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Simple model for daily evaporation from fallow tilled soil under spring conditions in a temperate climate

J. J. T. I. Boesten[1] and L. Stroosnijder[2]*

[1] Institute for Pesticide Research, Marijkeweg 22, 6709 PG Wageningen, Netherlands

[2] Department of Soil Science and Plant Nutrition, Agricultural University, P.O. Box 8005, 6700 EC Wageningen, Netherlands

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Abstract

A simple parametric model is presented to estimate daily evaporation from fallow tilled soil under spring conditions in a temperate climate. In this model, cumulative actual evaporation during a drying cycle is directly proportional to the square root of cumulative potential evaporation. The model contains only one soil parameter. Evidence from a literature study indicates that this model is an improvement on models proposed previously in which cumulative actual evaporation is related to the square root of time.

The model was used to calculate evaporation from fallow loamy sand in the Netherlands in spring and summer. A literature study showed that evaporation characteristics of sieved soils as determined in the laboratory are not valid for field soils. Therefore the single evaporation parameter was determined by a quick and cheap microlysimeter technique. In a limited field test, measured and predicted cumulative evaporation in periods of 5, 8 and 34 days were found to correspond reasonably well. The evaporation model together with a simple soil water flow model were found to describe quite well moisture profiles in field soil under a range of conditions.

Introduction

The model for evaporation described is part of a model for herbicide movement in tilled soils under spring conditions in the Netherlands. It is written in the simulation language CSMP (Speckhart & Green, 1976) and the herbicide part is similar to the model described by Leistra (1980).

* Present address: c/o UNIBRAW, Kotak pos 176, Malang, Indonesia.

In principle, evaporation from the soil can be calculated with a mechanistic model which describes the soil water flux in both the liquid and vapour phases as induced by the gradient of the water potential, including the effect of temperature. This has been done, for example, by van Keulen (1975), Rosema (1975), Hammel et al. (1981) and Camillo et al. (1983). Some of these models do not take into account water flow due to temperature gradients (e.g., van Bavel & Hillel, 1976; Bernard et al., 1981). However, all these models require input which is not readily available for field soils. Furthermore, as few of these models have been field-tested for ploughed layers under spring conditions, their applicability is questionable. A further problem is that they require time steps several orders of magnitude smaller than those required for the movement of the herbicides. Therefore, in the present study a parametric model was used to describe evaporation from the soil. In this model the physical process of evaporation is simplified. Physical processes taking place in reality on a small time scale can often be described on a larger time scale with models using overall parameters (Stroosnijder, 1982).

In a parametric approach to evaporation from the soil, three stages of evaporation may be distinguished (Bond & Willis, 1970): stage 1, in which actual evaporation rate, E_{act}, is equal to the potential rate, E_{pot}; stage 2, in which the soil surface has become dry and E_{act} is a rapidly decreasing proportion of E_{pot}; stage 3, in which E_{act} is very low and relatively constant. Under temperate climate conditions and a shallow water-table, usually only stages 1 and 2 are important. There seems to be no agreement about the relative importance of stage 1 in comparison with stage 2. Most studies on the duration of stage 1 or on cumulative actual evaporation at the end of stage 1, ΣE_1, have been carried out on sieved soils in the laboratory. From the results of a number of these experiments summarized in Table 1, it may be concluded that ΣE_1 is in the range of 20 to 60 mm and that the duration of stage 1 is at least several days. Also, there seems to be no clear relationship between duration or cumulative actual evaporation and soil texture.

In a computer simulation study, Hillel (1977) calculated ΣE_1 for three soils with

Table 1. Cumulative evaporation at the end of stage 1 as reported in laboratory experiments with sieved soils.

Soil texture	Column length (m)	Column diameter (m)	Dry soil bulk density (Mg m^{-3})	Average volume fraction of water at the start (m^3 m^{-3})	Potential evaporation rate (mm d^{-1})	Cumulative evaporation at the end of stage 1 (mm)	References
Fine sandy loam	0.61	0.30	1.25	0.32	10	40	Gardner & Hanks (1966)
Sand	0.45	0.10	1.53	0.3	10	30	Hanks et al. (1967)
Loamy sand	0.45	0.10	1.48	0.3	10	25	Hanks et al. (1967)
Silt loam	0.45	0.10	1.25	0.4	10	40	Hanks et al. (1967)
Fine sandy loam	0.45	0.15	1.26	0.31	1-12	30-60	Bond & Willis (1970)
Fine sandy loam	0.60	0.13	1.32	0.33	8	40	Willis & Bond (1971)
Silt loam	0.90	0.04	1.4	0.32	15	60	van Keulen (1975)

E_{pot} = 14 mm d^{-1}. For sand, loam and clay ΣE_1 was 20, 40 and 70 mm respectively. These values are as high as those obtained in laboratory experiments but show an unexpectedly strong effect of texture. The hydraulic properties of the soil used by Hillel (1977) were probably derived from sieved samples in the laboratory, and thus it is not surprising that the range of ΣE_1 values obtained corresponds with those in Table 1.

However, field experiments have given considerably lower values of ΣE_1. Ritchie (1972) reported values of 6, 9, 12 and 6 mm for sand, loam, clay loam, and clay respectively. Al-Khafaf et al. (1978) obtained values between 6 and 8 mm for clay loam, and Smelt (pers. comm., 1983) values of 0-4, 4-8 and 4-8 mm for sand, loamy sand and clay respectively. Also, no clear relationship with texture was observed in these experiments. As the values for field experiments were an order of magnitude lower than those reported for sieved soils in the laboratory, it was concluded that data from laboratory experiments with sieved soils cannot be used to describe evaporation behaviour in soils under field conditions. Probably the looser soil structure in the top few centrimetres in the field is responsible for part of the discrepancy.

With regard to the effect of soil tillage on evaporation, there seems also to be a discrepancy between the results obtained from experiments with sieved soils and those with field soils. In laboratory experiments with sieved soil, tillage was simulated by stirring the soil to depths varying from 0.02 to 0.12 m. The results showed that evaporation is lower in tilled than in untilled soil (Willis & Bond, 1971; Gill et al., 1977; Gill & Prihar, 1983). In field experiments with a loam soil (loess) in the period May to November, Ehlers & van der Ploeg (1976) found no difference in cumulative actual evaporation for tilled and untilled plots. Hamblin (1982) carried out three tillage treatments on two soil types in the field. Ten weeks after seeding, the results of an evaporation reduction experiment carried out in the laboratory showed the differences in cumulative actual evaporation between the treatments to be less than 20 %. Thus it was concluded that results of laboratory experiments with simulated tillage cannot be extrapolated to tilled soils in the field. Evaporation characteristics of tilled soils should be determined in situ under prevailing tillage conditions.

Theory

Parametric evaporation models

Black et al. (1969) formulated one of the earliest parametric models to estimate evaporation. Cumulative actual evaporation during a drying cycle, ΣE_{act}, was described with

$$\Sigma E_{act} = \alpha_1 t^{1/2} \quad (1)$$

in which α_1 is a parameter characterizing the evaporation process (mm $d^{-1/2}$) and t is the time (d) after preceding rainfall. For sand in a lysimeter experiment over a period of 12 d, Black et al. (1969) obtained an α_1 value of 5 mm $d^{-1/2}$. In a lysimeter experiment over a period of 9 d, Klaghofer (1974) obtained an α_1 value of 7 mm $d^{-1/2}$.

Gill & Prihar (1983) measured evaporation from tilled soil in laboratory columns under various constant levels of E_{pot} for 50 d. They found that the measurements could be described quite well with Eq. 1, but that α_1 increased from 7 to 13 mm d$^{-½}$ when E_{pot} increased from 4 to 16 mm d^{-1}.

Eq. 1 does not take into account stage 1 evaporation. Ritchie (1972) modified this equation to include both stage 1 and stage 2:

$$\begin{aligned} \Sigma E_{act} &= \Sigma E_{pot} && \text{for } t \leqslant t_1 \text{ in which } \Sigma E_{pot} \leqslant \Sigma E_1 \\ \Sigma E_{act} &= \Sigma E_1 + \alpha_2 (t - t_1)^{½} && \text{for } t > t_1 \end{aligned} \tag{2}$$

in which ΣE_{pot} is the cumulative potential evaporation during a drying cycle (mm), t_1 (d) is the duration of stage 1 and α_2 is a parameter (mm d$^{-½}$). Ritchie (1972) reported α_2 values between 3 and 5 mm d$^{-½}$ for four field experiments with sand, loam, clay loam and clay. In field experiments with loam, Jackson et al. (1976) found that α_2 was 2 mm d$^{-½}$ in winter and 4 mm d$^{-½}$ in summer.

Stroosnijder & Koné (1982) modified Eq. 2 slightly:

$$\begin{aligned} \Sigma E_{act} &= \Sigma E_{pot} && \text{for } t \leqslant t_1 \\ \Sigma E_{act} &= \Sigma E_1 + \alpha_3 (t^{½} - t_1^{½}) && \text{for } t > t_1 \end{aligned} \tag{3}$$

in which α_3 (mm d$^{-½}$) is a parameter. In field experiments on sandy and on clay soils in West Africa, they obtained t_1 = 2 d and α_3 = 3.5 mm d$^{-½}$. Hall & Dancette (1978) using a precursor of this model in which t_1 was fixed at 1 d obtained an α_3 value of 3.3 mm d$^{-½}$ for a coarse sandy soil in Senegal.

Values of α_1, α_2 and α_3 reported in the literature indicate that the effect of soil texture on E_{act} in stage 2 is rather small.

Measurements of Jackson et al. (1976) and of Gill & Prihar (1983) indicate that E_{pot} has an appreciable effect on E_{act} in stage 2 and thus on α_1, α_2 and α_3.

The square root of time relationship in Eq. 1 originates from the solution of the equation for horizontal isothermal flow assuming a constant initial moisture content and an instantaneous lowering of the moisture content at the evaporating soil surface (Gardner, 1959). Although these conditions are not completely fulfilled under field evaporation conditions, a square root type of equation usually describes soil evaporation quite reasonably.

New parametric evaporation model

In spring in the Netherlands, the daily average E_{pot} may vary considerably from 1 to 6 mm d^{-1}. However, as already shown, parameter values obtained with the models discussed are a function of E_{pot}, and therefore a new model is developed. The criteria for this model are:

– it should contain only one or two parameters which can be easily measured in tilled fields;

– these parameters should not depend on E_{pot} because in the Netherlands this varies considerably between 1 and 6 mm d^{-1};

– the model should make use of the fact that for constant E_{pot} a $t^{½}$ type relationship

fits most experimental data;
- if possible, the model should make use of meteorological data available.

The parametric evaporation model is described as

$$\begin{aligned} \Sigma E_{act} &= \Sigma E_{pot} && \text{for } \Sigma E_{pot} < \beta^2 \\ \Sigma E_{act} &= \Sigma E_{pot} && \text{for } \Sigma E_{pot} = \Sigma E_1 = \beta^2 \\ \Sigma E_{act} &= \beta(\Sigma E_{pot})^{1/2} && \text{for } \Sigma E_{pot} > \beta^2 \end{aligned} \tag{4}$$

in which β ($mm^{1/2}$) is the evaporation characteristic soil parameter to be determined experimentally. This equation contains only one parameter, β which determines both ΣE_1 and the slope of the ΣE_{act} versus $(\Sigma E_{pot})^{1/2}$ relationship in stage 2.

In Eq. 4, ΣE_{act} depends on ΣE_{pot}, not on time. This implies that to each day, a weight is attached which is directly proportional to the potential evaporation rate for the day. To show that β is less dependent on E_{pot} than α_1 is dependent on E_{pot}, the data of Gill & Prihar (1983) were reanalysed. β values of 3.4, 3.1 and 3.2 $mm^{1/2}$ were obtained for E_{pot} values of 4, 8, and 16 mm d^{-1}, respectively. Thus, while values of E_{pot} differed by a factor of four, β values differed by only about 10 %, thus β can be considered to be a constant.

An implicit assumption in Eq. 4 is that ΣE_1 (that is, $\int_0^{t1} E_{pot} dt$) does not depend on E_{pot}. This assumption was also made in the model of Ritchie and confirmed in a laboratory experiment by Bond & Willis (1970), who found that the duration (t_1) of stage 1 was directly proportional to $E_{pot}^{-1.2}$. Thus ΣE_1 was almost constant.

Use is made of the potential soil evaporation, E_{pot}, which depends on atmospheric evaporativity, that is mainly on net radiation and vapour removal characteristics of the prevailing weather conditions. E_{pot} depends to a small extent only on the properties of the soil (van Bavel & Hillel, 1976; see also ten Berge, 1986). At present, a variety of methods to measure atmospheric evaporativity are used by meteorological services. One of the earliest methods still widely used is evaporation from an open water surface, E_o. Penman (1948) compared measured values for E_o and E_{pot}. In lysimeter studies carried out in England under spring and summer conditions (for two years), he obtained $E_{pot} = 0.9\ E_o$ (monthly averages). McIlroy & Angus (1964) obtained the same result in similar studies in Australia. Penman (1948) devised a formula to calculate E_o from weekly or monthly averages of duration of sunshine, air temperature, wind speed and water vapour deficit. De Bruin & Lablans (1980) modified this formula to use daily averages to calculate E_o. In the Netherlands, daily values for E_o are calculated with their method by the Royal Dutch Meteorological Institute for five weather stations.

When Eq. 4 is used to calculate evaporation during a long period of wetting and drying events, there is a problem of how to proceed with the calculation if daily rainfall excess (rainfall – E_{pot}) is not sufficient to moisten the dried soil profile to field capacity. For such situations two options have been developed. In option A, it is assumed that at any time the deficit in soil water throughout the soil profile determines actual evaporation. The calculation is as follows. On days of no excess in rainfall (rainfall < E_{pot}), ΣE_{act} and thus also E_{act} is calculated from the updated value of ΣE_{pot} by Eq. 4, that is

$$(\Sigma E_{pot})_n = (\Sigma E_{pot})_{n-1} + (E_{pot} - \text{rainfall})_n \quad (5)$$

in which the index n is day number. $(\Sigma E_{act})_n$ is calculated from $(\Sigma E_{pot})_n$ with Eq. 4 and E_{act} is calculated with

$$(E_{act})_n = (\text{rainfall})_n + (\Sigma E_{act})_n - (\Sigma E_{act})_{n-1} \quad (6)$$

On days of excess in rainfall (rainfall > E_{pot})

$$(E_{act})_n = (E_{pot})_n \quad (7)$$

and the excess of rainfall is subtracted from ΣE_{act}

$$(\Sigma E_{act})_n = (\Sigma E_{act})_{n-1} - (\text{rainfall} - E_{pot})_n \quad (8)$$

Thereafter $(\Sigma E_{pot})_n$ is calculated from $(\Sigma E_{act})_n$ with Eq. 4. If daily rainfall excess is greater than $(\Sigma E_{act})_{n-1}$, then both $(\Sigma E_{act})_n$ and $(\Sigma E_{pot})_n$ are set at zero and the excess is considered to be drainage.

To demonstrate the necessity of the development of an alternative option (option B), the effect of rainfall on calculated evaporation in option A is considered in detail. In option A, ΣE_{act} is not reset at zero if excess in rainfall is less than ΣE_{act} (see calculation path in Fig. 1). This has the same effect as the soil being moistened from below, that is the lowest soil layers having a water content below field capacity (FC) become moistened until FC, while the upper soil layer remains as dry as before. Because under field conditions the upper layer is not dry after rainfall, option A may underestimate the evaporation rate. Therefore, option B was developed, in which ΣE_{act} is always set at zero if there is an excess in rainfall (see calculation path in Fig. 1). This is based on the field situation that soil is moistened from above and consecutive layers are moistened to FC. Calculation of E_{act} in the subsequent drying cycle is described by Eqs 5, 4 and 6 up to the point at which all water from the last rainfall event has been evaporated. Then ΣE_{act} jumps to the value which it had just before

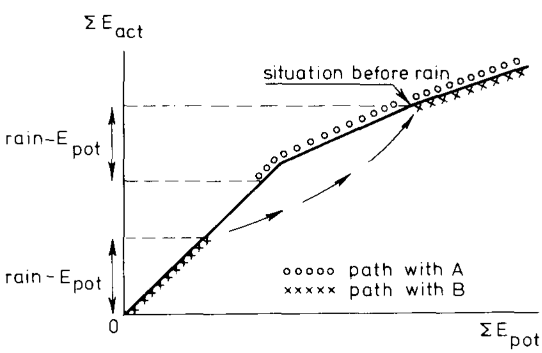

Fig. 1. Calculation path in relationship between ΣE_{act} and ΣE_{pot} after rainfall with options A and B.

the rainfall (see Fig. 1). Option B implies that excess in rainfall remains in the upper soil layers at FC and is not redistributed in the drier deeper layers. However, redistribution of moisture in field soils can be expected to be between that implied by options A and B.

Procedure

Experimental fields

In 1981 and 1982, field experiments on herbicide movement in soil were carried out on a loamy sand soil on an experimental farm near Creil, Noordoost Polder, Netherlands. The plot size was 8 m × 25 m in 1981 and 12 m × 30 m in 1982. During the experimental periods, May to July in 1981 and May to September in 1982, the soil was fallow. In both years, after ploughing in winter and a few weeks before the start of the experiment, the soil was tilled with a harrow and a roller. The bulk density of the top 0.20 m of the soil profile was measured regularly and no change was found during the experimental periods. This implies that in both years, the period immediately after tillage in which bulk density and soil hydraulic conductivity decrease rapidly due to compaction was past (Stroosnijder & Hoogmoed, 1984). At the start of each experiment a surface crust a few millimetres thick had already formed.

Rainfall at 1.2 m above ground level was recorded throughout the experimental period with a Lambrecht rain gauge (type 1509-10H). Evaporation experiments were carried out in 1982 only.

Determination of the evaporation parameter

The evaporation parameter, β, was determined using a method similar to the microlysimeter method proposed by Boast & Robertson (1982). In the morning of Julian day 243 in 1982, 15 undisturbed soil columns were taken in PVC cylinders (0.07 m diameter, 0.12 m height). The average volume fraction of water (and standard deviation) of the columns was 0.26 ± 0.02 m^3 m^{-3} which was very close to the field capacity of the soil of 0.27 ± 0.02 m^3 m^{-3}, as determined in the laboratory from four soil columns on a suction plate at −8 kPa. Field capacity was considered to be a good starting water condition for a test of the usefulness of Eq. 4.

The columns were closed at the bottom and carefully replaced in the soil with the rims at soil surface level. Five columns were kept wet by adding water to their surfaces several times a day, and the remaining ten columns were allowed to dry. All cylinders were weighed several times per day for four consecutive days (days 243-246). No rain fell on the columns on these days. From the measurements with the wet and the drying columns, E_{pot} and E_{act} were calculated.

At the end of the experiment (day 246), the ten dried soil columns were sliced into layers and the moisture profiles determined. On that day the moisture profile in the field soil was also measured and found not to differ from that in the dried columns. Only 15 % of the water in the soil columns had evaporated during the experiment.

Table 2. Results of evaporation measurements for soil columns during the field experiment in 1982.

Length of measuring period (d)	Cumulative rainfall (mm)	Cumulative evaporation (mm)			Average volume fraction of water at the end of the period (m^3 m^{-3})			
		measured		calculated (option A)	in columns		in the field (0-0.18 m)	
		mean	s.d.		mean	s.d.	mean	s.d.
5	0	3.8	0.3	2.9	0.239	0.003	0.235	0.005
8	12	13	0.4	13	0.223	0.005	0.225	0.004
34	19	29	1	29	0.179	0.008	0.189	0.003

Validation experiments

Validation experiments were carried out on the soil in the same field throughout spring and summer 1982. The sampling and measuring techniques were the same as described above. Three steel cylinders (0.12 m diameter, 0.18 m height) were used which could drain freely through a perforated bottom. The percolated water was collected in a tray. The columns were weighed on the sampling date and again at the end of the measuring period. At the end, the columns were sliced into layers and the moisture profiles determined. In cases where percolated water was found in the trays or where moisture profiles differed significantly from those in the field soil, the evaporation measurement was excluded as being not representative of field soil conditions. Duration of measuring periods varied from 5 to 34 d. Results for periods with accepted evaporation measurements are presented in Table 2.

Calculation of evaporation

The computer model as described in Eqs 4-8 was devised to calculate actual evaporation (option A). It was assumed in the model that E_{pot} is 0.9 times E_0 as calculated by the Royal Dutch Meteorological Institute. Since the experimental field was located between the meteorological stations at De Bilt, Eelde and De Kooy, an average value for these stations was taken as E_0 at the experimental field.

The model is given in Fig. 2 and is coded in CSMP (Speckhart & Green, 1976). It consists of an INITIAL part which is carried out only at the start of the simulation, and a DYNAMIC part which is computed at least once per time step, DELT, that is one day in this model. The integration method is known as the rectangular (RECT) method (line 32) where $\mathrm{Y} = \mathrm{IY} + \dot{\mathrm{Y}} \cdot t$ and IY is the initial or previous value of Y.

The model starts with a TITLE. Space for all array variables must be reserved in STORAGE. Day number, NDAY, which is updated each time step, has to be treated as a fixed variable or integer and specified with FIXED.

Daily rainfall (mm d^{-1}) as measured in the experimental field is specified as RAINT. Values of E_0 as calculated at the meteorological stations De Bilt, Eelde and De Kooy are specified as EOBILT, EOEELT and EOKOOT respectively.

The evaporation characteristic β ($mm^{1/2}$) is given as BETA and conversion factors are specified to convert rainfall measured at 1.2 m above ground level to rainfall at

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1   TITLE CALCULATION OF EVAPORATION WITH A PARAMETRIC MODEL
2   INITIAL
3   STORAGE RAINT(121),EOBILT(121),EOEELT(121),EOKOOT(121)
4   FIXED NDAY
5   TABLE RAINT(1-121)=19.5,3.0,1.5,8*0.0,0.1,2*0.0,11.6,0.0,9.1,0.4,    ...
6   TABLE EOBILT(1-121)=1.2,2.2,2.7,4.8,4.3,4.4,4.3,5.7,6.2,5.8,4.9,5.5,...
7   TABLE EOEELT(1-121)=2.5,1.7,1.8,4.0,3.7,3.6,4.2,4.3,4.2,5.2,5.0,3.1,...
8   TABLE EOKOOT(1-121)=1.3,3.3,2.3,3.7,3.5,3.5,4.2,4.5,4.7,3.6,4.3,4.5,...
9   PARAM BETA=1.73
10  PARAM CFACT1=1.07
11  PARAM CFACT2=0.9
12  INCON SEPOT=0.0,SEACT=0.0
13  DYNAMIC
14  NOSORT
15        NDAY=TIME+1
16        RAIN=CFACT1*RAINT(NDAY)
17        EO=(EOBILT(NDAY)+EOEELT(NDAY)+EOKOOT(NDAY))/3
18        EPOT=CFACT2*EO
19        IF (KEEP.NE.1) GO TO 20
20        IF (RAIN.GE.EPOT) GO TO 10
21        SEPOT=SEPOT+(EPOT-RAIN)
22        EACT=RAIN+(AMIN1(SEPOT,BETA*SQRT(SEPOT))-SEACT)
23        SEACT=AMIN1(SEPOT,BETA*SQRT(SEPOT))
24        GO TO 20
25     10 EACT=EPOT
26        SEACT=AMAX1(0.0,SEACT-(RAIN-EACT))
27        SEPOT=AMAX1(SEACT,SEACT**2/BETA**2)
28     20 CEACT=INTGRL(0.0,EACT)
29        CEPOT=INTGRL(0.0,EPOT)
30        CRAIN=INTGRL(0.0,RAIN)
31  PRINT EACT,EPOT,RAIN,CEACT,CEPOT,CRAIN
32  METHOD RECT
33  TIMER DELT=1.0,PRDEL=20.0,FINTIM=120.0
34  END
```

Fig. 2. CSMP listing of the parametric model used to calculate actual evaporation (option A).

ground level, CFACT1, and to convert E_o into E_{pot}, CFACT2. The two accumulators used in the DYNAMIC part, that is ΣE_{act} (SEACT) and ΣE_{pot} (SEPOT) are set at zero in the last line of the INITIAL part.

Since the DYNAMIC part contains Fortran statement which must remain in the prescribed order, the automatic sorting option of CSMP is suppressed by NOSORT. Lines 16 and 17 find rainfall and E_o respectively from the tables and the current day number, NDAY, and line 18 computes E_{pot}. Line 19 prevents the algorithm between lines 19 and 28 being carried out more than once per time step. In line 20 a separation is made between days with and without an excess of rainfall. For days without an excess of rainfall, lines 21-23 calculate a new (higher) ΣE_{pot} with Eq. 5, then E_{act} with Eq. 6, and finally ΣE_{act}. For days with an excess of rainfall, lines 25-27 firstly compute $E_{act} = E_{pot}$ (Eq. 7), then ΣE_{act} is reduced for the excess of rainfall with Eq. 8, and the new reduced ΣE_{pot} is calculated with Eq. 4. As already stated, this is option A. For simplicity option B has been omitted from Fig. 2. Lines 28, 29 and 30 calculate cumulative rainfall and cumulative potential and actual evaporation, respectively. Line 31 specifies the output and line 33 the timer variables.

Results and discussion

The relationship between measured ΣE_{act} for days 243-246 and the square root of measured ΣE_{pot} is shown in Fig. 3. Measuring points during stage 1 evaporation were omitted from the figure because then $\Sigma E_{act} = \Sigma E_{pot}$ (see Eq. 4). Linear regression with least squares optimization yielded a value for β of 1.7 mm$^{1/2}$, which implies that ΣE_1, that is β^2, was only 3 mm. This is in the low range of the values for field soils as found in the literature study. Fig. 3 shows that Eq. 4, which has only one parameter, describes the measurements reasonably well. If a given set of measurements cannot be described well by Eq. 4, ΣE_{act} may be described as a function of ΣE_{pot} with equations equivalent to Eq. 2 or Eq. 3, which contain two parameters.

In order to test the sensitivity of the β determination, twice the standard deviation in the ΣE_{act} measurements was added to each point in Fig. 3, and twice the standard deviation subtracted. The resulting range of ΣE_{act} may then be expected to cover about 95 % of all possible variation. β values were selected by linear regression with least squares optimization and upper and lower limits for β of 2.0 and 1.4 mm$^{1/2}$ were found respectively. Thus, the effect of spatial variability of evaporation reduction properties of the soil was rather small. This is in agreement with results obtained by Lascano & van Bavel (1982) from a computer model.

As already stated, two options (A and B) were developed to enable evaporation after moderate rainfall to be calculated. Evaporation was calculated with both options for the period between day 126 and day 245 in the experimental field in 1982. Cumulative actual evaporation calculated with option A always differed by less

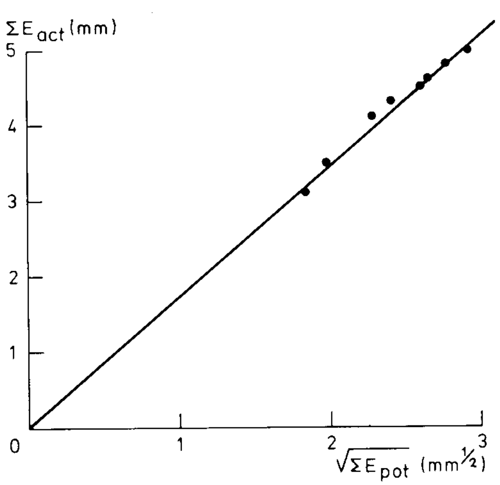

Fig. 3. Relationship between ΣE_{act} and the square root of ΣE_{pot}. Points are averages of measurements and the line is the best fit to these points according to the last part of Eq. 4.

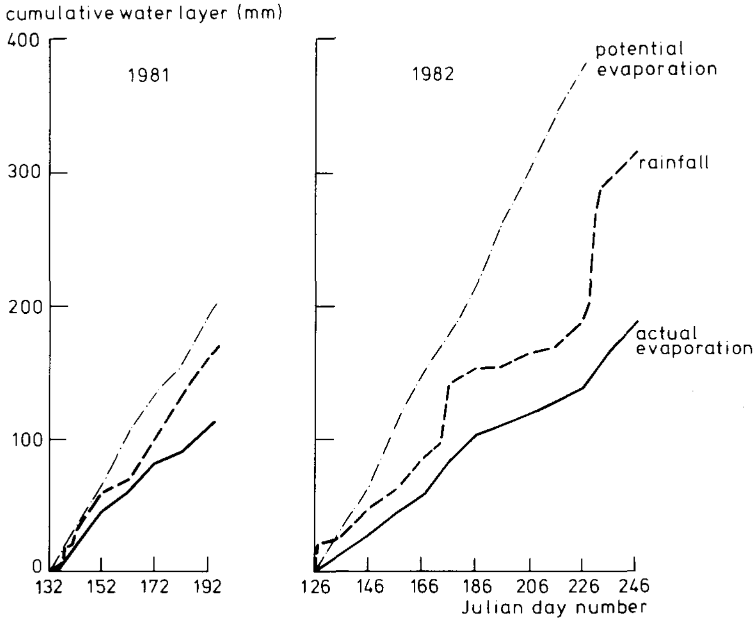

Fig. 4. Cumulative rainfall and cumulative potential and actual evaporation in soils in the experimental field in 1981 and 1982.

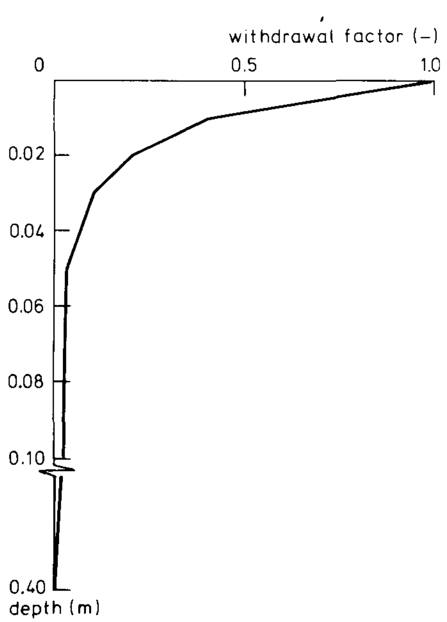

Fig. 5. The withdrawal function used to describe water withdrawal from soil during evaporation.

than 6 % from that calculated with option B. Thus, as the choice of option was of minor importance, all further calculations were done with option A.

From the calculated evaporation for the validation experiments given in Table 2, it can be concluded that the calculated values correspond quite well with the measured values. However, it is recognized that the model requires further testing.

Evaporation was calculated during the full test period of herbicide experiments carried out in 1981 and 1982. For both years, the value $\beta = 1.7$ mm$^{1/2}$ was used as determined in one single short experiment in 1982 (see Fig. 3). Cumulative rainfall and cumulative actual and potential evaporation are shown in Fig. 4. Cumulative actual evaporation was usually between 40 % and 60 % of cumulative potential evaporation. Cumulative rainfall was usually greater than cumulative actual evaporation but less than cumulative potential evaporation. Thus there was mostly an excess of rainfall because of drying of the surface layer of soil.

In the experiment used to determine β, E_{pot} was measured in the experimental field in order to obtain an accurate value of β. In the model, E_{pot} was calculated from the average E_0 value of the three nearest weather stations. Daily values of E_0 are not accurate, because the values from the three weather stations often vary by a factor of 2 (average monthly values usually do not vary more than 10 %). Therefore, cumulative actual evaporation was calculated with the values of E_0 of each weather station separately. This was carried out for the period between days 126 and 245 in 1982. Cumulative actual evaporation calculated with the individual E_0 values differed less than 5 % from that calculated with the averaged E_0 value (the standard procedure).

Coupling with a model for water flow in soil

In studies on herbicide movement in soil, not only the water flux at the soil surface but also the fluxes of water at various depths in the soil should be known. A parametric model was also used to describe water flow in soil. This model is an extension of that described earlier by van Keulen (1975) and Stroosnijder (1982). In the model, the soil is divided into a series of layers. On days of excess in rainfall, water fills these layers from top to bottom to volume fractions of water at field capacity. It is assumed that thereafter no further redistribution takes place. On days of excess in evaporation, the water volume withdrawn from each soil layer is proportional to its thickness, the volume fraction of water, and a withdrawal factor. The relationship between withdrawal factor and depth is referred to as the withdrawal function. The water flow model described by van Keulen (1975) and Stroosnijder (1982) did not describe water fluxes in soil on days of excess in evaporation explicitly. In the model used in the present study water fluxes on days of excess in evaporation were calculated on the assumption that all evaporation takes place at the soil surface and that in each layer, the water flux through the bottom is equal to that through the top minus extraction from that layer as calculated with the withdrawal algorithm.

The soil system of 0.40 m was divided from top to bottom into 10 layers each of 5 mm, 15 layers each of 10 mm, and 10 layers each of 20 mm. In the 1981 experiment, the moisture profile at field capacity was derived from a profile measured in the

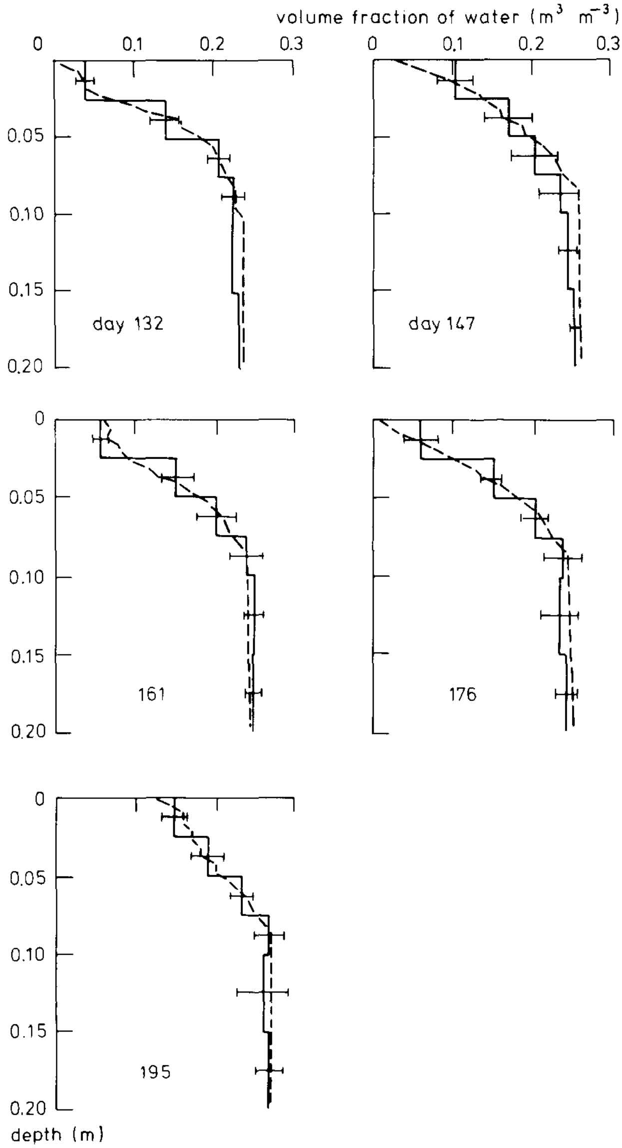

Fig. 6. Moisture profiles on sampling dates in the field experiment in 1981. Vertical solid line segments are averages of 5 measured profiles; horizontal bars are standard deviations; and dotted lines are simulated profiles.

field after rainfall on day 195. For the 1982 experiment, the moisture profile was derived from laboratory measurement of four soil columns on a suction plate at −8 kPA. The withdrawal function was adjusted by trial and error to obtain the best fit of the moisture profiles as measured in the field in both 1981 and 1982. The resulting function is given in Fig. 5. Measured moisture profiles and those calculated with Eq. 4 together with the water flow model for the 1981 and 1982 experiments are

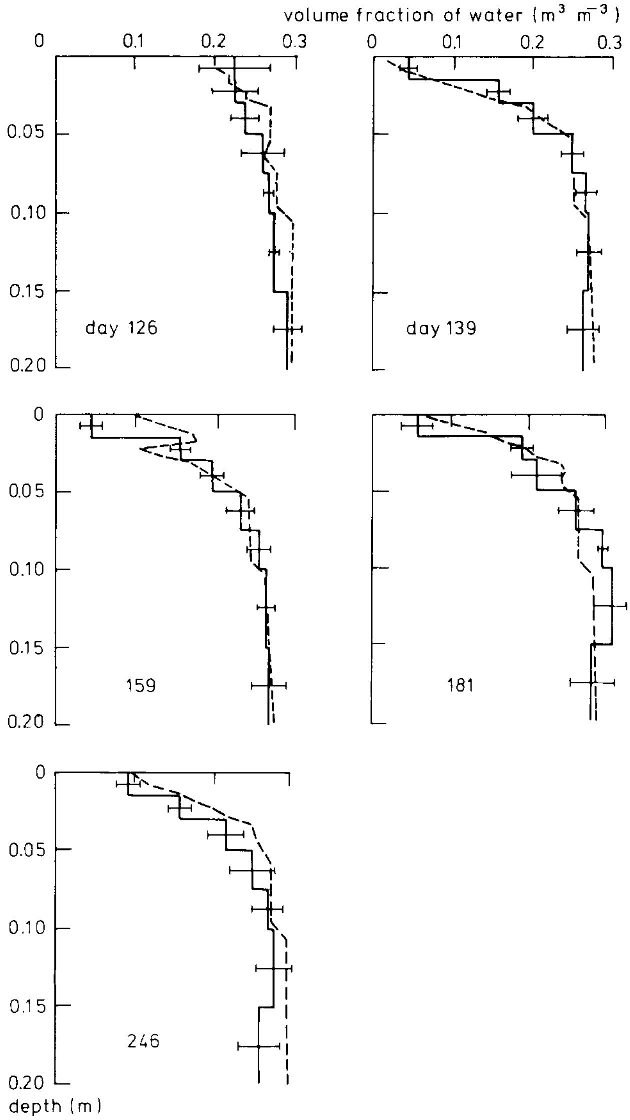

Fig. 7. Moisture profiles on sampling dates in the field experiment in 1982. Vertical solid line segments are averages of 5 measured profiles; horizontal bars are standard deviations; and dotted lines are simulated profiles.

presented in Figs 6 and 7, respectively. It was concluded that an acceptable description of measured moisture profiles in both years was obtained using only one withdrawal function.

The above procedures for the calculation of water fluxes and water contents in soil were incorporated in a convection/dispersion/diffusion model for transport of solutes (Leistra, 1980). In the 1982 field experiment, movement of bromide ion was measured. Bromide as a negative ion is considered to be a tracer of soil water and its movement may be used to check the validity of the evaporation and water flow models (Boesten, in preparation).

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