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Soil evaporation: test of a practical approach under semi-arid conditions

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Abstract

The role of soil evaporation in the field water balance is briefly reviewed. With an increasing demand for improved soil and water management, the common practice of combining evaporation with transpiration into a single term, i.e. evapotranspiration, is no longer justified.

Though soil evaporation is basically a complicated physical process, a practical approach has been followed. This was made possible by combining practical experience with computer modelling.

Bare field soils evaporate at a potential rate only during one or a few days after rainfall (stage 1). Thereafter, evaporation is reduced due to drying of the soil surface (stage 2). Both deterministic and parametric modelling often show a roughly linear increase in cumulative evaporation with the square root of time. Theoretically, this holds only if the potential evaporation is rather constant in time. This is not the case in various climates; daily potential evaporation rates commonly fluctuate between 1 and 6 mm day^{-1} or more in temperate climates and under some (sub)tropical circumstances. In such cases it appears that cumulative actual evaporation relates better to the square root of cumulative potential evaporation than to the square root of time. Evaporation can be described then with a simple equation containing only one soil parameter. The latter can be easily measured, even in tilled fields, with a fast and cheap microlysimeter technique.

This practical approach is illustrated with measurements in the African Sahelian zone as well as in the Netherlands.

Introduction

In many agroclimatological and soil water balance studies, water loss from the soil-plant system as a whole is considered as a single variable, the evapotranspiration

ET. In many cases this is justified, but in other cases separation of evaporation E and transpiration T will give a better understanding of the relevant process(es) under consideration. Examples of both categories will be given.

For some applications the combined use of E and T as the single variable ET is justified. In the soil-plant energy balance, as studied in agroclimatology, the high value of the latent heat of vaporization (2.5 MJ kg^{-1}) plays a dominant role. In many cases it is of minor interest to distinguish whether the transfer of liquid water into water vapour takes place through the plant (transpiration) or via the soil surface (evaporation).

In estimating water requirements in irrigation, or in calculations of drainage capacity or stream outflow, the interest is in ET as a 'loss term' in the soil water balance. The partitioning of ET into T and E is then of less interest.

In crop suitability studies, an estimate of ET may provide information about the length of the growing season and about drought risks. Methods are available to estimate the potential value of ET by using climatological data (e.g. Penman, 1948) as well as crop parameters (Doorenbos & Pruitt, 1977). Furthermore, calculation procedures have been proposed to estimate actual ET in case water stress in the soil-plant system does not allow ET to proceed at its potential rate (Rijtema, 1965).

Some situations, on the other hand, may require the separation of E and T. In agronomical studies yield is often related to evapotranspiration and systems are judged by the ratio of yield over cumulative evapotranspiration. This may, however, give rise to strongly varying and even controversial results and conclusions. One reason for this is the often unknown contribution of soil evaporation to total water loss, especially in tropical climates and farming systems. Relating yield to ET is usually only permitted in temperate climates with optimum crop growing conditions (e.g. proper seedbed preparation, weed control, high seed quality, crop protection, application of fertilizers, etc). These conditions ensure that germination and crop establishment is rapid and that growth rate is high so that the canopy is closed in due time. Then transpiration can make up for 90% of the cumulative ET over the crop's growing season. Since for a given climate a good relation exists between transpiration and dry matter production (de Wit, 1965), the same should also hold if ET is used instead of T under the above conditions.

However, under less favourable crop growing conditions (slow germination and plant establishment, wide row spacing, nutrient stress and limited plant protection) crop growth and hence transpiration may stay below the potential rate. As a result E can be the dominant factor in ET and can make up for up to 90% of the cumulative ET value over the growing season (Stroosnijder & Koné, 1982). In this case a comparison of the dry matter production with ET is less sensible and may produce strongly varying results from year to year. Variations in meteorological conditions then dominate the picture and no conclusions can be drawn on crop performance. This is especially disappointing in cases where expensive field trials were designed to test varieties on water use efficiency, drought resistance, etc.

Also into the field of soil and water management it is crucial to distinguish between E and T to evaluate the effects of certain management practices. Examples are measures to reduce E to conserve soil moisture by tillage or to increase T (and hence yield) by improving the soil water regime.

An extreme case presents itself for bare soils. Bare soils may exist in temperate climates during winter and spring periods as well as in tropical climates during 'dry' seasons. In a number of cases evaporation from bare soils is of agronomic interest since it affects the amount of stored soil water available to the next crop (dry-land farming), the rate at which the soil is warmed during spring in colder regions, etc.

The most common method to separate E and T in soil water balance studies is to measure or estimate both ET and E. T is then obtained by subtraction. Repeated measurements of moisture stored in the soil profile may yield the term ET. Such measurements often employ neutron probes or gravimetric sampling of the profile. Alternatively, ET may be obtained by flux measurements above the crop canopy or by energy balance methods.

To obtain the term E, on the other hand, a standard procedure is not available. Two methods by which data for E, the actual soil evaporation, can be obtained will be summarized in this contribution. One method refers to direct measurement in the field. The other method is a calculation procedure based on a simple formula with a characteristic soil evaporation parameter and 'reference evaporation' values as provided by meteorological stations. They are considered to be the best choice, at present, out of a variety of possible methods. The selected methods are both cheap, simple and easy in operation. This makes them also suitable for application under difficult conditions, as often prevail in developing countries.

Measurement of actual evaporation

A good method to directly measure E in the field is the use of microlysimeters. This method was described in detail by Boast & Robertson (1982). Basically, the method is very simple. Small undisturbed samples are collected in rings of limited height which are subsequently closed at the bottom, weighed and reinstalled in the field. Weighing of these rings can be repeated a few times each day, thus enabling one to calculate the course of E over the day from the weight losses of the rings. Obviously, the limited height makes that after some time, normally 1-5 days, the samples start behaving differently from the surrounding soil. This, of course, should be avoided by frequently taking fresh samples. The method therefore is labour-intensive and cannot be automated. The method's simplicity, on the other hand, makes it easy and cheap and allows application under almost any conditions. In addition, the ease and price at which a great number of samples can be chosen permits a better spatially averaged value of E to be obtained than a single though more precise measurement could yield (ten Berge et al., 1983).

An alternative to the microlysimeter method is the repeated measurement of soil water content throughout the soil profile. This method may give good results if a zero flux plane is present and if noise due to spatial variability is reduced by employing non-destructive methods (e.g. neutron, gamma, capacitive or reflectometry techniques). Both techniques, i.e. microlysimeters and soil water profile measurements, might be used to validate theoretical models for soil evaporation. The model discussed in the present contribution was validated by microlysimetry (Boesten &

Stroosnijder, 1986) and will now be tested on the basis of soil water profile measurements.

Calculation of actual evaporation

Recently, Boesten & Stroosnijder (1986) proposed to use the following set of equations to calculate the actual evaporation between two rain events:

$$\Sigma E_{act} = \Sigma E_{pot} \quad \text{for} \quad \Sigma E_{pot} < \beta^2 \text{ (stage 1)} \qquad (1)$$

$$\Sigma E_{act} = \beta (\Sigma E_{pot})^{1/2} \quad \text{for} \quad \Sigma E_{pot} \geqslant \beta^2 \text{ (stage 2)} \qquad (2)$$

$$E_{act} = \Sigma E_{act,n} - \Sigma E_{act,n-1} \qquad (3)$$

In the above equations E_{act} is the actual evaporation in mm day^{-1}, E_{pot} is the potential evaporation in mm day^{-1}; the summation indicates cumulative evaporation in mm, n is the day number and β (in mm$^{1/2}$) is an evaporation characteristic soil parameter to be determined experimentally. E_{pot} can be obtained from calculated (i.e. Penman, 1948) or measured (e.g. class-A pan evaporation) reference evaporation, E_o, provided a proper conversion factor between E_{pot} and E_o is used (often a value of 0.9 is used).

Eq. 1 to 3 contain only a single parameter, i.e. β. This parameter determines both the duration of stage 1 (the soil is not limiting) as well as the development of evaporation in stage 2 (the soil limits evaporation rate). (For a detailed treatment of these stages of evaporation, see e.g. Hillel, 1980.). It can be noted that in the above set of equations time does not enter as the independent variable. Time, used in other parametric equations such as those proposed by Black et al. (1969), Ritchie (1972) and Stroosnijder & Koné (1982), has been transformed into the variable ΣE_{pot}. This makes that Eq. 1 to 3 also hold in situations with strongly varying daily values of E_{pot} where the classical formulas fail. Moreover, it makes β independent of E_{pot}, another advantage over previously proposed formulas.

The practical use of Eq. 1 to 3 will be as follows (for a programmed version to be used on a micro-computer, see Boesten & Stroosnijder, 1986):

1. Usually the calculation is started on a day that a considerable soil depth (e.g. the top 30 cm) is at field capacity as is the case after irrigation or heavy rainfall. This wetting is assumed to occur at day number n. At this event both $\Sigma E_{pot,n}$ and $\Sigma E_{act,n}$ are reset to 0. Calculation of E_{act} at day $n + 1$ then proceeds as follows:

step 1: $\Sigma E_{pot,n+1} = \Sigma E_{pot,n} + E_{pot,n+1}$

step 2: $\Sigma E_{act,n+1} = \Sigma E_{pot,n+1}$ if $\Sigma E_{pot,n+1} < \beta^2$
$= \beta (\Sigma E_{pot,n+1})^{1/2}$ if $\Sigma E_{pot,n+1} \geqslant \beta^2$

step 3: $E_{act,n+1} = \Sigma E_{act,n+1} - \Sigma E_{act,n}$

For following days $n + 2$, $n + 3$ etc., the calculation proceeds in a similar fashion provided there is no rainfall.

In Table 1 an example of the above method is worked out. Heavy rain on Julian day (ordinal date) 169 wets a loamy soil over a depth of 30 cm to field capacity on day 170. Calculation starts on that day. The evaporation process for this soil is characterized by a value $\beta = 2.0\ mm^{1/2}$. E_{pot} values were taken from a nearby weather station.

2. When there is another day with rainfall, as on day 176 in the above example, one must distinguish between 3 cases, depending on the amount of effective rain, ER $\equiv Rain_n - E_{pot,n}$

a) $ER > 9.6$ mm
b) $ER < 0$
c) $0 < ER < 9.6$ mm

The procedure to be followed is expounded for each of these cases.

a) The soil is again wetted completely and the same procedure as explained above can be used by resetting $\Sigma E_{pot,176}$ and $\Sigma E_{act,176}$ in the above examples to zero. Note that the next calculated value of E_{act} is its value on day 177. It is assumed that on days with effective rainfall $ER > 0$, $E_{act} = E_{pot}$. So, this will be the value for E_{act} on day 176 in the above example.

b) In this case, ΣE_{pot} is not being reset because the rain is not 'effective', i.e. it does not rewet entirely the dried soil profile. The small amount of rain only slightly reduces the increase in ΣE_{pot} and contributes to E_{act}.

step 1: $\Sigma E_{pot,n} = \Sigma E_{pot,n-1} + E_{pot,n} - rain_n$

step 2: $\Sigma E_{act,n}$ is calculated according to Eq. 1 or Eq. 2

step 3: $E_{act,n} = rain_n + \Sigma E_{act,n} - \Sigma E_{act,n-1}$

c) In this case the rain is effective but only partly rewets the dried soil. In order to take this into account, Boesten & Stroosnijder (1986) used 2 options for the partial resetting of the independent variable ΣE_{pot}. Here we will only give their option A.

Table 1. Example of the calculation of E_{act} according to Eq. 1 to 3 after heavy rainfall on Julian day 169.

Julian day No	E_{pot} (mm day^{-1})	ΣE_{pot} (mm)	ΣE_{act} (mm)		E_{act} (mm day^{-1})
170	1	1	1.0	Eq. 1	1.0–0 = 1.0
171	3	4	4.0		4.0–1.0 = 3.0
172	6	10	$2 \times 10^{1/2} = 6.3$	Eq. 2	6.3–4.0 = 2.3
173	2	12	$2 \times 12^{1/2} = 6.9$		6.9–6.3 = 0.6
174	7	19	$2 \times 19^{1/2} = 8.7$		8.7–6.9 = 1.8
175	4	23	$2 \times 23^{1/2} = 9.6$		9.6–8.7 = 0.9
176	3	there is rainfall again			

Table 2. An example of the calculation of E_{act} with 6 mm of rain on Julian day 176 causing only partly rewetting of a dried soil profile.

Julian day No	E_{pot} (mm day^{-1})	ΣE_{pot} (mm)	ΣE_{act} (mm)	E_{act} (mm day^{-1})
176	3	$(6.6/2)^2 \sim 10.9$	9.6–(6–3) = 6.6	= 3.0
177	2	12.9	$2 \times 12.9^{1/2} = 7.2$	7.2–6.6 = 0.8
178	4	16.9	$2 \times 16.9^{1/2} = 8.2$	8.2–7.2 = 1.0
179	1	17.9	$2 \times 17.9^{1/2} = 8.5$	8.5–8.2 = 0.3
180	6	23.9	$2 \times 23.9^{1/2} = 9.8$	9.8–8.5 = 1.3

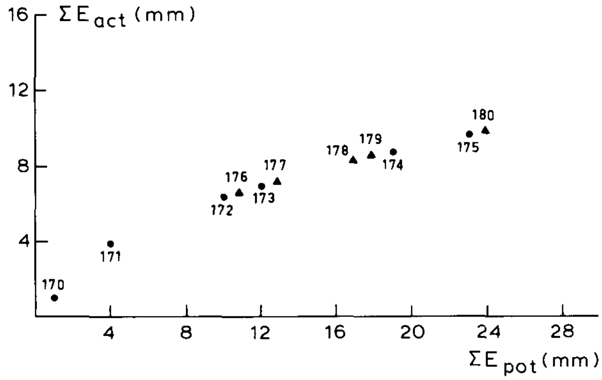

Fig. 1. Development of ΣE_{act} as a function of the independent variable ΣE_{pot} after complete wetting of the soil (●, days 170-175) and after partial rewetting by rain (▲, days 176-180).

step 1: The excess rain is subtracted from ΣE_{act}, i.e.:

$$\Sigma E_{act,n} = \Sigma E_{act,n-1} - rain_n + E_{pot,n}$$

step 2: A new reduced value for ΣE_{pot} is calculated from Eq. 2:

$$\Sigma E_{pot,n} = [\Sigma E_{act,n}/\beta]^2$$

step 3: $E_{act,n} = E_{pot,n}$

On following days E_{act} is again calculated with the standard procedure as explained under 1. An example is worked out in Table 2. The development of ΣE_{act} as a function of the independent variable ΣE_{pot}, as calculated in the above examples and listed in Tables 1 and 2, is graphically summarized in Fig. 1.

Validation

A first validation of the presented parametric soil evaporation model was given by Boesten & Stroosnijder (1986). Their data were obtained by microlysimeters in the Netherlands on a loamy sand in the Noordoost Polder. A good agreement was found between model and field data; a value of $\beta = 1.73$ mm$^{1/2}$ was found by linear regression (Fig. 2). Under the circumstances governing the Dutch experiments,

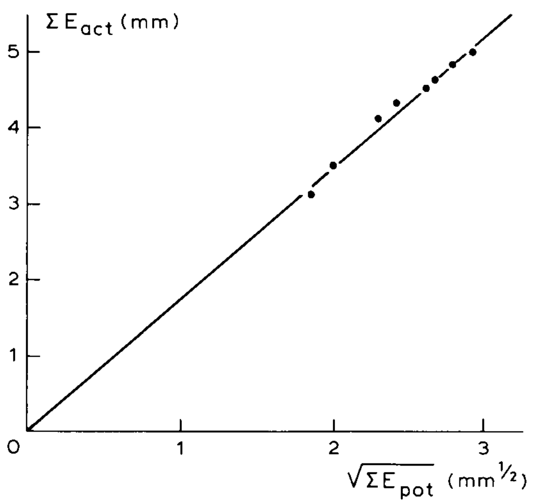

Fig. 2. Cumulative actual evaporation against the square root of cumulative potential evaporation for Creil, Netherlands. Points are averages of measurements, the line is the best fit to these points, yielding a value $\beta = 1.73\ mm^{1/2}$. (After Boesten & Stroosnijder, 1986.)

E_{pot} showed strong fluctuations with minima of 1 and maxima of 6 mm d^{-1}, but the average value of E_{pot} was rather low (2 mm d^{-1}).

To validate the model under different climatic conditions, a data set I obtained in the West-African Sahel is used here. The data were collected on a loamy sand near Niono in the Republic of Mali during a 12-day experiment in June 1978.

Soil moisture profiles in the top 30 cm of the soil were determined by gravimetric sampling in thin layers (thickness from the surface downward 1, 1, 2, 2, 2, 2, 5, 5, and 10 cm, respectively. The soil was irrigated with an amount of 17 mm water on Julian day 166 (15 June 1978) at 18h00. In view of the sandy texture of the soil it was assumed that the soil was at field capacity the next morning. The original sampling data are given in Table 3.

Table 3. Amount of water in the top 15 cm of a loamy sand subject to evaporation after wetting on 15 June 1978 (Julian day 166) at an experimental field near Niono, Mali.

Julian day No	Time	Amount of water in top 15 cm of soil (mm)
167	07.45	16.22
168	07.45	13.39
169	07.00	10.58
171	16.00	8.50
173	10.00	6.42
175	08.00	5.54
177	09.00	2.97
179	09.00	4.15

Table 4. Calculation of $\Sigma\ E_{act}$ and $(\Sigma\ E_{pot})^{1/2}$ for 12 days evaporation from loamy sand at an experimental field near Nino, Mali.

Julian day No	$\Sigma\ E_{act}$ (mm)	E_{pot} (mm day^{-1})	$\Sigma\ E_{pot}$ (mm)	$(\Sigma\ E_{pot})^{1/2}$ (mm$^{1/2}$)
167	16.22–13.39 = 2.83	5	5	2.2
168	16.22–10.58 = 5.64	5	10	3.2
169		5	15	3.9
170		5	20	4.5
171	16.22– 8.50 = 7.72	5	25	5.0
172	16.22– 6.42 = 9.80	5	30	5.5
173		5	35	5.9
174	16.22– 5.54 = 10.68	5	40	6.3
175		5	45	6.7
176	16.22– 2.97 = 13.25	5	50	7.1
177		5	55	7.4
178	16.22– 4.15 = 12.07	5	60	7.7

Daily values of E_{pot} were not measured but were estimated at 5 mm day^{-1}. Weather conditions were such that E_{pot} could be considered constant during the experiment.

In Table 4, values of $\Sigma\ E_{act}$ calculated on the basis of Table 3 are shown with corresponding values of $(\Sigma\ E_{pot})^{1/2}$. This relation is shown graphically in Fig. 3. Again, in spite of the quite different circumstances, a linear relation can be observed, yielding a value for β of 1.65 mm$^{1/2}$.

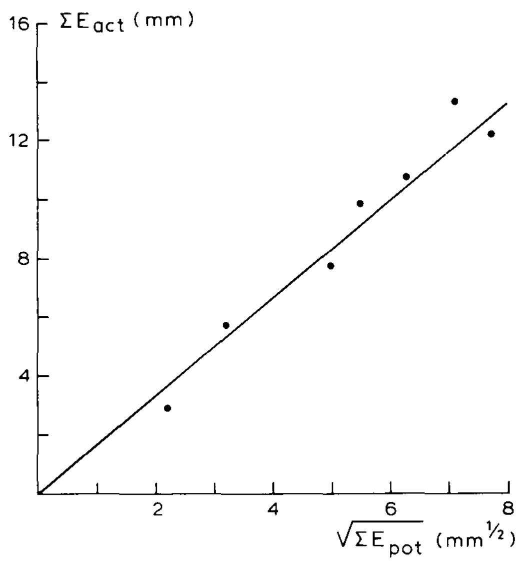

Fig. 3. Cumulative actual evaporation versus square root of cumulative potential evaporation for Niono, Mali. The line is the best linear fit, yielding a value of β = 1.65 mm$^{1/2}$.

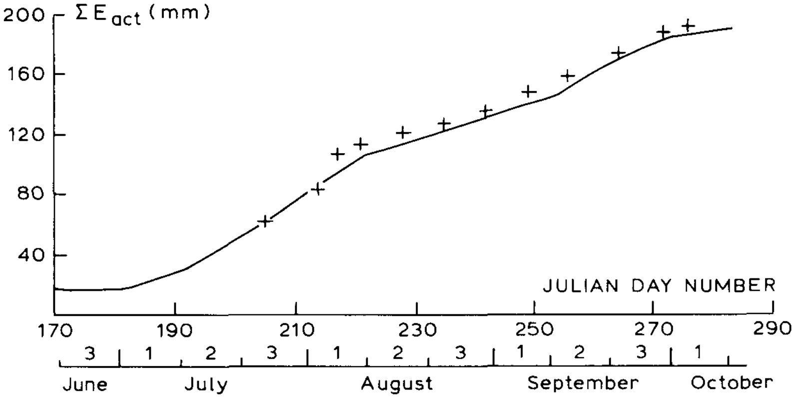

Fig. 4. Measured (+) and calculated (–) cumulative actual evaporation of a clay loam soil during the 1978 wet season at Niono, Mali, West Africa.

Similar experiments on a clay loam soil gave approximately the same value for β. This β value of 1.65 $mm^{1/2}$ was used to calculate the course of Σ E_{act} for a bare soil over a complete growing season for a clay loam. These values were compared with measurements of E_{act} as derived from soil water balance studies by neutron probes. The agreement between measured and calculated values is very good, as shown in Fig. 4.

Conclusions

From two validation experiments with strongly differing conditions it may be concluded that Eq. 1 to 3 yield promising results. Further investigations, undertaken at present, will show whether these formulas will also give satisfactory results for conditions prevailing in East-Java, Indonesia. It should be verified whether good results can also be obtained in describing soil evaporation under a crop canopy. The present experiments will also give a better insight in the range of variation of β and probably confirm the results of previous experiments which show only little variation in β for different soils and under conditions varying strongly in terms of potential evaporation.

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