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A SIMPLE METHOD OF ESTIMATING THE SOIL WATER BALANCE*

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ABSTRACT

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A simple method of computing daily evapotranspiration is described. The main inputs to the model are easily measurable parameters such as rainfall and pan evaporation. The model takes into account evaporative demand and soil and crop factors, and can be used for the estimation of soil water loss in both fallow and cropped situations. In developing and testing the model, both published experimental information and data collected at ICRISAT Center were used. Estimated values of evapotranspiration and soil moisture storage were found to compare favourably with the observed values.

INTRODUCTION

Soil moisture budgets from rainfall and evaporation have been studied by several researchers as a first step in calculating the expected productivity of agricultural systems under a wide range of climatic conditions. They have also been used to develop alternative choices and decision strategies for use of the limited available water.

A realistic model is one that differentiates between fallow and cropped conditions and takes into account differences among soil types (Denmead and Shaw, 1962; Holmes and Robertson, 1963; Baier and Robertson, 1966), the evaporative demand (Denmead and Shaw, 1962), the crop cover (Jensen and Haize, 1963) and the stage of crop growth (Ritchie, 1972).

Evapotranspiration is one of the most important components to be estimated in determining the soil water balance. Various attempts have been made, because of instrumental limitations, to employ micrometeorological methods (such as aerodynamic or mass transfer methods, energy balance methods, a combination of aerodynamic and energy balance methods, etc.) or empirical formulae in order to compute evapotranspiration and thereby, indirectly, soil moisture content. The micrometeorological methods of modelling soil moisture distribution within the soil profile are now at

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a stage to be useful in research, but are not yet ready for agricultural applications which require such information over time and space. However, meteorological water-budgeting techniques have been extensively used, both for research and for application (e.g. Baier, 1981). However, many of the models are soil- or climate- or crop stage-specific (Baier et al., 1972). The generalized water-balance models of Holmes and Robertson (1959), Shaw (1964), Baier and Robertson (1966) and Fitzpatrick and Nix (1969) were developed for application to specific crop systems (Nix, 1975). In the case of Baier and Robertson's (1966) model, Baier et al. (1979) noted large deviations between observed and estimated soil moisture under fallow and wheat crop conditions. Huda et al. (1980) found that Ritchie's (1972) model needs considerable modification for application under dryland conditions.

The objectives of this paper are (a) to synthesise the location-, climate-, soil- and crop-specific results presented in the literature according to certain characteristics, (b) to develop a simple method of soil water balance using these synthesised facts (used to build up a basic heuristic framework), and (c) to test the model against field data, primarily soil moisture, leaf area index (LAI) and light interception (LI) taken from FSRP (Farming Systems Research Program), ICRISAT reports. The resulting model should be applicable under diverse soil, crop and climatic conditions, with inputs that are easily measurable, such as rainfall and open-pan evaporation, and with estimates that have an acceptable degree of accuracy.

THE MODEL FOR COMPUTING EVAPOTRANSPIRATION

The term "soil water balance" relates the miosture added through precipitation and/or irrigation to that lost through evapotranspiration, runoff and drainage. It also includes the changes in water content of the soil profile. The daily soil balance equation is generally written (Slatyer, 1967) in the form

$$\Delta M_n = R_n - AE_n - RO_n - D_n \tag{1}$$

where R_n, AE_n, RO_n, D_n and M_n represent the amount of rainfall or irrigation, actual evapotranspiration, surface runoff, deep drainage and soil moisture storage, respectively, on Day n, and ΔM_n is the soil moisture change on Day n. In the equation, the component evapotranspiration (AE_n) is to be determined by the model presented here.

The proposed model for estimating AE_n is derived by taking into account published concepts based on field data. Hence, it is a "heuristic approach" and its value has to be judged on its predictive ability. Evapotranspiration can be divided into two parts. First, under fallow conditions, the soil loses water through evaporation. The rate of water loss with time, in turn depends upon soil type (soil factor), the available soil moisture in the top few cm of the soil profile (i.e. frequency of wetting of the soil) and evaporative demand.

Secondly, under a crop, the soil loses water through evaporation and transpiration. The latter in turn depends upon the soil factor, evaporative demand, available water in the root zone and type of crop cover at different stages of crop growth (crop factor). Thus, a realistic AE_n model should take into account the evaporative demand, crop and soil factors. As a first step, AE_n can be expressed as

$$AE_n = f(E)\, f(S)\, f(C) \tag{2}$$

where $f(E)$, $f(S)$ and $f(C)$ represent functions of evaporative demand, soil and crop factors, respectively. As these three factors are mutually interactive, the multiplicative type of function is chosen and to determine their appropriate functional forms, an examination was made of the ways in which they appear in existing models.

Fallow case

Models for the estimation of evaporation from a fallow soil have been presented by Gardner and Gardner (1969), Gardner (1974) and Ritchie (1972). The model of Gardner and Gardner (1969) requires specifications of the depth of wetting, which cannot be conveniently measured in the field. Later, Gardner (1974) modified this model by eliminating depth of wetting. However, the model is independent of the soil factors that determine the potential evaporation period, the rate of decay of evaporation with time, and the evaporative demand. Ritchie's (1972) model is also independent of the evaporative demand factor.

Usually, immediately after wetting, the evaporation from a wet bare soil is approximately the same as that from a free water surface, E_n (Hide, 1954; Lemon, 1956). The duration of this stage depends upon the evaporative conditions of the atmosphere and the soil (Stanhill, 1955; Bond and Willis, 1970; Kijne, 1973). The period is shortened under coarse textured soils and lengthened under fine textured soils (Lemon, 1956; Kijne, 1973). The model of Ritchie (1972) incorporates this factor using a term U, which is defined for each soil, but the magnitude of U presented is small, i.e. 6—10mm, compared to the value quoted by Penman (1963), i.e. 25mm. ICRISAT lysimeter data (unpublished ICRISAT data) show that this amount is nearly equal to the available water content held, between -0.3 and -15 bar, in the top 10-cm layer of the soil profile.

In the models of Ritchie (1972) and Gardner (1974), the cumulative soil evaporation is a function of the square root of time ($t^{1/2}$). Gardner and Gardner (1969) have suggested different exponents for t as time progresses, but it is not clear from these studies how the exponent should be adjusted. In order to take account of the soil factor in the second phase of the soil evaporation, Ritchie (1972) multiplied $t^{1/2}$ by a soil dependent term, α. This procedure excludes the suggestion of Gardner and Gardner (1969), which is confirmed by the lysimeter data referred to earlier, that the exponent of time should change with time. With regard to these observations, eq. 2 was solved for the fallow case as follows:

Step 1

The rate of fall of $(AE/E)_n$ with time is very sharp under coarse textured soils compared to fine textured soils. With time, $(AE/E)_n$ decreases exponentially until, at infinity, the change is zero, while $(AE/E)_n$ is at unity during the potential evaporation stage. This phenomenon can be represented mathematically as follows

$$(AE/E)_n = \exp(-t'_n/bK) \tag{3}$$

and

$$t'_n = t_n - a; \ (AE/E)_n \leqslant 1$$

In eq. 3, K is the maximum available soil moisture storage capacity of the soil in the root zone (mm) (here defined as the water held at 100% up to 90 cm depth and 50% beyond this depth in the soil between -0.3 and -15 bar); t_n is the time, in days, after rain or irrigation; a is the number of days following a rainy day for which the available soil moisture in the top 10-cm soil layer can meet potential evaporation demand, assuming that water is removed from this layer only; b is a constant to be determined.

To solve b, a "least squares" statistical analysis was adopted using approximately 300 data points collected from four lysimeters (one gravimetric lysimeter in Vertisol with $K = 175$ mm; three hydraulic lysimeters, one in Alfisol with $K = 120$ mm and two in Vertisols with $K = 250$ mm) situated at the ICRISAT centre. The data was collected during the summer, winter, rainy and post-rainy seasons (i.e. under variable evaporative demand conditions with E_n varying from 3 to 15 mm/day) over a three-year period (1977–79). The value of b, determined from this analysis, was 0.02, with a correlation coefficient (r) of 0.45. Equation 3 can now be written as

$$(AE/E)_n = \exp[(-t_n + a)/0.02K] \tag{4}$$

Step 2

To simplify the problem, all 300 data points in Step 1, were expressed only as a function of soil type, i.e. f(S), irrespective of the evaporative demand. The same data has been subdivided, according to evaporative demand, in order to obtain f(E). Based on the above synthesised patterns, f(E) can be expressed as

$$\mathrm{f}(E) = 1 + B \tag{5a}$$

where B is a factor to be determined, dependent upon time (Gardner and Gardner, 1969) and evaporative demand (E_n) (Denmead and Shaw, 1962). For simplicity, data obtained by Denmead and Shaw (1962) were used. Even though data were for crop condition, this assumption may not have serious limitations as the relative patterns only were used. From their results it was assumed that

$B = 0$ when $E_n = 5$ mm /day

$B > 0$ when $E_n < 5$ mm /day

$B < 0$ when $E_n > 5$ mm /day

With these assumptions, f(E) can be written as

$$\mathrm{f}(E) = 1 + (5 - E_n)d \tag{5b}$$

To determine d, the AE/E data for all the 300 points were plotted against time under different E_n ranges and then, by a simple trial and error approach, the best functional form for d (after introducing eq. 5b in eq. 4) was found to be

$$d = d'(t_n/E_n)^{1/2} \tag{5c}$$

Equation 5b can now be rewritten as

$$\mathrm{f}(E) = [1 + (5 - E_n)(t_n/E_n)^{1/2} d'] \tag{5d}$$

and the final equation for $(AE/E)_n$ becomes

$$(AE/E)_n = [1 + d'(5 - E_n)(t_n/E_n)^{1/2}] \exp[(-t_n + a)/0.02K] \tag{6}$$

Equation 6 was solved by " least squares" using the 300 data points, and the value of d' was obtained as 16, with a correlation coefficient (r) of 0.73. This represents a considerable improvement in the goodness of fit of the model.

Under fallow conditions, the empirical solution to eq. 2 thus becomes

$$(AE/E)_n = [1 + ((5 - E_n)/16)(t_n/E_n)^{1/2}] \exp[(-t_n + a)/0.02K] \tag{7}$$

This equation clearly reflects all the synthesised patterns discussed earlier. A favourable comparison is found between observed and estimated values of soil evaporation for three values of K and two values of E over three ranges of time interval (Table Ia).

Crop case

Evapotranspiration from a cropped area consists of soil evaporation and transpiration by the plant. Soil evaporation from a cropped area is not the same as from fallow. In the initial stages of crop growth, evaporation is the major source of moisture loss, while at the rapid vegetative growth stage and the flowering/reproductive stage, transpiration plays the major role. As the crop develops through the various stages of growth, its roots appear in varying locations of the soil at different times. Hence, depths to which drying takes place, and the amounts of water available for evaporation or evapotranspiration, are different and even if the entire soil profile is at field capacity the available soil moisture for evapotranspiration differs at each stage of crop growth (Holmes and Robertson, 1959). Therefore,

TABLE I

Comparison of observed and estimated values of AE_n
a. Under fallow conditions ($b_n = 0.02$)

t_n (days)	K (mm)	K'' (mm)	ΣAE_n						Remarks
			E_n = 7 mm/day*			E_n = 10 mm/day*			
			a (days)	O (mm)	C (mm)	a (days)	O (mm)	C (mm)	
1–3	120	12	1	15	15	1	23	19	$K = 120$ Alfisols
	175	20	2	15	18	2	25	24	175,250 Vertisols
	250	20	2	18	18	2	25	24	
1–7	120	12	1	19	20	1	26	24	
	175	20	2	27	27	2	35	36	
	250	20	2	31	30	2	39	40	
1–10	120	12	1	21	20	1	29	25	
	175	20	2	33	30	2	41	39	
	250	20	2	35	35	2	46	45	

* average E_n for the ten day period; O = observed (lysimetric data collected at ICRISAT Center); C = computed (using Eq. 7 with $b_n = 0.02$).

b. Under full crop cover ($b_n = 0.24$)

t_n (days)	ΣAE_n							
	$K = 75$ mm, $K'' = 7$ mm, $a = 1$ day		$K = 125$ mm, $K'' = 12$ mm, $a = 2$ days		$K = 175$ mm, $K'' = 18$ mm, $a = 3$ days		$K = 225$ mm, $K'' = 24$ mm, $a = 4$ days	
	O (mm)	C (mm)	O (mm)	C (mm)	O (mm)	C (mm)	O (mm)	C (mm)
1–5	22	22	23	23	24	24	24	24
1–10	40	38	43	43	45	45	47	46
1–15	49	49	58	55	63	63	67	65
1–20	58	58	73	69	80	79	84	83
1–25	62	65	81	77	91	92	98	100
1–30	66	69	88	88	103	104	112	113
1–35	69	73	97	96	114	115	125	125
1–40	71	74	102	102	121	122	137	137

O = observed (Thornthwaite and Mather, 1954, Transpiration); C = computed 0.8 × AE_n, where AE_n is estimated using eq. 7 with $b_n = 0.24$ and E_n = 6 mm/day. The factor 0.8 is used because the observations were of transpiration only).

the crop factor in eq. 2, i.e. f(C), does not act independently of the soil factor, f(S). Hence, eq. 2 must be modified to

$$AE_n = \mathrm{f}(E)\,\mathrm{f}(S,C) \tag{8}$$

where f(S,C) is the effective soil factor, which varies with the stage of crop growth.

Jensen and Haize (1963) accounted for the effect of growth stage on the extractable soil moisture in terms of crop coefficients, which vary with the crop/cropping pattern. Ritchie (1972) used a term 'β', which is related to leaf area index (LAI), that is the percentage light transmission through the crop canopy. These studies assumed the effect of crop stage on $(AE/E)_n$ as a simple constant multiplier, which does not appear valid under variable soil moisture situations (Reddy, 1983).

Baier et al. (1972) synthesised different models for estimating transpiration and presented normalized curves relating to soil and evaporative demand. Their results suggest that the relative transpiration rate declines in a clay soil (high evaporative demand situation) at a higher available soil moisture content than in a sandy soil (low evaporative demand situation), where the actual transpiration rate is close to the potential over a much wider range of soil moisture content. Also, the potential rate stage of the crop case is extended to a much wider range compared to the fallow case. However, the patterns in the declining stage resemble those of the fallow case. These points are clearly evident from ICRISAT lysimeter results (Reddy, 1983).

Step 3

Although evapotranspiration is a function of soil evaporation and plant transpiration, the basic process involved in both cases may be different. In the natural system, the soil evaporation gradually changes to evapotranspiration with the stage of crop growth, and the stage of the crop growth defines the depth of water extraction only.

With this assumption, eq. 7 was solved for b, for a full crop cover, keeping all other terms the same as those in the case of fallow. Curves, derived from eq. 7, were drawn for different values of K and E_n with different values of b, and were then matched with some of those presented by Baier et al. (1972). The best fit for b was obtained as 0.24. This procedure was adopted because sufficient data points were not available and from later results it is seen that the choice is verified. To check the validity of this estimate, $(AE/E)_n$ values with $b = 0.24$ in eq. 7 were compared with another independent data set of Thornthwaite and Mather (1954). The comparison between the observed and computed data sets was found to be favourable (Table Ib).

Thus, parameter b was set at 0.02 for the fallow case and 0.24 for a full crop cover. The following procedure was adopted in order to determine values of b for different stages of crop growth.

Step 4

Because the degree of crop cover influences both evaporation and transpiration, the growth stage of a crop can be specified in terms of LAI and/or by the fraction of the incoming radiation that reaches the soil surface (LI). It was assumed that once LAI reaches $\geqslant 2.75$, transpiration does not change significantly (Ritchie, 1972). Therefore, when LAI $\geqslant 2.75$, b is taken as 0.24. Thus, b increases from 0.02 under fallow conditions to 0.24 at LAI $\geqslant 2.75$. Between these two extremes, b_n varies according to the growth stage of the crop from sowing to harvest.

For each crop or cropping pattern, both LAI and LI curves under conditions of no moisture stress were drawn for as many seasons as FSRP, ICRISAT data permitted. During the vegetative phase, measured LAI and LI showed similar, nearly linear, increases with time. Therefore, b_n was taken as a linear function of time for the period when $0 < \text{LAI} \leqslant 2.75$. During maturation, LAI normally falls more quickly than LI and the b_n curve was taken as intermediate between the LAI and LI curves. Between the vegetative and grain-filling stages, b_n is constant at 0.24 once LAI $\geqslant$ 2.75. The worth of this simple approximation has to be judged on the basis of its predictive power.

The b_n curves for crops with different lengths of growth season (normalized to a growing season of 100 days) are shown in Fig. 1. In the case of other regions, the period of different growth stages can be adjusted using cumulative heat units for the respective phases. The differences in the slope of the b_n curves for sorghum and pearl millet (Fig. 1) emphasize the need to develop additional, and possibly more precise, crop growth-stage curves for different crops and cropping patterns. By using the values of b_n in Fig. 1, a comparison was made between evapotranspiration estimated from eq. 7 and that observed in lysimeters for approximately 400 data points (Reddy,

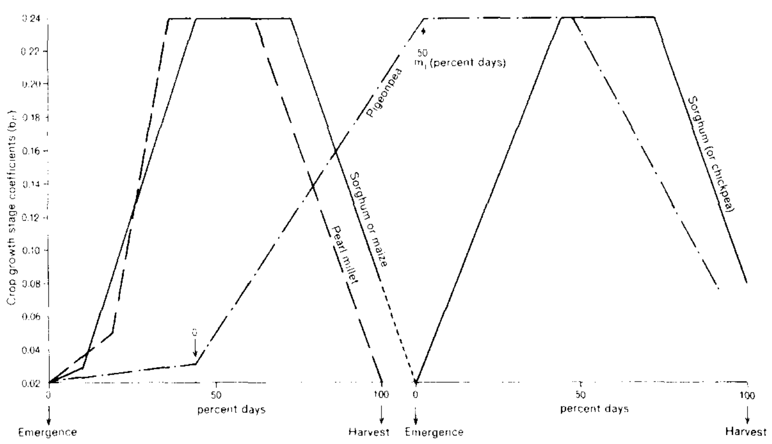


Fig. 1. Relationships of crop growth stage coefficient (b_n) with age of the crop (pearl millet, maize (or sorghum) pigeonpea intercrop, and sorghum (or chickpea) (double crops) and length of growing season).

1983). The correlation coefficient (r) of 0.75 suggests a useful predictive ability for the model.

The final equation for the computation of evapotranspiration under fallow and cropped conditions can now be written as

$$(AE/E)_n = [1 + ((5 - E_n)/16)(t_n/E_n)^{1/2}]\exp[(-t_n + a)/b_n K] \qquad (9)$$

USE OF MODEL FOR ESTIMATING SOIL WATER BALANCE

The method of computing evapotranspiration (AE_n) using eq. 9 is shown in Fig. 2 and is explained briefly below.

Basic imputs

(1) Weather factors (a) daily rainfall or irrigation (mm) — R_n
(b) open pan evaporation (mm/day) — E_n

(2) Crop factors (a) date(s) of emergence (l)
(b) length of crop(s) growing period (days) — L

(3) Soil factors (a) initial soil moisture (mm) — M_0
(b) maximum available soil moisture-holding capacity of the soil in the root zone (mm) — K
(c) maximum available water-holding capacity of the soil in the top 10-cm layer of the soil (mm) — K''

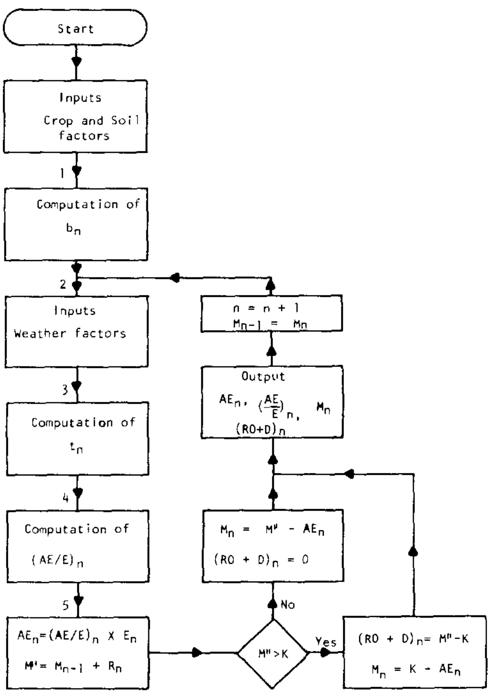


Fig. 2. Flow chart of ICSWAB model.

Determination of the time factor (t_n)

One of the major components to be determined for the computation of $(AE/E)_n$ in this model is the time factor (t_n), which depends on the frequency of wetting of the soil. Precipitation falling on a partially dried soil, without increasing the moisture content of the transpiration zone to the critical value (K'') for potential evapotranspiration, is not distributed over the transpiration zone, but remains in the top layers of the soil. Therefore, depletion of precipitation falling on the soil has priority, irrespective of the moisture content of the soil.

When soil is wetted either by rainfall or irrigaiton after a long dry period, then $t_n = 1,2,3, \ldots . x$ days, where 1 stands for the rainy day, 2 for the first non-rainy day, 3 for the second non-rainy day through the subsequent rainfree periods. For subsequent rains, if $R_n < E_n$, then the value of t_n proceeds uniterrupted, i.e., $t_n = x + 1, x + 2, \ldots$ etc. If, however, $R_n > E_n$ and $M_{n-1} = 0$, or $AE_{n-1} = 0$, then $t_n = 1, 2, \ldots . x$. When R_n is greater than the depletion that occured in the preceding drying period, $t_n = 1, 2, \ldots . x$; if R_n is less than that amount, then t_n proceeds as $t_n = 1,2, \ldots Y$ until R_n has been removed and then it shifts to the sequence of the earlier depletion cycle, i.e. $t_n = x + 1, x + 2, \ldots$ etc.

Computation of (a)

The available soil moisture in the top 10-cm soil layer is denoted by M'_n. If $M'_{n-1} = 0$ when R_n mm of rainfall occurs, then a is obtained as follows: when $R_n > K''$, then $M'_n = K''$, otherwise $M'_n = R_n$ and a is the number of days for which M'_n mm can meet potential evaporation demand, assuming that water is removed only from the surface 10 cm of soil. It thus represents the duration of Stage 1 evaporation. If a subsequent rain event occurs before 'a' days, then M'_n will be equal to R_n plus the residual soil moisture (M'_{n-1}) in the top 10 cm of soil before the rain. If $K'' < E_n$, then $a = 1$ only and $(AE/E)_n = M'_n/E_n$ on the rainy day.

Computation of evapotranspiration (AE_n)

The relative evapotranspiration $(AE/E)_n$ is obtained from eq. 9. However, in its computation the following special provisions apply:

(1) At the end of the depletion of a partially recharged soil ($t_n = Y$), the remaining residual moisture is allocated to the $(AE/E)_n$ of the transitional day. Thus, when $t_n = Y + 1$

$$(AE/E)_n = (AE/E)_{x+1} + (R_{n-Y} - \sum_{j=1}^{Y} AE_{n-j})/E_n$$

(2) When $R_n < E_n$, then $(AE/E)_n = (R_n/E_n) + (AE/E)_x$

TABLE II

Verification of the model

References	Location	Soil type	Period	Crop	Method of Observation	N	χ^2
Kowal and Kassam (1973)	Samaru (Nigeria)	Sandy loam	1971	Cotton	L	8	31.32[a]
Kowal and Falkner (1975)			1972	Maize	L	12	3.05
Kassam and Kowal (1975)			1973	Groundnut	L	10	13.99
Kassam et al. (1975)			1974	Gero millet	L	9	7.12
FSRP (ICRISAT)	Hyderabad (India)		1975–76	Fallow	S	6	2.37
				Maize + Chickpea	S	3	0.37
				Chickpea	L	12	2.25
			1976–77	Fallow	L	8	5.47
				Chickpea	L	11	11.47
				Sorghum	S	3[b]	0.86
		Vertisols	1977–78	Fallow	S	6	6.06
				Maize/P.pea	S	6	2.70
				Sorghum (irrigated)	S	6	1.77
				Sorghum (non-irrigated)	S	7	1.20
			1978–79	Maize + C.pea	S	7	9.00
			1977–78	Pearl millet (Kharif)	L	16	7.08
		Alfisols		Pearl millet (Rabi)	L	11	2.75
				Sorghum	S	9	9.29
				Fallow	S	9	4.41
			1978–79	Groundnut	S	6	1.26
Bond and Willis (1970)		Sandy loam	7 mm/day	Fallow	Weighing	6	0.15

C. pea = chickpea, P. pea = pigeonpea; L = evapotranspiration estimated by hydraulic lysimeters; S = soil profile water content measured by neutron moderation; N = No. of periods in an experiment — one period is defined as the period between any two measurements (by S or L).

[a] Significant at 95% level.

[b] Three controlled experiments under different irrigation treatments.

(3) If, during a year, the soil moisture reaches 50% of soil storage capacity on any day, then in the later part of the crop-growing period on any day when $(AE/E)_n < 0.10$, as estimated from eq. 9, it is set at 0.10.
(4) On any rainy day when $R_n > E_n$, if $E_n > 7$ mm/day and $E_{n-1} > 0.75E_n$, then it is assumed that $(AE/E)_n = 0.50$ provided $(AE/E)_{n-1} < 0.11$ (based on observations — unpublished ICRISAT data).

TESTING OF MODEL

The model, ICRISAT soil water balance (ICSWAB) has been tested with data sets representing several soils, crop/cropping patterns, evaporative demands and locations in which AE had been measured several times during the season by a hydraulic lysimeter (L), or by changes in soil profile water contents (S) measured by neutron moderation. Details of these data sets are given in Table II. It should be noted that the data used for testing the model are independent of those used to derive it. The χ^2 test was used to compare the observed and estimated evapotranspiration for various periods.

TABLE III
Comparison of observed and estimated evapotranspiration

Year	Day[a] number	ΣE_n (mm)	Set I Cropping sequence	Set I ΣAE_n (mm) O	Set I ΣAE_n (mm) C	Set II Cropping sequence	Set II ΣAE_n (mm) O	Set II ΣAE_n (mm) C
1970	150–177	124	Wheat	90	66	Fallow	93	58
	178–201	133		115	115		52	76
	202–229	148		102	104		31	34
	230–326	200		64	65		83	40
1971	125–166	198	Fallow	40	51	Wheat	65	58
	167–186	103		50	52		87	89
	197–233	276		43	43		78	79
	234–294	161		05	13		18	13
1972	116–151	143	Wheat	35	42	Fallow	44	49
	152–178	143		84	77		50	77
	179–222	217		62	38		36	44
	223–263	174		15	13		16	16
1973	122–156	141	Fallow	25	21	Wheat	29	29
	157–183	151		25	25		69	40
	184–220	222		31	23		65	56
	221–322	229		66	50		54	77
1974	122–172	205	Wheat	105	104	Fallow	87	87
	173–196	131		75	77		54	56
	197–233	154		115	117		68	73
	234–291	124		57	55		55	26

O = observed data (at Swift Current, Sask. — clay loam soil); C = computed (using eq. 9).
[a] Day number: 1 stands for January 1; 32 stands for February 1, etc.

In all but one case, the differences between the observed and estimated evapotranspiration values were not statistically significant.

Table III presents the observed and estimated evapotranspiration from a clay loam soil at Swift Current, Sask., for a data set presented by Baier et al. (1979). Here, two sets of 2-year wheat—fallow crop rotations were available from 1970 to 1974. The years 1970 and 1974 represent good rainfall years and 1971—73 poor rainfall years. With the exception of a few cases, ICSWAB shows very good agreement between observed and estimated AE_n for both crop and fallow fields. For the same data set, Baier et al. (1979) found that their model showed quite large deviations between observed and estimated evapotranspiration.

The seasonal course of soil moisture as computed by the ICSWAB model compared excellently with values measured by neutron moderation (unpublished ICRISAT data) at the ICRISAT Center, Hyderabad (Fig. 3). These results show that the model works on a daily basis, over quite long periods, for a variety of crops under a variety of regimes. The results in Fig. 3d—e also bring out the importance of precipitation in calculating t_n.

CONCLUSIONS

The paper presents a simple method (ICSWAB) of computing daily evapotranspiration. The major inputs into this model are easily measurable weather parameters such as rainfall and open-pan evaporation. The model successfully differentiates between fallow and cropped areas, and adequately accounts for differences in the evaporative demand as well as soil and crop factors. The growth stage of a crop is represented by coefficients which are based on LAI and LI and these permit the model to account for the variable amount of water available at different stages of crop growth.

Maximum available soil moisture in the top 10-cm soil layer and also in the total profile is an important input in the model. Available water in the top 10-cm soil layer at a given stage is used to determine the potential evaporation demand. The evaporative demand is represented by a function of open-pan evaporation. Actual evapotranspiration is computed as a function of time after wetting of the soil, irrespective of available soil moisture. Hence, for extraction of water, the model gives preference to recent rains which wet the top layers of the soil, compared to water in the deeper layers.

The ICSWAB model has been tested for different locations, soils, climates and crop conditions, and favourable results have been obtained for comparisons between observed and estimated evapotranspiration and soil moisture storage. It thus promises to be a useful tool, not only for characterization of climate, but also for the development of yield forecasting models and for monitoring supplemental irrigation. The model has been written in BASIC + and has been operated on a PDP—11/45 computer at ICRISAT since 1977.

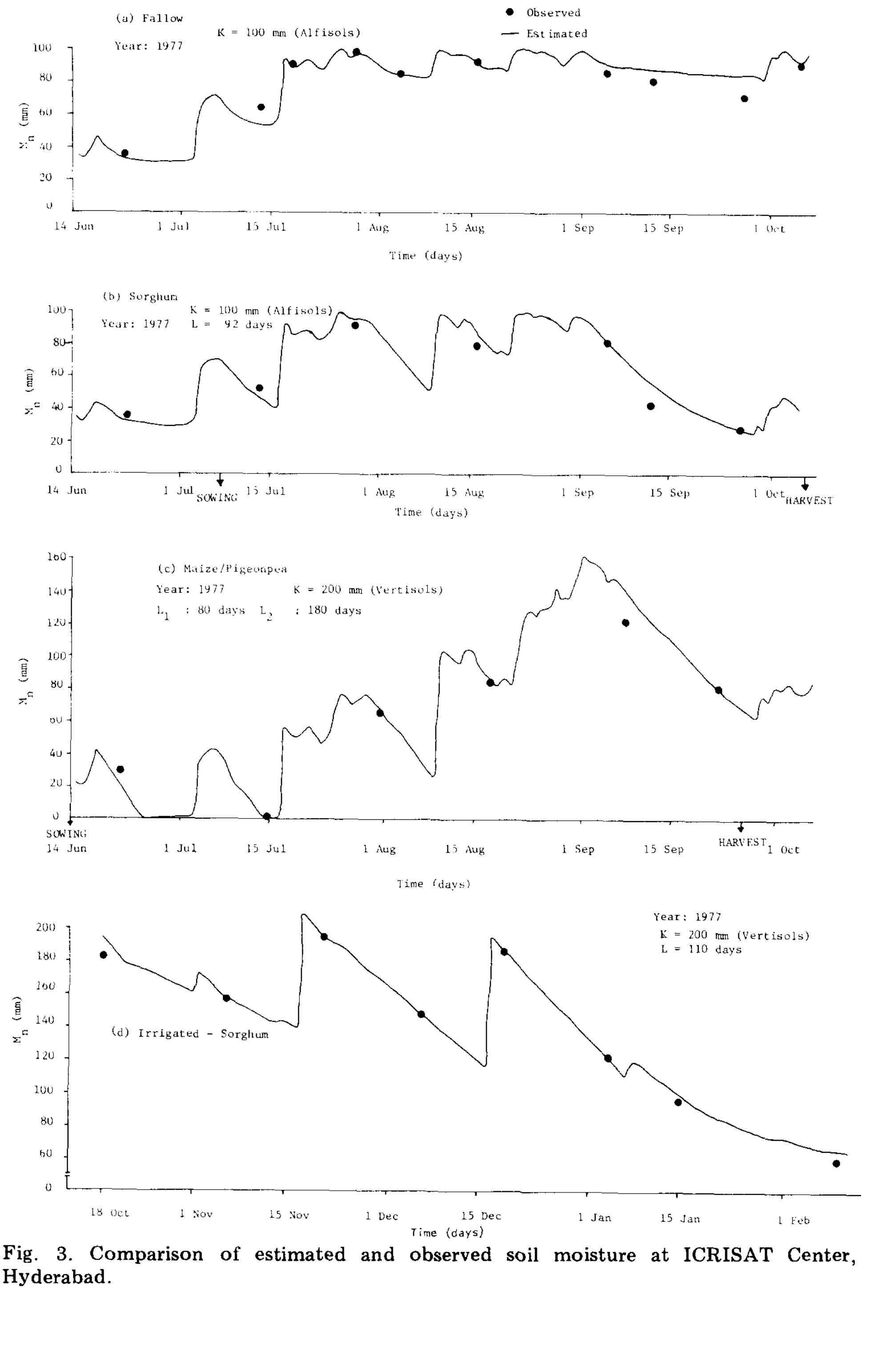
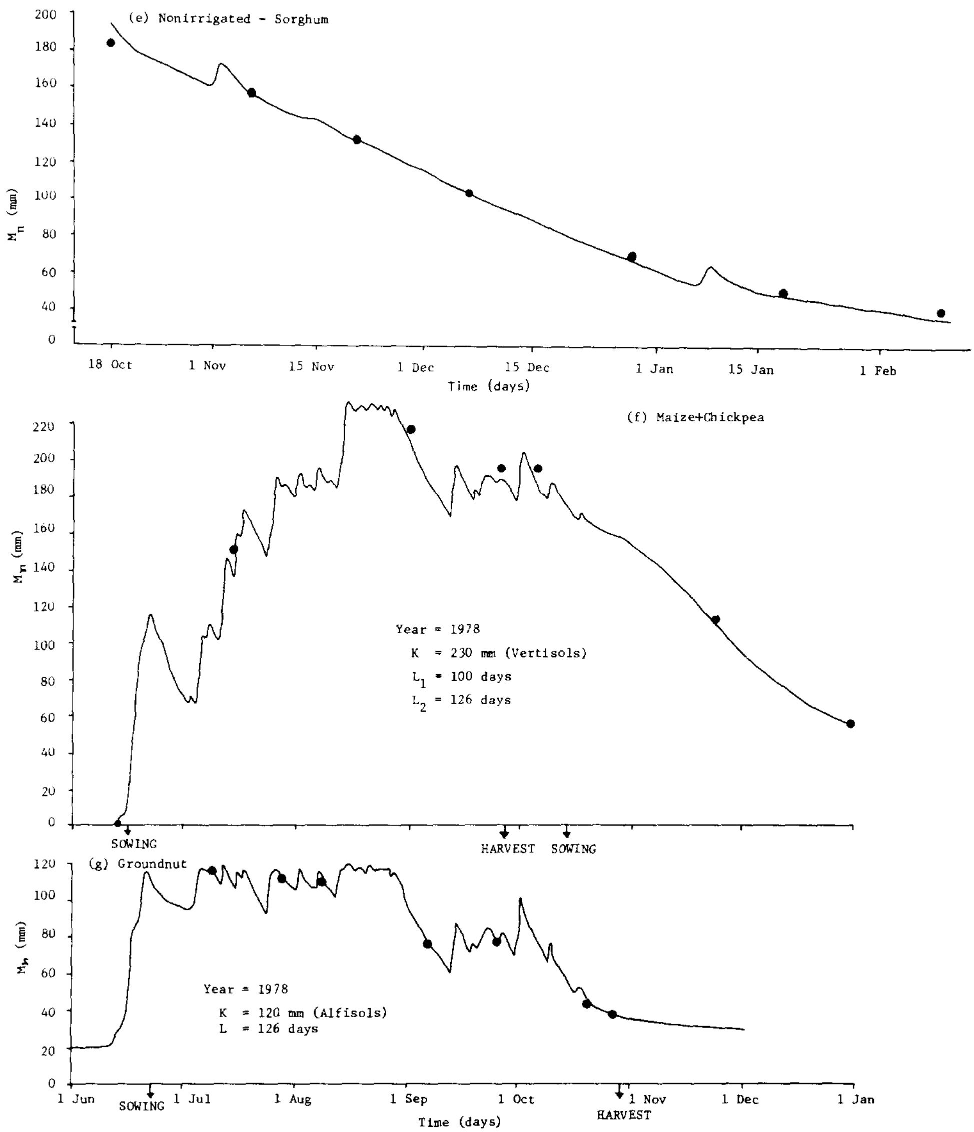


Fig. 3. Comparison of estimated and observed soil moisture at ICRISAT Center, Hyderabad.



LIST OF SYMBOLS USED

n	=	Day number in days (if the computation starts on June 1, then $n = 1$ on June 1, $n = 2$ on June 2, etc.)
AE_n	=	Actual evapotranspiration on n^{th} day (mm/day)
E_n	=	Open pan evaporation on n^{th} day (mm/day)
$(AE/E)_n$	=	Relative evapotranspiration on n^{th} day (AE_n/E_n)
a	=	Number of days following a rainy day for which the available soil moisture in the top 10-cm soil layer can meet potential evaporative demand

Y = Number of days required to use rain which only partially recharges the soil profile
l = Value of n on day of emergence (days)
L = Length of period of crop growth (emergence to harvest) (days)
i = Serial designation of days from emergence to harvest
b_n = Crop growth stage coefficient
K = Maximum available soil moisture storage capacity of the soil in the root zone (mm)
K'' = Maximum available water-holding capacity of the top 10-cm of the soil (mm)
M'_n = Available soil moisture ($M'_n \leqslant K''$) in the top 10-cm soil layer on any rainy day (mm)
R_n = Rainfall or supplemental irrigation on the n^{th} day (mm)
RO_n = Surface runoff on n^{th} day (mm)
D_n = Deep drainage on n^{th} day (mm)
ΔM_n = Soil moisture change ($M_n - M_{n-1}$)
M_n = Soil moisture ($M_n \leqslant K$) at the end of n^{th} day (mm)
t_n = Time after rainfall (days)

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