SIMULATION OF THE EFFECT OF WATER STRESS ON SOYBEAN YIELD AND WATER USE EFFICIENCY

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ABSTRACT

Yield-Stress model was calibrated and validated for soybean yield and consumptive use with data of four-year field trial at Beni Sweif Governorate, Egypt under two treatments of irrigation water quality (fresh and drainage). The goodness of fit between measured and predicted values by the model was tested by calculated percent difference between measured and predicted values of yield and consumptive use, in addition to root mean squared error and Willmott index of agreement. Then, the model was used to predict the effect of four deficit irrigation treatments (95, 90, 85, and 80% of full irrigation). Water use efficiency was calculated under all cases. The results showed that the model performance was highly acceptable in predicting soybean yield and consumptive use. Low yield losses occurred under both fresh and drainage deficit irrigation water as a result of saving of 15% of irrigation water. Water use efficiency was the highest under irrigation with 80% of full fresh or drainage water irrigation, which suggested that there is a high potentiality to save an ample amount up to 20% of the irrigation water to be used in cultivating more lands and increase soybean production.

Keywords: Yield-Stress model, Consumptive use, Fresh and drainage water irrigation

INTRODUCTION

Soybean occupies a unique position in science and agriculture, in addition of being a crop with enormous uses. Soybean is grown in almost all parts of the world for human consumption, industry and animal feed (Boydak et al. [1]). In Egypt, soybean growth period ranges usually between 100 and 120 days and requires 325-436 mm of irrigation water depending on the location (Ainer et al. [2]). The most important phenological growth stages of soybean, which need adequate water, are during pod development and seed fill (Kranz et al. [3]). These are the stages when water stress can lead to a significant decrease in yield. Stressful conditions, such as moisture deficiency reduces soybean yield. As the soybean plant ages from R1 (beginning bloom) through R5 (seed enlargement), its ability to compensate under stressful conditions decreases and yield losses could increase (Foroud et al. [4]).

Using simulation models to predict soybean yield under different water stress conditions could be very helpful in the management of deficit irrigation applications. Soil water balance based irrigation scheduling models use soil water budgeting over the root zone. A number of computerized simulation models for crop water requirements have been developed using this approach (Camp et al. [5]; Smith [6] and Foroud et al. [7]). These models need to be run by professionals. However, Yield-Stress model (Ouda [8]) was design to predict the effect of deficit irrigation scheduling on the yield of several crops and their consumptive water use. Furthermore, the model was designed to be used by non-professionals, where the input of the model is easy to prepare and the output of the model is very descriptive of the process of readily available water depletion from root zone after the application of each single irrigation. The model was used in irrigation optimization for sunflower grown under saline conditions (Ouda et al. [9]). The model was also used to predict maize yield grown under water stress (Ouda et al. [10]). Furthermore, the model was validated under skipping the last irrigation for barley then the model was exploited in irrigation management (Khalil et al. [11]). Similarly, the model was validated under deficit irrigation for sesame yield (Tantawy et al. [12]). These findings proved that the Yield-Stress model can be use with confidence to predict the yield of other crops.

The objectives of this research were: (i) To calibrate and validate Yield-Stress model for soybean yield and consumptive data for four growing seasons; (ii) To use Yield-Stress model in predicting soybean yield under deficit irrigation treatments; (iii) To determine water use efficiency of soybean under these deficit irrigation treatments

MATERIALS AND METHODS

1. Soybean field trials

Data for soybean yield and consumptive use were available from a four-year farm trial conducted at Beni Sweif Governorate (Middle Egypt) in 1998 to 2001 growing seasons. These data was obtained from a project called "Soil and Water Resource Management" done by Agricultural Research Center, Egypt in collaboration with ICARDA. Sufficient NPK was applied to insure optimum plants growth. Irrigation was applied according to governmental enforced irrigation intervals. Applied irrigation amounts were measured through discharge from defined portable pump. Soil moisture sampling was collected before irrigation to calculate the needed amount of applied irrigation water to reach field capacity. Consumptive use was calculated using the following equation (Israelsen and Hansen [13]):

$$CU = (\Theta_2 - \Theta_1) * Bd * ERZ \quad (1)$$

Where: CU = the amount of consumptive use (mm), Θ_2 = soil moisture percentage after irrigation, Θ_1 = soil moisture percentage before the following irrigation, Bd = bulk density (g/cm^3) and ERZ = effective root zone. Irrigation treatments were two treatments of water quality i.e. fresh and drainage irrigation. EC value of fresh water was equal to 0.48 dS/m, and it was equal to 0.9 dS/m for agricultural drainage water, which did not impose any salinity stress on the growing plants. Season length and seasonal weather parameters are included in Table (1).

Table (1): Season length and seasonal weather parameters of soybean grown in four growing seasons

Growing season	Season length (days)	Mean temperature (°C)	Relative humidity (%)	Wind speed (m/sec)	Solar radiation (MJ/m^2/day)
1998	101	28.6	56	1.4	25.8
1999	111	30.1	59	1.4	25.6
2000	100	31.0	58	1.4	25.8
2001	104	32.7	58	1.4	25.7

2. Yield-Stress model description

Yield-Stress model is a multi-year and a multi-crop simulation model. The model can be used by non-professionals, where the input of the model is easy to prepare and the output of the model is very descriptive of the process of the depletion of readily available water from root zone after the application of each single irrigation. Thus, the user can easily determine at which irrigation he could apply deficit irrigation. The Yield-Stress model uses a daily time step. The model requires weather data, management data and soil data. Weather data consist of maximum, minimum and mean temperature, relative humidity, solar radiation, wind speed. Management data composed of planting and harvest dates, season length, irrigation date and amount, FAO's crop coefficient at each growth stage (Allen et al. [14]). Soil data are consist of clay, silt, sand, organic matter, and $CaCO_3$ percentages. The model has three main components: soil water balance calculation routine, salinity stress routine and crop yield calculation routine.

3. Yield-Stress model calibration and validation

The model was calibrated for soybean yield and consumptive use and then the model was validated using the field trials data. The goodness of fit between measured and predicted values by the model was tested by calculated percent difference between measured and predicted values of soybean yield and consumptive use, in addition to root mean squared error (RMSE) (Jamieson et al. [15]) and Willmott index of agreement (Willmott [16]).

4. Prediction of soybean yield under deficit irrigation

Soybean yield was predicted under 95, 90, 85 and 80% of full irrigation with either fresh or drainage water irrigation amounts.

5. Water use efficiency calculation

Water use efficiency (kg/m^3) values under deficit irrigation were calculated by the following equation (Vites [17]).

$$\text{WUE} = \text{Grain yield (kg/ha)/Applied irrigation amount (m}^3\text{/ha)} \qquad (2)$$

RESULTS AND DISCUSSION

1. Soybean field trials

The measured amounts of applied irrigation water for soybean and its corresponding measured yield values are shown in Table (2). Soybean yield under the application of full irrigation amounts were significantly differed (one sided t-test, $P < 0.005$). Results in that table showed that the highest applied irrigation amount in both fresh and drainage water produced the highest soybean yield in 1999 growing season. This could be attributed to the fact the growing season of 1999 was the longest, compared with the rest of the growing seasons as a result of relatively low mean seasonal temperature (Table 1), which positively reflected on the final yield (Gardner et al. [18]). Contrary to that, the lowest applied irrigation water in 2001 growing season produced medium yield under fresh water irrigation and low yield under drainage water irrigation (Table 2). This is could be attributed to the high mean seasonal temperature that was prevailing during that growing season (Table 1), which could negatively affected soybean final yield.

Table (2): Irrigation amounts and corresponding soybean yield values under fresh and drainage water irrigation

Growing season	Fresh water irrigation		Drainage water irrigation	
	Irrigation amount (m^3/ha)	Yield (ton/ha)	Irrigation amount (m^3/ha)	Yield (ton/ha)
1998	4178	1.21	4236	1.34
1999	4558	2.26	4716	1.78
2000	4236	1.73	4306	1.56
2001	3901	1.73	4023	0.88

2. Yield-Stress model Validation

2.1. Prediction of soybean yield

The model predicted soybean yield with high degree of precision under both fresh and drainage irrigation amounts, except for 2001 growing season. Percent difference between measured and predicted yield values was less than 1% in 1998 and 1999 growing season for both fresh and drainage water irrigation. It was less than 2% in 2000 growing season and it was 3.47 and 2.27% for fresh and drainage irrigation water, respectively in 2001 growing season. RMSE was 0.0340 and 0.0189 ton/ha under fresh and drainage water irrigation, respectively. Willmott index of agreement was close to one under both fresh and drainage irrigation amounts (Table 3). Similar results were obtained when soybean yield was predicted by Yield-Stress model at Giza Governorate (Ouda et al. [19]) and at Nubaria region (Ouda et al. [20]). CROPGRO-Soybean model predicted soybean seed yield with a percent difference between measured and predicted values about 4.26% (Dogan et al. [21]). Whereas, RZWQM model simulated soybean seed yield by a 0.7% overestimation (Neilsen et al. [22]).

Table (3): Measured versus predicted soybean yield grown under fresh and drainage irrigation

Growing Season	Fresh water irrigation			Drainage water irrigation		
	Yield (ton/ha)		PD %	Yield (ton/ha)		PD %
	Measured	Predicted		Measured	Predicted	
1998	1.21	1.20	0.83	1.34	1.33	0.75
1999	2.26	2.24	0.88	1.78	1.77	0.56
2000	1.73	1.70	1.73	1.56	1.54	1.28
2001	1.73	1.67	3.47	0.88	0.86	2.27
RMES	0.0340			0.0189		
WI	0.9898			0.9899		

PD%= percent difference between measured and predicted values; RMSE= root mean square error; WI= Willmott index of agreement.

2.2. Prediction of consumptive use

Regarding to soybean consumptive use prediction under both fresh and drainage water irrigation amounts, there was a good agreement between measured and predicted values. Percent difference between actual and predicted values were less than 4%, RMSE was 0.0940 cm and Willmott index of agreement was 0.9598 under fresh water irrigation (Table 4). Regarding to drainage water irrigation, Percent difference between measured and predicted was less than 3%, RMSE was 0.0884 cm and Willmott index of agreement was 0.9698. These results were in agreement with what was found by Ouda et al. [20] and Ouda et al. [19]. CROPGRO-Soybean model predicted consumptive use of soybean with a percent difference about 5.30% (Dogan et al. [21]).

Whereas, RZWQM model simulated soybean consumptive use by 4.00% overestimation between measured and predicted values (Neilsen et al. [22]).

Table (4): Measured versus predicted consumptive use for soybean grown under fresh and drainage irrigation

Growing season	Fresh water irrigation			Drainage water irrigation		
	CU (cm)		PD	CU (cm)		PD
	Measured	Predicted	%	Measured	Predicted	%
1998	34.67	33.40	3.66	35.68	34.72	2.69
1999	39.36	38.19	2.97	39.10	38.29	2.07
2000	37.26	36.75	1.37	37.90	36.83	2.82
2001	38.29	39.11	2.14	40.17	39.55	1.54
RMSE WI	0.0940 0.9598			0.0884 0.9698		

PD%= percent difference between measured and predicted values; RMSE= root mean square error; WI= Willmott index of agreement.

Figures (1) and (2) illustrated the accuracy of the model in predicting consumption use of soybean plants between individual irrigations under fresh and drainage water irrigations in 1998 growing season. Under both water quality treatments, soybean received 6 irrigations. Regarding to fresh water irrigation (Figure 1), the predicted consumptive use after the application of each irrigation was very close to the measures values, except for the measured values after the first irrigation. Similar results are shown for drainage water irrigation (Figure 2), with larger difference between the predicted and the measured values of the consumptive use after the first irrigation.

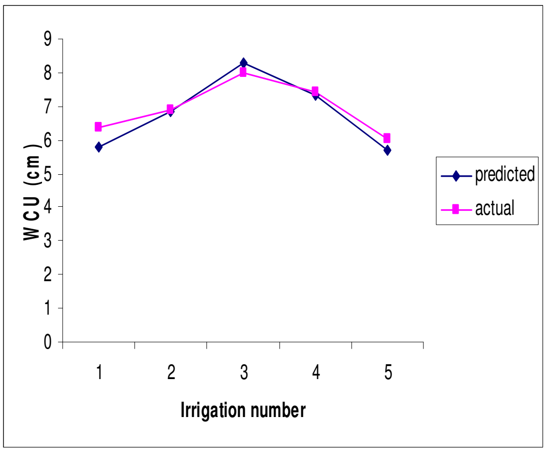

Figure (1): Actual and predicted water consumptive use for each individual fresh water irrigation for soybeans 1998 growing season.

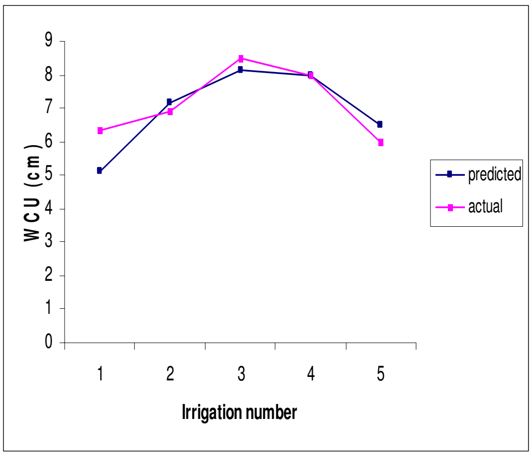

Figure (2): Actual and predicted water consumptive use for each individual drainage water irrigation for soybeans planted in 1998 growing season.

3. Prediction of the effect of deficit irrigation

3.1. Prediction of soybean yield

Predicted soybean yield under different deficit irrigation treatments and its reduction percentage under fresh water irrigation are presented in Table (5). The results indicated that in 1998, 2000 and 2001 growing seasons, 15% of full irrigation could be safely saved with yield reduction around 5%. However, in 1999 growing season, only 10% of full irrigation could be saved with less than 4% yield reduction. Ouda et al. [19] stated that saving 7% of the applied irrigation water for soybean reduce yield by 4% at Giza Governorate.

Table (5): Predicted soybean yield and its reduction percentage under different deficit fresh irrigation water

Irrigation	1998		1999		2000		2001	
	Predicted yield (ton/ha)	PR %	Predicted yield (ton/ha)	PR %	Predicted yield (ton/ha)	PR %	Predicted yield (ton/ha)	PR %
FI	1.20	0	2.24	0	1.70	0	1.67	0
95% of FI	1.19	0.83	2.22	0.89	1.69	0.59	1.65	1.20
90% of FI	1.17	2.50	2.16	3.57	1.67	1.76	1.61	3.59
85% of FI	1.15	4.17	2.07	7.59	1.63	4.12	1.58	5.39
80% of FI	1.12	6.67	2.04	8.93	1.58	7.06	1.53	8.38

FI= full irrigation (m^3/ha); 95% of FI= 95% of full irrigation; 90% of FI= 90% of full irrigation; 85% of FI= 85% of full irrigation; 80% of FI= 80% of full irrigation; PR%= percent reduction between measured and predicted yield.

Under drainage water irrigation, 15% of full irrigation water could be saved under the four growing seasons, with yield reduction as high as 5% (Table 6). Applying 80% of full irrigation reduced soybean yield by up to 9% in all growing seasons.

Table (6): Predicted soybean yield and its reduction percentages under different deficit drainage irrigation water

Irrigation	1998		1999		2000		2001	
	Predicted yield (ton/ha)	PR %	Predicted yield (ton/ha)	PR %	Predicted yield (ton/ha)	PR %	Predicted yield (ton/ha)	PR %
FI	1.34	0	1.77	0	1.54	0	0.86	0
95% of FI	1.32	0.75	1.75	1.13	1.53	0.65	0.85	1.16
90% of FI	1.29	3.01	1.72	2.82	1.50	2.60	0.83	3.49
85% of FI	1.26	5.26	1.68	5.08	1.47	4.55	0.82	4.65
80% of FI	1.21	9.02	1.62	8.47	1.43	7.14	0.80	6.98

FI= full irrigation (m^3/ha); 95% of FI= 95% of full irrigation; 90% of FI= 90% of full irrigation; 85% of FI= 85% of full irrigation; 80% of FI= 80% of full irrigation; PR%= percent reduction between measured and predicted yield.

3.2. Prediction of consumptive use

The reduction in soybean consumptive use as a result of applying either fresh or drainage deficit irrigation was tabulated with its corresponded yield reduction values (Tables 7 and 8). The presented results showed that under the investigated deficit fresh irrigation treatments, the reduction in the consumptive use values under deficit irrigation followed a trend similar to the reduction percentages of soybean yield under all growing seasons. This is clearly reflecting the existed relationship between the two studied parameters. The lesser is the volume of applied irrigation water, the greater is the reduction in both soybean yield and consumptive use percentages. This was also the case when irrigation was practiced with drainage water. However, within the four successive growing seasons, the reduction in soybean consumptive use under irrigation with drainage was lower, compared with irrigation using fresh water amount (Tables 7 and 8).

Table (7): Percent reduction in predicted soybean yield and consumptive use under deficit fresh irrigation water

Irrigation	1998		1999		2000		2001	
	PY %	PCU %	PY %	PCU %	PY %	PCU %	PY %	PCU %
95% of FI	0.83	1.02	0.89	1.10	0.59	1.17	1.20	1.94
90% of FI	2.50	2.46	3.57	4.08	1.76	2.56	3.59	5.50
85% of FI	4.17	4.52	7.59	9.24	4.12	4.49	5.39	8.00
80% of FI	6.67	7.66	8.93	10.40	7.06	7.40	8.38	10.53

FI= full irrigation (m^3/ha); 95% of FI= 95% of full irrigation; 90% of FI= 90% of full irrigation; 85% of FI= 85% of full irrigation; 80% of FI= 80% of full irrigation; PY%= percent reduction between measured and predicted yield; PCU= percent reduction between measured and predicted consumptive use.

Generally, under irrigation with water of EC values exceeding that of the fresh water, it is expected that the predicted reduction in the consumptive use under the investigated deficit irrigation treatments (Table 7) will be with lower percentages than those where irrigation was practiced with fresh water (Table 8). This was quite evident in the case of the soybean crop. The reduction percentages in the consumptive use under deficit drainage irrigation treatments shown to be with values either very near or slightly greater than those predicted under fresh water irrigation. Such dissimilarity in this parameter under the drainage irrigation as compared with the fresh water irrigation could be attributed to the variation in the soybean yield under both irrigation water sources and the predicted yield losses under deficit irrigation.

Table (8): Percent reduction in predicted soybean yield and consumptive use under deficit drainage irrigation water

Irrigation	1998		1999		2000		2001	
	PY %	PCU %	PY %	PCU %	PY %	PCU %	PY %	PCU %
95% of FI	0.75	1.01	1.13	0.73	0.65	1.17	1.16	0.94
90% of FI	3.01	2.94	2.82	2.32	2.60	2.77	3.49	3.84
85% of FI	5.26	5.70	5.08	6.24	4.55	4.70	4.65	5.71
80% of FI	9.02	9.01	8.47	10.86	7.14	7.52	6.98	8.42

FI= full irrigation (m^3/ha); 95% of FI= 95% of full irrigation; 90% of FI= 90% of full irrigation; 85% of FI= 85% of full irrigation; 80% of FI= 80% of full irrigation; PY%= percent reduction between measured and predicted yield; PCU= percent reduction between measured and predicted consumptive use.

4. Water use efficiency under deficit irrigation

The highest value of water use efficiency could be obtain under 80% of full irrigation for either fresh or drainage irrigation under all growing seasons (Table 9). The highest value of water use efficiency under both fresh and drainage water irrigation was obtained in 1999 growing season i.e. 0.56 and 0.43 kg/m^3, respectively. Soybean yield was the highest in 1999 growing season, which was produced with large amount of irrigation amount of both fresh or drainage irrigation water (Table 2). This result implied that the agro-climatological condition that was prevailed in 1999 growing season were suitable for soybean plants (Table 1), which enhanced growth and resulted in higher yield (Table 2). The results in that table also implied that, under the four growing seasons, it is very safe to conserve 20% of the applied irrigation water (fresh or drainage) because water use efficiency was the highest.

Table (9): Water use efficiency for soybean grown under both fresh and drainage water irrigations

Irrigation	Water use efficiency (kg/m^3)							
	1998		1999		2000		2001	
	Fresh	Drainage	Fresh	Drainage	Fresh	Drainage	Fresh	Drainage
FI	0.29	0.32	0.49	0.38	0.40	0.36	0.43	0.21
95% of FI	0.30	0.33	0.51	0.39	0.42	0.37	0.45	0.22
90% of FI	0.31	0.34	0.53	0.41	0.44	0.39	0.46	0.23
85% of FI	0.32	0.35	0.53	0.42	0.45	0.40	0.48	0.24
80% of FI	0.34	0.36	0.56	0.43	0.47	0.42	0.49	0.25

FI= full irrigation (m^3/ha); 95% of FI= 95% of full irrigation; 90% of FI= 90% of full irrigation; 85% of FI= 85% of full irrigation; 80% of FI= 80% of full irrigation.

CONCLUSION

Modeling has become a major research tool in agriculture for resource management, which could help in extending findings and conclusions to conditions not tested in the field. Because water scarcity became a major cause of crops yield reduction, a more rational use of irrigation water should be adapted and deficit irrigation principles should be accepted with a certain level of reduction in yield level (Hamdy et al. [23]). Therefore, modeling yield reduction under deficit irrigation is very important procedure to be done to conserve time and effort.

Yield-Stress model employed the soil water depletion equations to instantly predict potential soybean yield and consumptive use. The good agreement between measured and predicted yield values strongly suggested that the model can be used with confidence in simulating soybean yield under different levels of deficit irrigation.

Our results showed that applying irrigation water with 85% of full irrigation volume to soybean could be safely practiced, which resulted in less than 5% reduction in soybean yield under both fresh and drainage water irrigation. Furthermore, water use efficiency was the highest under deficit irrigation application of 80% of full irrigation, which could emphasize on the benefits of saving more irrigation water to be used in cultivating more land and increase crops production horizontally.

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