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Estimation of Potential and Actual Evapotranspiration

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A model for determining the potential and actual evapotranspiration from agricultural crops is presented. The model requires only a limited number of meteorological variables, i.e. global radiation, air temperature and precipitation. The vegetation is characterized by the crop surface area and the efficient root depth. The soil is characterized by the root zone capacity. The model simulates evaporation of intercepted water, evaporation from the soil surface and transpiration from plants. The evapotranspiration pressure (potential evapotranspiration) is divided between crop and soil by use of Beer's law.

Introduction

Aslyng and Hansen (1982) have described the root zone water balance and dry matter production simulation model WATCROS based on climate, soil and plant variables and parameters. In developing the model it has been the aim to limit the required meteorological variables to a minimum. The model consists of a number of submodels. A crop surface area model and a root growth model act as submodels to the evapotranspiration model. Grass, w-wheat, s-barley, potato and f-beet crops have been considered.

Potential Evapotranspiration

To determine the evaporative possibility of a given surface or crop the concept of potential evapotranspiration is often applied. It can be defined as the maximum evaporation and transpiration from a surface with ample water supply. This definition leads to different potential evapotranspiration rates for different crops because the quantity of energy available for evapotranspiration is influenced by the surface conditions. The radiation balance is influenced by the reflectivity, the emissivity and the temperature of the surface. The ground heat flux is influenced by the surface temperature, the heat conductivity and the capacity of the soil (the latter varying with the soil water content). The distribution of energy between latent and sensible heat is governed by the transport process which is influenced by the temperature and the aerodynamic roughness of the surface. Thus, in order to perform an accurate calculation of the potential evapotranspiration extensive investigation and measurements are required. By use of the Penman equation the measurements can be limited somewhat, but still the requirements are so demanding that they seldom will be fulfilled for the actual surface under consideration. The measurements are often performed for a "representative surface", the results must therefore be transferred to the actual surface. In this case it is very important that the "representative surface" really is representative. This can be illustrated by the data in Table 1, estimated from measurements performed at Karup, Jutland, and Tåstrup, Sealand.

The surface was in both cases short grass. Although both global radiation, temperature, saturation deficit and wind speed were larger at Tåstrup than at Karup the potential evapotranspiration calculated by the Penman equation was larger at Karup than at Tåstrup. This is mainly caused by the surface conditions. At Tåstrup the grass cover was dense and green and amply supplied with water while at Karup the grass cover was open, less dense, and frequently suffering from water stress.

A simple way of obtaining the potential evapotranspiration is by measuring the evaporation with the HL 315 evaporimeter. In dry years the method especially requires that the evaporimeter is surrounded by an irrigated area with grass to prevent oasis effect, caused by thermal advection from dry surroundings. Mogensen and Hansen (1979) found that the oasis effect in dry years could amount to 80

Table 1 – Potential evapotranspiration (April-October) assessed by different methods. Average of 9 years 1968-1976.

Method	Karup	Tåstrup
Penman Eq.	551	528
HL 315	514	499
Makkink Eq.	493	527

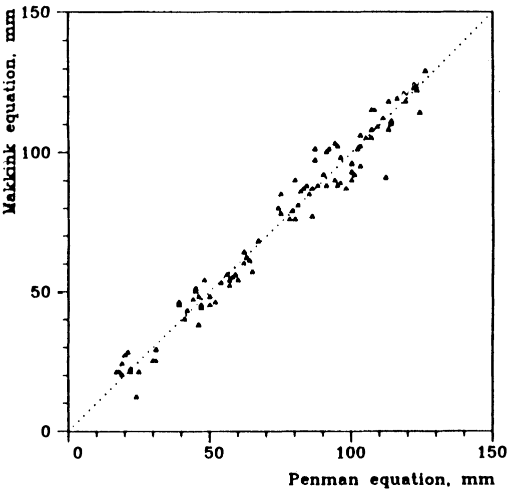

Fig. 1.

Potential evapotranspiration calculated daily by the Penman and Makkink equations. Monthly values from the climate station at Tåstrup, April to October, 1966-1979.

mm or 15-20% of the April-September potential evaporation. The value given in Table 1 for Karup is likely to be too high because of this oasis effect.

For many cases a simple empiric approach is sufficient or even preferable. For estimating potential evapotranspiration from grass Makkink (1957) proposed the equation

$$E^* = 0.61 \frac{\Delta}{\Delta+\gamma} \frac{S_i}{\lambda} - 0.12 \text{ mm/day} \tag{1}$$

where Δ is the slope of the curve of the saturation vapour pressure vs. the temperature, γ is the psychrometric constant, S_i is the global radiation and λ is the latent heat of vaporization of water.

On the basis of later investigation in the Netherlands (Makkink and van Heemst 1967) and of investigations at Tåstrup (Hansen, Jensen and Aslyng, 1981) we proposed the following form of the Makkink equation (Aslyng and Hansen 1982)

$$E^* = 0.7 \frac{\Delta}{\Delta+\gamma} \frac{S_i}{\lambda} \tag{2}$$

The results obtained by this modified Makkink equation have been compared with the results of the Penman equation, which was found to be reliable for grass at Tåstrup (Hansen, Jensen and Aslyng 1981).

Potential evapotranspiration was calculated on a daily basis by means of Eq. (2) and the Penman equation. Monthly sums are presented in Fig. 1.

A linear regression between the Eq. (2) values as dependent variables and the Penman values as independent values was carried out. The result showed that the intercept was not significant and that the slope was not significantly different from 1. The correlation coefficient was 0.98 but the residuals from the linear model

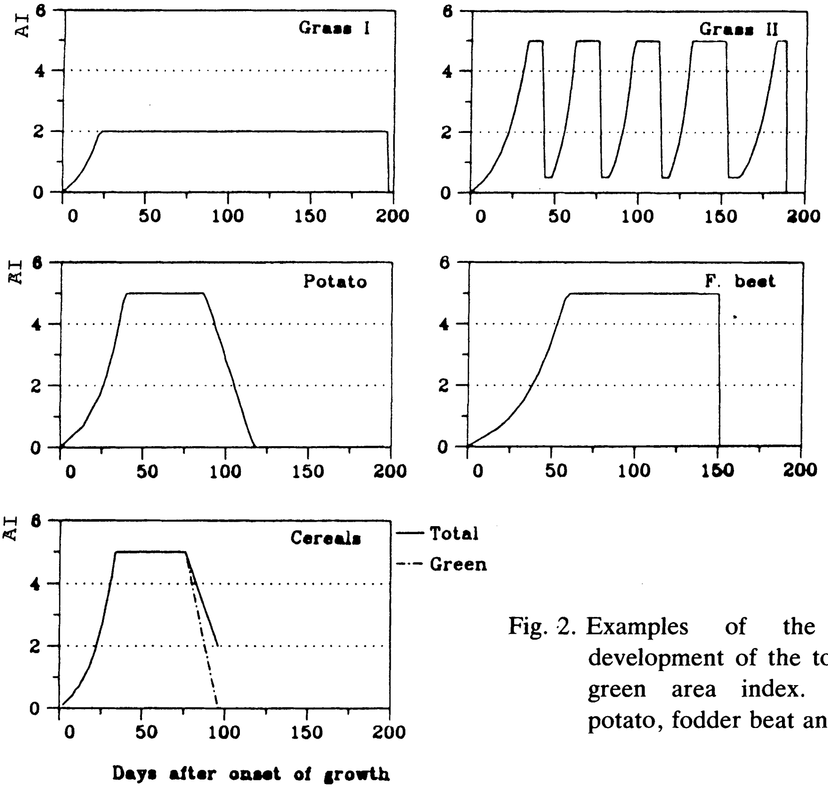

Fig. 2. Examples of the simulated development of the total and the green area index. For grass, potato, fodder beat and cereals.

showed systematic variation over the year. The greatest mean deviation from the Penman value was found in the months, April, May and June where the deviation amounted to -2, -2 and -3 mm, respectively.

It is found that the empiric Makkink equation gave satisfactory results at Tåstrup and it is believed that the result at Karup is more reliable than the results obtained by the HL 315 method (due to the oasis effect) and the Penman equation (due to lack of representativity of the input data, especially net radiation).

In the simulation model WATCROS it is assumed that the potential evapotranspiration determined for short grass, as that at Tåstrup, can represent the potential evapotranspiration for any dense, green, growing agricultural crop.

Vegetation Characteristics

The crop cover is characterized by a crop total area index CAI and a green area index GAI. The area index is shown in Fig. 2 as function of time. The area index is assumed to be a function of the temperature sum beginning from March 1st, except in the case of cut of grass, which is determined on the basis of age of the cut or of the dry matter production.

Actual Evapotranspiration

This root zone water balance model is especially designed to work in connection with the crop production model.

An a priori assumption is that the actual evapotranspiration E, can reach but not exceed the potential evapotranspiration. The E/E^* ratio varies according to the evaporative demand and the availability of soil water (Denmead and Shaw 1962). For climatic conditions, such as they are in Denmark, we have adopted a break point from $E/E^* = 1.0$ corresponding to utilization of 50% of the actual root zone capacity for available water (Kristensen 1961).

The total water consumption is not greatly influenced by some variation in the break point. For ample water supply there is no influence and for limited water supply the influence is mainly a question of when the water is used.

The evaporation demand or potential evapotranspiration is divided between the soil E_s^* and the crop E_c^*. This is done by the expressions

$$E_s^* = E^* e^{-KC} \tag{3}$$

$$E_c^* = E^*(1 - e^{-KC}) \tag{4}$$

assuming that the evaporative demand behaves in the same way as net radiation and by using Beer's law. K is an extinction coefficient and C is the crop area index.

On account of the production model E_c^* is further divided into

$$E_{c,g}^* = E_c^*(1 - e^{-KG}) \tag{5}$$

$$E_{c,y}^* = E_c^* - E_{c,g}^* \tag{6}$$

where $E_c^*{}_{,g}$ is the evaporative demand of green active areas, G is the area index of green active materials and $E_c^*{}_{,y}$ is the evaporative demand from yellow non active materials.

The extinction coefficient K is chosen equal to the extinction coefficient for net radiation, 0.6. If neither the crop nor the top soil can 'fulfill' the evaporative demand, the energy is not used for evaporation.

The model is operated as a book-keeping system and in the beginning of each step precipitation, P, and irrigation, I, are supplied to the reservoirs, on which the model operates. The P and I are supplied to the interception storage. The capacity of this reservoir is stated equal to

$$S_I^* = 0.5C \tag{7}$$

On account of the production model S_I^* is subdivided into

$$S_{I,g}^* = 0.5G \tag{8}$$

$$S_{i,y}^* = S_I^* - S_{I,g}^* \tag{9}$$

The value of 0.5 mm was proposed by Jensen (1979).

If P or I are not fully intercepted, the rest is supplied to the top soil reservoir and the root zone reservoir. The top soil reservoir is not an independent reservoir but part of the root zone reservoir. The capacity of the top soil reservoir $S_t{}^*$ is assumed independent of the soil and crop and is stated to be 10 mm. The capacity of the root zone reservoir $S_r{}^*$ is a function of soil and effective root depth. It has a minimum value equal to $S_t{}^*$. Water in surplus of the capacity of the interception capacity, the top soil storage capacity and the root zone storage capacity, is transferred to a through-flow reservoir where the surplus remains for 3 days and if not evapotranspirated during that period, is drained out of the root zone as deep percolation.

The evaporative demand is met in the following way: $E_s{}^*$ extracts water from the top soil with a potential rate as long as there is water in the reservoir, whereupon it extracts water from the root zone with a rate equal to 0.15 $E_s{}^*$, which is

$$E_s = \begin{cases} E_s^* & S_t \geq E_s^* \\ 0.15E_s^* & S_t < E_s^* \end{cases} \tag{10}$$

where S_t is the top soil water storage.

$E_c{}^*{}_{,y}$ extracts water from the yellow area interception $S_{I,y}$ resulting in the evaporation

$$E_{c,y} = \begin{cases} S_{I,y} & S_{I,y} \leq E^*_{c,y} \\ E^*_{c,y} & S_{I,y} > E^*_{c,y} \end{cases} \tag{11}$$

$E_c{}^*{}_{,g}$ extracts water from the green area interception $S_{I,g}$

$$E_{c,g} = \begin{cases} E^*_{c,g} & S_{I,g} \geq E^*_{c,y} \\ S_{i,g} + E_T & S_{I,g} < E^*_{c,g} \end{cases} \tag{12}$$

where E_T is the transpiration. If $E_{c,g} = E_c{}^*{}_{,g}$ the $E_T = 0$, but if not, there exists a transpiration demand.

$$E^*_T = E^*_{c,g} - S_{I,g} \tag{13}$$

If there is water in the through-flow reservoir, this is used first. Then water is extracted from the root zone. If $S_r > ½\, S_r{}^*$ where S_r is the soil moisture content in the root zone, water is extracted at a potential rate. If $S_r < ½\, S_r{}^*$ then the transpiration is reduced

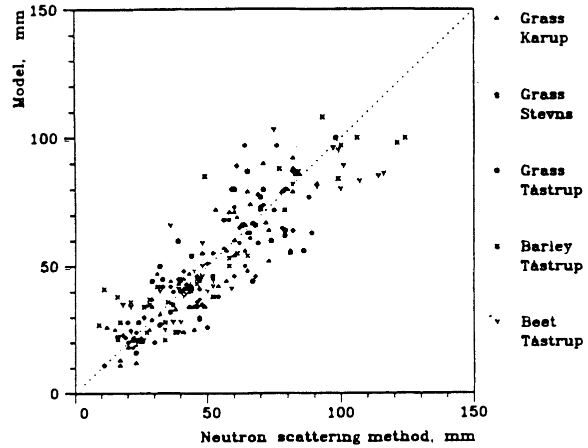

Fig. 3.
Scatter diagram of monthly evapotranspiration determined by neutron scattering method versus the simulated evapotranspiration.

$$E_T = \begin{cases} E_T^* & S_r \geq \frac{1}{2}S_r^* \\ E_T^* \dfrac{S_r}{\frac{1}{2}S_r^*} & S_r < \frac{1}{2}S_r^* \\ 0 & S_r \leq 0 \end{cases} \qquad (14)$$

A special case occurs when the root zone water storage has been exhausted to a certain degree, i.e. more than half of the effective root zone capacity is used, and the soil is rewetted by precipitation or irrigation. If the supplied water is not sufficient to fill up the root zone storage, only the upper layer of the soil will be wetted. The soil moisture in this layer will assume a state near field capacity. The vegetation will then use this water primarily as source for transpiration. In this case half the added water is used for transpiration at a potential rate before the whole root zone is considered.

The actual evapotranspiration is calculated as follows

$$E = E_s + E_{c,y} + E_{c,g} \qquad (15)$$

and the new water status of the different storage can be calculated.

In Fig. 3 simulated monthly evapotranspiration is plotted against monthly evapotranspiration assessed by neutron measurements.

A liniear regression with the simulated values as depending variables and the "measured" values as independent variables gave a correlation coefficient equal to 0.87 and a standard deviation of the residuals equal to 11.4 mm. The intercept was accepted equal to 0 and the slope equal to 1. Though the model fails to describe all situations with equal accuracy, it is believed on the whole to describe reality with an accuracy sufficient for our purpose. An improvement of the model would require additional information about the soil, vegetation, rooting, leaf development and the meteorological variables. Information which is seldom at hand.

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