Sensitivity of different evapotranspiration calculation methods in different crop-weather models

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Abstract: The calculation of evapotranspiration and its components transpiration and evapotranspiration is of crucial importance in dynamic crop-weather models, irrigation models and SVAT models. Although many approaches were developed and adapted for various applications and based on available input data, there is still a remarkable range of uncertainty related for a representative calculation. However, many of the problems are based on weak quality of model input data, but others are related to the method itself and its sensitivity to various environmental conditions. In our study, several methods of evapotranspiration estimation in different crop weather models are compared and tested against data from lysimeters at a location in Austria. An analysis shows differences in the results, related sensitivities in the used methods and crucial parameters for their parameterisation.

Keywords: evapotranspiration; crop-weather models, sensitivity analysis

1. INTRODUCTION

The water balance of agroecological systems is a key parameter for most physical and physiological processes within the system soil–crop–climate. Therefore it is of great importance to calculate the water budget parameters in the required scale in time and space as accurately as possible to reduce potential uncertainties in simulated outputs of e.g. ecosystem models [Aggarwal, 1995; Addiscot et al, 1995].

One of the most critical parameters is evapotranspiration (ET); it has a great impact on water losses, depending on various and complex factors. In the last few decades the theoretical and applied analysis of this biophysical phenomenon has received much attention [e.g. Monteith and Unsworth, 1990; Hatfield, 1988]. As pointed out by Burman and Pochop [1994] many authors stress, that it is important to carefully define the methods used and to keep methodologies consistent. This is important for the entire process of predicting ET for a specific vegetation and involves data collection and assembly, the calculation of the reference crop ET, and the application of crop coefficients to obtain estimates of crop ET at a specific time and place. It is important that the particular model versions being used is clearly identified along with a careful indication of any assumtions made (e.g. thermodynamic, meteorological and other functions which may be calculated in alternative ways). The computational methods for calculating potential evapotranspiration (ETp) vary in data demands from very simple (more empirically based), requiring only information on monthly average temperatures, to complex (more physically based), requiring daily data on maximum and minimum temperature, solar radiation, humidity, wind speed, as well as characteristics of the vegetation. Some methods, such as the earlier versions of the Blaney-Criddle method, were intended to predict monthly ET for a specific crop at a specific time. Others, such as current versions of the Penman method, have been used to predict reference ET, and then a suitable crop coefficient has been used for estimating vegetative ET. After reviewing single level models for estimating ET, Jensen et al. [1990] recommended the Penman-Monteith model [Monteith, 1965] as presented by Allen et al. [1998] as the preferred method for predicting ETp or reference ET (ET from short grass maintained under optimum soil moisture and nutritional conditions) on a daily basis.

Many authors studied important plant factors, like canopy and stomatal resistance, which are included in the Penman Combination equation, as a function of environmental and specific plant factors [Jarvis et al., 1981; Turner, 1991; Saylan and Eitzinger, 1998]. A milestone in the modeling of actual evapotranspiration is the work of Jarvis [1976], in which the canopy resistance is described as a function of environmental variables as well as crop water status which is related to the availability of soil moisture.

Crop-weather models are using different potential evapotranspiration calculation methods and relate it to model simulated crop development and soil water status in order to estimate actual evapotranspiration in various ways. This paper describes various results from selected models by comparing it to measured data from lysimeters.

2. METHODS

2.1 Measurements

The data, which were used as reference data in our study, were obtained from lysimeters at the Federal Office and Research Centre for Agriculture located in Hirschstetten, Vienna, Austria. The lysimeters are located in north-eastern part of Austria (latitude 48° 12´N, longitude 16° 34´E and altitude 153 m above the see level) within a main agricultural region (Marchfeld) with relatively low precipitation and no groundwater impact to the rooting zone. The mean annual sum (1961-1990) of precipitation is 577 mm and the mean annual temperature is 9,9 °C [Müller, 1993]. The lysimeters contain 3 different soil profiles (2m depth) with 6 replications, respectively. The soils are representative main soil types for the Marchfeld region. Soil water content in the lysimeters is measured continuosly by TDR-method in 30cm depth intervals. Water balance components (e.g. soil water depletion) was calculated only for longer time periods to avoid uncertainties through time lags in soil water movement. During the measurement period of 2 years (1999-2000), which is considered in our study, spring wheat (year 1999) and spring barley (year 2000) were grown on the lysimeters. Only one soil type in the lysimeters (a sandy ‘czernosem’ with 264mm available soil water storage capacity) was considered in this study.

2.2 Crop weather models and related evapotranspiration calculation methods

The models and approaches for calculation of water balance, potential and actual evapotranspiration, used in this study, are described as follows :

2.2.1. The simplified FAO method [Allen, 1998] :

a. Calculation of daily water balance of the upper soil layer (no transpiration assumed) :

$$D_{e,i} = D_{e,i-1} - [P_i - RO_i] - I_i/f_w + E_i/f_{ew} + DP_i \quad (1)$$

whereas :

$D_{e,\,i-1}$ = potential cumulative evapotranspiration of the previous day
$D_{e,i}$ = potential cumulative evapotranspiration of the actual day
P_i = precipitation
RO_i = runoff
I_i = irrigation
E_i = evaporation
$DP_{e,i}$ = drainage
F_w = proportion of water infiltration at soil surface during irrigation
F_{ew} = proportion of wet soil surface during irrigation

and

$$0 \le De,i \le TEW \quad (2)$$

$$TEW = 1000\,[FC - 0.5\,WP]\,Z_e \quad (3)$$

$$E_i = K_e\,Et_o \quad (4)$$

$$K_e = K_r\,[K_{c\,max} - K_{cb}] \le F_{ew}\,K_{c\,max} \quad (5)$$

$$K_r = [TEW - D_{e,i-1}] / [TEW - REW] \text{ für } D_{e,i-1} > REW \quad (6)$$

whereas :

TEW = maximum evaporation
REW = decrease of soil water where K_r=1
FC = field capacity
WP = wilting point
Z_e = upper soil layer thickness [10-15 cm]
Et_o = potential evapotranspiration [calculated by FAO Penman-Monteith or Hargreaves; Allen et al., 1998]
K_e = coefficient of soil evaporation
K_{cb} = basal crop coefficient [calculated, Allen et al., 1998]
$K_{c\,max}$ = maximum evapotranspiration [calculated, Allen et al., 1998]
K_r = factor for reduction of soil evaporation

b. Calculation of daily water balance of the lower rootet layer [only transpiration including crop water stress is considered] :

$$D_{r,i} = D_{r,i-1} - DP_{e,i} - CR_i + ET_{c,i} + DP_i (7)$$

whereas :
$D_{r,\,i-1}$ = soil water content at the previous day
$D_{r,i}$ = soil water change of actual day
CR_i = capillary rise
$ET_{c,i}$ = evapotranspiration
$DP_{e,i}$ = drainage from upper layer (Eq. 1)
DP_i = drainage downward
and :

$0 \leq De,i \leq TAW$ (8)

$TAW = 1000\ [FC - 0.5\ WP]\ Z_r$ (9)

$RAW = p\ TAW$ (10)

$ET_c = K_s\ K_{cb}\ Et_o$ (11)

$K_s = [TAW - Dr,i] / [TAW - RAW]$ (12)

whereas :
TAW = total soil water in soil layer
FC = field capacity of soil layer
WP = wilting point of soil layer
Z_r = soil layer thickness
RAW = plant available soil water in layer
p = proportion of TAW reduction till water stress occurs
K_s = coefficient of reduction of transpiration through crop water stress

2.2.2. WOFOST and SWAP model

The WOFOST (WOrld FOod STudies) explanatory and dynamic crop model was used in our study [Van Diepen et al., 1989]. This model has been frequently evaluated and used in European climate change impact studies on agricultural crop production [e.g. Eitzinger et al., 2000; Wolf, 1993; Wolf and Van Diepen, 1995]. The major processes taken into account are phenological development, assimilation, respiration and evapotranspiration. The water-limited production level is used in our study. WOFOST uses the Penman approach to calculate potential evapotranspiration [evaporation and transpiration]. It uses parameters and functions describing the effects of temperature, radiation and water stress on important physiological crop processes as a function of the development stage and crop status. Biomass partitioning is a function of the development stage of the crop, while temperature determines the development rate of the crop. At the water-limited production level, the soil and plant water balance is also included in the simulation of crop growth with the interactions between transpiration, stomata opening, CO_2 assimilation and water uptake being considered. A documentation of WOFOST can be found at *http://www.iwan-supit.cistron.nl/~iwan-supit/contents/.*

SWAP (Soil, Water, Atmosphere and Plant) is a sophisticated soil water balance model [Kroes et al., 1999], which includes the basic WOFOST crop growth modules. It simulates vertical transport of water, solutes and heat in unsaturated/saturated soils. The program is designed to simulate the transport processes at field scale level and during entire growing seasons. Basic, daily meteorological data are used to calculate daily, potential evaporation according to Penman-Monteith. SWAP employs the Richards' equation for soil water movement in the soil matrix. The Darcy equation is used to calculate infiltration and evaporation fluxes at the soil surface. A physical description rather has been chosen beyond a parametric description of water flow, as it allows the use of soil physical data bases and the simulation of all kind of management scenario's. Root water extraction at various depths in the root zone is calculated from potential transpiration, root length density and possible reductions due to wet, dry, or saline conditions (see *http://www.alterra.nl/models/swap/index.htm* for a documentation).

2.2.3. EPIC model

The Erosion-Productivity Impact Calculator (EPIC) [Williams et al., 1984a,b] model was developed to assess the effect of soil erosion on soil productivity. EPIC is a continuous simulation model that can be used to determine the effect of management strategies on agricultural production and soil and water resources. The model offers four options for estimating potential evaporation : Hargreaves and Samani [1985], Penman [1948], Priestley-Taylor [1972], and Penman-Monteith [Monteith, 1965]. The Penman and Penman-Monteith methods require solar radiation, air temperature, wind speed, and relative humidity as input. If wind speed, relative humidity, and solar radiation data are not available, the Hargreaves or Priestley-Taylor methods provide options that give realistic results in most cases. The model computes evaporation from soils and plants separately, as described by Ritchie [1972]. Potential soil water evaporation is estimated as a function of potential evaporation and leaf area index (LAI, area of plant leaves relative to the soil surface area). Actual soil water evaporation is estimated by using exponential functions of soil depth and water content. Plant water evaporation is simulated as a linear function of potential evaporation and leaf area index. Full documentation can be found at *http://www.brc.tamus.edu/epic/documentation/index.html*.

The above models, used in our study, were adapted to the growing characteristics of the crops as well as to the soil characteristics at the lysimeters. However, no additional parametrisation of the evapotranspiration and soil water balance modules was carried out.

3. RESULTS

Lysimeter data from 1999 and 2000 were analysed to be compared with model results of crop water balance. In Fig. 1 the cumulative precipitation and soil water content at the upper soil layer related to the spring wheat and barley growing period of both years at the lysimeter is shown. The year 2000 was relatively dry during spring compared to 1999.

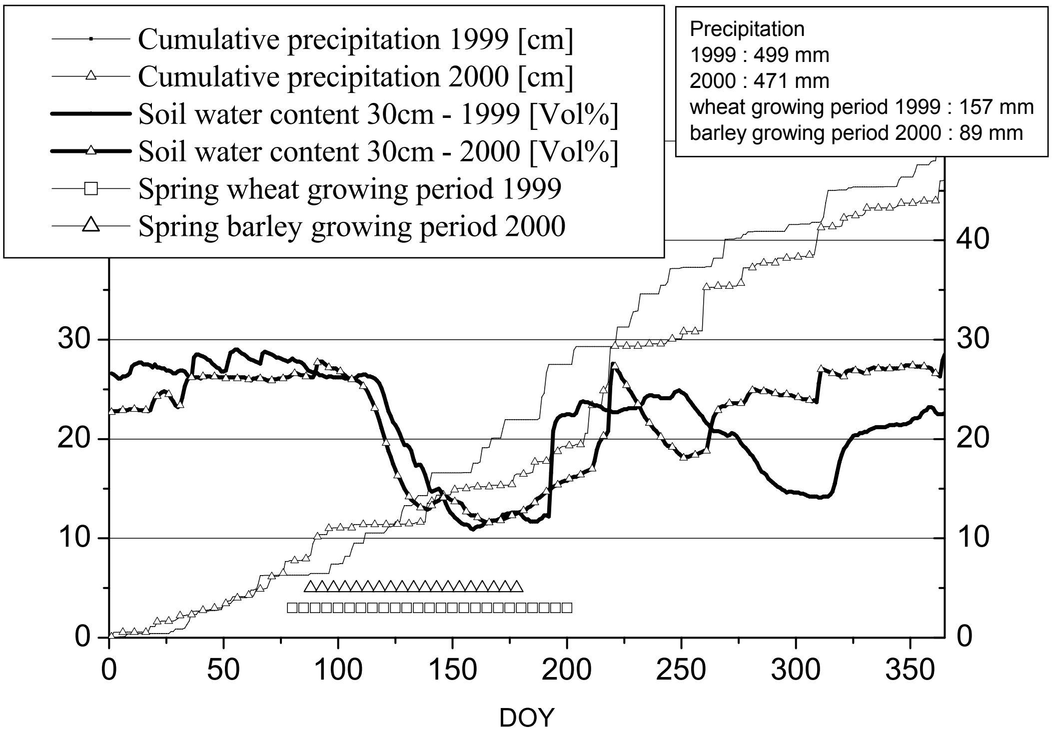

Fig.1 : Crop growing period, cumulative precipitation and measured soil water content (sandy czernosem, mean of 6 replications) at the lysimeters in 1999 and 2000.

Potential evapotranspiration (ETPp) for both years was calculated by the different methods incorporated within the various crop-models. It is obvious that even the same methods can show different results, caused by their different parametrization in the various models. In our case the yearly sum of calculated ETPp ranged between 870-1240 mm in 1999 and 935-1360 mm in 2000 between the applied methods (Fig.2). With the exception of EPIC Penman and EPIC Penman-Monteith, which simulated the highest values, the results are seen within a relatively small range (860-1010 mm in 1999 and 890-1100 mm in 2000). Actual evapotranspiration (ETPa), and its components evaporation (Ea) and transpration (Ta) are the important factors for soil and crop water balance. Through different model approaches, uncertainties can cause significant deviations in the results, which is shown clearly in our study. Although we only can compare directly with measured ETPa in our study, we can interprete deviations in Ea and Ta by comparing model results. The FAO Penman-Monteith method (see 2.2.1.) and SWAP showed the best results for ETPa during growing season in 1999, compared to the measured data (Lysimeter). During the relatively dry growing period in 2000, however, most models (except WOFOST) showed an significant overestimation of ETPa. Especially the FAO method, is calculating a much too high transpiration Ta. It is caused by the fact, that available water of the whole soil profile of 2m depth was assumed to be fully available for the plants, which is not realistic.

Therefore only the effective rooting depth or a reduction factor related to crop development should be incorporated if soil profile depth is exceeding the rooting depth of the plant. The EPIC methods, however, seem to calculate too high evaporation in both years, which results in an overestimated ETPa. The crop models used in our study, however, are considering root development in their simulations and showing similar Ta values. The WOFOST model showed better results for 2000 (barley) than for 1999, which is probably caused by differences in the crop growth routine (including root growth) and its related calculation of Ta. Further analysis has to be carried out, especially on the relationship of simulated actual evaporation and transpiration and attention has to be paid on proper parametrization of the applied approaches.

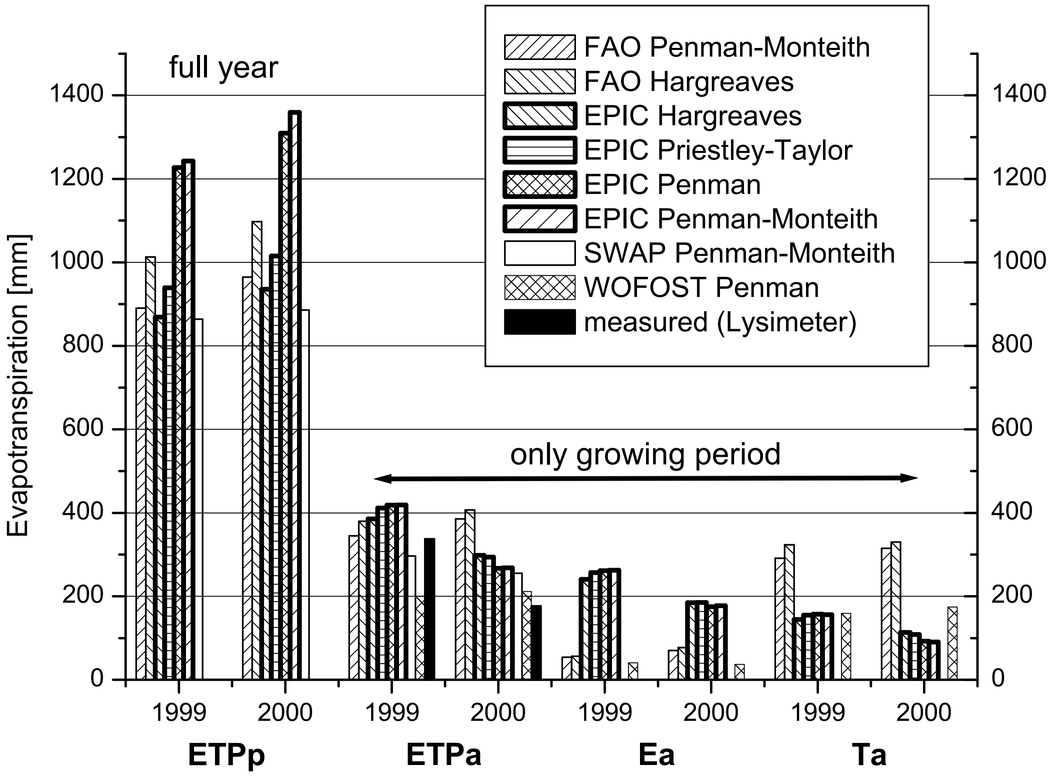

Fig.2 : Simulated and measured components of evapotranspiration (ETPp= potential evapotranspiration, ETPa=actual evapotranspiratio, Ea=actual evaporation, Ta=actual transpiration) at the lysimeter site considering sandy czernosem soil type. In 1999 only the growing period of spring wheat (March 15th – July 21st, 128 days) and in 2000 only the growing period of spring barley (March 23rd – June 30st, 93 days) is shown for actual evapotranspiration.

We conclude that crop models and related incorporated methods for calculating ETp, ETa, Ea and Ta are showing a significant range of uncertainty in our case. It is of importance, either to estimate the range of uncertainty between different approaches, or to compare and test it against measured values before model application. Further research is needed, especially for model intercomparisons and site specific model evaluation.

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