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Using Yield-Stress Model in Irrigation Management for Wheat Grown in Egypt

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Abstract

Two field trials were conducted at three sites in Egypt to study the effect of deficit irrigation on wheat yield and consumptive water use. The first trial was conducted at Beni Sweif governorate, where data was available from 1998/99 to 2001/02 growing seasons. The second trial was conducted at two sites i.e. El-Monofia and Demiatte governorates, where data were available for the 2005/06 growing season for 3 and 4 farms, respectively. The objectives of this research were: (i) to validate the Yield-Stress model for wheat yield data at three sites in Egypt; (ii) to predict wheat yield under reducing the amount of applied irrigation water; (iii) to test the capability of the Yield-Stress model in irrigation scheduling and conserving water. The Yield-Stress model was validated under the application of the full irrigation amounts at the three sites and under deducting about 20% of full irrigation at El-Monofia and Demiatte sites. Afterward, the model was used to predict wheat yield under deducting 30% of full irrigation at the three sites. Results showed that there was a good agreement between measured and predicted yield at the three sites. Results also indicated that under deducting 30% of full irrigation, wheat yield will be reduced by less than 6% at the three sites. Furthermore, using the model in studying the depletion of readily available water from the root zone at the three sites could help in saving up to 24% of the applied irrigation water with almost no wheat yield losses.

Key words: consumptive water use, readily available water, irrigation rescheduling, irrigation water saving.

INTRODUCTION

In Egyptian agriculture, more irrigation water is applied than crops need. A common irrigation practice of Egyptian farmers is to apply a large amount of irrigation water every three weeks for winter crops, without any estimates of soil water contents in the root zone. Their rationale for doing so is that the assumption that more irrigation water means more yields. On the contrary, eliminating unnecessary irrigation water could help in conserving irrigation water, provided that it can be done with low yield losses. The estimation of soil water reserve in the root zone area is essential for best irrigation management. Irrigation management can be done by modeling water depletion from root zone under the application of different amounts of irrigation water [1]. Models that simulate crop growth and water flow in the root zone can be a powerful tool for extrapolating findings and conclusions from field studies to conditions not tested [2]. Several simulation models for crop water requirements have been developed using this approach ([3], [4], [5], and [6]). These models have been widely accepted, but their adoption by farmers has been very slow because it needs to be run by professionals.

In this context, the Yield-Stress model [7] was designed to predict the effect of deficit irrigation scheduling on the yield of several crops and their consumptive water use. The model was developed to be used as an easy irrigation management tool by non-professionals. Basically, the Yield-Stress model assumes that there is a linear relationship between available water and yield, where reduction in available water limits evapotranspiration and consequently reduced yield. This assumption is supported by the work of several researchers ([8], [9], [10] and [11]).

The Yield-Stress model was tested in irrigation management for several crops under different stress conditions and its performance was acceptable. The model was used in irrigation optimization for sunflower grown under saline conditions [12] and was used to predict maize yield grown under water stress [13. Furthermore, the model was validated under skipping the last irrigation for barley and then the model was exploited in different irrigation management practices [1]. Similarly, the model was validated under deficit irrigation for sesame yield [14]. Therefore, the Yield-Stress model could be utilized for developing different irrigation management scenarios for an important crop, such as wheat to save irrigation water and to minimize yield losses.

Wheat is a very important cereal crop in Egypt. The crop is very sensitive to the timing of a water deficient period rather than the reduction of the applied irrigation water. Exposing wheat plants to high water stress reduced seasonal consumptive use and grain yield ([15] and [16]). During vegetative growth, phyllochron decreases in wheat under water stress [17], leaves become smaller, which might reduce the leaf area index [18] and the number of reproductive tillers could decrease, in addition to limit their contribution to grain yield [19]. Furthermore, water

Table 1. Soil chemical and physical analyses at the three sites

Site	N (ppm)	P (ppm)	K (ppm)	Sand %	Silt %	Clay %	pH (1:2.5)	EC dS/m
Beni Swief	88	12.2	1050	13.20	36.60	50.20	7.4	0.48
El-Monofia								
Farm 1	100	24	430	27.37	32.10	40.53	8.1	0.51
Farm 2	95	17	420	23.98	32.96	43.26	8.2	0.41
Farm 3	75	13	390	31.48	37.41	31.11	8.0	0.44
Demiatte								
Farm 1	36	11	570	23.99	26.43	49.58	8.1	1.9
Farm 2	35	10	600	18.90	32.28	48.22	8.3	2.2
Farm 3	40	12	620	17.76	37.95	44.29	8.2	1.8
Farm 4	33	10	680	22.15	32.41	45.44	8.4	2.8

stress occurring during grain growth could have a severe effect on the final yield compared with stress occurring during other stages [20]. The amount of wheat yield reduction as a result of water stress is affected by the stage of grain development, where the early grain development stage is the most vulnerable [21]. Thus, modeling can assist in determining when to reduce the amount of applied irrigation water to wheat plants and what would be the estimated yield losses.

The objectives of this research are: (i) to validate the Yield-Stress model for wheat yield data at three sites in Egypt; (ii) to predict wheat yield under reducing the amount of applied irrigation water; (iii) to test the capability of the Yield-Stress model in irrigation rescheduling to conserve water.

MATERIALS AND METHODS

The aim of this study was to use Yield-Stress model in predicting wheat yield under deficit irrigation and to use the model in irrigation water saving. Data of wheat yield and consumptive water use were available from two trials at three sites in Egypt. The first trial was carried out at Beni Sweif governorate (Middle Egypt), where data from 1998/99 to 2001/02 growing seasons were available. These data were obtained from a project called "Soil and Water Resource Management" of the Agricultural Research Center, Egypt in collaboration with ICARDA. The second trial was conducted at two sites i.e. El-Monofia governorate (Delta region) and Demiatte governorate (costal region). These data was obtained from a current project called "Community-Based Optimization of the Management of Scarce Water Resources in Agriculture in West Asia and North Africa" also implemented by Agricultural Research Center, Egypt in collaboration with ICARDA in the 2005/06 growing season. At El-Monofia site, data were available from three farms, whereas at Demiatte site data were available from four farms. At all three sites, wheat was planted in rows. Data on soil chemical and chemical analyses (done before planting) for the three sites are presented in Table 1.

The recommended doses of NPK were applied at the three sites. Nitrogen fertilizer was divided into 3 doses, at sowing, at tillering and at boating stages and was applied in the form of urea (46% N). Phosphorus fertilizer was incorporated into the soil during land preparation in the form of mono super phosphate. Potassium in the form of potassium sulphate (48% K_2O) was applied at boating stage at the El-Monofia and Demiatte sites only. Irrigation was applied according to governmental enforced irrigation intervals at the three sites. Table (2) shows seasonal weather parameters for the studied growing seasons at the three sites.

On-farm trials

Beni Sweif governorate (old land)

Beni Sweif governorate is classified as an old land. Wheat was planed in the recommended 2nd week of November on all the four growing seasons. The applied amounts of nitrogen and phosphorus fertilizer were 168 and 36 kg/ha, respectively. Applied amounts of irrigation water were measured through discharge from a calibrated portable pump. The soil water content was determined before irrigation to calculate the required amount of applied irrigation water to reach field capacity. The applied amount of irrigation water was the amount of soil water that removed from the soil profile plus 20% to satisfy the leaching requirement. Consumptive water use was calculated before each irrigation using the following equation [22].

$$CWU = (\Theta_2 - \Theta_1) * BD * ERZ \quad (1)$$

Table 2. Seasonal weather parameters for wheat planted at the three sites

Season	Mean temperature (ºC)	Relative humidity (%)	Wind speed (m/sec)	Solar radiation (Mj/m²/day)	Rain (mm)
Beni Swief 1998/99	16.5	62	1.3	16.1	6
1999/00	18.0	63	1.3	16.1	5
2000/01	19.1	64	1.3	16.3	7
2001/02	19.1	63	1.3	16.3	4
El-Monofia	15.4	69	2.3	14.76	41
Demiatte	15.1	70	2.6	13.99	78

Where: CWU=the amount of consumptive use (mm); Θ_2=soil water percentage after irrigation; Θ_1=soil water percentage before the following irrigation BD=bulk density in g/cm^3; ERZ= effective root zone. The wheat plants were harvested in the last week of April

El-Monofia governorate (old land)

Three farms were picked at that site. The first two farms were located on an improved water mesqua (=small water canal), whereas the third one was located on a non-improved water mesqua. Wheat was planed on November 18, 2005 at the three farms. The planted variety was Gemiza 9. NPK rates were 180, 36 and 57 kg/ha, respectively. At this site, irrigation water is usually more frequently available in the improved water mesqua, compared with the non-improved water mesqua. The farmer decided on when to apply irrigation water and the amount he wanted to apply. The applied amount of irrigation water was determined using cutthroat flume for surface irrigation. Two irrigation treatments were used: the farmer irrigation and about 80% of farmer irrigation, which was imposed on the third irrigation. Consumptive water use was calculated using CROPWAT model [4]. Seasonal weather parameters during the growing season of 2005/06 are shown in Table (2). During harvest, in the last week of April, wheat yield was measured at each farm.

Demiatte Governorate (marginal land)

With their salt affected soil, the lands of this site are considered marginal. However, soil salinity at that site did not impose a stress on wheat plants because soil EC was less than EC threshold of wheat (Table 1). Wheat was planted during the first two weeks of November at the four farms. The applied amount of NPK fertilizer was similar to that applied at the El-Monofia site. Four farms were used in the trial. The first two farms used fresh water (EC =0.48 ds/m) for irrigation, whereas the other two farms used either fresh or agricultural drainage water, depending on the availability of fresh water in the water mesqua. Similar to the El-Monofia site, the amount of irrigation water was determined using a cutthroat flume for surface irrigation. Two irrigation treatments were used: farmer irrigation and about 80% of farmer irrigation. Furthermore, consumptive water use was calculated using equation (1). At harvest in the last week of April, wheat yield was measured at each farm.

Yield-Stress Model Description

The main premise of Yield-Stress model [7] is to predict crop yield under deficit irrigation for a certain farm, based on measured yield under the application of full irrigation amount. Furthermore, it is necessary that the predicted yield value under the application of full irrigation amounts to be as the same as the value of measured yield or a little bit lower; otherwise predicted yield under deficit irrigation will be far from the measured yield value under deficit irrigation. 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 the root zone after the application of each individual irrigation. Thus, the user can easily determine at which irrigation he can reduce the applied amount.

The Yield-Stress model uses a daily time step. The model requires two types of input data. Input data by the user and input data file. The model asks the user to input planting and harvesting date, the length of the growing season, and crop yield. The model also asks the user to input soil characteristics i.e. clay, silt, sand, organic matter, and $CaCO_3$ percentages. The other input data source is a file represent the whole growing season, starts with sowing month and date, and ends with harvesting month and date. The file contains maximum, minimum and mean temperature, relative humidity, solar radiation, wind speed, FAO's crop coefficient and the date and the amount of each individual irrigation. The model has two components, soil water balance estimation and crop yield estimation.

Soil water balance is determined by calculating daily crop evapotranspiration (ET_{crop}) using Penman Montieth method and the amount of readily available water in the root zone using the methods describes in FAO publication Nº 56 [23]. Then, the model calculates the depletion of readily available water from the root zone by deducting the calculated daily value of ET_{crop} from the amount of readily available water at the root zone. If the amount of readily available water at the root zone completely depleted before the occurrence of the following irrigation, water stress prevailed and a water stress coefficient is calculated and used to calculate ET_{crop} adjusted.

The model calculates crop yield on a daily basis as a function of water consumption. The model calculates a daily value of the accumulated yield throughout the growing season by divided the measured yield by season length. The model accumulates yield by choosing one of two alternatives. If predicted readily available water is greater than predicted ET_{crop}, the daily value of accumulated yield would equal to the calculated mean yield value. On the contrary, if predicted readily available water is lower than predicted ET_{crop}, the value of the predicted yield will be reduced in relation to the reduction in daily water consumption.

Validation of the Yield-Stress model under full and deficit irrigation

The model was validated under full and deficit irrigation for El-Monofia and Demiatte sites. Furthermore, the model was used to predict potential yield reduction, if 30% of the full applied amount was deducting at these two sites. Regarding to Beni Sweif site, the model was validated under full irrigation amounts, where no data were available for deficit irrigation yield. Then, the model was used to predict the expected yield if full irrigation amount was reduced by 20 and 30% for Beni Sweif site. Under full irrigation at the three sites, if the predicted yield was lower than measured yield by more than 0.5%, the data of this farm was excluded from the analysis. Furthermore, the model was also used in irrigation rescheduling to save irrigation water at the three sites.

Finally, the accuracy of the model was tested by calculated percent difference between measured and predicted values of wheat yield and consumptive water use, in addition to root mean squared error (RMSE) and Willmott index of agreement [24]. Regression analysis was done to test the strength of the relationship between measured and predicted values.

RESULTS

On-field trials

The measured amounts of applied irrigation water and its corresponding measured yield values at Beni Sweif site are shown in Table (3). Wheat yields were significantly different (one sided t-test, $P < 0.05$) under the application of full irrigation amounts. Results in that table showed that the lowest measured irrigation amount produced the highest measured wheat yield in 2001/02 growing season.

Table 3. Irrigation amounts of applied water and corresponding wheat yield at Beni Sweif site

Growing season	Applied irrigation amounts (mm)	Wheat yield (ton/ha)
1998/99	493.2	5.28
1999/00	542.6	5.73
2000/01	492.0	5.74
2001/02	489.1	6.82

Results in Table (4) indicated that there is a quite large variation in the measured yield of the three farms at El-Monofia site and the four farms at Demiatte site, probably because each farmer applied his own technique in growing wheat. Regarding to El-Monofia site, results in that table also showed that there is a potential to save irrigation water in farm 1 and 2 under deducting 20% of full irrigation, where yield reduction was 0 and 2.89%, respectively. However, the situation was different for the third farm, where the reduction was 14.32%. Wheat yields under the application of full irrigation amounts were significantly higher than those under applying 80% of full irrigations (one sided t-test, $P < 0.05$) at El-Monofia site.

Low yield reduction was also observed in three farms out of four at Demiatte site, where yield reduction was between 1.79-3.30% under deducting 20% of full applied irrigation amounts (Table 4). Whereas, yield reduction was 8.06% for the fourth farm. Wheat yields under the application of full irrigation amounts were significantly different than those under applying 80% of full irrigations (one sided t-test, $P < 0.01$) at Demiatte site.

Table 4. Irrigation amounts, corresponding wheat yield and percent of yield reduction under deficit irrigation at El-Monofia and Demiatte sites

Farm	Irrigation amounts (mm)		Wheat yield (ton/ha) under		Yield reduction (%)
	Full	Deficit	Full irrigation	Deficit irrigation	
El-Monofia Farm 1	540.0	435.7	9.43	9.43	0
Farm 2	557.1	430.0	7.61	7.39	2.89
Farm 3	511.0	396.2	7.75	6.64	14.32
Demiatte Farm 1	595.1	463.1	5.60	5.50	1.79
Farm 2	587.0	455.0	5.25	5.15	1.90
Farm 3	590.0	449.0	4.55	4.40	3.30
Farm 4	592.0	447.0	6.20	5.70	8.06

Yield-Stress model evaluation

Wheat yield prediction under the application of full irrigation amounts

The Yield-Stress model was run using full irrigation amounts at the three sites. Results in Table (5) showed that, at Beni Swief site, percent difference between measured and predicted wheat yield was either zero or less than 0.5%. Zero percent difference between measured and predicted yield implied that the amount of readily available water at soil profile was abundant and there was no water stress. On the other hand, low percent difference between measured and predicted yield implied that the growing plants suffered from few days of water stress. Similarly, the predicted consumptive water use was close to the measured value of the four growing seasons. The highest difference between measured and predicted consumptive water use was obtained in 1998/99 growing season (Table 5).

Table 5. Measured versus predicted wheat yield and consumptive water use at Beni Sweif site under applying full irrigation amounts

Season	Yield (ton/ha)		% difference	CWU (mm)		% difference
	Measured	Predicted		Measured	Predicted	
1998/99	5.28	5.28	0	400.4	410.3	2.47
1999/00	5.73	5.73	0	412.8	418.8	1.45
2000/01	5.74	5.73	0.17	447.3	443.2	0.92
2001/02	6.82	6.79	0.44	449.0	458.4	2.09

CWU= consumptive water use

Similar results were obtained at El-Monofia site, where percent difference between measured and predicted yield was also less than 0.5% (Table 6). The highest difference between measured and predicted consumptive water use was obtained for the first farm (1.77%).

Table 6. Measured versus predicted wheat yield and consumptive water use at El-Monofia site under applying full irrigation amounts.

Farm	Yield (ton/ha)		% difference	CWU (mm)		% difference
	Measured	Predicted		Measured	Predicted	
Farm 1	9.43	9.41	0.21	321.5	315.8	1.77
Farm 2	7.61	7.61	0	312.2	311.5	0.22
Farm 3	7.75	7.74	0.13	321.5	319.0	0.78

CWU= consumptive water use

Regarding to Demiatte site, there was no difference between measured and predicted yield (Table 7). This is an indication that the amount of applied irrigation water was enough to meet evapotranspiration demand. Furthermore, the difference between measured and predicted consumptive water use was less than 0.5%, except for the 4th farm, where it was 1.63% (Table 7).

Table 7. Measured versus predicted wheat yield and consumptive water use at Demiatte site under applying full irrigation amounts.

Farm	Yield (ton/ha)		% difference	CWU (mm)		% difference
	Measured	Predicted		Measured	Predicted	
Farm 1	5.60	5.60	0	318.6	319.9	0.41
Farm 2	5.25	5.25	0	312.8	314.2	0.45
Farm 3	4.55	4.55	0	337.4	336.2	0.36
Farm 4	6.20	6.20	0	343.8	349.4	1.63

CWU= consumptive water use

Wheat yield prediction under deficit irrigation amounts

The model was used to predict wheat yield under applying about 80% of the full applied irrigation amounts at El-Monofia site (Table 8). Predicted wheat yield was close to measured yield for two farms out of the three. RMSE was 0.048 ton/ha and Willmott index of agreement was 0.977. [25]Lobell and Ortiz-Monasterio (2006) stated that CERES-Wheat model was able to predict wheat yield for the different irrigation trials quite well with a RMSE of 0.23 ton/ha. Regression analysis between measured and predicted wheat yield at El-Monofia site had a significant linear relationship ($P < 0.05$), with equation $y = -2.278 + 1.278\ x$ ($R^2 = 0.991$). Predicted consumptive water use was also close to the measured consumptive water use, except for the 3rd farm. RMSE was 0.040 cm and Willmott index of agreement was 0.999 (Table 8). A statistically significant relationship ($P < 0.05$) was found between measured and predicted consumptive water use, with equation $y = 30.00 + 0.018\ x$ ($R^2 = 0.691$).

Table 8. Measured versus predicted wheat yield and consumptive water use at El-Monofia site under deducting 20% of the full irrigation

Farm	Yield (ton/ha)		% difference	CWU (mm)		% difference
	Measured	Predicted		Measured	Predicted	
Farm 1	9.43	9.18	2.65	305.4	306.8	0.45
Farm 2	7.39	7.45	0.81	306.0	309.9	1.29
Farm 3	6.64	7.07	6.48	305.4	288.6	5.51
RMSE		0.048		0.040		
Willmott index		0.977		0.999		

CWU= consumptive water use

Regarding to Demiatte site and under about 20% deficit of farmer applied amount, there was a good agreement between measured and predicted wheat yield and consumptive water use at three farms out of the four. Percent difference between measured and predicted yield and consumptive water use was high for the 4th farm. RMSE was 0.039 ton/ha and 0.040 cm for yield and consumptive water use, respectively. Whereas, Willmott index of agreement was 0.999 for both yield and consumptive water use (Table 9). A statistically significant linear relationship ($P < 0.01$) between measured and predicted wheat yield at Demiatte site was found with equation $y = 0.129 + 0.978x$ ($R^2 = 0.999$) and between measured and predicted consumptive water use, with equation $y = 9.197 + 0.686\ x$ ($R^2 = 0.753$). Panda, *et al.*, [26] indicated that a reasonably good agreement was found between simulated wheat yield values by CERES-Wheat model and measured values under deficit irrigation treatments, with $R^2 = 0.970$.

Table 9. Measured versus predicted wheat yield and consumptive water use at Demiatte site under deducting 20% of the full irrigation

Farm	Yield (ton/ha)		% difference	CWU (mm)		% difference
	Measured	Predicted		Measured	Predicted	
Farm 1	5.50	5.50	0	302.7	312.2	3.15
Farm 2	5.15	5.11	0.78	297.2	302.6	1.83
Farm 3	4.40	4.37	0.68	320.5	319.8	0.23
Farm 4	5.70	6.05	6.14	321.4	339.4	5.58
RMSE		0.039		0.040		
Willmott index		0.999		0.999		

CWU= consumptive water use

The above situation assumed that applying about 80% of full amounts of these farmers irrigation would slightly reduce wheat yield on farm level. However, these on-farm trials provide only a limited evaluation of the model, and as data from more treatments in different locations and years become available, the model should be further tested. However, for the purposes of this study we felt that the model worked sufficiently well to warrant the exploration of saving 30% of the full irrigation.

Wheat yield prediction under saving irrigation water

The model was used to predict potential wheat yield after deducting 30% of full applied irrigation amount at El-Monofia site (Table 10). The value of the yield of the third farm was excluded from the prediction because percent difference between measured and predicted wheat yield under deficit irrigation was high. Therefore, the first two farms were only included in Table (10). Results in that table indicated that wheat yield at El-Monofia site might be reduced by 5.40%, if the applied irrigation water was reduced by 30%.

Similar to El-Monofia site, the yield of the fourth farm was excluded from the analysis at Demiatte site. Results in Table (10) showed that if 30% of the full applied irrigation water was saved, wheat yield might be reduced by 5.94%.

Table 10. Measured and predicted wheat yield under the application of full irrigation less 30% at Demiatte site

Farm	El-Monofia			Demiatte		
	Yield (ton/ha)		% reduction	Yield (ton/ha)		% reduction
	Measured	Predicted		Measured	Predicted	
Farm 1	9.43	8.92	5.41	5.60	5.14	8.20
Farm 2	7.61	7.2	5.39	5.25	5.00	4.76
Farm 3	--	--	--	4.55	4.33	4.84
Average	8.52	8.06	5.4	5.13	4.82	5.94

Furthermore, the model was used to predict potential wheat yield at Beni Sweif site under deducting 20 and 30% of the full irrigation. Results in Table (11) showed that wheat yield might reduced by an average of 2.35 or 5.99%, if 20 or 30% of applied irrigation water was saved, respectively.

Table 11. Measured and predicted wheat yield under the application of full irrigation less 20% and 30% at Beni Sweif site

Season	Full irrigation less 20%			Full irrigation less 30%		
	Yield (ton/ha)		% difference	Yield (ton/ha)		% difference
	Measured	Predicted		Measured	Predicted	
1998/99	5.28	5.16	2.27	5.28	5.07	3.98
1999/00	5.73	5.68	0.87	5.73	5.52	3.66
2000/01	5.73	5.59	2.44	5.73	5.31	7.33
2001/02	6.79	6.53	3.83	6.79	6.18	8.98
Average	5.88	5.74	2.35	5.88	5.52	5.99

A comparison was made between the three sites regarding to yield losses under each amount of saved irrigation water. Results in Table (12) suggested that percentage of wheat yield reduction under deducting either 20 or 30% of the full irrigation was close to each other at the three sites. This could be another indication of the applicability of Yield-Stress model in predicting potential wheat yield under different amounts of deficit irrigation.

Table 12. Irrigation amounts and percent reduction in wheat yield under deducting 20 or 30% of full irrigation at the three sites.

Site	Average full irrigation amount (mm)	% reduction in yield under	
		Saving 20% of full amount	Saving 30% of full amount
Beni Sweif	504.2	2.35	6.13
El-Monofia	548.6	2.89	5.40
Demiatte	590.7	2.33	5.94

Using Yield-Stress model as irrigation management tool

Beni Sweif site

Depletion of readily available water from root zone was studied for the four growing seasons at Beni Sweif site. The growing season of 1999/00 was found to be the one that did not contains any water stress days (Figure 1). In another word, the amount of applied irrigation water was abundant. The figure illustrated the depletion of readily available water from the root zone under the application of full irrigation amounts. Figure (1) indicated that there are six hills, each top of these hills represent irrigation day and the amount of readily available water at the root zone. The graph also showed that there was a plenty of water at root zone after the 4th, 5th and the 6th irrigations. Therefore, a proposed scenario was used to save irrigation water (Figure 2), where the last irrigation could be omitted and the interval between 4th and the 5th irrigations could be increased. Under that scenario, the amount of saved irrigation water was around 21% of the full applied water, with no yield losses (Table 13).

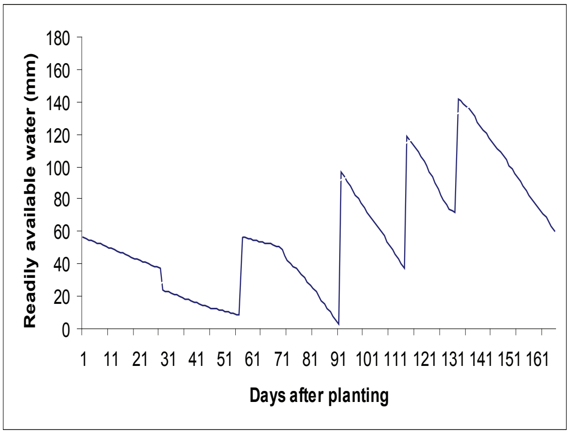

Figure 1. Readily available water depletion from root zone after the application of each individual irrigation for wheat under full irrigation amount in 1999/00 growing season at Beni Sweif site.

El-Monofia site

Regarding to El-Monofia site, the 2nd farm was picked because there was a plenty of readily available water at root zone after the 5th and the 6th irrigations (Figure 3). Therefore, the amount of these two irrigations was reduced (Figure 4), which could save around 22% of the applied water and yield losses was 0.13% (Table 13).

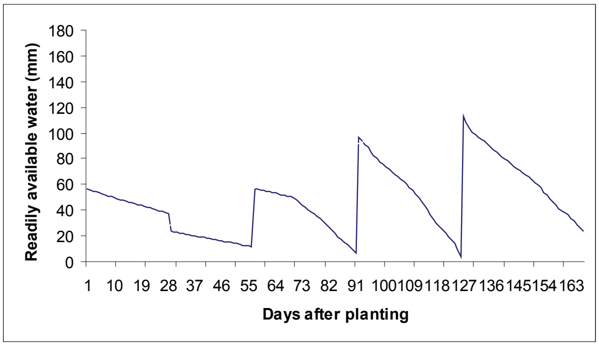

Figure 2. Readily available water depletion from root zone after the application of each individual irrigation for wheat under deducting 21% of full irrigation in 1999/00 growing season at Beni Sweif site.

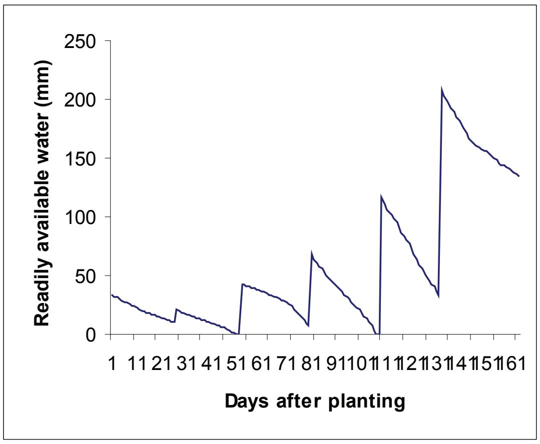

Figure 3. Readily available water depletion from root zone after the application of each individual irrigation for wheat under full irrigation amount (El-Monofia, farm 2)

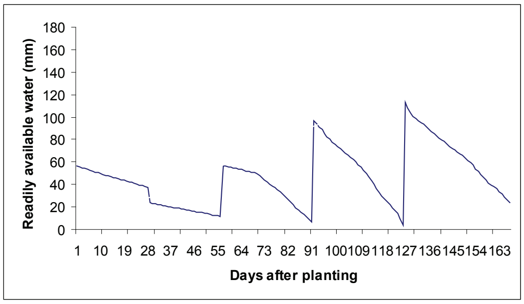

Figure 4. Readily available water depletion from root zone after the application of each individual irrigation for wheat under total irrigation amount less 22% (El-Monofia, farm 2)

Demiatte site

Similar results could be obtained for the 3rd farm at Demiatte site. The 3rd farm was picked because there was also a plenty of readily available water at root zone after the 4th, the 5th and the 6th irrigations (Figure 5). For that reason, the amount of these three irrigations was reduced (Figure 6) and that could lead to conserve around 24% of the applied water with no yield losses (Table 13).

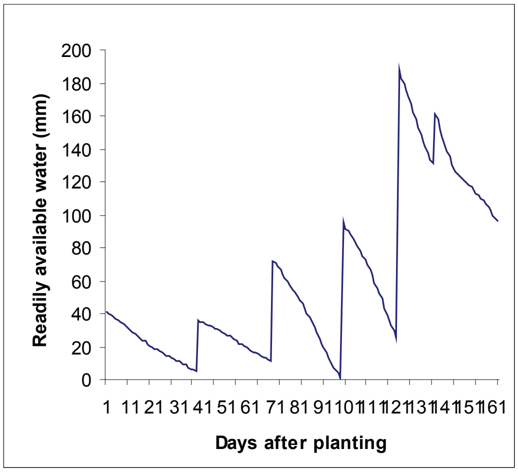

Figure 5. Readily available water depletion from root zone after the application of each individual irrigation for wheat grown under full irrigation amount (Demiatte, farm 3)

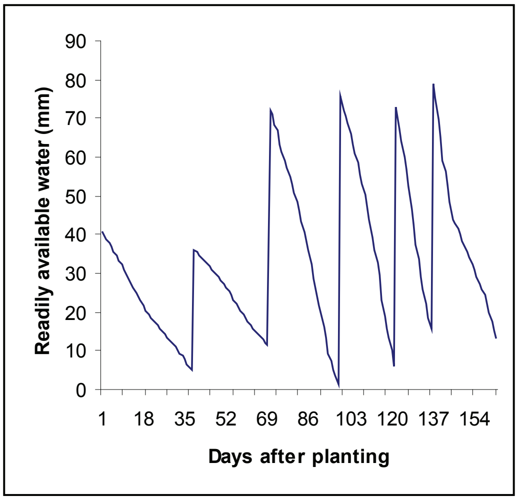

Figure 6. Readily available water depletion from root zone after the application of each individual irrigation for wheat grown under full irrigation amount less 24% (Demiatte, farm 3)

Table 13. Percent of saved irrigation water and corresponded percent of yield reduction at the three sites.

Site	% of saved irrigation amount	% of yield reduction
Beni Sweif: 1999/00 growing season	21	0
El-Monofia: farm 2	22	0.13
Demiatte: Farm 3	24	0

DISCUSSION

The traditional goal in irrigated agriculture is the achievement of the highest yield per unit land surface; only in relatively recent years it was realized that such a goal entails a wasteful use of water resources and the principles of deficit irrigation were developed [27], aiming to obtain the highest yield per unit of water. Although an appreciable progress was made towards more rational use of water, adopting deficit irrigation principles implies the acceptance of a certain level of yield reduction [28]. As long as that certain level of yield reduction is low, there is a good chance that farmers will adopt deficit irrigation. In our trials, at El-Monofia and Demiatte sites, where deficit irrigation was applied, and even at Beni Sweif site, each farm had its own characteristics and each farmer applied his own technique in growing wheat, which may or may not the right one for high yields. However, all these farmers have one thing in common; they applying more irrigation water than wheat requires. That practice can be clearly observed at El-Monofia and Demiatte sites (Table 4). Furthermore, Results in Table (3) also implied that there is a potential for saving irrigation water at Beni Swief site, where the lowest amount of applied irrigation water produced the highest wheat yield in 2001/02 growing season, compared with the other studied years.

The harm of applying large amount of irrigation water on wheat yield can be also detected at El-Monofia site on farm #2 compared with farm #1. Although both are located on an improved water canal, there was a quite large difference in the yield of these two farms (Table 4). This could be a result of applying higher irrigation amount by the farmer #2 compared with farmer #1 (Table 4 and Figure 3), especially for the last irrigation (data not shown), which might have caused oxygen deficiency at the root zone and reduced yield. Furthermore, nitrogen leaching from root zone could have occurred under these conditions. Similar situation were noticed at Demiatte site, where the yield of the 3rd farm was the lowest, compared with the other three farms (Table 4). Farmer #3 applied large amount of irrigation water during the 5th and the 6th irrigations (Figure 5), which might also cause oxygen deficiency during the seed development stage and reduced final yield. With respect to the yield obtained from the 4th farm (Table 4), it was the highest, compared with the rest of the farms. The reason for that may be that the farmer was able to apply more fresh water than drainage water, which helped him to leach the salts from the root zone and improve the yield.

At El-Monofia site, comparing measured yield under full irrigation amount (Table 6) to measured yield under deficit irrigation (Table 8) indicated that yield reduction was relatively high at the 3rd farm as a result of 20% reduction of the full irrigation. This might be a result of being located on a non-improved water canal, where water is less available and that could be the reason that force farmer #3 to apply only five irrigations instead of six as the other two farmers did. Furthermore, the land of the 3rd farm has the lowest NPK level compared with the other two farms (Table 1). As a result the wheat plants may have suffered from both water and nutrients stresses resulting in high yield reduction. The model failed to capture that situation, which resulted in high percent difference between measured and predicted yield for that farm (Table 8). Similarly, the yield of farm #4 at Demiatte was relatively low; however there is no apparent explanation for that.

Running the model under the full applied irrigation amounts at the three sites indicated that there were a few days of water stress exited at Beni Swief (Table 5) and at El-Monofia sites (Table 6), which resulted in some yield reduction. However, that reduction was less than 0.5%, therefore it was ignored.

Validating the model under deducting 20% of the full irrigation at El-Monofia and Demiatte implied that the model was suitable for these two sites (Table 8 and 9). Similar results were obtained from the model when it was used to predict wheat and barley yield under skipping the last irrigation ([7] and [1]) and for sesame yield under deficit irrigation [14].

Furthermore, running the model for the three sites under the application of full irrigation (Tables 5, 6 and 7) and under deficit irrigation for El-Monofia and Demiatte sites (Table 8 and 9) showed the good performance of the model for most of the cases under study, which implied that the model can be exploited with confidence in wheat yield prediction with different deficit irrigation amounts. Our results suggested that deducting 30% of the full applied irrigation amount, could reduced wheat yield by 5.40 and 5.94% at El-Monofia and Demiatte, respectively. Furthermore, running the model for Beni Swief site with 20% and 30% deficits showed that wheat yield could be reduced by 2.35 and 5.99%, respectively.

Our results also indicated that using the model in studying the depletion of readily available water from the root zone could be very helpful in saving irrigation water and in reducing unnecessary water losses, while maintaining minimal yield reduction. Figure (1) and (2) showed that at Beni Swief site, around 21% of the full applied irrigation water could be saved with no yield losses. Moreover, at El-Monofia and Demiatte sites, around 22 and 24% of the full applied irrigation water could be saved with very low or no yield losses (Figures 3, 4, 5 and 6).

CONCLUSION

Over the last two decades, modeling has become a major research tool in agriculture for resource management. Because saving irrigation water became a necessity recently, different water management practices should be explored. However, that could be expensive to perform from all aspects. Therefore, using simulation models to predict the effect of applying different irrigation amounts on the yield could be the ultimate solution.

Yield-Stress model employed soil water depletion equations to instantly predict potential wheat yield under varying degree of water stress, which could partially replace expensive field experiments. Based on the comparative analysis between measured and predicted wheat yield data, it could be concluded that the model can adequately predict yield reduction as a result of imposing water stress. The use of the model can provide useful insights into the design of different irrigation treatments. Furthermore, the easiness of using the model by non professionals could help in spreading the concept of deficit irrigation among Egyptian farmers. The results of the model validation under full irrigation amounts and under deficit showed that this approach confirmed to be appropriate for wheat yield prediction at El-Monofia and Demiatte sites, which implies that the model is capable of exploring radical alternatives of deficit water irrigation. Furthermore, the results also suggested that the model can be used in irrigation rescheduling at the three sites to conserve irrigation water with almost no yield reduction.

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