

Evaluation of the FAO CROPWAT model for deficit-irrigation scheduling for onion crop in a semiarid region of Ethiopia

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Abstract

Deficit irrigation conserves water and minimizes adverse effects of excess irrigation. In this study, the applicability of the CROPWAT model in management of deficit irrigation was evaluated at Sekota Agricultural Research Center, Ethiopia. Water was applied using low head drippers. There were eight treatments with three replications: stress at 1st, 2nd, 3rd, and 4th growth stages and partial stresses of 50% ETC, 75% ETC with two controls of 25% ETC and 100% ETC of the water requirement throughout the growing season. The input data for CROPWAT program were climatic, rainfall, crop and soil data. Yield reductions simulated by CROPWAT program were comparable with yield reduction measured under field condition. Model efficiency and correlation coefficients of 98% were obtained. Based on the above comparative analysis, CROPWAT program could adequately simulate yield reduction resulting from water stress.

Key words: Growth stages, deficit irrigation, Ethiopia, CROPWAT model, onion.

Introduction

Regulated deficit irrigation provides a means of reducing water consumption while minimizing adverse effects on yield. CROPWAT model could play a useful role in developing practical recommendations for optimizing crop production under conditions of scarce water supply and instrument limitations for soil moisture monitoring (Smith, 1993). CROPWAT is a computer program for irrigation planning and management developed by FAO (Doorenbos and Pruitt, 1977). Based on daily water balance computations, the CROPWAT model can evaluate alternative water supply conditions and associated reductions in crop yield. However, it has been tested only in limited areas and only for few crops (Smith *et al.*, 2002). Results reported by the limited earlier evaluations of CROPWAT were not conclusive.

In north eastern parts of Ethiopia (Sekaota), onion is grown under irrigation for domestic use as well as for commercial purposes. The water application method is generally a low head or gravity drip irrigation. Because of acute water shortage during the dry season, much of the cultivable land in close proximity to the irrigation canals is left as fallow. In addition, water related dispute among farmers are common in the area. Therefore, optimal allocation of locally available water resources is a key to increase crop production. In this study, the FAO CROPWAT model was evaluated by comparing its predicted yield reductions against results of field experiment using onion as a test crop.

Materials and methods

Description of the study area: The field experiment was conducted at *Woleh* irrigation scheme, a research site of *Sekota* Dryland Agricultural Research Center in north eastern part of Ethiopia. The test crop, onion, is one of the major irrigable and marketable crops in the area. The mean annual rainfall in the area is 635 mm. The mean annual temperature ranges from 8°C to 21°C. The soil is medium textured.

Treatment setting: Bombay Red variety of onion was planted with a spacing between crops of 10 cm and spacing between rows of 20 cm in a 3 x 4 m plots. The experimental design consisted of completely randomized blocks with three replications. Within each block, eight irrigation regimes were randomly distributed (Table 1).

Installation of drip system: Low head drip irrigation was used for applying water. Each irrigation treatment consisted of 15 drip lines of length 4 m and each line serves 40 onion plants with a total of 600 plants in each plot. A total of 24 barrels were put on an elevation of one meter above ground to supply water to each of the treatments. The barrels height was calibrated and marked at

Table 1. Treatment setting for deficit irrigated onion field experiment at *Sekota* (Ethiopia)

Treatment*	Growth stage/period				Description
	P1	P2	P3	P4	
	Control				
1111 (T1)	1	1	1	1	All normal watering
0000 (T2)	0	0	0	0	All stress
	One period stress				
0111 (T3)	0	1	1	1	Stress during P1
1011 (T4)	1	0	1	1	Stress during P2
1101 (T5)	1	1	0	1	Stress during P3
1110 (T6)	1	1	1	0	Stress during P4
	Partial stress (%)				
50% Deficit (T7)	50	50	50	50	Throughout the growing season
25% Deficit (T8)	25	25	25	25	Throughout the growing season

*1- indicates normal watering - watering 100% of ETC.

0- (75% deficit) indicates stressed watering - watering 25% of ETC.

25%- Deficit was watering 75% of ETC.

50%- Deficit was watering 50% of ETC.

Table 2. Onion crop parameters for input into FAO CROPWAT deficit irrigation program in *Sekota* (Ethiopia)

Parameter	Growth stage (planted on 11 th November 2005)				
	Initial stage	Development	Mid-season	Late season	Total/ Seasonal
Length of growing season (days)	20	30	30	15	95
CROPWAT standard K _c (FAO, 1998)	0.70	>>>+	1.05	0.95	
Crop height (m)	0.12	0.30	0.40	0.40	
Rooting depth (m)	0.10	0.20	0.30	0.30	
Depletion level (fraction)	0.30	>>>	0.45	0.50	
Yield response factor (K _y) (FAO, 1998)	0.80	0.40	1.20	1.00	1.00

+ Intermediate values

one litre intervals. The amount of water that is needed to reach the plants was controlled by throttle valves on the sub-main lines.

CROPWAT input data: Calculations of water and irrigation requirements utilize inputs of climatic, crop and soil data, as well as irrigation and rain data. The climatic input data required are reference evapotranspiration and rainfall. Reference evapotranspiration was calculated using Eq. (1). The crop parameters used for estimation of crop evapotranspiration, water balance calculations, and calculation of yield reductions due to water stress include crop coefficient K_c, length of the growing season, critical depletion level, p and yield response factor K_y. Literature values of these parameters were adopted (Table 2) (Allen *et al.*, 1998).

The soil data include information on total available soil water content, initial soil water content at the start of the season, and maximum infiltration rate by double ring infiltrometer for runoff estimates.

Equations of FAO CROPWAT deficit irrigation model: The FAO Penman-Monteith method (Allen *et al.*, 1998) was used to calculate ET_o in CROPWAT Program as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2(e_a - e_d)}{[\Delta + \gamma(1 + 0.34U_2)]} \quad (1)$$

Where, ET_o = reference crop evapotranspiration (mm/day),

R_n = net radiation at crop surface (MJ/m².day),

G = soil heat flux (MJ/m².day),

T = average temperature (°C),

U₂ = wind speed measured at 2m height (m/s),

e_a - e_d = vapour pressure deficit (kpa),

Δ = Slope vapor pressure curve (kpa/°C),

γ = Psychometric constant (kpa/°C),

900 = conversion factor.

Crop water requirements (ET_c) over the growing season were determined from ET_o according to the following equation using crop coefficient K_c as:

$$ET_c = K_c \times ET_o \quad (2)$$

Where, ET_c = Crop water requirement, K_c = Crop coefficient, ET_o = reference evapotranspiration.

Crop coefficient K_c values as presented by (Allen *et al.*, 1998) were used. Crop irrigation requirements were calculated assuming optimal water supply and effective rainfall. Given water input into and output from the irrigation system, soil water retention and infiltration characteristics along with estimates of rooting depth; the model performs a daily soil water balance calculation to predict root zone soil water content.

Stress conditions in the root zone were in terms of critical soil water content, expressed as the fraction of total available soil water (soil water held between field capacity and wilting point), The critical soil water content is defined here as the soil moisture level below which crop transpiration is limited by soil water content. It varies for different crops and different crop growth stages and is determined by the root density of the crop, evaporation rate, and to some extent by the soil type. Allen *et al.* (1998) updated the estimates of critical soil moisture, representing onset of stress, previously reported by Doorenbos and Pruitt (1977) and Doorenbos and Kassam (1979). The effect of water stress on yield was quantified by relating the relative yield decrease to the relative evapotranspiration deficit with an empirical yield response function (Eq. 3):

$$\frac{Y}{Y_m - 1} = K_y \left(1 - \frac{ET_a}{ET_m}\right) \quad (3)$$

Where, Y and Y_m are expected and maximum crop yields, corresponding to ET_a and ET_m = ET_c, actual and maximum evapotranspiration, respectively; K_y is a crop yield response factor that varies depending on species, variety, irrigation method and management, and growth stage when deficit evapotranspiration is imposed.

Treatment setting for the CROPWAT program: The selected crop, onion was subjected to different watering regimes using the FAO-CROPWAT program in deficit irrigation mode. Four treatments in relation to stress during a specific growth stage, additional two treatments in relation to putting the crop (onion) under stress with a certain amount of irrigation water throughout the whole growth stages, and two controls, so a total of eight treatments were implemented.

Evaluation of the CROPWAT model as a deficit irrigation scheduling tool: Data from field experiment was used to verify the utility of the CROPWAT model in simulating deficit irrigation scheduling. The field experiment applied various irrigation water levels to onion crop, thus inducing water stress at various growth stages and throughout the growing season. Climatic, soil, and crop data collected through field experiments were used as inputs to the CROPWAT model. The yield of onion crop was used to validate the yield reduction extracted from the CROPWAT model.

Model efficiency (ME) developed by Nash and Sutcliffe (1970) is commonly used and seems appropriate to evaluate performance of models. The model efficiency was similar to the coefficient of determination (r²). However, the residual variation is calculated using the means of actual observations rather than values from the best regression line between observed and predicted values (Risse *et al.*, 1994; De Roo, 1993). Model efficiency was used to

determine goodness of fit between model prediction and measured values. It is defined as:

$$ME = \frac{\sum_{t=1}^n (Y_o - Y_p)^2}{\sum_{t=1}^n (Y_o - Y_m)^2} \quad (4)$$

Where, ME is model efficiency, Y_o and Y_p are measured and predicted values for event t and Y_m is the mean value of measured values for all events considered in the simulation study, and n = total number of events .

Results and discussion

Irrigation depths of water applied to each treatment is presented in Table 3. The depth of application presented is with variable depth and variable intervals to refill the soil moisture deficit. Irrigation was applied daily.

Table 3. Irrigation depths of deficit irrigated tomato experiment at Sekota (Ethiopia)

Date	Interval (d)	Treatments							
		T1	T2	T3	T4	T5	T6	T7	T8
Irrigation (mm)									
15 Nov	4	11.7	2.9	2.9	11.7	11.7	11.7	5.8	8.8
21 Nov	6	14.1	3.5	3.5	14.1	14.1	14.1	7.0	10.6
27 Nov	6	14.0	3.5	7.0	7.0	14.0	14.0	7.0	10.5
3 Dec	6	14.2	3.6	14.2	3.6	14.2	14.2	7.2	10.7
9 Dec	6	15.5	3.9	15.5	3.9	15.5	15.5	7.8	11.6
15 Dec	6	17.0	4.3	17.0	4.3	17.0	17.0	8.6	12.8
21 Dec	6	18.4	4.6	18.4	4.6	18.4	18.4	9.2	13.8
27 Dec	6	19.8	5.0	19.8	5.0	19.8	19.8	10.0	14.9
2 Jan	6	21.2	5.3	21.2	21.2	5.3	21.2	10.6	15.9
8 Jan	6	21.8	5.5	21.8	21.8	5.5	21.8	11.0	16.4
14 Jan	6	22.3	5.6	22.3	22.3	5.6	22.3	11.2	16.7
20 Jan	6	22.7	5.7	22.7	22.7	5.7	22.7	11.4	17.0
26 Jan	6	22.6	5.7	22.6	22.6	5.7	22.6	11.4	17.0
31 Jan	5	19.6	4.9	19.6	19.6	4.9	9.8	9.8	14.7
6 Feb	5	23.2	5.8	23.2	23.2	5.8	11.6	11.6	17.4
12 Feb	6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	95	278.1	69.8	251.7	207.6	195.3	246.0	139.6	208.8

Yield and water use efficiency of onion: Treatment T2 (0000) that received only one-fourth of the optimal irrigation water throughout the growing season produced 5.5 t ha⁻¹. As presented in Table 4, water deficit at first and fourth growth stages, resulted in non-significantly different yields from the optimum application T1 (1111). However, in no case the yields were higher than that in T1 (1111). When the water deficit is at the second and third growth stages (treatments T4 (1011) and T5 (1101), or during all stages T2 (0000), 50%, and 75%, the yields were significantly different from treatment T1 (1111).

Simulation of yield reduction of onion with CROPWAT model: Climatic, soil, and calibrated onion crop parameters presented in Table 2 were entered into FAO CROPWAT program for simulation of yield reduction. The next step was to analyze the treatments by entering the net irrigation requirement to refill the soil moisture deficit in the CROPWAT program to achieve the yield reduction to water stress imposed during the various crop growth stages and throughout the growing season. The simulated onion crop depletion levels in the experimental area were 0.30,

Table 4. Mean yield (t ha⁻¹) comparison using Duncan’s Multiple Range Test (DMRT)

Treatment	Yield*
T1 (1111)	25.00a
T2 (0000)	5.50e
T3 (0111)	24.00a
T4 (1011)	20.76b
T5 (1101)	17.50c
T6 (1110)	23.86a
T7 (50%)	13.80d
T8 (75%)	21.26b
Mean	18.96
Coefficient of variation	5.80

*Values followed by similar letters are not significantly different,

0.38, 0.45, and 0.50 at the initial, development, mid season, and late season stages respectively (Table 2). This implies that onion can not tolerate depletion levels of more than 30, 38, 45 and 50% at the initial, development, mid, and late stages, respectively. There will not be yield reduction until the respective depletion levels are reached at the respective stages. Yield reduction starts whenever the depletion is beyond the above indicated limits at the respective growth stages.

The simulated yield response factor values (K_y) in the respective growth stages indicated that whenever the value of K_y is less than unity, the relative yield reduction is less than relative evapotranspiration deficit. Stressing during those stages was advantageous to increase the overall water use efficiency. This means stressing at first and second stage was advantageous than stressing at the third stage. Table 5 presents the simulated yield reductions under different deficit irrigation levels using FAO CROPWAT program.

Table 5. Simulated yield reductions of onion under different water stress levels

Treatment	Irrigation (mm)	Yield reduction (%)	Rank
T1 (1111)	278.1	0.0	8
T2 (0000)	69.8	63.8	1
T3 (0111)	251.7	8.0	6
T4 (1011)	207.6	22.1	4
T5 (1101)	195.3	24.8	3
T6 (1110)	246.0	6.6	7
T7 (50%ETc)	139.6	41.6	2
T8 (75%ETc)	208.8	19.7	5

Comparison of yield reduction under field conditions and CROPWAT model simulation: Table 6 presents comparisons of measured yield reduction for each treatment at field conditions with the yield reductions simulated by the CROPWAT model. The yield reductions were expressed as percentages of the yield obtained under optimal irrigation T1 (1111).

From Table 6 it can be observed that the measured yield reductions are comparable to the simulated ones. Both model efficiency and correlation coefficient were 98%. From the student’s t-test, the value of t was calculated to be 17.15. Further, in the two tailed test, the value of r was calculated to be $r > 0.707$ and $r < -0.707$. Even if the value of r^2 was 0.98, the model was efficient at 5% significance level for the r values greater than 0.707 and less than -0.707 on the two tailed graphs.

Furthermore, in agreement to the field data, the simulated results

Table 6. Comparison of measured and CROPWAT simulated yield reductions for onion

Irrigation treatment	Measured		CROPWAT
	Yield (kg ha ⁻¹)	Yield reduction (%)	Yield reduction (%)
T1 (1111)	25000	0.0	0.0
T2 (0000)	5500	78.0	63.8
T3 (0111)	24000	4.0	8.0
T4 (1011)	20750	17.0	22.1
T5 (1101)	17500	30.0	24.8
T6 (1110)	23860	4.5	6.6
T7 (50%ETc)	13750	45.0	41.6
T8 (75%ETc)	21250	15.0	19.7

show that the impact of water stress on onion crop yield depends on growth stages. For example, water stresses at the third growth stage leads to a larger yield reduction than stress at second stage. Smith *et al.* (2002), in the validation of CROPWAT for deficit irrigation, had stated that yield reduction at third stage was more severe than yield reductions at first, second and fourth stages.

Data from field study were used to verify the applicability of the CROPWAT model in simulating deficit irrigation scheduling in the area. The yield reductions simulated by CROPWAT were comparable with the measured yield reduction at field condition with model efficiency and coefficient of correlation values of 98%. Furthermore, the simulated results reflected the impact of stress at different growth stages on yield reduction: stress at third stage leads to a higher yield reduction than stress at first, second and

fourth stages. Based on the above comparative analysis, it can be concluded that the CROPWAT model could adequately simulate yield reduction resulting from water stresses in the study area.

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