower than 20%, whereas a 20% variation in the crop coefficients leads to a mean deviation percentage greater than 20%.

3.3. Applications

The model described above can be used to follow and monitor the soil water status for irrigation purposes. However, the principal advantage of

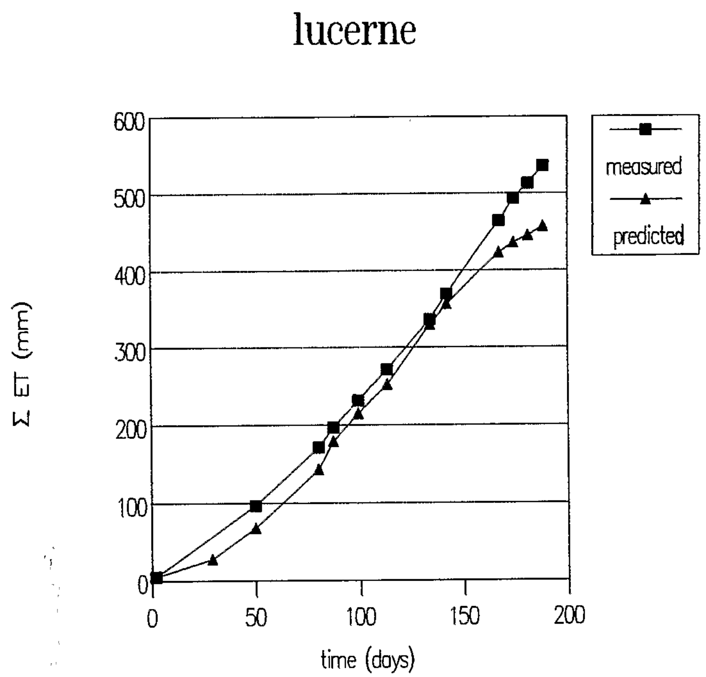

Fig. 6. Lucerne: variation as a function of time in the cumulative actual evapotranspiration ΣET since an initial date (5 April 1978).

this model is its possible agroclimatological applications in tropical conditions, where water is often the main limiting factor. For rainfed tropical cropping based on the optimization of rainfall water use, such a model can be very useful in assessing the duration of the rainfed cropping season and in evaluating different cropping strategies (Radulovich, 1989). This model

TABLE 1

Test of the sensitivity of the model as explained in the text for the wheat crop. The values of the parameters used as a reference are: $MAM_n = 25$ mm, $MAM_x = 80$ mm, $\alpha = 0.5$, $k_1 = 0.3$, $k_2 = 1.1$, $k_3 = 0.1$. σ is the sensitivty indicator calculated as the mean quadratic deviation percentage with respect to the daily outputs simulated with the reference parameters.

Parameter	Variation (%)	σ(ET) (%)	σ(AM) (%)
Maximum available	+20	15	(32)
moisture (MAM)	−20	14	(25)
Coefficient α in	+20	7	16
ET submodel	−20	7	15
Crop coefficients	+20	23	24
k_1, k_2, k_3	−20	29	42

TABLE 2

Test of the sensitivity of the model, as explained in the text, for the lucerne crop. The values of the parameters used as reference are: MAM = 200 mm, $\alpha = 0.33$, $k_1 = 0.5$, $k_2 = 1.1$. σ is the sensitivity indicator calculated as the mean quadratic deviation percentage with respect to the daily outputs simulated with the reference parameters.

Parameter	Variation (%)	σ(ET) (%)	σ(AM) (%)
Maximum available	+20	18	(41)
moisture (MAM)	−20	15	(31)
Coefficient α in	+20	4	8
ET submodel	−20	9	7
Crop coefficients	+20	23	26
k_2, k_3	−20	29	59

also allows one to estimate a global crop water stress index (Gommes, 1983), which can be used for purposes such as yield prediction and sowing date determination.

Foe each day D of the simulation a crop water deficit can be defined as the difference between the maximum and the actual evapotranspirations:

$$\mathrm{WD}(D) = \mathrm{ET_m}(D) - \mathrm{ET}(D) \tag{18}$$

This daily water deficit can be summed up over the duration of the crop cycle or over any sensitive phase of the cycle and denoted by ΣWD. Defining the water needs over the same period as the cumulative maximal evapotranspiration, denoted by $\Sigma \mathrm{ET_m}$, a simple water stress index can be derived as:

$$\mathrm{WSI} = \sum \mathrm{WD} / \sum \mathrm{ET_m} \tag{19}$$

WSI is zero when there is no water deficit and one when the water deficit is a maximum.

The manner in which the water deficit affects crop growth and yield production varies with the type of crop and the phase of the growth cycle. In a constraint-free environment and for high-producing crop varieties grown under a high level of crop management, the index WSI can be directly related to the yield reduction according to the classical relationship proposed by Doorenbos and Kassam (1979):

$$1 - Y/Y_m = k_y \mathrm{WSI} \tag{20}$$

where Y is the actual yield, Y_m is the maximum yield obtained when $\mathrm{ET} = \mathrm{ET_m}$ and k_y is the yield reduction factor for the phenological stage considered. The values of k_y are determined on the basis of experimental field data covering a wide range of growing conditions.

The water stress index can also be used to determine the best sowing date of annual crops, provided the daily rainfall data are available over several years. Trying successive dates, for each of them and for each year of record the crop water balance model is implemented with the corresponding parameters. The WSI values are calculated. For each date, a mean value of the index is calculated over the number of years recorded, and the date retained as the best sowing date is the one that minimizes the mean value of the index. An example of such a technique, applied to a potato crop on the Bolivian Altiplano, is given in Lhomme and Eldin (1985).

4. CONCLUSIONS

The simple agrometeorological model described above does not pretend to be a very accurate tool to calculate the different components of the crop water balance. First of all, our intention was to reduce to a minimum level the number of input parameters used in the simulation process, in such a way that the field of application is the largest possible. On the other hand, the time step (one day) and the daily meteorological data used in the simulation in fact impose a certain degree of imprecision. It would be useless to intend to describe with accuracy some aspects of water dynamics in the field, which can be taken into account only by using mechanistic models on a smaller time scale.

Perhaps the main problem in this kind of model lies in assigning a correct value to the maximum available moisture. The model is fairly sensitive to the value of the MAM and it is often difficult to determine a correct working value in any other way than a tentative trial for the best fitting. Another problem, which is not taken into account in this paper, is capillary rise. This process, similar to infiltration except that it takes place in the opposite direction, is difficult to model in a simple way. However, in deep soils and during dry periods, it can contribute substantially to the soil water balance.

As a concluding remark it seems worthwhile to point out the main reasons why such a model is of interest for monitoring annual crops with respect to the other models that are available in the literature:

(1) the mathematical relationships involved are simple and the corresponding parameters have a clear physical meaning;

(2) the input data, that is the crop characteristics and the meteorological data, are easily available;

(3) the model is well suited to agroclimatological applications such as rainfed crop management, yield prediction or sowing date determination.

REFERENCES

Baier, W. and Robertson, G.W., 1986. A new versatile soil moisture budget. Can. J. Plant Sci., 46: 299–315.

Belmans, C., Wesseling, J.G. and Feddes, R.A., 1983. Simulation model of the water balance of a cropped soil: SWATRE. J. Hydrol., 63: 271–286.

Calder, I.R., Harding, R.J. and Rosier, P.T.W., 1983. An objective assessment of soil-moisture deficit models. J. Hydrol., 60: 329–355.

Choisnel, E., 1985. Un modèle agrométéorologique opérationnel de bilan hydrique utilisant des données climatiques. In: A. Perrier and Ch. Riou (Editors), Conf. Int. Les Besoins en Eau des Cultures, 11–14 September 1984, Paris, 1984. INRA, Paris, pp. 115–132.

Doorenbos, J. and Kassam, A.H., 1979. Yield response to water. FAO Irrig. Drain. Pap. 33, 193 pp.

Doorenbos, J. and Pruitt, W.O., 1975. Les besoins en eau des cultures. FAO Irrig. Drain. Pap. 24, 144 pp.

Eagleman, J.R., 1971. An experimentally derived model for actual evapotranspiration. Agric. Meteorol., 8: 385–394.

Fitzpatrick, E.A. and Nix, H.A., 1969. A model for simulating soil water regime in alternating fallow-crop systems. Agric. Meteorol., 6: 303–319.

Forest, F., 1984. Simulation du bilan hydrique des cultures pluviales: présentation et utilisation du modèle BIP. IRAT-CIRAD, France, 61pp.

Franquin, P. and Forest, F., 1977. Des programmes pour l'évaluation et l'analyse fréquentielle des termes du bilan hydrique. Agronomie Tropicale, 32: 1: 7–1.

Frere, M. and Popov, G., 1979. Agrometeorological crop monitoring and forecasting. FAO Plant Prod. Prot. Pap. 17, 64 pp.

Gommes, R.A., 1983. Pocket computers in agrometeorology. FAO Plant Prod. Prot. Pap. 45, 140 pp.

Hillel, D., 1982. Introduction to Soil Physics. Academic Press, New York.

Jensen, M.E., 1968. Water consumption by agricultural plants. In: T.T. Kozlowski (Editor), Water Deficits and Plant Growth. Vol. 2. Academic Press, New York.

Katerji, N., Daudet, F. and Valancogne, C., 1984. Contribution des réserves profondes du sol au bilan hydrique des cultures. Agronomie. 4: 779–787.

Lhomme, J.P., 1986. Suivi agrométéorologique des conditions hydriques des cultures. In: Climat et Développement. Sém. 15–16 October 1985, Paris. Orstom, Paris, pp. 167–177.

Lhomme, J.P. and Eldin, M., 1985. Un modèle agroclimatologique de simulation du bilan hydrique des cultures. In: A. Perrier and Ch. Rion (Editors), Conf. Int. Les Besoins en Eau des Cultures, 11–14 September 1984, Paris. INRA, Paris, pp. 841–852.

Perrier, A., Itier, B., Bertolini, J.M. and Blanco de Pablos, A., 1975. Mesure automatique du bilan d'énergie d'une culture. Ann. Agron., 26: 19–40.

Radulovich, R., 1987. AQUA, a model to evaluate water deficits and excesses in tropical cropping. Agric. For. Meteorol., 40: 305–321.

Radulovich, R., 1989. Optimization of rainfed tropical cropping in semi-dry areas: a case study. Agric. Water Manage., 16: 337–352.

Reddy, S.J., 1983. A simple method of estimating the soil water balance. Agric. Meteorol., 28: 1–17.

Rowse, H.R., Mason, W.K. and Taylor, H.M., 1983. A microcomputer simulation model of soil water extraction by soya beans. Soil Sci., 136: 218–225.