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CropSyst model for wheat irrigation water management with fresh and poor quality water

**Samiha A. OUDA¹⁾ ABCDEF, Tahany NORELDIN¹⁾ ABCDEF,
Oussama H. MOUNZER²⁾ ACDEF, Magdi T. ABDELHAMID³⁾ ABCDEF**

1) Water Requirements and Field Irrigation Research Department, Soils, Water and Environment Research Institute, Agricultural Research Center; 9 El-Gamah Street, Giza, Egypt.
2) Irrigation Department, CEBAS-CSIC, Campus Universitario de Espinardo 30100 Espinardo, Apartado 164, Spain
3) Botany Department, National Research Centre, 33 El Behouth Street, Dokki, 12622, Giza, Egypt;
e-mail: magdi.abdelhamid@yahoo.com

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Abstract

CropSyst model can be used as irrigation water management tool to increase wheat productivity with poor quality water. The objective of this study was to calibrate CropSyst model for wheat irrigated with fresh and agricultural drainage water. To do so, three field experiments were conducted during three successive seasons in Nubaria Agricultural Research Station, Egypt representing the newly reclaimed calcareous soils. In the first season the treatments were 100% crop evapotranspiration (*ETc*) of fresh water (*FW*) and 100% *ETc* of agricultural drainage water (*DW*), while in the second and the third seasons, the treatments were 100% *ETc* of *FW*, 100% *ETc* of *DW*, 120% *ETc* of *DW* and 130% *ETc* of *DW*. From these results one can concluded that deducting 5% of the applied water to all treatments reduced yield by 3, 5 and 7% in the first, second and third growing season, respectively as a result of heat stress existed in the 2nd and 3rd seasons during reproductive phase. Furthermore, deducting 5% of the applied water from all treatments in the vegetative phase only resulted in lower yield losses. Thus, using CropSyst model could guide us to when we could reduce the applied irrigation water to wheat to avoid high yield losses.

Key words: *agricultural drainage water, deficit irrigation, fresh water, water stress index*

INTRODUCTION

Crop simulation models are the dynamic simulation of crop growth by numerical integration of constituent processes with the aid of computers [MATTHEWS *et al.* 2000]. An example of these models is CropSyst [STOCKLE *et al.* 1994; 2003]. CropSyst is a process based simulation model. It uses the same approach to simulate the growth and development of potentially all herbaceous crops. To reach this aim, simplifications have been introduced to describe some processes (e.g. monolayer canopy, constant specific leaf area absence of daily assimilates partitioning). This makes CropSyst easier to be calibrated and a reduced set of crop parameters is needed. These aspects and the possibility of simulating rotations make CropSyst a useful tool for large-scale simulations [CONFALONIERI, BECHINI 2004]. For these considerations, CropSyst can be considered a management-oriented model. In Egypt, the model was applied on some crops, e.g., wheat grown in clay soil [ABDRABBO *et al.* 2013; KHALIL *et al.* 2009] and wheat in sandy soil [OUDA *et al.* 2010b; TAHA 2012]. The model was calibrated for wheat grown in three soil conditions, i.e., clay and sandy soil and salt affected soils as well [OUDA *et al.* 2013]. The model was applied for wheat grown in salt affected soil [NORELDIN *et al.* 2013]. The model was also validated for maize yield [OUDA *et al.* 2009] and barley [OUDA *et al.* 2010a] and for cotton [OUDA *et al.* 2013].

Wheat (*Triticum aestivum* L.) is the most important crop in Egypt, where its production is not sufficient to meet its demand. The crop is more sensitive to the timing of a water deficit period rather than the total reduction of applied irrigation water. Exposing wheat plants to high moisture stress depressed seasonal consumptive use and grain yield [BUKHAT 2005]. During vegetative growth, phyllochron decreases in wheat under water stress [MCMASTER 1997] and leaves become smaller, which could reduce leaf area index [GUPTA *et al.* 2001] and number of reproductive tillers, in addition to limit their contribution to grain yield [DENCIC *et al.* 2000]. Furthermore, wheat is very sensitive to high temperature [SATORRE, SLAFER 1999]. Wheat experiences heat stress to varying degrees at different phenological stages, but heat stress during the reproductive phase is more harmful than during the vegetative phase due to the direct effect on grain number and dry weight [WOLLENWEBER *et al.* 2003]. The amount of wheat yield reduction as a result of water stress is affected by the stage of grain development, where early grain development stage is more vulnerable to water stress than latter grain development stage [EL-KHOLY *et al.* 2005]. Therefore, modeling can assist in determining when to reduce the amount of applied irrigation water to wheat plants and what is the expected yield losses would be.

Water of poor quality is often used to irrigate crops in Egypt. However, the use of such water may result in decrease in crop productivity and reduction in soil water infiltration capacity due to high concentrations of soluble salts [QADIR *et al.* 2000]. Agricultural drainage water is a product of irrigation that may be viewed as a valuable resource, providing an alternative agricultural water resource [DUDLEY *et al.* 2008]. Wheat is ranked as a moderately salt-tolerant crop [MAAS, GRATTAN 1999] that can be safely irrigated with moderately saline water, although an increase in water salinity may cause a reduction in wheat grain yield. Agricultural drainage irrigation water is used widely in Egypt after blending it with fresh water, where its *EC* (electrical conductivity) became equal to 1 $dS \cdot m^{-1}$. Furthermore, the direct use of drainage water (*EC* = 3 $dS \cdot m^{-1}$) is also a familiar practice of some farmers in Egypt to grow several crops, such as wheat [AMER, RIDDER 1988]. MASHLI [1985] reported that, at El-Fayoum, Egypt, wheat yield resulted from irrigation with fresh water was similar to the one obtained under saline water with *EC* = 2.8 $dS \cdot m^{-1}$. Pilot studies carried out in two Governorates in Egypt showed that by applying appropriate management practices, agricultural drainage water with *EC* of 2–2.5 $dS \cdot m^{-1}$ can be safely used for irrigation without long term hazardous consequences to crops or soils [RHOADES *et al.* 1992].

Therefore, the objectives of this study were (i) to calibrate CropSyst model for wheat irrigated with fresh and agricultural drainage water; (ii) to use the simulation results to analyze the relationship between applied irrigation amount and the resulted yield; and (iii) to simulate the effect of saving irrigation water on wheat productivity.

MATERIALS AND METHODS

Field experiments were conducted during three successive seasons (2010/2011, 2011/2012 and 2012/2013) at Nubaria Agricultural Research Station, North Tahrir, Egypt representing the newly reclaimed calcareous soils (30°54'21"N 29°57'24"E). The experimental area has an arid climate with cool winters and hot dry summers. The data of maximum and minimum temperature, relative humidity, solar radiation, and wind speed were obtained from weather station installed at the Nubaria Agricultural Research Station. The soil of experimental site is classified as sandy loam soil. Some physical and chemical properties of the experimental soil are shown in Table 1, 2, and 3. Irrigation water was obtained from an irrigation channel passing through the experimental area. The experimental field was deep ploughed before planting. First disc harrow, then duck food was used for further preparation of the field for planting. A combined driller that facilitated concurrent application of fertilizer and seeds was used.

Table 1. Main physical properties of soil, particle size distribution, and texture class at the experimental site

Soil depth cm	*FC*	*WP*	*ASM*	*BD* $g \cdot cm^{-3}$	Particle size distribution, %			Texture class
	%				sand	silt	clay	
0–15	29.8	16.2	13.6	1.10	58.9	24.2	16.9	sandy loam
15–30	28.5	15.9	12.6	1.18	60.3	24.5	15.2	sandy loam
30–45	27.7	15.2	12.5	1.23	56.7	26.1	17.2	sandy loam

Explanations: *FC* = field capacity, *WP* = wilting point, *ASM* = available soil moisture, *BD* = bulk density.
Source: own study.

Table 2. Chemical properties of soil at the experimental site

Soil depth cm	pH 1:2.5	*EC* $dS \cdot m^{-1}$	*CEC* $cmol \cdot kg^{-1}$	$CaCO_3$ %	OM %
0–15	8.5	3.86	14	25.9	0.12
15–30	8.3	4.89	20	24.9	0.24
30–45	8.2	5.37	17	26.7	0.26

Explanations: *EC* = electrical conductivity, *CEC* = cation exchange capacity, *OM* = organic matter.
Source: own study.

Table 3. Concentration of cations and anions of soil at the experimental site

Soil depth cm	Soluble cations, $cmol \cdot m^{-3}$				Soluble anions, $cmol \cdot m^{-3}$			
	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	CO_3	HCO_3	Cl	SO_4
0-15	20.0	13.0	4.8	0.9	–	10.0	25.0	3.6
15-30	9.6	5.1	29.8	5.2	–	11.1	30.1	7.7
30-45	29.7	11.5	38.0	6.4	–	20.0	35.0	28.7

Source: own study.

Wheat cultivar (Sakha 93) was planted on 29.11.2010, 11.12.2011, and 10.12.2012 on three successive seasons. Harvest was done on 25.5.2011, 12.5.2012, and 10.5.2013, respectively for the three successive seasons. The driller setting was such that it applied 170 kg of seed per hectare. Fertilizer applications were based on soil analysis recommendations. All plots received the same amount of fertilizer. A compound fertilizer was applied as follow: 285 kg $N{\cdot}ha^{-1}$ as ammonium nitrate, ten percent applied to the soil before planting and at tillering, the remainder was applied in irrigation water, 70 kg $P_2O_5{\cdot}ha^{-1}$ as single superphosphate applied to the soil in two equal doses before planting and at tillering stage and 115 kg $K_2O{\cdot}ha^{-1}$ as potassium sulphate applied in three doses (half applied to the soil before planting, one quarter at tillering and one quarter during the growing season in irrigation water).

The experimental design was complete randomized block with four replicates. Soil moisture contents were determined in calcareous soil gravimetrically as average of three samples per strip taken at 0–15, 15–30, 30–45 and 45–60 cm depth just before and one day after each irrigation to determine water consumption. The amount of irrigation water was measured by flow meter connected with the irrigation pump, where surface irrigation was used. Field capacity (*FC*), wilting point (*WP*), available soil moisture (*ASM*) bulk density (*BD*), particle size distribution, and texture class values at the experimental site are presented in Table 1.

For determination of the crop water requirements (*CWR*), crop evapotranspiration was calculated under standard conditions (*ETc*). The FAO Penman–Monteith method was used to calculate potential evapotranspiration (*ETo*). This equation used the standard climatological records of daily solar radiation (sunshine), air temperature, humidity and wind speed. *ETc* was calculated by multiplying *ETo* by a crop coefficient (*kc*). Amount of irrigation water was calculated according the following equation for the surface irrigation systems:

$$AW = \frac{ETc}{Ea(1 - LR)} \tag{1}$$

where:

AW = applied irrigation water depth, mm;

Ea = application efficiency equals 60% for surface irrigation system;

LR = leaching requirements.

In 2010/2011 growing season, where no leaching requirements were applied, wheat was grown under the two irrigation treatments as follows:

1. 100% *ETc* of fresh water (FW).
2. 100% *ETc* of agricultural drainage water (DW).

In the second and the third growing seasons, leaching requirements were added to represent 20 and 30% of agricultural drainage water as high yield losses occurred in the first growing season. Thus, wheat was grown under four irrigation treatments as follows:

1. 100% *ETc* of fresh water (FW).
2. 100% *ETc* of agricultural drainage water (DW).
3. 120% *ETc* of agricultural drainage water (DW1).
4. 130% *ETc* of agricultural drainage water (DW2).

Date of irrigation (d/m/y), amount of irrigation water (AMT), and its electrical conductivity (*EC*) for each irrigation and total amount of water applied per growing season are shown in Table 4. Wheat grain and biological yields were measured at harvest and harvest index was calculated.

Table 4. Date of irrigation (d/m/y), amount of irrigation water (AMT, $m^3{\cdot}ha^{-1}$), its electrical conductivity (*EC*, $dS{\cdot}m^{-1}$) for each irrigation and total amount of water applied per growing season

Season	Treatment	1st Irrig			2nd Irrig			3rd Irrig			4th Irrig			5th Irrig			Total AMT
		date	AMT	*EC*	date	AMT	*EC*	date	AMT	*EC*	date	AMT	*EC*	date	AMT	*EC*	
1st	FW	29/11/10	1533.3	0.5	22/1/11	1566.7	0.5	25/2/11	1180.0		23/3/11	1510.5	0.5	–	–	–	5790.5
	DW	29/11/10	1533.3	5.5	22/1/11	1566.7	5.8	25/2/11	1180.0	6.2	23/3/11	1510.5	5.9	–	–	–	5790.5
2nd	FW	11/12/11	1000.0	0.6	30/1/12	719.8	0.6	23/2/12	1092.3	0.6	18/3/12	1760.0	0.6	10/4/12	2005.9	–	6578.0
	DW	11/12/11	1000.0	6.2	30/1/12	719.8	6.2	23/2/12	1092.3	6.1	18/3/12	1760.0	6.5	10/4/12	2005.9	6.3	6578.0
	DW1	11/12/11	1000.0	6.2	30/1/12	863.8	6.2	23/2/12	1310.8	6.1	18/3/12	2112.0	6.5	10/4/12	2407.1	6.3	7693.7
	DW2	11/12/11	1000.0	6.2	30/1/12	935.7	6.2	23/2/12	1420.0	6.1	18/3/12	2288.0	6.5	10/4/12	2607.7	6.3	8251.5
3rd	FW	10/12/12	1000.0	0.8	25/1/13	515.5	0.5	27/2/13	1598.4	0.6	1/4/13	2690.4	0.5	20/4/13	1190.1	0.7	6994.4
	DW	10/12/12	1000.0	5.9	25/1/13	515.5	5.9	27/2/13	1598.4	6.4	1/4/13	2690.4	5.8	20/4/13	1190.1	6.3	6994.4
	DW1	10/12/12	1000.0	5.9	25/1/13	618.5	5.9	27/2/13	1918.1	6.4	1/4/13	3228.4	5.8	20/4/13	1428.1	6.3	8193.2
	DW2	10/12/12	1000.0	5.9	25/1/13	670.1	5.9	27/2/13	2077.9	6.4	1/4/13	3497.5	5.8	20/4/13	1547.2	6.3	8792.7

Explanations: FW = 100% *ETc* of fresh water; DW = 100% *ETc* of agricultural drainage water; DW1 = 120% *ETc* of agricultural drainage water; DW2 = 130% *ETc* of agricultural drainage water; AMT = amount of irrigation water, $m^3{\cdot}ha^{-1}$; *EC* = electrical conductivity, $dS{\cdot}m^{-1}$.

Source: own study.

CropSyst model [STOCKLE *et al*. 1994] was used in this study to allow us to simulate the effect of the salinity level in the used agricultural drainage water on wheat yield. Figure 1 showed flow chart for CropSyst model. CropSyst objective is to serve as an analytical tool to study the effect of cropping systems management on crop productivity and the environment. The model simulates crop development as the progression of a crop through phenological stages, as it governed by growing degree days. Therefore, in all

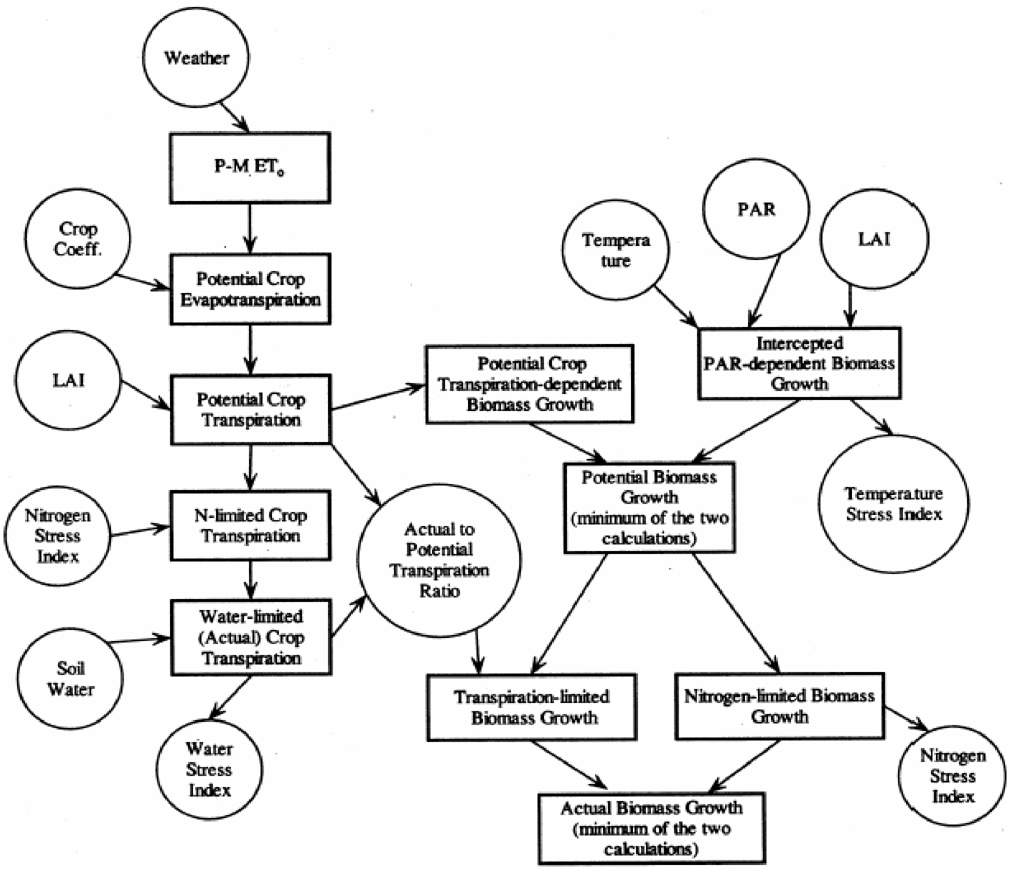

Fig. 1. Flowchart of biomass growth calculations in CropSyst; LAI = leaf area index, P-M ETo = potential evapotranspiration calculated by Penman–Monteith method; source: own elaboration

the experiments described above, leaf area index was measured at three crop growth stages. The dates of these stages were recorded and the growing degree days required to the establishment of each growth stage was calculated. Furthermore, optimal crop growth in the model is governed by the most limiting condition, either radiation or transpiration, where actual biomass growth is obtained after growth limitations have been applied. Water stress index in the model takes into account the effect of water shortage, as well as salinity stress. The overall stress index is partitioned into light, temperature, water, and nitrogen stress indices. These quantities are used as indicators of the plant response to environmental conditions. All these indices range from 0 to 1, where 0 is no stress and 1 is maximum stress. Details on the technical aspects and use of the CropSyst model have been reported elsewhere [STOCKLE *et al.* 1994; STOCKLE, NELSON 1994].

Input files required by CropSyst model for wheat crop were prepared and use to run the model. One management file was prepared represent each irrigation treatment. The date of each phenological stage was used to calculate growing degree days for that stage. The values of the crop input parameters were either taken from the CropSyst manual [STOCKLE, NELSON 1994] or set to the values observed in the experiments. The model was calibrated using the data obtained from the three experiments. The calibration consisted of fine tuning adjustments of wheat input parameters to reflect reasonable simulations. These adjustments were around values that were either typical for the crop species or known from previous experiences with the model. These parameters were: aboveground biomass-transpiration coefficient (kPa·kg·m^{-3}) and light to aboveground biomass conversion (g·MJ^{-1}). PALA *et al.* [1996] suggested that adjustments of some of these parameters, accounting for cultivar-specific differences, are desirable whenever suitable experimental information is available.

To test the goodness of fit between the measured and predicted data, the percentage of difference between measured and predicted values for grain and biological yields in each growing season were calculated. Furthermore, root mean square error was calculated [JAMIESON *et al.* 1998], which describes the average difference between measured and predicted values. In addition, Willmott index of agreement (*d*) was calculated and it takes a value between 0.0–1.0 with value of 1.0 meaning a perfect fit [WILLMOTT 1981].

The effect of saving 5% of the applied irrigation water on wheat yield was simulated in all experiments. Deduction of 5% of applied water of each irrigation was imposed for each treatment and in each growing season. Furthermore, 5% of the applied water in each single irrigation was deducted during vegetative phase. New irrigation files were developed and used to run CropSyst model.

RESULTS AND DISCUSSION

The percentage of difference between measured and predicted value of both grains and biological yield was low (Tab. 5). It ranged between 0.29–1.64% for grain yield, whereas it ranged between 0.08–2.10% for biological yield. *RMSE* was 0.04 and 0.25 $t \cdot ha^{-1}$ for grains and biological wheat yield, respectively. The value of *d* was 0.99 for both grains and biological yield. Similar results were obtained for *RMSE* and *d* values between measured and predicted wheat yield by KHALIL *et al.* [2009] and OUDA *et al.* [2010a, b]. Several publications highlighted the accuracy of the CropSyst model, such as BENLI *et al.* [2007] and SINGH *et al.* [2008]. Both papers indicated that the model prediction gave low *RMSE* value.

Table 5. Measured versus predicted wheat grain and biological yield planted in three growing seasons

Season	Treatment	Grain yield, $t \cdot ha^{-1}$			Biological yield, $t \cdot ha^{-1}$		
		measured	predicted	PD%	measured	predicted	PD%
1st	FW	5.11	5.08	0.60	13.39	13.36	0.20
	DW	4.27	4.24	0.78	12.10	12.11	0.08
2nd	FW	5.72	5.70	0.29	17.90	18.09	1.08
	DW	3.81	3.79	0.55	14.45	14.70	1.91
	DW1	4.26	4.23	0.78	15.30	15.64	2.00
	DW2	4.49	4.42	1.64	16.10	16.39	1.50
3rd	FW	6.38	6.36	0.39	19.60	19.87	1.15
	DW	4.39	4.36	0.60	15.40	15.04	2.10
	DW1	4.91	4.87	0.80	16.90	16.78	0.45
	DW2	5.03	5.01	0.39	17.50	17.29	1.40
RMSE		0.04			0.25		
d		0.99			0.99		

Explanations: FW, DW, DW1, DW2 as in Table 1; PD% = percentage of difference between measured and predicted values; *RMSE* = root mean square error; *d* = Willmotte index of agreement.
Source: own study.

Results in Table 5 also implied that application of 120 and 130% *ETc* of agricultural drainage water increase wheat yield compared with applying 100% *ETc*. This can be attributed to increasing applied water above 100% *ETc* increases salts leaching away from root zone and improve root growth environment, which positively reflected on final wheat yield.

The model was used to simulate above ground biomass and water stress index to study the relationship between the amount of applied irrigation water and simulation of dry matter accumulation. Figure 2 showed that in the 1st growing season, above ground biomass was the lowest. Whereas, biomass accumulation in the 2nd and 3rd growing season was similar, except at the end of grain filling period. Thus, although the applied water was close to optimum, there was some variation of the rate of dry matter accumulation between the three growing seasons. Examining water stress index (*WSI*) throughout the three growing seasons revealed that, in the 1st growing season, water stress prevailed in three growth stages (Fig. 3). The first period was for 3 days at the end of vegetative growth, where *WSI* was 0.3 or lower. Water stress before anthesis can reduce number of heads and numbers of kernels per ear [DENCIC *et al.* 2000; GUTTIERI *et al.* 2001]. The second and the third periods were early in the grain filling period for 10 days, where *WSI* was 0.5 or lower and late in the grain filling period, where water stress prevailed for 10 days and *WSI* was 0.6 or lower. Water stress imposed during later stages might additionally cause a reduction in number of kernels per ear and kernel weight, which could negatively, reflected on final yield [BAQUE *et al.* 2006; SAEEDIPOUR 2011]. In the 2nd growing season (Fig. 3), water stress existed for 10 days during flowering stage and in the beginning of grain filling stage. During flowering stage, *WSI* was 0.3 or lower, whereas it was 0.5 or lower during early grain filling stage. Furthermore, water stress existed during mid grain filling stage for 2 days and late grain filling stage, with *WSI* value lower than 0.4. Wheat above ground biomass yield was higher by 34% in the 2nd growing season, compared by the 1st growing season. Regarding to the 3rd growing season, Fig. 3 indicated that low water stress existed for 4 days during early grain filling stage, where *WSI* was 0.3 or lower. The

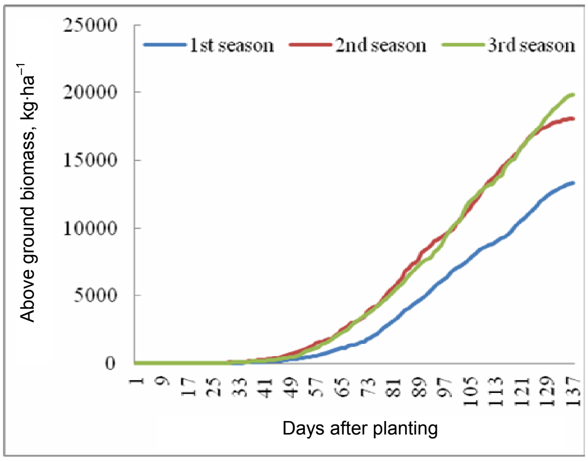

Fig. 2. Simulated above ground biomass for wheat grown under irrigation with 100% *ETc* of fresh water in the three growing seasons; source: own study

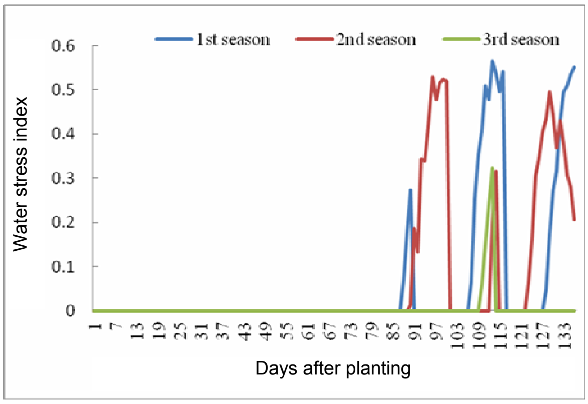

Fig. 3. Simulated water stress index for wheat grown under irrigation with 100% *ETc* of fresh water in the three growing seasons; source: own study

above ground biomass in the 3rd season was higher by 10%, compared to the 2nd growing season.

The applied agricultural drainage water was characterized by high *EC* concentration. Under these circumstances, salinity stress is expected to occur. Salts in the soil water solution can reduce evapotranspiration by making soil water less available for plant root extraction [ALLEN *et al.* 1998]. Figure 4 indicated that the lowest above ground biomass was obtained in the 1st growing season and the highest was obtained in the 3rd growing season. The highest water stress period occurred in the 1st growing season (Fig. 5). The total number of water stress days in the 1st growing season was 12 days: 2 of them was during late flowering and the rest was during the early grain filling period, where the highest value of *WSI* was 0.65, which is considered relatively high. In the 2nd growing season, water stress period existed during flowering stage and early grain filling period. The 3rd growing season experience the lowest water stress days, where the stress existed during mid grain filling stage for 6 days only, with *WSI* value less than 0.4 (Fig. 4). These results can be explained by that the plants suffer from physiological drought stress, ion toxicity, and mineral deficiency, which then lead to reduced growth and productivity [ASGARI *et al.* 2012]. This was obvious in our experiments, salinity inhibited wheat growth aspects, such as leaf area index, where similar results was reported by EL-HENDAWY *et al.* [2005]. It could also attribute to reduction in root growth rate [GHAVAMI *et al.* 2004] and root/shoot ratio [FLOWERS 2004]. Wheat grain and biological yield irrigated with agricultural drainage water was lower compared to its counterpart irrigated with fresh water (Tab. 5).

Above ground biomass accumulation in the 2nd season was close to the 3rd year under irrigation with 120% agricultural drainage water. However, the final biomass was higher under the 3rd season (Fig. 6). Water stress index was higher in the 2nd growing season, compared with the 3rd growing season (Fig. 7). In the 2nd growing season, water stress occurred for 11 days, 5 of them during flowering and the rest was during beginning of grain filling, where the highest daily value of *WSI* reached 0.7. Furthermore, another water stress period started during mid grain filling period and at the end of grain filling period. However, the

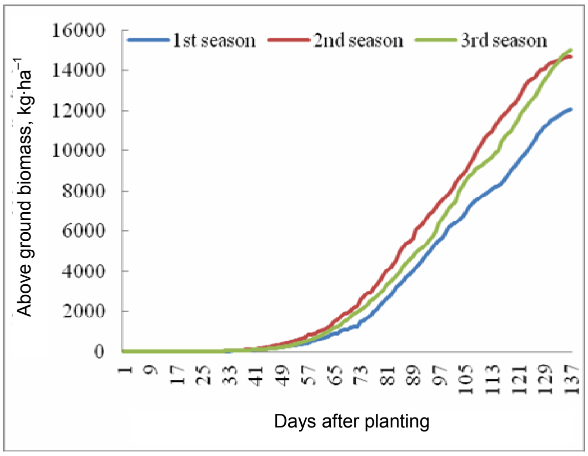

Fig. 4. Simulated above ground biomass for wheat grown under irrigation with 100% *ETc* of agricultural drainage water in the three growing seasons; source: own study

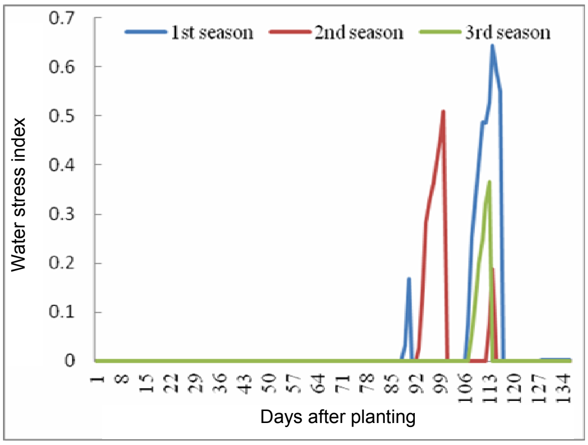

Fig. 5. Simulated water stress index for wheat grown under irrigation with 100% *ETc* of agricultural drainage water in the three growing seasons; source: own study

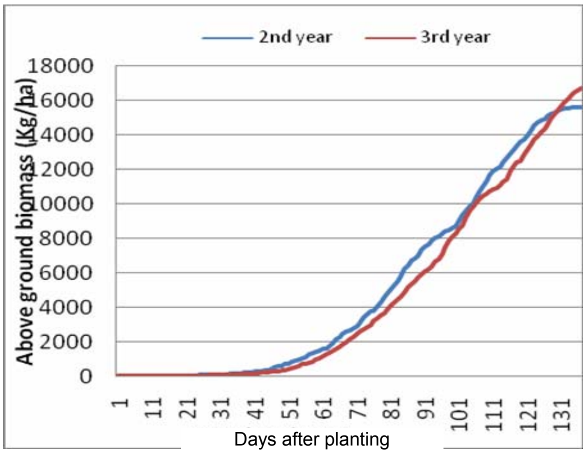

Fig. 6. Simulated above ground biomass for wheat grown under irrigation with 120% *ETc* of agricultural drainage water in the 2nd and 3rd growing seasons; source: own study

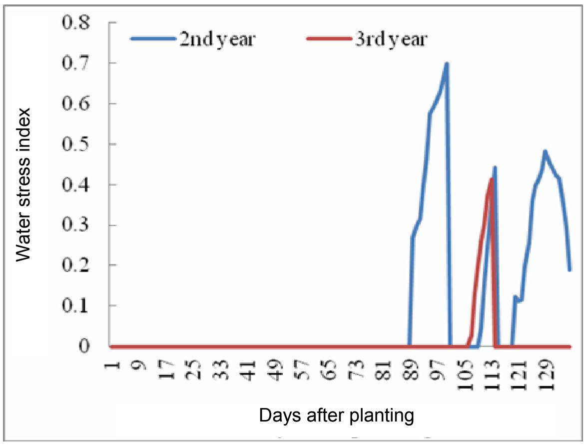

Fig. 7. Simulated water stress index for wheat grown under irrigation with 120% *ETc* of agricultural drainage water in the 2nd and 3rd growing seasons; source: own study

highest daily value of *WSI* was 0.4 or lower. In the 3rd growing season, water stress prevailed only during mid grain filling period for 7 days, where *WSI* was 0.4 or lower.

Similar trend was observed under irrigation with 130% agricultural drainage water, where above ground biomass was higher in the 3rd growing season (Fig. 8) and water stress period was lower (Fig. 9).

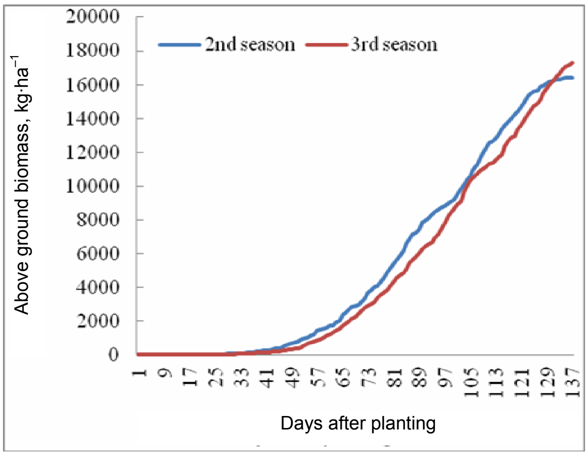

Fig. 8. Simulated above ground biomass for wheat grown under irrigation with 130% *ETc* of agricultural drainage water in the 2nd and 3rd growing seasons; source: own study

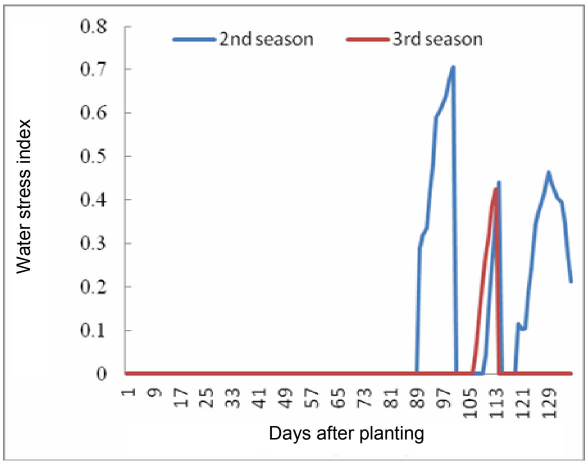

Fig. 9. Simulated water stress index for wheat grown under irrigation with 130% *ETc* of agricultural drainage water in the 2nd and 3rd growing seasons; source: own study

The results of the application of 120 and 130% *ETc* of agricultural drainage water indicated that wheat grain and biological yield were higher, compare to application of 100% *ETc* of agricultural drainage water. This can be attributed to high application of water could leach accumulated salts away from root zone and reduce the negative effect of salinity on growing wheat plants. The above results implied that, in the three growing seasons, the applied water during vegetative stage was sufficient to assure proper growth. Furthermore, water stress was more pronounced in the flowering and early grain filling stages. Water stress in the flowering stage could have great damage to the final yield, especially if it prevailed throughout the stage. These results could explain yield variability between treatments and growing seasons.

Saving 5% of the applied irrigation water in all treatments resulted in yield losses (Tab. 6). In the 1st growing season, wheat yield was reduced by 4% for both fresh and agricultural drainage irrigation. With respect to the 2nd growing season, yield losses were higher, i.e. 5% under fresh water and 6% under agricultural drainage irrigation. Similarly, yield losses were increased in the 3rd growing season.

Table 6. Measured versus predicted wheat grain yield under 5% saving in irrigation water in whole growing season

Growing season	Treatment	Grain yield, t·ha⁻¹		
		measured	predicted	PD%
1st	FW	5.11	4.90	4
	DW	4.30	4.08	4
2nd	FW	5.72	5.45	5
	DW	3.81	3.57	6
	DW1	4.26	3.99	6
	DW2	4.49	4.23	6
3rd	FW	6.38	5.99	6
	DW	4.39	4.10	7
	DW1	4.91	4.55	7
	DW2	5.03	4.66	7

Explanations: FW = 100% *ETc* of fresh water; DW = 100% *ETc* of agricultural drainage water; DW1 = 120% *ETc* of agricultural drainage water; DW2 = 130% *ETc* of agricultural drainage water; PD% = percentage of difference between measured and predicted values.
Source: own study.

The higher yield losses in the third growing season as a result of saving 5% of the applied water could be attributed to higher temperature prevailed during the third growing season. Figure 10 indicated that temperature stress index (*TSI*) was the lowest in the 1st growing season and was the highest in the 3rd growing season. The figure also showed that *TSI* was the highest during vegetative growth period in the third growing season, which could affect tillering and booting stages. Therefore, the growing wheat plants suffered from temperature stress and water stress as well, which reflected on final yield and increase yield losses in the third season. Wheat tolerate heat stress to varying degrees at different phenological stages, but heat stress during the reproductive phase is more harmful than during the vegetative phase due to the direct effect on grain number and dry weight [WOLLENWEBER *et al.* 2003].

During vegetative phase, 5% of the applied water was saved. The results indicated that lower yield losses could occur in the three growing seasons. Regarding to fresh water irrigation, the losses in wheat yield was the lowest, compared with agricultural drainage water application (Tab. 7). Furthermore, the losses were the highest in the third growing season as result of the additive effect of temperature stress.

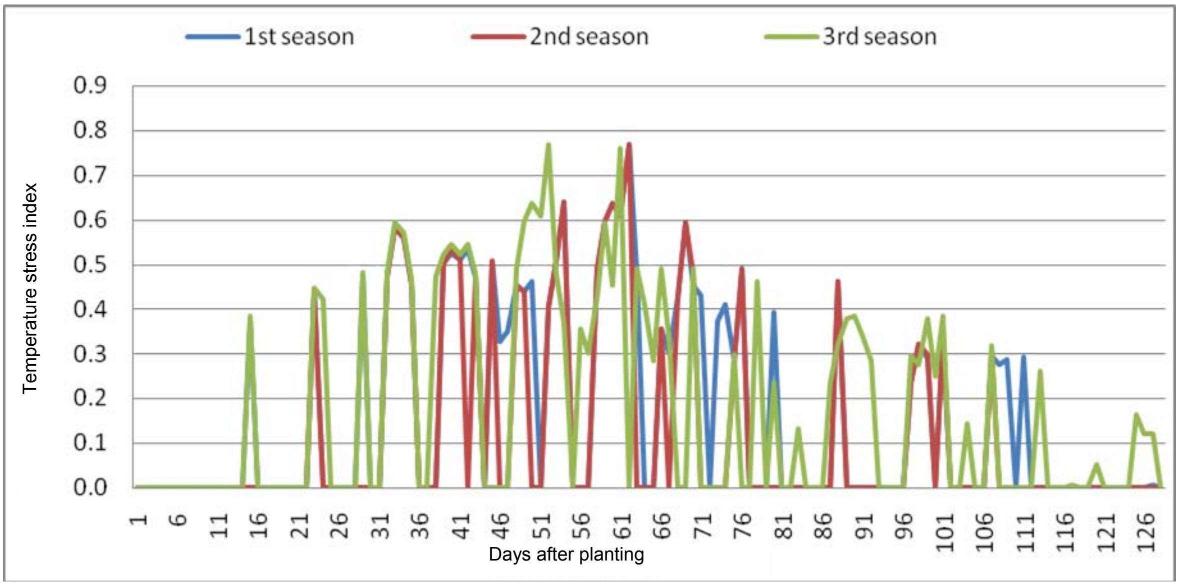

Fig. 10. Simulated temperature stress index for wheat grown in three growing seasons; source: own study

Table 7. Measured versus predicted wheat grain yield under deducting 5% of irrigation water during vegetative phase

Growing season	Treatment	Grain yield, t·ha^{-1}		
		measured	predicted	PD%
1st	FW	5.11	4.99	2
	DW	4.30	4.18	3
2nd	FW	5.72	5.63	2
	DW	3.81	3.70	3
	DW1	4.26	4.19	2
	DW2	4.49	4.39	2
3rd	FW	6.38	6.19	3
	DW	4.39	4.21	4
	DW1	4.91	4.71	4
	DW2	5.03	4.81	4

Explanations: FW = 100% *ETc* of fresh water; DW = 100% *ETc* of agricultural drainage water; DW1 = 120% *ETc* of agricultural drainage water; DW2 = 130% *ETc* of agricultural drainage water; PD% = percentage of difference between measured and predicted values.
Source: own study.

CONCLUSIONS

The roper management of irrigation water requires timely applied irrigation when the plants need with proper amount. The advantage of using simulation models is it can give insights on events occurs during the growing season and cannot be easily measured in the field. Therefore, CropSyst model could be used to analyze the behavior of the growing wheat plants and its response to soil, weather and management. Our results confirmed that the application of fresh irrigation water was adequate to guarantee proper growth for wheat plants during vegetative phase. However, during reproductive stage water stress existed, which negatively affected the final yield. The results also indicated that yield losses were higher under agricultural drainage water, as a result of the existence of salinity and temperature stresses. Reducing the applied water by 5% during the whole growing season, revealed that extra water stress occurred during reproductive growth resulted in yield losses in the three growing seasons. When 5% saving in the applied water during vegetative phase only was done, low yield losses occurred under fresh and agricultural drainage irrigation. Thus, using CropSyst model could guide us to when we could reduce the applied irrigation water to wheat to avoid high yield losses.

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Samiha A. OUDA, Tahany NORELDIN, Oussama H. MOUNZER, Magdi T. ABDELHAMID

Model CropSyst do zarządzania nawadnianiem pszenicy wodą słabej jakości

STRESZCZENIE

Słowa kluczowe: *deficyt nawodnień, indeks stresu wodnego, wody drenarskie, wody naturalne*

Model CropSyst może znaleźć zastosowanie jako narzędzie w zarządzaniu systemem nawodnień wodą niskiej jakości w celu zwiększenia produkcji pszenicy. Przedmiotem przedstawionych badań było skalibrowanie modelu CropSyst do nawodnień pszenicy wodą naturalną i wodą z rolniczych systemów drenarskich. W tym celu przeprowadzono trzy eksperymenty polowe w trzech kolejnych sezonach realizowane w Nubaria Agricultural Research Station w Egipcie na ostatnio zmeliorowanych glebach wapiennych. W pierwszym sezonie warianty eksperymentalne obejmowały: 100% ewapotranspiracji (*ETc*) wody naturalnej (*FW*) i 100% *ETc* wody z systemów drenarskich (*DW*); w drugim i trzecim sezonie wariantami eksperymentalnymi były: 100% *ETc* z użyciem *FW*, 100% *ETc* z użyciem *DW* oraz 120% i 130% *ETc* z zastosowaniem *DW*. Uzyskane wyniki dają podstawy do wnioskowania, że zmniejszenie ilości wody zastosowanej do nawodnień o 5% we wszystkich wariantach zmniejszyło plony o 3, 5 i 7% odpowiednio w pierwszym, drugim i trzecim sezonie wskutek stresu termicznego, jaki wystąpił w drugim i trzecim sezonie w fazie reprodukcji. Ponadto, zmniejszenie ilości stosowanej wody o 5% jedynie w trakcie fazy wegetatywnej skutkowało mniejszymi stratami plonu. Podsumowując, zastosowanie modelu CropSyst umożliwia nam stwierdzenie, kiedy można ograniczyć ilość wody do nawodnień i uniknąć znaczących strat w plonie pszenicy.