Jour. Agric. Physics, Vol. 3, No. 1 & 2, pp. 90-94 (2003)

Simulation of Field Water Budgets

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ABSTRACT

A model was developed and used to simulate field water balance components i.e. [irrigation (IR), rain (R), transpiration (T), evaporation from soil (E), ground water recharge (GR) and change in soil water storage (ΔS)] on coarse (loamy sand) and medium (sandy loam) textured soils with varying dates of sowing/ transplanting for maize of Ludhiana-Punjab. The weather data used was of twenty years (1981-2000) and dates of sowing/transplanting were June 1, June 11 and June 21. The simulated water balance components showed that irrigation water required for raising the crops decreased with delaying the date of sowing/ transplanting and was lesser in medium texture compared with that in the coarse textured soils. The contribution of recycled water to ground water, represented by the difference between IR and the GR, increased with delaying the date of sowing i.e. from June 1 to June 21 in both the crops on the two soils. However, the magnitude of contribution was more in mulched soil conditions and in coarse textured soils compared to un-mulched and medium textured soil, respectively. In medium textured soils, the contribution of recycled water in earlier transplanted rice was negative, which indicates decline in water table. Thus, to sustain ground water resources it is desirable to grow maize crop, if possible use crop residue as mulch or delay transplanting of rice in such soils.

Under field conditions soil water is changed dynamically with accretion and depletion of water in and from the soil by different processes. The water added into the soil by precipitation (P) and irrigation (I) enhances soil water storage (DS), which is lost by evaporation from soil (E) as determined by the potential evaporation rate, soil texture, wetting by rains as well as irrigation and initial soil water content, transpiration from the plants (T) depending upon its root penetration rate and periodic leaf area index, run off (R) depending on the slope, surface conditions and permeability of the soil and deep drainage (D) as determined by the retention and transmission properties of the soil. The quantitative relationships among the different components into which I and P are partitioned into E, T, R and D is called soil water balance or field water budget. For field water budget mass balance equation (equation 1) is solved, in which I and P are measured inputs but all other terms are estimated since direct measurements of these are not possible in most of the cases.

$$P + I = E + T + D + \Delta S + R \qquad (1)$$

For estimation of these components, models ranging from simple to complex (which consider the dynamics of water flow in soil-plant-atmosphere system) are used. The generally used models are DSSAT, EPIC and SPAW etc. These models differ in details and use various empirical and bio-physical relationships, but all these models use soil, plant and weather data as input. Recently, Jalota and Arora (2002) synthesized a process based field water balance model (FWB), which has modest input data requirement and is conceptually efficient. This model was used to simulate field water budget in some kharif and rabi crops.

Description of the Model

A simplified model (FWB) for estimating soil water evaporation and drainage under bare soil (Jalota *et al.*, 2000) was modified to include transpiration component (Hanks and Hill, 1980) for assessing daily water balance under cropped soils. In the present model, R loss was not accounted for as majority of the lands have flat topography and the soils are coarse textured in nature. Moreover, irrigation scheduling to crops is based on deficit-irrigation concept leading to maximum profile water use (Prihar *et al*, 1974 and Prihar and Sandhu, 1987) and minimizing the probability of R. In the model, evaporation from the USWB Class A pan was taken as potential evapo-transpiration (PET) rather than with equations to calculate PET (Penman, 1941; Priestley and Taylor, 1972) because of the non-availability of detailed meteorological data required for the use of these equations. The PET was partitioned between potential transpiration (T_m) and potential soil water evaporation (E_m) through green canopy factor, (K_t) as follows:

$$T_m = PET * K_t \quad (2a)$$

$$E_m = (1- K_t) * PET \quad (2b)$$

Green canopy factor, K_t, for a given crop is obtained from the experimental information generated by different researchers on progressive leaf area index (LAI). It was assumed to have a maximum value of 0.9 (Hanks and Puckridge, 1980) for LAI equal to or greater than 3.0. However, for LAI less than 3.0, K_t was made to decrease gradually through a square root relation with decrease in LAI as:

$$K_t = 0.9\ (LAI\ /3.0)^{0.5} \quad (3)$$

In soil covered with crop residue (used as mulch), the potential evaporation rate at the soil surface (E_m) is reduced due to cover effect (equation 4).

$$E_{0m} = E_m\ [a \exp (b\ RR + c\ E_m)] \quad (4)$$

Where E_{0m} is reduced potential evaporation rate from mulched soil (cm d^{-1}), E_m is the potential evaporation rate from bare soil (cm d^{-1}), RR is the mass of the residue per unit area (t ha^{-1}), and a, b and c are coefficients, the values of which vary with soil texture (Prihar *et al*., 1996). Cumulative evaporation from soil (SE) for the energy-limited and soil-limited stages of evaporation was estimated by modified pan-E based functional model of Jalota (1998). Cumulative evaporation from the soil and cumulative potential evaporation during the wetting events were adjusted depending upon the rainfall (P) excess using the procedure of Boesten and Stroosnijder (1986). Extraction of soil water for transpiration was based on the interacting effects of depth of root penetration and soil water status. The root penetration depth (RPD) was related to time after seeding through a sigmoid function

$$RPD = D_m\ /\ (1+a.\exp\ b.t) \quad ...\ (5)$$

Where D_m is maximum rooting depth in cm, t is days after seeding, 'a' and 'b' are regression coefficients. As long as available water fraction in a rooted soil layer was more than 50%, the entire transpiration (T_m) was extracted from the rooted layer having maximum available water fraction (Hanks and Hill, 1980). When a soil layer could not meet Tm for a given day, un-extracted Tm was reallocated to another rooted layer having next higher soil water status. This procedure was followed till the entire Tm was extracted or all the rooted layers were considered. The water content in each layer of the soil profile is updated daily. Addition of a given amount of water (as P+I) in the soil profile was distributed in the top layer by an amount equivalent to the deficit {upper limit water content (θ_u) - actual water content (θ_a)} prevailing in the layer. If the added water is more than the deficit, the remaining water cascades to lower layers and continues through the bottom layer of the profile. Drainage of soil water below the upper limit water content (field capacity) was accounted by using the algorithm of Arora *et al.* (1987), who extended the concept of Richards *et al.* (1956) to compute drainage rate (dSW/dt) in relation to water stored (SW) at different depth planes.

$$dSW/\ dt = AB\ (SW/A)^{B-1/B} \quad ...\ (6)$$

Where A and B are drainage coefficients computed experimentally (Table 1).

In the model, irrigations were scheduled when the ratio of depth of irrigation water (IW) to cumulative (PET-P) reached pre-set values (Prihar *et al.*, 1974) for different crops as given in the model analysis section or water storage in 0-30 cm soil profiles equaled the lower limit of the water availability. The model was employed for assessing water balance components (E, T and D) for a given crop during two periods i.e from bare soil during the pre-sowing irrigation to sowing of crop (first) and during the cropped period (second).

Model validation

The performance of the model (FBW), with respect to water balance components was compared with other two models *viz.* SPAW and EPIC using the already published experimental results (Arora

Table 1. Soil hydraulic characteristics of the soil used in the simulation study

Soil depth (cm)	Moisture parameters (cm^3 cm^{-3})			Soil thickness (cm)	Drainage constants	
	θ_l^1	θ_u^2	θ_i^3		A^4	B^5
0-30	5.0	25.0	20.0	0-30	7.50	-0.0520
30-60	7.0	27.0	20.0	0-60	15.60	-0.0510
60-90	9.0	29.0	20.0	0-90	24.30	-0.0480
90-120	9.0	29.0	20.0	0-120	33.0	-0.0475
120-150	9.0	29.0	20.0	0-150	41.70	-0.0470
150-180	9.0	29.0	20.0	0-180	50.40	-0.0465

θ_l^1, θ_u^2 and θ_i^3 are air-dry, field capacity and initial soil water content, respectively.
A^4 and B^5 are regression coefficients of equation SW =AtB where SW is in cm and t is in days.

Table 2. Performance of water balance components (cm) of maize by three models

Model	PET*	T	E	D	ΔS	I	P
FWB	55.4	25.6	23.8	1.0	1.6	25.0	23.8
SPAW	56.0	23.1	24.9	2.0	0.4	25.0	23.8
EPIC	50.0	25.6	10.0	9.7	3.5	25.0	23.8

*PET, T, E, D, ΔS, I and P represents pan-evaporation, transpiration, evaporation from soil, change in soil water storage, irrigation and rainfall, respectively

and Gajri, 1996) for maize crop grown during the year 1991 (Table 2). All the components were almost comparable in the FWB and SPAW models but E and D components were different in EPIC model. This may be due to the use of different relationship for estimation of E, for example in EPIC model E was estimated with Ritchie's (1972) relationship and in FWB model by Jalota *et al.* (2000). The change in soil water storage calculated with FWB model also matched well with the measured values in different treatments of maize grown during 2002 (Table 3).

Simulated results

Since FWB model gave comparable estimates of water balance components with other models

Table 3. Comparison of change in water storage measured in different treatments of maize and calculated with FWB model

Treatment	Change in soil water storage, cm	
	Measured	Calculated
Date of sowing (June 4)		
Without mulch	4.3	3.9
With mulch	6.0	5.1
Date of sowing (June 10)		
Without much	6.8	7.0
With mulch	8.5	8.2

and change in soil water storage of an independent experiment, it was used to simulate water balance components for maize, soyabean, rice, winter-maize and wheat crops under water stress free environment using 20 years' weather data (1981-2000) of Ludhiana. The soil used for simulation study was medium textured, the hydraulic characteristics of which are given in Table 1. Kharif crops were sown on the same date i.e. June 11 and rabi crops in the first week of November.

Field water balance components estimated for different crops are given in Table 4. In maize, soyabean and rice crops during the first period, out of the total water added through irrigation and rain, 29.5, 39.3 and 30.4% was lost as evaporation from soil and 69.6, 59.8 and 68.8% was used to enhance soil water storage, respectively while drainage loses were negligible. During the cropped period, transpiration losses from soyabean and rice crops were same (29 cm), which were more by 6cm than that of maize. Evaporation loss from soil was maximum (32 cm) in soyabean, which was more by 5 cm and 7 cm than that in rice and maize crops, respectively. The drainage losses were maximum (97 cm) in rice, which was more by 71 cm and 67 cm than that in maize and soyabean crops. To meet E+T+D losses, irrigation water required was 98.5 cm in rice, 21.3 cm in maize and 30.6 cm in soyabean. In all the three crops there was increase in soil water storage at time of harvest of the crops. As expected, in mulched crops compared to un-mulched there was a decrease in evaporation loss from the soil because of the cover effect of the mulch, which has retained higher water storage and subsequently increased the drainage.

Table 4. Model based (average of 20 year's ,1981-2000) estimated field water balance components in different crops on representative medium textured soils for Ludhiana district in Punjab

Crop	Water input, cm			Water loss, cm				Change in soil water storage
	Irri. (I)	Rain (P)	Total (I+P)	Trans. (T)	Evap. (E)	Drainage (D)	Total (E+T+D)	(ΔS)
Kharif								
Maize	21.3 (10.0)*	57.9 (1.2)	79.2 (11.2)	23.2 (0.0)	25.2 (3.3)	26.4 (0.1)	74.8 (3.4)	+ 4.4 + (7.8)
Maize-mulched	14.5 (10.0)	57.9 (1.2)	72.4 (11.2)	23.1 (0.0)	8.9 (3.3)	34.5 (0.1)	66.5 (3.4)	+ 5.9 + (7.8)
Soyabean	30.6 (10.0)	60.9 (1.2)	91.5 (11.2)	28.6 (0.0)	31.9 (4.4)	30.1 (0.1)	90.6 (4.5)	+ 0.9 + (6.7)
Soyabean-mulched	19.5 (10.0)	60.9 (1.2)	80.4 (11.2)	28.8 (0.0)	10.0 (4.3)	40.5 (0.1)	79.3 (4.4)	+ 1.1 + (6.8)
Rice	98.5 (10.0)	59.1 (1.2)	157.6 (11.2)	29.0 (0.0)	26.9 (3.4)	96.9 (0.1)	152.8 (3.5)	+ 4.8 + (7.7)
Rabi								
Winter-maize	44.3 (10.0)	14.0 (0.5)	58.3 (10.5)	38.0 (0.0)	15.8 (2.2)	9.2 (1.9)	63.2 (4.1)	- 4.7 + (6.4)
Wheat	27.0 (10.0)	11.4 (0.2)	38.4 (10.2)	24.9 (0.0)	13.3 (2.7)	9.8 (2.2)	48.0 (4.9)	- 9.6 + (5.3)

* Figures in the parentheses are of the period between pre-sowing irrigation and sowing of the crop

In winter maize and wheat during the first period, out of the total water added by pre-sowing irrigation and rain, 21 and 26.5% was lost as evaporation from soil, 61 and 52% was used to enhance soil water storage and 18.1 and 21.6% was lost as drainage, respectively. In winter maize transpiration was 13.1 cm more than that of wheat (24.9 cm) and evaporation from soil was 2.5 cm more than that of wheat (13.3 cm). Drainage losses were comparable. Irrigation water requirement was 44.3 cm in winter maize and 27 cm in wheat.

These results indicate that during kharif season, maize and during rabi season, wheat has low water requirement and use of mulch during kharif season decrease the water requirement of crops further.

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