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Simulating the effects of irrigation scheduling on cowpea yield

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A b s t r a c t. The CRPSM model developed by Hill *et al.* (1996) was modified, calibrated and tested using cowpea-water use and weather data collected under line source sprinkler system at Ile-Ife, Nigeria. Three sets of data were collected. The first was used to calibrate and modify the model and the other two for testing. Simulated irrigation schedules were then applied using two of the four management options in the model to select the best schedules for the region. The water yield index (WYI) defined as the products of the model predicted relative yield (percent) and the transpiration water ratio (transpiration/water applied) was used to select the best schedule.

The results showed that WYI ranged from 52% for irrigation level one in 1999 to 8% for irrigation level five in 1997, when the model was applied to actual field data. However, with simulation runs, a six day interval provided a WYI of 66% for irrigation level one in 1999 and a two day interval provided a WYI of 9% for irrigation level five in 1997 using almost the same amount of water. The model, therefore, proved to be useful in estimation of possible irrigation schemes to maximize yields.

K e y w o r d s: cowpea yields, water use index, irrigation scheduling, modelling

INTRODUCTION

Nigeria has two distinct seasons – the rainy season, lasting from mid of March to the end of October, and the dry season, lasting from November to March. In the dry season, there is virtually no rain and irrigation remains the only option for crop production. Cowpea is a major crop produced by irrigation, using mostly the sprinkler system. There is stiff competition for water by the agricultural, domestic and industrial users during the dry season, hence there is the need for farmers to conserve and make judicious use of the available water. The crop water use efficiency has been shown to depend on irrigation amount and frequency (Adekalu and Okunade, 2006; Fapohunda, 1992). Also the type of irrigation system (Yohannes and Tadesse, 1998) and tillage practices (Adekalu and Okunade, 2006; Kayombo *et al.*, 2002) can influence the water use efficiency for a given irrigation frequency. The irrigation number, amount and uniformity of water applications are used mainly to determine the efficiency of irrigation scheduling. Excessive doses of infrequently applied water will lead to high percolation losses. The water saved by reducing drainage losses can be used to obtain higher yields by giving additional application to irrigate other farmlands or to store it as an insurance against the more severe periods of drought. While real-time irrigation schedulers can be used to maximize the yield for a specific growing season, they are less useful for planning and management as simulation models.

In this study, the crop yield and water management simulation model (CRPSM) developed by Hill *et al.* (1996) was modified and calibrated with application to actual field data on cowpea from Nigeria. The field experiment was carried out using a line source sprinkler system to generate sets of water use-yield data. The study was done in an attempt to determine some possible irrigation schedules that can optimise water use. The CRPSM model was selected because of its simplicity and minimum data requirement, which will make it attractive to developing countries.

MATERIALS AND METHODS

Model description

The crop yield and water management simulation model (CRPSM) developed at Utah State University (Hill *et al.*, 1996) predicts crop phenologic stages and shows the effects of climate, planting date and soil-water crop interactions on yield.

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The model consists of a main program and twelve subroutines. The model simulates an actual field experiment by computing daily available soil moisture in each layer and daily potential and actual evapotranspiration given the required site, soil, crop, and weather information. If desired, any of the four different irrigation options could be used in the management option in the model; the four irrigation options are:

1. Finding the best day to irrigate with a specified water increment.
2. Irrigating at a specified interval with fixed amount.
3. Irrigating on specified dates with specified amounts (historical data).
4. Irrigating at a specified depletion with a fixed amount.

The model was modified by adding: (1) coefficient to allow for drainage below field capacity in the root zone; (2) runoff equation and (3) coefficient to allow evaporation to depend on the soil water content at the start of soil drying.

Seasonal yield is determined as a function of relative transpiration:

$$\frac{Y}{Y_m} = \left[\frac{T_1}{T_{p1}}\right]^{\lambda_1} \left[\frac{T_2}{T_{p2}}\right]^{\lambda_2} \left[\frac{T_3}{T_{p3}}\right]^{\lambda_3} \left[\frac{T_4}{T_{p4}}\right]^{\lambda_4} \left[\frac{T_5}{T_{p5}}\right]^{\lambda_5}, \quad (1)$$

in which Y and Y_m are actual and potential yields (t ha^{-1}), respectively, T_i and T_{pi} are actual and potential transpiration (mm), respectively, and λ_i is growth stage weighing factor for stage i.

Potential evapotranspiration, ET_P, is calculated as:

$$ET_p = K_c ET_r. \quad (2)$$

Potential transpiration (T_p) is defined as:

$$T_p = K_t ET_r, \quad (3)$$

in which K_c, K_t are crop water use and crop transpiration coefficients, respectively, obtained from a separate lysimeter experiment, and ET_r is reference crop evapotranspiration (mm), obtained using the Penman-Monteith equation (FAO, 1998). K_t is a fraction of K_c used to split ET_p into potential transpiration and evaporation based on the leaf area index. Values of crop water use coefficient K_c, have earlier been reported by Adeogun and Ahaneku (2002).

Actual transpiration, T, is:

$$T = T_p \text{ when } SWS/AVW > FAW, \quad (4)$$

$$T = (T_p/FAW)(SWS/AVW) \quad (5)$$

when $SWS/AVW < FAW$,

in which SWS is existing soil moisture in the root zone (mm), AVW is available moisture at field capacity (mm); and FAW is the fraction of available water below which plant stress occurs.

Potential evaporation, E_p, is defined as:

$$E_p = ET_p - T_p. \quad (6)$$

Actual evaporation, E, is defined as:

$$E = \alpha E_p / N^{(t-1)}, \quad (7)$$

$$\alpha = \theta_1 / \theta_{f1}, \quad (8)$$

in which t is time in days after irrigation, N is a factor depending on soil texture (N = 3.0 and 3.5 for sandy loam and sandy clay loam soils used in this study, respectively), θ_1 is moisture content after irrigation in top 30 cm soil depth (m^3 m^{-3}), and θ_{f1} is moisture content at field capacity in the top 30 cm soil depth (m^3 m^{-3}).

Root depth, RT, is computed in the model as:

$$RT = BR + RDPTH(RTMX - BR), \quad (9)$$

where: BR is the initial root depth (mm); $RTMX$ is the maximum root depth (mm); and $RDPTH$ is the ratio of days since emergence to total days from emergence to $RTMX$.

Deep percolation, DP, and soil moisture content are then determined from the soil water budget equation as:

$$DP_i = (\theta_i - FC_i)Z_i + B_i(FC_i - PWP_i)Z_i,$$

$$IF\ \theta_i > FC_i, \quad (10)$$

otherwise

$$DP_i = B_i(\theta_i - PWP_i)Z_i, \quad (11)$$

$$\theta_i = (\theta_{is}Z_i + DP_{(i-1)})Z_i, \quad (12)$$

where: θ_i is moisture content of a given soil layer in the root zone (m^3 m^{-3}), B_i is the drainage coefficient for the ith layer in the root zone (the root zone was divided into two distinct layers), FC_i is moisture content at field capacity (m^3 m^{-3}), Z_i is the soil depth (mm), PWP_i is moisture content at wilting point (m^3 m^{-3}), θ_{is} is the initial moisture content of a given layer (m^3 m^{-3}), DP_i is the deep percolation from a given layer (mm), and $DP_{(i-1)}$ is the deep percolation from the preceding layer (mm).

Actual evapotranspiration, ET_a, is defined as:

$$ET_a = E + T. \quad (13)$$

Transpiration water ratio, TWR, defined by actual transpiration/ total water supply, indicates the efficiency of the water consumed by plants relative to the total amount of water made available during the season.

Runoff was calculated as:

$$R = P - FT_r - S_w, \quad (14)$$

where: R is runoff (mm), P is precipitation (mm), F is the infiltration capacity of the soil (mm h^{-1}), T_r is the duration of the precipitation (h), and S_w is the surface storage (mm).

The water yield index, *WYI*, is defined as:

$$WYI = PRY \times TWR, \tag{15}$$

where: *PRY* is the model predicted relative yield (percent of potential yield) and *TWR* is transpiration water ratio.

Input data required by the model include: site elevation, longitude and latitude, root zone depth, soil layers thickness, initial moisture content, wilting point and field capacity of each layer, weather data for the calculation of reference crop evapotranspiration by Penman-Monteith, Blanney-Criddle, Jensen-Haise, Hargreaves, Thornwaith or pan-evaporation in the model, dates of growth stages and harvest.

Field experiment

The experiment was conducted on a piece of land near the dam at the Teaching and Research Farm of the Obafemi Awolowo University, Ile-Ife, Nigeria. The approximate plot dimension was 30 x 60 m, including border areas and a walking path, 1 m wide, running between adjacent sub plots. The land was ploughed and harrowed after slashing the shrub. Cowpea (*Vigna unguiculata, L Walp*) variety VITA5 was planted at the recommended spacing of 30 cm on rows, 60 cm apart. Weeds and insect pests were controlled as necessary using standard procedures.

A line source irrigation system developed by Hanks *et al.* (1976), consisting of a single line of sprinklers spaced 6.1 m apart, provided uniform water distribution parallel to the irrigation line and a water gradient perpendicular to the irrigation line. Preliminary tests showed that in the absence of wind the water application pattern was constant in time. The irrigation line was placed on a central guard line and depths of water application to each line on both sides of the irrigation line were measured at each irrigation. The line source created five irrigation levels decreasing from rate 1 to 5. The farthest level from the line, irrigation level 5 (IL5), (either east or west) received very little irrigation (about 100 mm including rainfall) while irrigation level 1 (1L1), just adjacent to the line, received a maximum water supply (average of about 280 mm). The line source irrigation system used impact sprinklers rain bird 30, 4.76 by 2.38 mm – 70° slotted nozzles spaced at 6.1 m along the lateral. Pressure at the inlet averaged 300 kPa and the average discharge per sprinkler was 0.5 l s^{-1} with a wetted area 30 m in diameter. The experiments were conducted on different fields for three years (1995, 1997, and 1999). The 1995 data were used for calibration and those of 1997 and 1999 were used for testing. The soil for 1995 and 1997 is a sandy loam soil classified as an Alfisol while that of 1999 is a sandy clay loam soil classified as Inceptisol (Soil Survey Staff, 1992).

Soil water contents were monitored before and after each irrigation using gravimetric and neutron probe for the top 15 cm and neutron probe over a range of 75 cm at an increment of 15 cm. Soil matric potential values were measured over the same range using tensiometers. Meters were only installed at irrigation levels 1, 3 and 5 in 1995 and 1997, and at irrigation levels 1, 2 and 3 in 1999.

The moisture retention characteristic was measured using standard pressure plates on undisturbed soil cores. The drainage and actual evapotranspiration were estimated from the mass balance of the water content profiles over the wetted depth using the zero-flux plane method (Mcgowan and Williams, 1980). Weather data were obtained from the station at the Farm and used to estimate reference crop evapotranspiration, according to Penman-Monteith equation (FAO, 1998). Irrigation was scheduled according to estimated crop evapotranspiration.

Irrigation/rainfall depths were measured using catch cans placed at right angles to the line source. There were two cans per irrigation level. Rainguages were placed at two rows alongside the catch cans. The readings of the rainguages were used to calibrate the catch cans data. The dates of attainment of the various phenologic stages were observed and recorded. The root depth was monitored at the end of each growth stage and linear interpolation of values was used between the stages. The root monitoring was done by taking soil cores (5 cm in diameter and 5 cm deep) up to 75 cm, two on either side of the first irrigation level, and for each depth; soil samples were combined to give a composite and living root obtained by washing with congo red. At the end of the season, the crops were harvested separately for each row. The pods were removed and weighed. The weight was converted to yield per hectare using the row spacing.

Data from the yield in 1995 were used to determine the growth period weighing factors, λ's, and other parameters in the yield equation. The calibration of the yield equation was done with a pattern search technique (Hill *et al.*, 1972) using field-estimated transpiration by growth stages and the actual yield. The growth session was divided into five stages as follows:

- planting to emergence,
- emergence to beginning of flowering,
- beginning of flowering to beginning of pod fill,
- beginning of pod fill to end of flowering and
- end of flowering to physiological maturity.

RESULTS AND DISCUSSION

Results of calibration and testing

Figure 1 shows the transpiration coefficient curve for cowpea as determined and used in this study, using the data from a separate lysimeter experiment and the method of Wright (1982). The third-order polynomial sometimes used to describe the curve is as follows:

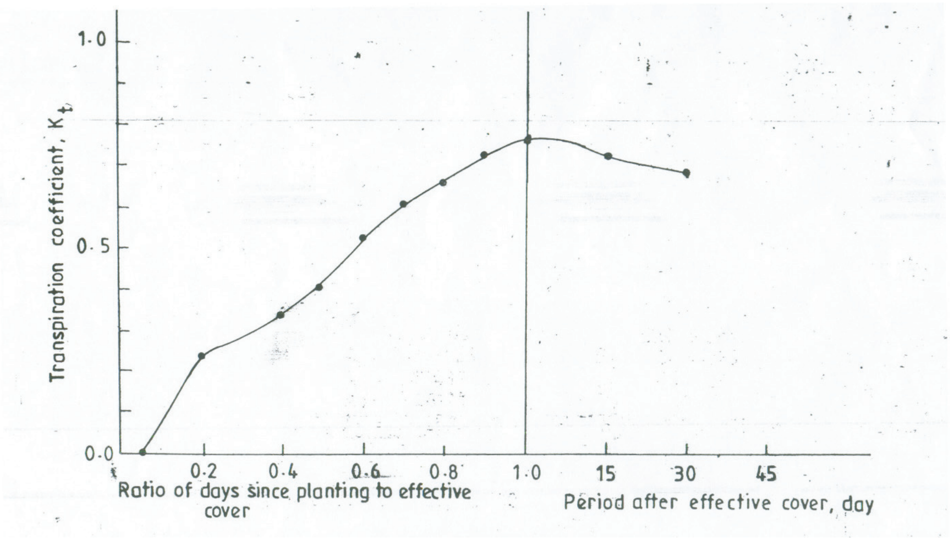

Fig. 1. Cowpea crop transpiration coefficient curve.

$$K_t = -0.17437X_1 - 0.26124X_1^2 + 0.12870X_1^3 + 0.853623 \quad (P < 0.05), \qquad (16)$$

where X_1 is ratio of days since emergence to effective cover:

$$K_t = -0.14333X_2 + 0.20473X_2^2 - 0.546451X_2^3 + 0.639725 \quad (P < 0.05), \qquad (17)$$

where X_2 is period after effective cover (days).

The calibrated yield parameter values were $\lambda_1 = 0.0, \lambda_2 = 0.4, \lambda_3 = 1.8, \lambda_4 = 1.2, \lambda_5 = 0.6$ and a potential yield of 1.8 t ha^{-1}. The calibrated values for B_i's were 0.02 and 0.01 for the two soil layers, respectively and S_w was 1 mm. Table 1 shows the depth of water applied for each level while Table 2 shows the values of predicted yield against measured yield. Figure 2 shows the plot of predicted relative yields against measured relative yields for the three years. The 1997 and

Table 1. Depth of water applied (mm) and days after planting (DAP) of actual water applied for different years and irrigation levels (IL)

Year	1997			1999			
DAP	Depth of water applied (mm)			DAP	Depth of water applied (mm)		
	IL1*	IL3	IL5		IL1	IL2	IL3
4	16	16	16	4	16	16	16
6	14	6	4	7	15	13	8
9	16	11	8	10	12	10	8
12	9	6	4	14	14	11	8
15	13	6	5	17	14	12	8
18	15	14	9	20	16	13	8
21	14	9	4	24	13	11	8
24	18	17	10	27	14	12	8
28	15	10	5	29	10	9	7
32	14	6	3	31	16	15	9
36	13	10	7	34	15	12	8
40	13	8	2	38	15	13	8
44	21	11	5	41	17	14	8
48	24	13	5	44	14	11	8
52	25	18	6	48	16	13	8
56	26	19	7	52	16	13	8
				56	17	12	9

*Irrigation level.

T a b l e 2. Comparison of actual and model predicted yield of cowpea

Year/ Irrigation level	Yield (t ha^{-1})			
	Actual		Model	
	(t ha^{-1})	(% of potential yield)	(t ha^{-1})	(% of potential yield)
1995/ILI	1.37	76.1	1.36	75.0
1995/IL2	1.29	71.6	1.33	73.8
1995/IL3	1.07	59.4	1.17	65.0
1995/IL4	0.73	40.5	0.72	40.0
1995/IL5	0.36	20.0	0.30	16.7
1997/IL1	1.36	75.5	1.37	76.1
1997/IL2	1.26	70.0	1.18	65.5
1997/IL3	0.90	50.0	0.79	43.9
1997/IL4	0.63	35.0	0.54	30.0
1997/IL5	0.47	26.1	0.32	17.8
1999/IL1	1.35	75.0	1.36	75.5
1999/IL2	1.30	72.2	1.22	67.7
1999/IL3	1.22	67.8	1.10	61.1
1999/IL4	0.78	43.3	0.85	47.2
1999/IL5	0.44	24.4	0.49	27.2

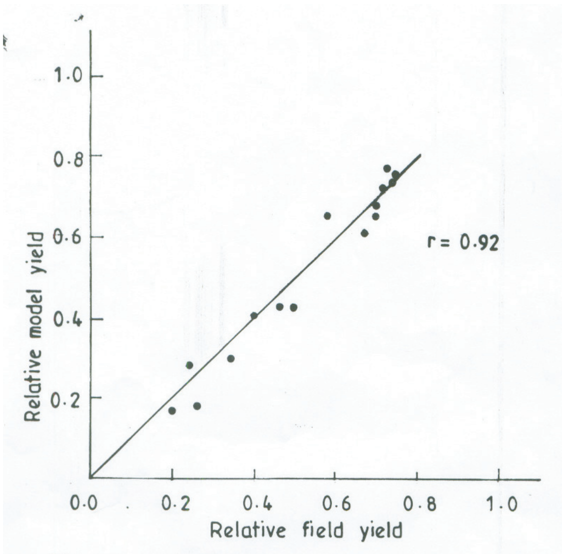

Fig. 2. Calibrated cowpea relative computed yield versus relative field yield.

1999 data served as independent data set. Table 3 shows the comparison between model predicted and actual soil water budget parameters. The table shows that the model gave very good estimates that agreed with field values. The agreement was better under the highest irrigation level. These results have increased the confidence in using the model for selecting irrigation schedules and for predicting yields.

Table 4 shows the theoretical values of the water requirement. From the table, it can be noted that the theoretical K_c is a little higher than the actual K_c values (Table 3), indicating that the first irrigation levels in both years almost received their optimum water requirements.

Application of irrigation simulation model

The model application is demonstrated by using two of the four different water management (*WM*) options:
(i) irrigate on specified dates with specified amounts (actual field data),
(ii) irrigate at specified interval with a fixed amount.

The intervals used are 2, 3, 4, 5, 6, and 7 days. The results are presented in Tables 5 and 6. Input data were selected from actual data and/or based on model computed transpiration and evaporation amounts. Runs WM_1, WM_4, WM_7 represent model application on actual data of 1997. Also, runs WM_1, WM_4, and WM_7 represent model application on actual data of 1999. All other runs are simulated runs made to determine the most suitable and efficient irrigation schedule which will result in optimum water use and maximum yields. For clarity, only the best and worst simulation runs are presented.

An explanation of the computational procedure for WM_1 for example is as follows. The total irrigation water amount applied was 266 mm. Rainfall during the season was 4 mm. Change in soil moisture content by the end of the season was 4.5 mm. The total water supply, *TWS*, was 274.5 mm. The model predicted relative yield, PRY, was given by the model to be 77.7% considering a maximum potential yield of 1.8 t ha^{-1} and the transpiration water ratio, *TWR*, of 0.66 (181.6/274.5) and water yield index, *WYI*, of 51 (0.66x 77.7). From Table 5, it can be seen that the model transpiration ratios for the three irrigation levels were 0.66, 0.50 and 0.34 and the corresponding values of the model predicted relative yield were 77.7, 42.7 and 18.8%. Runs WM_3 and WM_6, which is irrigating every six and five days,

T a b l e 3. Measured and computed soil water budget parameters

Parameter	1997			1999		
	IL1*	IL3	IL5	IL1	IL2	IL3
TWS (mm)**	274.5 (272.5)*	181.7 (178.8)	117.3 (112.4)	274.1 (276.6)	234.7 (233.6)	168.8 (165.5)
DP (mm)	17.2 (20.7)	15.3 (18.0)	2.0 (6.0)	11.6 (17.3)	10.0 (15.0)	9.3 (12.7)
ET (mm)	257.3 (251.8)	166.4 (162.1)	115.3 (107.4)	262.5 (259.3)	224.7 (221.3)	159.5 (151.8)
CWE (%)	93.7 (92.4)	91.5 (90.6)	98.5 (97.3)	95.8 (93.7)	95.7 (94.7)	94.9 (91.7)
Yield (t ha^{-1})	1.37 (1.36)	0.79 (0.90)	0.32 (0.47)	1.36 (1.35)	1.32 (1.30)	1.25 (1.20)
K_c	0.85 (0.82)	-	-	0.87 (0.85)	-	-

*Values in parenthesis are measured values, ***TWS* – total water supplied, *DP* – deep percolation, *ET* – evapotranspiration, *CWE* – consumptive water use efficiency (*ET*/*TWS*) and K_c – actual crop water use coefficient.

T a b l e 4. Model computed potential water requirement for cowpea

Parameter	Seasonal depth
Reference crop evapotranspiration, ET_r (mm)	304
Potential transpiration, T_p (mm)	185
Potential evaporation, E_p (mm)	89
Potential evapotranspiration, ET_p (mm)	274
Potential crop-water use coefficient, K_c	0.90

respectively, produced the best runs for irrigation levels 1 and 3, with transpiration ratio of 0.74 and 0.60 and model predicted relative yield of 92.6 and 84.3%. These gave water yield indices of 69 and 51, respectively. The two runs were able to reduce the deep percolation of the actual field runs by more than 50%, leading to higher water use efficiencies. Irrigating every 2 days (WM_2 and WM_5) produced the worst runs for both levels. This schedule produced higher deep percolation and evaporation. For irrigation level 5, the best schedule was irrigating every 2 days (WM_9), producing slightly higher relative yield than the actual field data and irrigating every six days (WM_8). Though the six-day interval produced higher transpiration water ratio, for this small irrigation amount the six-day interval must have caused the soil to get to stress conditions for greater periods, leading to lower relative yield and hence leading to lower water yield index.

Similarly for the 1999 data (Table 6), the model transpiration ratios for the actual field irrigation levels were 0.67, 0.62 and 0.49 and the corresponding model predicted relative yields were 77.2, 75 and 72.2%, respectively. For irrigation levels 1 and 2, the six-day interval (WM_3 and WM_6) gave the best runs with transpiration ratio of 0.73 and 0.70, respectively, and model predicted relative yield of 90 and 87.6 %, respectively. For irrigation level 3, the five-day interval (WM_9) produced the best run with a transpiration ratio of 0.57 and model predicted relative yield of 82.1%, giving water yield index of 47.

T a b l e 5. Model computed evaporation, transpiration, deep percolation, predicted yield percentage, transpiration water ratio and water yield index for various water management (*WM*) using 1997 data

Parameter	WM_1	WM_2	WM_3	WM_4	WM_5	WM_6	WM_7	WM_8	WM_9
Irrigation amount (mm)	266	270	260	180	180	180	100	100	90
Number of irrigation	15	30	10	15	30	12	15	10	30
Model evaporation (mm)	75.7	82.6	63.2	75.7	82.6	66.2	75.7	63.2	82.6
Model transpiration (mm)	181.6	147.9	198.9	90.7	82.9	110.7	39.6	53.2	27.9
Deep percolation (mm)	17.2	43.9	8.5	15.3	18.8	7.5	2.0	-	-
Total water supply (mm)	274.5	274.4	270.6	181.7	184.3	184.4	117.3	116.4	110.5
Model predicted relative yield (%)	77.7	66.8	92.6	42.7	50.5	84.3	18.8	17.8	36.0
Transpiration water ratio	0.66	0.54	0.74	0.50	0.45	0.60	0.34	0.45	0.25
Water yield index	51	36	69	21	28	51	8	8	9

T a b l e 6. Model computed evaporation, transpiration, deep percolation, predicted yield percentage, transpiration water ratio and water yield index for various water management (*WM*) using 1999 data

Parameter	WM_1	WM_2	WM_3	WM_4	WM_5	WM_6	WM_7	WM_8	WM_9
Irrigation amount (mm)	257	240	250	210	210	210	145	150	144
Number of irrigation	17	30	10	17	30	10	17	30	12
Model evaporation (mm)	77.1	84.6	64.5	77.1	84.6	64.5	77.1	84.6	67.8
Model transpiration (mm)	185.4	134.4	201.6	147.6	122.5	162.4	82.4	77.6	99.4
Deep percolation (mm)	11.6	44.6	8.5	10.0	28.5	6.5	9.3	9.4	6.2
Total water supply (mm)	274.1	263.6	274.6	234.7	235.6	233.4	168.8	171.6	173.4
Model predicted relative yield (%)	77.2	62	90	75.0	68.4	87.6	72.2	64.3	82.1
Transpiration water ratio	0.67	0.51	0.73	0.62	0.52	0.70	0.49	0.45	0.57
Water yield index	52	32	66	47	36	61	35	29	47

Generally, the evaporation values were very high, constituting between 33 to 92% of the evapotranspiration values. This led to low transpiration water ratios and low water yield indexes. The highest water yield index obtained in the field was 69 for WM_3. Evaporation suppression using mulching or suitable means will go a long way in increasing the transpiration water ratio and the yield index.

Using the fourth management option, which is irrigating at specific depletion with fixed amount, could probably lead to better water management and higher water yield indexes than the second option used in this study. The option, however, requires tensiometer monitoring of the soil water content, which may be not be easily adopted by farmers in developing countries.

CONCLUSIONS

1. Field data were collected and used to modify, calibrate and test the CRPSM model for soil water budget parameters and yield of cowpea prediction. There was good agreement between model predicted and actual measured data.

2. From the simulation runs for irrigation scheduling, irrigating at six/five day interval produced the best schedule for irrigation levels one to three where there was none or little water stress.

3. Whereas frequent application of the irrigation at 2-day interval produced the best schedule for the fifth irrigation level in which there was severe stress.

4. The study showed that the developed model could be used successfully in the tropics to test many experimental possibilities, once it is calibrated for the local condition. While this will not eliminate further field research, it would reduce it and identify the relevant ones to be tried for higher water use efficiency.

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