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AquaCrop Model for Evaluation of the Water Productivity of Bread Wheat has Affected Modern Irrigation System and Water Salinity in Sandy Soil

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Abstract

AquaCrop is a very famous model in the world for evaluating the crop water productivity. FAO has developed the AquaCrop model as a leading and powerful scientific tool for simulating the response of different field crops to managing quantitative and qualitative irrigation. Two field experiments were carried out during winter seasons 2020/2021 and 2021/2022 at the Research and Production Station, National Research Centre, El-Nubaria, El-Behira Governorate, Egypt. to evaluate yield and yield component for two bread wheat varieties (Giza 171 and Misr 1) under sprinkler and drip irrigation systems with using four concentrations of water salinity irrigation. A split-plot design with three replications was used. Wheat were randomly distributed in the main plots while, while water salinity treatments occupied the sub-plots in both seasons. Results found that the simulated and observed values of water productivity were rather well in agreement for the salinity water levels treatments SWLT. This means that differences in canopy cover CC, yield and water productivity of bread wheat crop had significant effect on the calibration results. There is an inverse relationship between the water productivity and salinity water levels treatments and bread wheat varieties, while a direct correlation was found between water productivity and irrigation systems. It could be concluded that using sprinkler irrigation systems with S1 and S2 of SWLT and Misr 1 varitey, and drip irrigation system with S1 and S2 of SWLT and Misr 1 varitiey. the maximum of water productivity due to that there is a direct relationship between the study factors, the characteristics of the canopy cover growth and yield of the bread wheat plants, the more measured values will be simulated by the Aquacrop model.

Keywords: AquaCrop; Bread wheat cultivars; Water salinity; Irrigation system; Micronutrient.

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1. Introduction

Simulation models for the growth of agricultural crops are very important for analyzing the influences and variables that affect plants and soils, such as the degree of water salinity, the quantities of water and the irrigation systems used, which have a great impact on the growth and quality of crops. Consideration must be given to the extent of the positive use of the available water, given the negative effects that help climate change, which also negatively affect current agricultural practices and the subsequent reduction in the provision of water needed for the irrigation process. This is very important for plants of great economic importance, such as wheat, which is used in the production of bread, which can be grown under irrigation conditions Vanuytrecht, *et al.* [1] and Vanuytrecht, *et al.* [2]; and Ghazzawy, *et al.* [3].

Wheat yield and wheat biomass were simulated using the AquaCrop model and studied in response to different water use rates. It was also required to calibrate with the Aquacrop model for wheat under unchanged climatic conditions, because doing so would make it easier to simulate crop performance and predict water yield using all of the data and inputs of the AquaCrop model [2].

AquaCrop model is a powerful tool for the simulation of crop response to the different quantitative and qualitative management of irrigation that advanced by FAO. Models can be defined as a simple or abstract representation of the real system [4]. Model simulations typically go through a calibration phase, where the modeller is tuning a model by making comparisons with the measured data. Biological systems such as crop cultivation are very complex systems, making them a challenge to the model. However, because of crops, annual crops, go through their complete life cycle in one year or a growing season, they belong to a repetitive biological system. Bread wheat (*Triticum aestivum* L) is the most important source of edible vegetable oil after soybean, rapeseed and peanut, with a worldwide seed production of 33.3 million tons destined almost exclusively to oil extraction, providing 8.5% of the total world volume, [5-7].

Bread wheat is an important oilseed crop because, it has a wide adaptability to different climatic conditions. Bread wheat seeds have a high medical use, which they can be applied as an addition to therapy of colon cancer, high blood pressure and migraine headaches. Bread wheat has a short growing season and thus lower irrigation needs have helped plant breeders more interest in this crop in different regions. The repeatable and reoccurring real systems can be validated independently making it possible to the developmental models and continue to build on them year after year, [4]. The development of crop growth models began in the 1960s and have advanced and become more refined since, [8]. Crop models can be useful for the agronomic research tools that predict of the growth, the development and crop yield in the response to the surrounding environment [9]. There are many existing crop models that are used around the world. All of the models have different structures, methods, inputs and algorithms for simulating crop growth [10]. The next section will provide the review of AquaCrop model used in this study.

AquaCrop model is defined by Steduto, *et al.* [9] as “canopy-level and the engineering type of the model, mainly focusing on simulating an attainable crop biomass and the harvestable yield in the response to water availability. The model was developed for purpose for using the fewer parameters in the balance of the simplicity, accuracy, and robustness. Water is used as the main driver in AquaCrop for simulating yield production. Water is very important for crop production and was proven early on to be one of the major limiting factors in crop growth [11]. Crops use the water to carry the minerals, the sucrose and the hormones through the plant. Water is also very critical factor in the chemical reaction of photosynthesis [12]. Water-limiting conditions will result in the lower yields at the end of the season, so it is an important factor for crop modelling.

The objectives of this research work are to evaluate water productivity by AquaCrop model for two bread wheat cultivars (Giza 171 and Misr 1) under sprinkler and dripp irrigation systems with using four concentrations of water salinity irrigation.

2. Material and Methods

The present study was carried out during winter seasons 2020/2021 and 2021/2022 at the Governorate, Egypt, to study the effect of four concentrations of water salinity irrigation (650, 1650, 2650 and 3650 ppm) on yield and yield components of two bread wheat cultivars (Giza 171 and Misr 1) under sprinkler and dripp irrigation systems.

The experimental soil was sandy in texture, pH value, organic matter (%) , CaCO3 (%) and EC (dSm-1) were 7.82, 0.62%, 1.70% and 1.61 average of the first and second seasons, respectively.

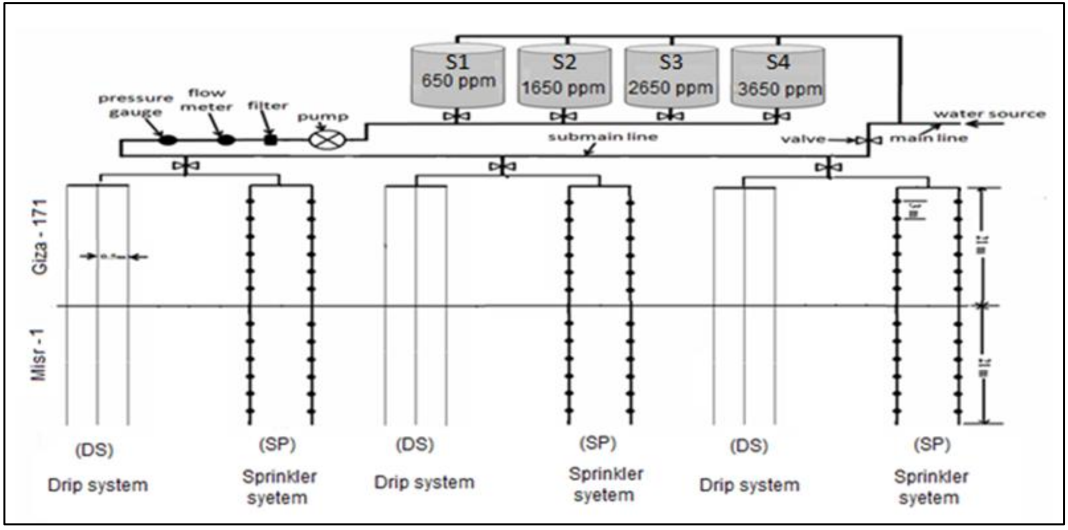
The treatments were designed in a split-plot design with three replications. Wheat cultivars were sorted at random in the main plots while, water salinity treatments occupied the sub-plots in the two seasons. The sub-plot area was 10.5 m2.

Cultivars of wheat were plowed on November 11th and 7th in the first and second seasons, respectively. P fertilizer with the average of 31 kg P2O5 fed-1 was one similar dose as calcium super phosphate form (15.5% P2O5) applied before drilling pending seedbed preparation. The common cultural pursuits were carried out like recommends in the region.

Fig-1. Wheat crop under sprinkler irrigation system

Fig-2. Wheat crop under drip irrigation system

Fig-3. Layout of the field experiments for the effect of different saline water and irrigation systems on different wheat varieties at (NRC's Farm, El-Noubaria region, Elbuhaira Governorate)



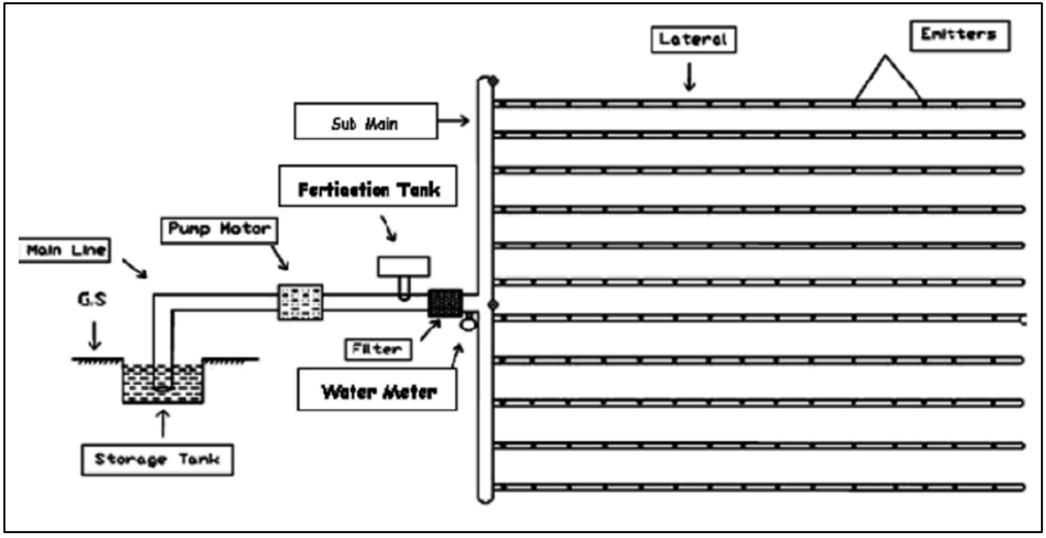
2.1. The Drip Irrigation System Consists of the Following Components, as Follows:

Control head: It is located at the water inlet and consists of:- Pump: centrifugal electric pump (0.75HP), n ≈ 2900 rpm and discharge 3 m^3/h., Filter: screen filter 1.5" (one unit), 155 mesh, Max. Flow 7.2 m^3/h and maximum pressure 150 (PSI)., Injection unit: venture in PE of 1", rang of suction capacity 34- 279 l/h., Measurement units: spring brass non return valve 2", Pressure gauges, control valves and flow meter.

Main line: PVC pipe of 63 mm diameter -6 bar, connects the control unit to convey the water to sub main line: PVC 32 mm diameter line, delivered from the main line to feed the group of the laterals which represent treatments.

Laterals: It is 16 mm diameter PE tubes, with 30 cm apart, built in drippers of 4 lph discharge at 1bar operating pressure. Distance between laterals was 0.9 m. Irrigation system design according to Mansour [13], Mansour and Abdullah [6], Mansour, *et al,* [7, 14-18].

Fig-4. Layout of drip irrigation system



At heading stage, Chlorophyll content was estimated in fresh leaves using the method of SPAD according to Minolta [19]. At harvest, the following characters were recorded capitulum values (diameter, fresh and dry weight), Grain values (fresh and dry weight, seed number and seed yield) and 1000 grain weight. Representative grain samples dried at 70 ^{0}C, ground and digested by a mixture of sulfuric and Perchloric acids then analyzed for micronutrients determined according to Motsara and Roy [20]. Nitrogen in plant analyzed using Microkjeldahl technique. Phosphorus determined by vando molybdtae color reagent and analyzed calorimetrically. Potassium determined using a flame photometer.

Canopy cover was estimated based on the method used by Farahani, *et al.* [21] and Farahani, *et al.* [21]:

$CC = 1\ \exp^{(-0.65LAI)}$ …………………………………………………………………………….(1)

Where CC is canopy cover as shown in Fig 1 and LAI is the leaf area index. LAI was calculated as LAP×NPM2, LAP is the leaf area per plant (m^2), and NPM^2 the number of plants per m^2 [22]. The nil biomass and grain yield were obtained from all plots after maturity from an area of 6 m^2 in all cropping seasons.

Fig-5. Canopy cover, flowering, effective root depth and yield formation of bread wheat by AquaCrop model

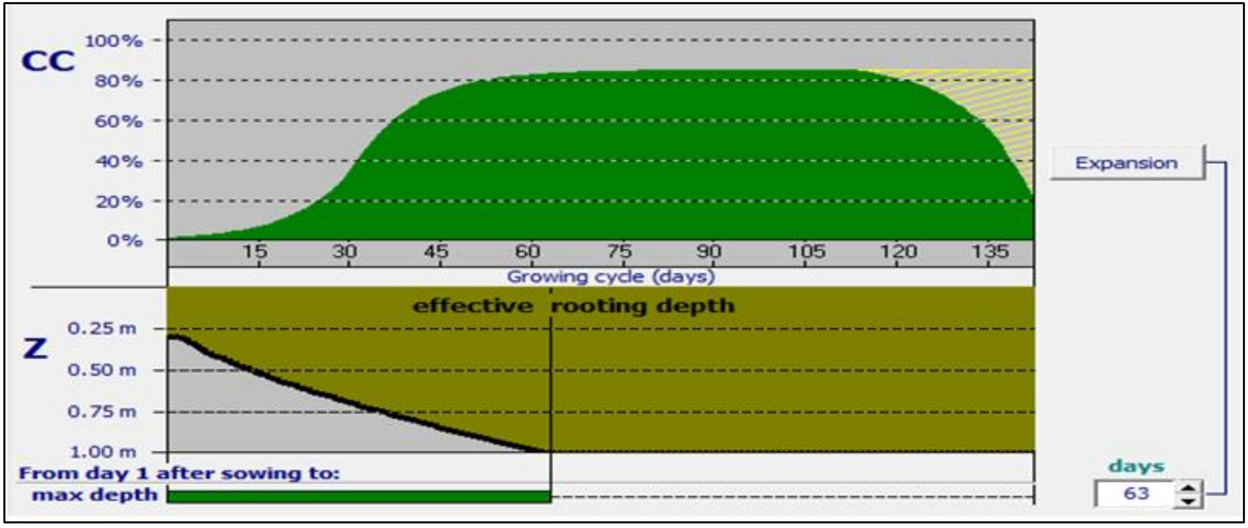
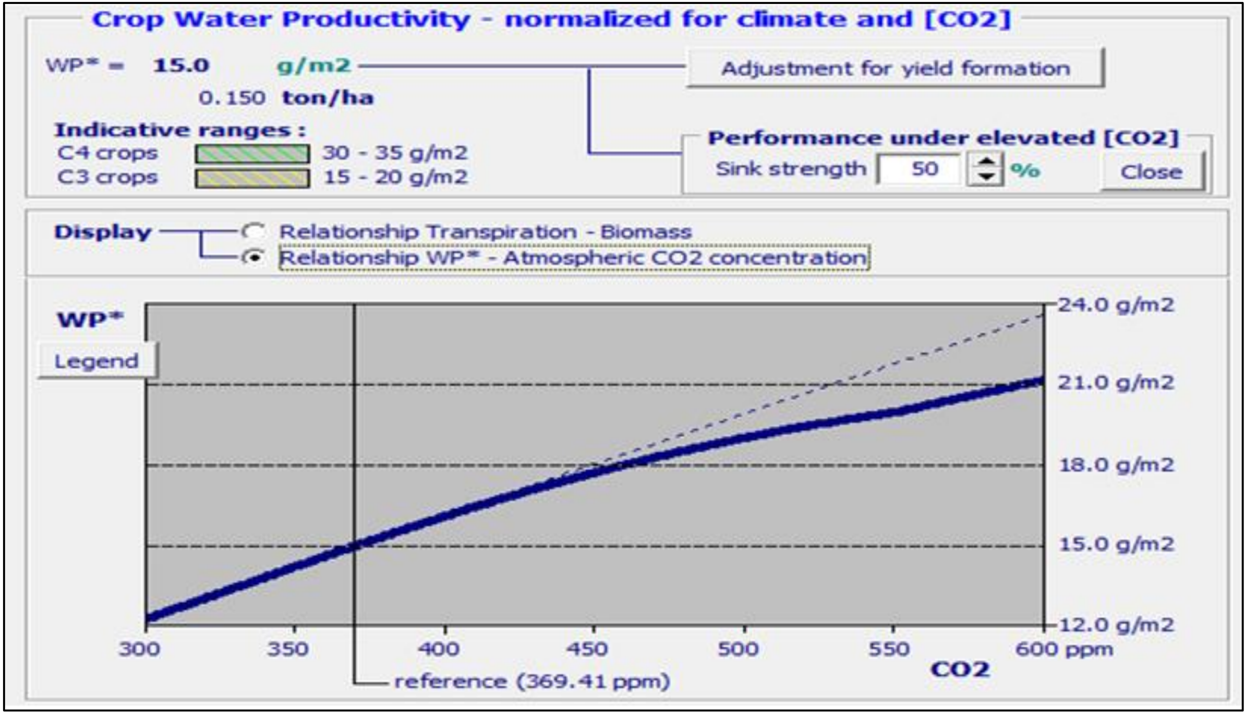


Fig-6. The relationship between bread wheat water productivity and CO2


Crop Water Productivity - normalized for climate and [CO2]

WP* = 15.0 g/m2
0.150 ton/ha

Indicative ranges :
C4 crops 30 - 35 g/m2
C3 crops 15 - 20 g/m2

Performance under elevated [CO2]
Sink strength 50 %

Display ○ Relationship Transpiration - Biomass
● Relationship WP* - Atmospheric CO2 concentration

AquaCrop has four sub-model components: (i) the soil (water balance); (ii) the crop (development, growth and yield); (iii) the atmosphere (temperature, rainfall, evapotranspiration (ET) and carbon dioxide (CO2) concentration); and (iv) the management (major agronomy practices such as planting dates, fertilizer application and irrigation if any). Fig. 4 Showing the relationship between Bread wheat biomass water productivity and transpiration/ETo and showing the relationship between Bread wheat water productivity and CO_2 draw by AquaCrop model.

AquaCrop calculates a daily water balance that includes all the incoming and outgoing water fluxes (infiltration, runoff, deep percolation, evaporation and transpiration) and changes in soil water content. There are five weather input variables required to run AquaCrop including daily maximum and minimum air temperatures (T), daily rainfall, daily reference evapotranspiration (ETo) and the mean annual CO_2 concentration in the bulk atmosphere. The advantage with AquaCrop is that it requires only a minimum of input data, which are readily available or can easily be collected. AquaCrop has default values for several crop parameters that it uses for simulating different crops, including bread wheat , however, some of these parameters are not universal and thus have to be adjusted for local conditions, cultivars and management practices.

Deviation % = 100- ((Oi.100)/Si) …………………………………………………………….(2)

Where Oi: Measured values and see: Simulated values.

The AquaCrop model uses the yield response to water equation (Eq. 3) As a starting point for the model. Doorenbos and Kassam [23] developed this equation, which has been widely used to estimate the yield response to water by planners, economists and engineers [24]. AquaCrop evolves from this approach (Eq. 3) By separating the evapotranspiration into crop transpiration and soil evaporation to develop a final yield as a function of the final biomass of the crop (Eq. 4). This separation allows for distinguishing the effects on the non-productive consumptive use of water, soil evaporation, to better simulate crop growth. The water productivity (WP, the biomass produced per unit of cumulative transpiration) is a conservative parameter, which is considered to be constant for giving climatic conditions [9].

$(Yx-Ya)Yx= ((ETx-ETa))$ ……………………………………………………………[Eq. 3]

Where Yx and Ya are maximum and actual yield, ETx and ETa are maximum and actual evapotranspiration and Ky is the proportionality factor between relative yield loss and relative reduction in evapotranspiration.

$B=WP* \Sigma Tr$ ……………………………………………………………………………...[Eq. 4]

Where B is the final biomass, WP is the water productivity (biomass per unit of cumulative transpiration), and Tr is the crop transpiration.

The WP parameter is based on the atmospheric evaporative demand and the atmospheric CO_2 concentration for the purpose of being applicable to diverse locations and simulating future climate scenarios. Equation 5 shows the procedure for calculating the normalized WP based on adjustments to annual CO_2 concentrations. This approach has a tendency to over-simulate future crop yields caused by CO_2 fertilized when compared to free air CO_2 enrichment (FACE) experiments [1]. This lead to the introduction of a crop sink strength parameter to address the response of WP, resulting in higher yields [1], but there are still many uncertainties and more research is needed for a better understanding of crop behavior with increased CO_2 concentrations.

$WP=(B\Sigma(TrETo))CO_2$ ……………………………………………………………………..[Eq. 5]

Where CO_2 is the mean annual CO_2 concentration and ETo is the atmospheric evaporative demand. The CO_2 outside the bracket is the normalization concentration for a given year. Once the final biomass are calculated at harvest, the final yield output is the function of the final biomass (B) and the Harvest Index (HI). HI is the ratio between the harvested product and the total above ground biomass. AquaCrop simulates the build-up of HI starting from the flowering stage to reach the reference HI, a crop parameter set by the user. The build-up of HI increases linearly with time, but adjustments of HI is made depending on crop stresses during simulations, resulting in lower yields or even zero yields under conditions of pollination failure caused by severe stress [9].

Vanuytrecht, *et al.* [2], performed a global sensitivity analysis of AquaCrop in an attempt to create guidelines for model simplification and efficient calibration. The parameters that were determined to be a priority for AquaCrop are parameters describing the crop phenology, a crop response to extreme temperatures, water productivity, root development, and soil water characteristics. These parameters require the most attention for model calibration for accurately simulating final yields.

AquaCrop is effective for modelling yields under a limited number of site locations. The current version of AquaCrop (6.0), This issue has been assessed by the creation of two external utility programs called Aqua Data and AquaGIS [25]. The flow chart (Fig. 4) Describes the process of using AquaCrop with the two utility programs Aqua Data and AquaGIS. This allows a spatial visualization of crop yields over a greater area, enabling the capability to perform a spatial analysis [25]. Aqua Data acts as a database that contains all data necessary for creating input files used in AquaCrop. FAO has developed an AquaCrop plug-in program that will run AquaCrop without a user interface, which allows an application like Aqua Data to automatically run multiple crop simulations much more efficiently [26]. The AquaCrop plug-in program can be used for iterative runs for calibration purposes or for inputting into a Geographical Information System (GIS) for subsequent spatial analysis. Using similar methods, AquaCrop can be used for calibrating and analyzing long-term climate change impacts on crop yields in southern Alberta.

The main concepts of connecting the soil-crop-atmosphere continuum in AquaCrop are illustrated in Fig. 4. The soil component of the continuum is focused on the water balance within the soil, the plant represents the growth, development and yield processes, and the atmosphere represented by air temperature, rainfall, evaporative demand, carbon dioxide concentrations and irrigation [9]. Figure 2, 3 shows the interaction of different variables that AquaCrop combines for simulating yield output. The model uses separate input components of climate data, crop parameters, management (irrigation and field), soil (soil characteristics and groundwater) and the simulation period for simulating crop yield.

Fig-7. Chart of AquaCrop indicating the main components of the soil–plant–atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production, and final yield (I) irrigation; (Tn) lowest air temperature; (Tx) highest air temperature; (ETo) reference evapotranspiration; (E) soil evaporation; (Tr) canopy transpiration; gas, stomatal conductance; (WP) water productivity; HI, harvest index [9].

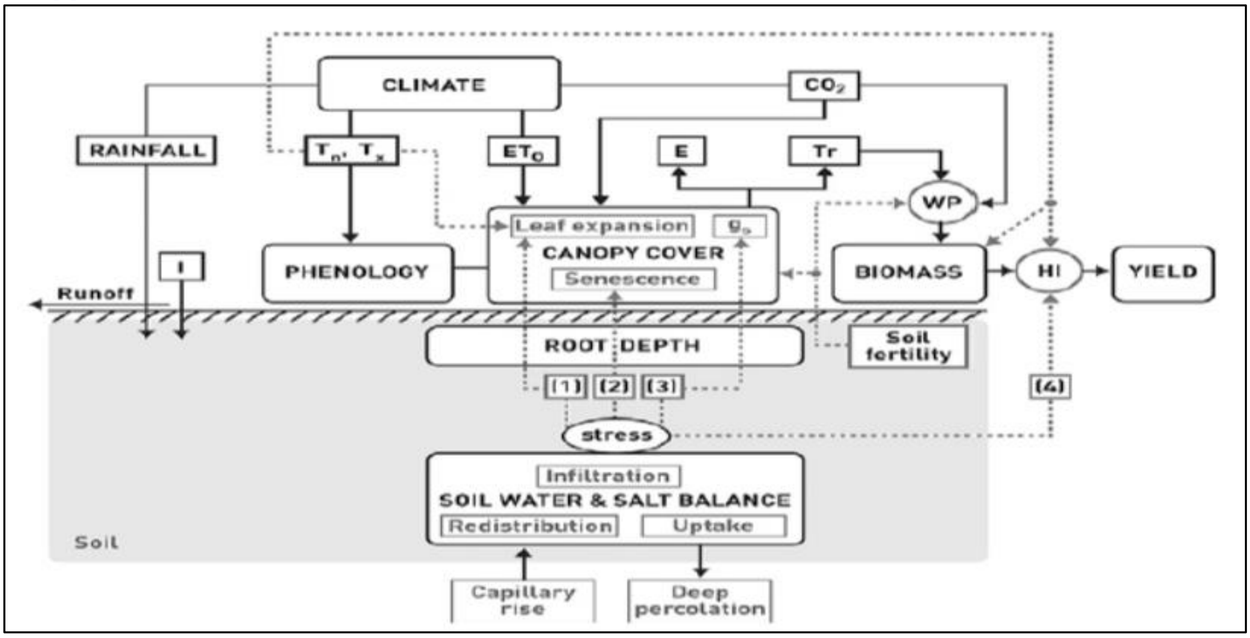


Table-1. AquaCrop default values and calibrated values for main parameters used in bread wheat simulation

Parameters	**Default**	**Calibrated**
Growth & production	-	-
Normalized crop water productivity (g m^{-2})	33.7	33.7
Reference harvest index (%)	48	52
Phenology		
Base temperature (^{o}C)	8	8
Cutoff temperature (^{OC})	30	30
Time from sowing to anthesis (GDD)	800	882.2
Time from sowing to maturity (GDD)	1700	1469
Morphology		
Initial canopy cover (%)	0.49	0.42
Canopy cover (CC) per seedling (cm^2/plant)	6.5	6.0
Maximum canopy cover (%)	96	94
Maximum rooting depth (M)	2.3	1.0
Canopy growth coefficient (% / day)	16.3	13.6
Canopy decline coefficient (% / day)	11.7	16.2
Crop coefficient for transpiration	1.05	1.02
Decline of crop coefficient (% / day)	0.30	0.30
Effect of CC on Reding evaporation (%)	50	50
Upper threshold for leaf expansion growth	0.14	0.14
Lower threshold for leaf expansion growth	0.72	0.72
Leaf growth, stress coefficient curve shape	2.9	2.9
Upper threshold for canopy senescence	0.69	0.69
Senescence stress coefficient curve shape	2.7	2.7
Upper threshold for stomatal closure	0.69	0.69
Stomata stress coefficient curve shape	6	6.0
Aeration stress coefficient (% vol. saturation)	5	5
Source: (Hsiao *et al.*, 2009 and Heng *et al.*, 2009)		

Random patterns of ten plants were taken from every sub-plot at maturing time to set the following traits: plant height (cm), weight of spike (g) and number of spikelets spike-1. For set tillers number and spikes/ m-2 a sample of one square meter from each sub-plot was taken. Grain (kg fed-1) were predestined on total sub-plot basis.

MSTATC program (Michigan State University) was used to carry out the statistical analysis. Treatment means were compared using the technique of analysis of variance (ANOVA) and the least significant difference (LSD) between systems at 1% had been done according to Snedecor and Cochran [27].

3. Results and Discussion

The calibrated by the model of AquaCrop (FAO), was validated using data of version 2016. The validation runs with calibrated data in AquaCrop showed good results for seed yield as indicated by observed and simulated values. It appears that the simulated and observed values of seed yield were rather well in agreement for the two varieties. This means that differences in canopy cover growth, yield and water productivity of bread wheat crop had no significant effect on the calibration results.

Tables 2, 3 and Fig. 4, 5) illustrate the effect of the addition of saline water levels treatments (SWLT) S1, S2 followed by treatment S3 and finally treatment S4 and different varieties Giza 171 and Misr 1 and Irrigation systems of simulation values by the Aquacrop model, which are field-estimated for each of the canopy cover growth characteristics, namely canopy cover as shown in Figure 8. Canopy covers of bread wheat has affected by salinity degrees S1, S2, S3 and S4. It can be observed that the simulation values in the AquaCrop model and the field measured values for the canopy cover growth characteristics, which are the water productivity WP of bread wheat were more approximate under treatments S1, S2 followed by treatment S3 and finally treatment S4 SWLT, the higher the amount of added water, the more the values of the canopy cover growth measurements of bread wheat crop plants increased with a clear direct proportional fit.

Table-2. Effect of irrigation system, Varieties, salinity level on WP of bread wheat (Season 2020/2021)

Irrigation system	**Varieties**	**Salinity levels**	**Water applied (m3/fed)**	**Yield (Kg/fed)**	**Observed WP (Kg/m3)**	**Simulated WP (Kg/m3)**
Sprinkler	Giza 171	S1	1200	2116.6	1.76	2.37
		S2	1200	1936.6	1.61	2.17
		S3	1200	1746.6	1.46	1.95
		S4	1200	1443.3	1.20	1.61
	Misr 1	S1	1200	2261.6	1.88	2.53
		S2	1200	2105.0	1.75	2.35
		S3	1200	1893.3	1.58	2.12
		S4	1200	1530.0	1.28	1.71
Drip	Giza 171	S1	2000	2205.0	1.10	1.48
		S2	2000	2126.6	1.06	1.43
		S3	2000	1836.6	0.92	1.23
		S4	2000	1600.0	0.80	1.07
	Misr 1	S1	2000	2248.3	1.12	1.51
		S2	2000	2070.0	1.04	1.39
		S3	2000	1853.3	0.93	1.24
		S4	2000	1650.0	0.83	1.11
LSD 0.05				10.153	0.04	0.06
Interaction	Irri Sys X V			7.568	0.01	0.04
	Irri Sys X S			8.045	0.04	0.05
	V x S			5.364	0.02	0.03
	Irri Sys X V X S			3.217	0.01	0.01

Table-3. Effect of irrigation system, Varieties, salinity level on WP of bread wheat (Season 2021/2022)

Irrig.Sys	Varieties	Salinity levels	Water applied (m3/fed)	Yield (Kg/fed)	Observed WP (Kg/m3)	Simulated WP (Kg/m3)
Sprinkler	Giza 171	S1	1200	2136.6	1.78	2.39
		S2	1200	2043.3	1.70	2.29
		S3	1200	1836.6	1.53	2.05
		S4	1200	1546.6	1.29	1.73
	Misr 1	S1	1200	2245.0	1.87	2.51
		S2	1200	2133.3	1.78	2.39
		S3	1200	1940.0	1.62	2.17
		S4	1200	1646.6	1.37	1.84
Drip	Giza 171	S1	2000	2180.0	1.09	1.46
		S2	2000	2046.6	1.02	1.37
		S3	2000	1836.6	0.92	1.23
		S4	2000	1660.0	0.83	1.11
	Misr 1	S1	2000	2306.6	1.15	1.55
		S2	2000	2223.3	1.11	1.49
		S3	2000	1953.3	0.98	1.31
		S4	2000	1746.6	0.87	1.17
LSD 0.05				9.587	0.07	0.04
Interaction	Irri Sys X V			6.354	0.03	0.05
	Irri Sys X S			4.236	0.05	0.03
	V x S			3.285	0.03	0.04
	Irri Sys X V X S			2.479	0.02	0.02

Fig-8. Simulated and measured canopy cover (CC) for the different irrigation water salinity (S1: 650ppm, S2: 1650ppm, S3: 2650ppm and S4: 3650ppm) treatments was used for bread wheat by AquaCrop model

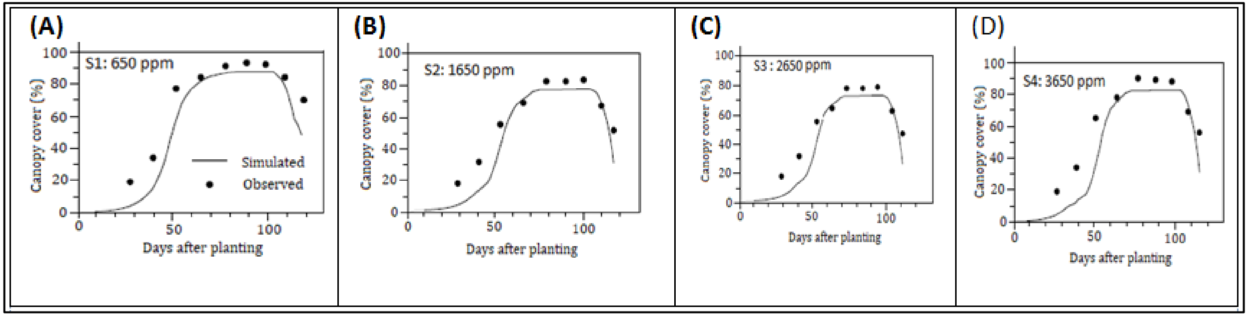
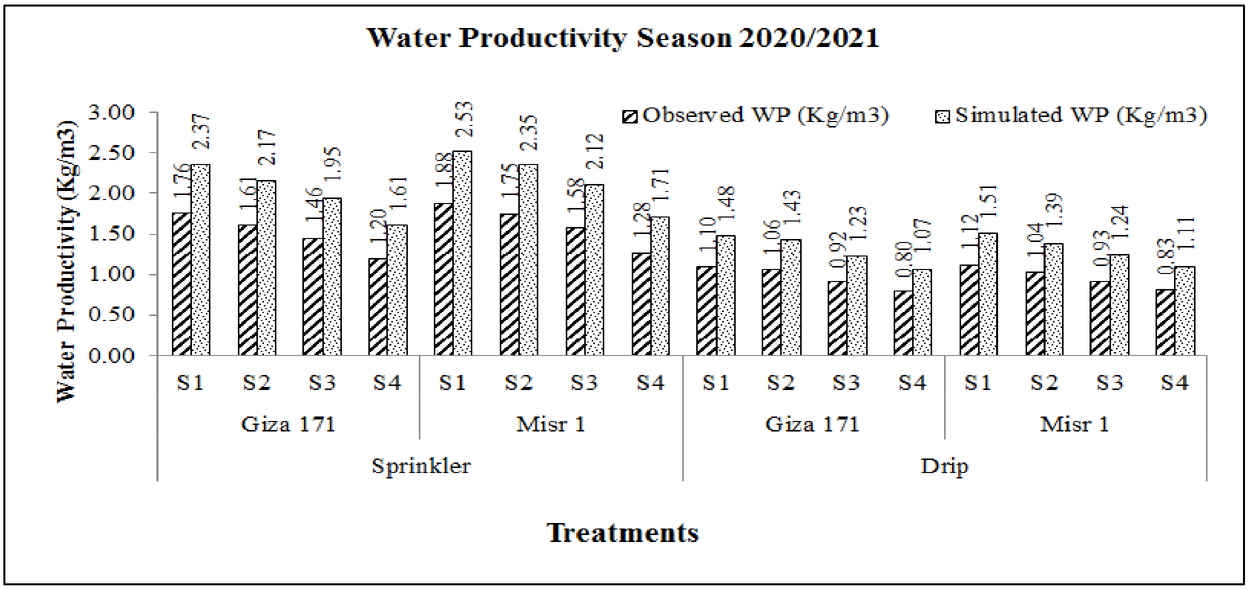
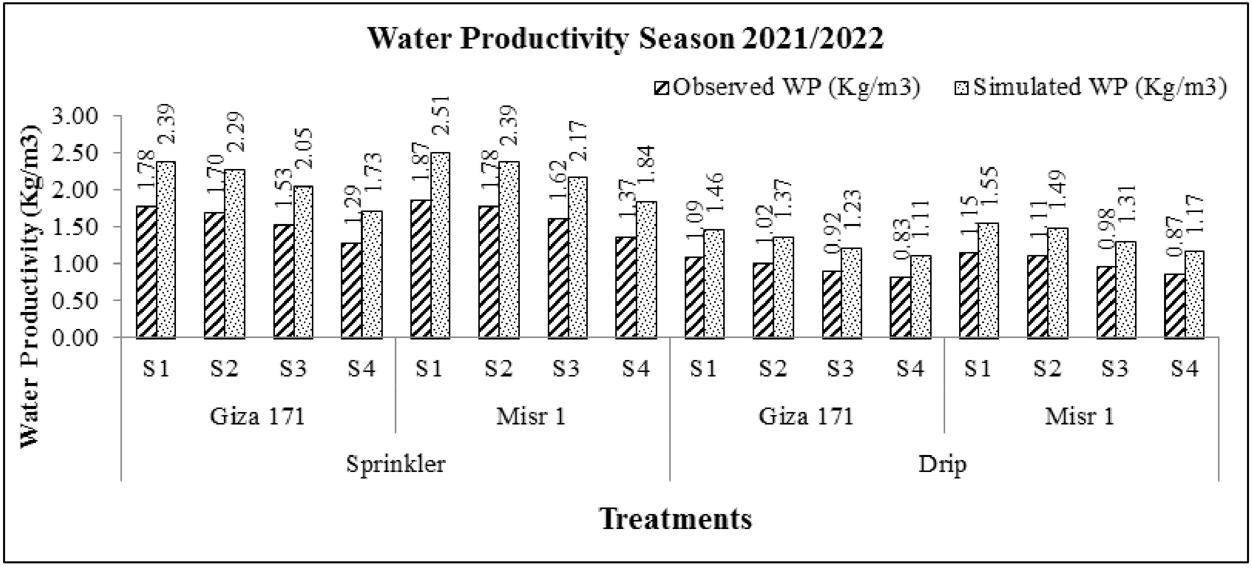


Fig-9. Water productivity of the bread wheat crop observed and simulated by AquaCrop Model season 2020/2021



(S1: 650ppm, S2: 1650ppm, S3: 2650ppm and S4: 3650ppm)

Fig-10. Water productivity of the bread wheat crop observed and simulated by AquaCrop Model season 2021/2022



(S1: 650ppm, S2: 1650ppm, S3: 2650ppm and S4: 3650ppm)

4. Discussion

AquaCrop model was able to simulate canopy cover development accurately. The simulated and observed data for canopy cover and water productivity under different treatments were normally distributed, The relationship between canopy cover and water productivity with water salinity levels treatments, bread weat varieties andirrigation systems treatments gave interesting results. The predicted maximum canopy cover data were observed under all treatments under study for bread wheat plants. However, important yield reduction can be caused by reducing canopy cover CC due to saline water stress. Severe water stress after crop establishment and at the end of the canopy cover stages has induced fast senescence as well as the decline of the canopy cover when compared with the non stressed treatments. The canopy cover for the stressed treatment 40% showed a rapid decline when compared with the irrigated by 80% and 60% water stress treatments, these data supported by Mansour [7, 14-18, 28], Mansour [29-34], Eldardiry, *et al.* [35], Hellal, *et al.* [36], Hsiao, *et al.* [37] and Heng, *et al.* [38], Vanuytrecht, *et al.* [2], Steduto, *et al.* [9] and Lorite, *et al.* [25].

We note that the simulation values have clearly approached the values that were estimated in bread wheat plants for water stress water treatments in the following order S1 greater than S2 greater than S3 greater than S4 of salinity water levels treatments SWLT, and also in the following order for bread weat varieties Misr 1 greater than Giza 171 and Sprinkler irrigation greater than drip irrigation, these results are due to the nature of the sandy soil in the lands for reclamation, as it does not maintain water and the percentage of deep leaching is large, and therefore we find that the S4 of the SWLT in the case of salinity water level tratment in sandy soil was the best in replacing the soil with the amount closest to the optimum condition and was followed by less quantities S1, S2 and S3, respectively, and this rsults has matched both Abd-Elmabod *et al* [39, 40]; Hellal, *et al.* [36], FAO [5], Mansour and Abdullah [6], Mansour, *et al,* [7, 14-18] and Mansour, *et al,* [29-34].

5. Conclusion

The relationship between canopy cover, yield and water productivity with salinity water level treatments SWLT and bread wheat varieties treatments and irrigation systems treatments gave interesting results. The predicted maximum canopy cover by AquaCrop model, the data were observed under all treatments under study for bread wheat plants. There is an inverse relationship between the water productivity, SWLT and bread weat varieties, while a direct correlation was found between water productivity and irrigation systems, and the water productivity in bread wheat yield was generally increased by decreasing the saline water level. It could be concluded that using sprinkler irrigation systems with S1 and S2 of SWLT and Misr 1 varitey, and drip irrigation system with S1 and S2 of SWLT and Misr 1 varitiey. the maximum of water productivity due to that there is a direct relationship between the study factors, the characteristics of the canopy cover growth and yield of the bread wheat plants, the more measured values will be simulated by the Aquacrop model.

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