Research Article

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Evaluating the water productivity by Aquacrop model of wheat under irrigation systems and algae

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Abstract: One of the most important simulation models in the field of water productivity (WP) management in the world is the Aquacrop model, which depends on many factors and conditions related to climate, soil, irrigation water, etc. Aquacrop model program simulates vegetative growth and the yield of both grains, biomass and irrigation WP. The purpose of this study is to evaluate the Aquacrop model of two Egyptian wheat varieties, Gemeza-9 (G-9) and Misr-1 (M-1), under the two modern irrigation systems, sprinkler and drip, and the application of algae solution. Experiment location of fieldwork for this research was in El-Nubaria area, El-Beheira Governorate, and Aquacrop in Egypt. Results obtained show that under both irrigation systems, the deviation percentages between simulated by Aquacrop and observed WP values were 40.6% and 68.34%, in the case of using untreated algae and treated algae, respectively. From LSD 0.05% values, there are significant differences between all study factors (irrigation system, wheat varieties, and applied algae). Moreover, the interactions between all factors were significant under wheat grain yield of two varieties but no significant differences were found under observed or simulated WP by the Aquacrop model. It can be concluded that it is possible to recommend to use the Aquacrop simulation model for different wheat varieties in the future, to predict the WP in these semi-arid areas, especially under different irrigation systems (Bradford and Hsiao 1982; Entz et al. 1992; Johnston et al. 2002; Heng et al. 2009; Araya et al. 2010; Bennett and Harms 2011).

Keywords: Aquacrop, wheat, varieties, irrigation systems, algae, water productivity

1 Introduction

Models are a simplified representation of real systems (Loomis et al. 1979). Sometimes some simulations of the model are carried out in the evaluation and calibration phase, where the person who modifies the model makes comparisons between the model's estimated values and the values from the measurement. Whereas the agricultural systems are more complicated than others, and this is why the models face difficulties and challenges to work with them, this is due to the annual crops that have a recycled biological system, whose production cycle or growth season takes many years.

Wheat (*Triticum aestivum* L.) is one of the most important crops worldwide, as it ranks fourth in terms of importance in the world, and represents one of the important crops in all morphological and genetic studies. Dawson et al. (2015) and Nevo and Chen (2010) have determined that the water stress criteria to produce some field crops and food supplies sometimes go through certain stages that depend on weather conditions and water shortages in the soil when high temperature and increased salt in the soil lead to an inappropriate pressure to complete the absorption of nutrients from the soil water.

The Aquacrop model was defined by Steduto et al. (2009) as one of the engineering models that simulate canopy cover (CC), biomass of the crop, grain yield, water productivity (WP) and crop response to available irrigation water, which it developed to simulating the studied traits where using irrigation water as the main source of the Aquacrop model for simulating crop yields, according to De Wit and Van Keulen (1987).

Verification of the work of Aquacrop simulation models is clearly and separately with a good focus for many future years (Loomis and Rabbinge 1979), and the process of developing simulation models for crops began in the sixties

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of the last century (El-Sharkawy 2011). Simulation models for field crops can be important and are of great benefit in the field of agricultural research, during which forecasting and future studies and scenarios for the response of field crops to environmental conditions are found (Steduto et al. 2009). Models around the world for field crop simulations are already in place and well used, and all these models have equations, properties and flowcharts which differ according to the type of field crop simulation (Todorovic et al. 2009).

During the process of photosynthesis of the plant, sucrose, minerals and hormones are carried using water to complete the production process for crops. In severe water stress cases, the grain yield decreases by the end of the agricultural season, and thus the occurrence of severe water stress is very important to complete the modeling process for field crops (Cotter et al. 2003; Bell et al. 2007; Sheaffer and Moncada 2008; Singh and Kumar 2017) and other simulation model studies – SWAT model implemented by Leh et al. (2018) and Kumar et al. (2020).

The objectives of this research are the evaluation of two Egyptian wheat varieties, Gemeza-9 (G-9) and Misr-1 (M-1), by the Aquacrop model under the two modern irrigation systems, sprinkler and drip, and the application of algae solution.

2 Materials and methods

The field experiments were conducted at the Research and Production Farm at the National Center for Research in Nubaria, Beheira Governorate, Norwegian Refugee Council,

Egypt. Meteorological data required by the Aquacrop model are the daily minimum and maximum values for air temperature, reference evaporation (ETo), precipitation and average annual CO_2 concentration. Reference evaporation was estimated using the ETo calculator using the maximum and minimum daily temperature, wind speed at 2 m aboveground, and mean relative humidity. Rain depths were 405.3, 313.8, and 411.0 mm during crop growth. Crop data were obtained from a pilot field. The experiment was placed in a random block random design. The plot of land was 2.5×6 m rows with a row distance of 0.20 m and the seeding density was adjusted to 300 g/m^2 . The crop component was divided into five sub-components including primary canopy, canopy development, flowering, yield formation and rooting depth. The yield and depth of rooting are both visually measured, while the field canopy is measured at regular intervals. The CC was estimated based on the method employed by Geerts et al. (2009) and Farahani et al. (2009):

$$CC = 1 \exp(-0.65LAI) \quad (1)$$

where LAI is the leaf area index (Figure 1). The LAI was calculated as $LAP \times NPM2$, where LAP is the leaf area per plant (m^2) and NPM2 is the number of plants per square meter (Royo et al. 2004). Biomass and cereal yield were obtained from all parts after ripening from an area of 6 m^2 in all crop seasons.

Aquacrop has four sub-model components as follows:

(i) soil and water balance; (ii) development CC and grain yield; (iii) climate data (temperature, rainfall, evapotranspiration [ET] and carbon dioxide [CO_2] concentration)

Figure 1: CC, flowering and yield formation of wheat varieties by the Aquacrop model.

and (iv) major agronomy practices such as planting dates, fertilizer application and irrigation if any. Figure 3 shows the relationship between wheat biomass, WP and transpiration/ET_o and depicts the relationship of wheat WP and CO₂ drawn by the Aquacrop model.

Aquacrop has calculated the water balance everyday which includes incoming or outgoing water fluxes by infiltration, runoff, deep percolation, evaporation and transpiration and changes in the soil water contents. Five weather input variables are required to run the Aquacrop model, including the daily maximum and minimum air temperatures (T), the daily rainfall, the daily of the reference evapotranspiration (ET_o) and the mean of annual CO₂ concentration in the bulk of the atmosphere. The advantages of the Aquacrop model are that it requires only a minimum of input data, which are readily available or can easily be collected. The Aquacrop model has default values for several crop parameters that it uses for simulating different crops including wheat; however, some of these parameters are not universal and thus have to be adjusted for local conditions, varieties and management practices.

$$\text{Deviation \%} = 100 - ((O_i \times 100)/S_i) \quad (2)$$

where O_i is the measured values and S_i is the simulated values.

The Aquacrop simulation model using the grain and biomass yield response to water (equation (3)) is a starting point for this simulation model. Doorenbos and Kassam (1979) had developed the equation water, which was used to estimate the grain and biomass yield responses to the water by the planners, the economists and the engineers (Vaux and

Pruitt 1983; Howell *et al.* 1990). The Aquacrop simulation model evolves from this approach (equation (3)) by separating the ET into the crop transpiration and the soil, and evaporation of the developing final grain yield as a function of final biomass of the wheat crop (equation (4)). This separation allows for studying the effect of the non-productive consumptive use of water, soil evaporation and for better simulation of crop growth. The WP (the biomass per unit of the cumulative transpiration) is the conservative parameter, which is considered to be constant for the given different climatic conditions (Steduto *et al.* 2009).

$$(Y_x - Y_a) Y_x = (ET_x - ET_a) \quad (3)$$

where Y_x and Y_a are the maximum and actual yield, ET_x and ET_a are the maximum and actual evapotranspiration (ET_c), and K_y is the proportion factor among the relative yield loss and relative reduction in ET.

$$B = WP \times \sum Tr \quad (4)$$

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

The WP parameter depends on atmospheric evaporation demands and atmospheric CO₂ concentrations for the purpose of being applicable to the diverse locations and the simulated future of the climate scenarios. Equation (5) shows the procedure for calculating the normalized WP, which depends on the adjustments to the annual CO₂ concentrations (Vanuytrecht *et al.* 2011).

$$WP = (B \sum (Tr ET_o)) \quad (5)$$

Figure 2: Effective root depth of wheat varieties by the Aquacrop model.

where CO_2 is the mean of the annual CO_2 concentration of year 2018, ETo is the atmospheric evaporative demand and CO_2 outside the bracket is the normalization concentration for the given year.

Once the final biomass has been calculated at the harvest time, final grain and biomass yield output (B) is the function of the harvest index (HI). HI is the ratio of the harvested product and total above ground biomass. The Aquacrop model has been evaluate the HI at the start of the flower stage to the reference HI ; and crop parameters set by the Aquacrop user (Steduto et al. 2009).

Vanuytrecht et al. (2014a) have performed by the global sensitivity analysis for the Aquacrop model in an attempt to create the guidelines of the model simplification and the efficient calibration.

The main concepts of the connecting of the soil and crop atmosphere continuum in the Aquacrop model are illustrated in Figure 4. The soil component of the continuum is focused on water balance within the soil, plant represents the CC and yield components; and atmosphere represented by air temperature, rainfall precipitation, the required evaporation, the carbon dioxide concentrations and the irrigation (Steduto et al. 2009). Figures 2 and 3 show the effective root depth of wheat varieties by the Aquacrop model and the relationship among wheat, WP and CO_2 . In Figure 4, flowchart of the Aquacrop model indicates the main components of the soil–plant atmosphere continuum, parameters driving penology, CC, transpiration, biomass yield production and finally yield (Steduto et al. 2009).

The drip irrigation system consisted of the following:

The control head: It is located in the water inlet and consists of:

Pump: centrifugal electric pump (0.75 HP), $n \approx 2,900$ rpm and discharge $3 \text{ m}^3/\text{h}$

Filter: screen filter 1.5" (one unit), 155 mesh, maximum flow $7.2 \text{ m}^3/\text{h}$ and maximum pressure 150 PSI

Injection unit: venturi PE of 1", range 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: 16 mm diameter PE tubes, with 30 cm apart, built in drippers of 4 l/h discharge at 1 bar operating pressure. Distance between laterals was 0.9 m.

Irrigation system design according to Mansour et al. (2014, 2015a,b,c,d) (Table 1).

3 Results

Table 2 and Figure 5 show the effect of the irrigation systems, wheat varieties and algae on observed and simulated WP. The effect of both the use of the observed method and the simulated use of the Aquacrop model on the WP was estimated for the Egyptian wheat varieties. Data on hand revealed that using a drip irrigation system, the method of observed WP showed the lowest values in the case of using algae control (untreated algae) or that exposed to WP (2.01 and 1.47 kg/m^3); while in the case of using algae 1.5 g/l (treated algae), the WP values were 2.49 and 2.45 kg/m^3 for G-9 and M-1 wheat varieties, respectively. On the other side, when using the sprinkler irrigation system, the method of observed WP showed the lowest values in the case of using untreated algae or that exposed to WP (1.18 and 1.17 kg/m^3); while in the case of using treated algae, WP values were recorded between 1.66 and 1.46 kg/m^3 for G-9 and M-1 wheat varieties, respectively.

The simulated data by Aquacrop model, showed that in case of using drip irrigation system, the method of observed WP was the lowest values in the case of algae control or that exposed to WP (3.39 and 2.47 kg/m^3); while in the case of using algae, the WP values were recorded at 4.19 and 4.12 kg/m^3 for G-9 and M-1 wheat varieties, respectively. On the other side under sprinkler irrigation system, the method of observed WP exhibited the lowest values in the case of algae control or that exposed to WP (1.99 and 1.97 kg/m^3); while in the case of using treated algae, the WP values were 2.79 and 2.46 kg/m^3 for G-9 and M-1 wheat varieties, respectively.

Under both irrigation systems, the deviation percentage between simulated and observed WP values was 40.6 and 68.34, in the case of using algae control (untreated algae) and treated algae, respectively. LSD 0.05% values in Table 2 show significant differences between all values of four factors (irrigation system, wheat varieties, applied algae and Aquacrop model). Interactions between factors showed significant differences under wheat grain yield but no significant differences were found under observed or simulated WP by the Aquacrop model (WP).

4 Discussion

In Table 2 and Figure 5, under both irrigation systems, the deviation percentage between simulated and observed WP values were 40.6 and 68.34, in the case of untreated algae and treated algae, respectively. The reason due to that the WP by Aquacrop model under both irrigation systems, algae were found in the same trend. These results are supported by

Figure 3: The relationship between wheat, water productivity and CO₂.

the findings of Kiniry *et al.* (1995), Touré *et al.* (1995), Louise, Zeleke *et al.* (2011), Mkhabela and Bullock (2012), Raes *et al.* (2012), Lorite *et al.* (2013), Raes *et al.* (2013), Robertson *et al.* (2013), and Vanuytrecht *et al.* (2014b).

Figure 4: Flowchart of the Aquacrop model (Steduto *et al.* 2009). I = irrigation; T_n = minimum air temperature; T_x = maximum air temperature; ET₀ = soil evaporation; T_r = canopy transpiration; WP = water productivity; HI = harvest index.

Table 1: The conservative and the non-conservative crop parameters for wheat obtained from different sources

Non-conservative parameters	Wheat
The base temperature (°C) below which crops development does not progress	0.0
The upper temperature (°C) above which crop the developer no longer increases with an increase in temperature	15.0
The number of the plants per hectare	1,500,000
The maximum effective of the rooting depth (m)	1.3
The HI (%)	33
Conservative parameters	
The water productivity normalized of ETo and CO ₂ (WP) (g/m ²)	15.0
The water productivity normalized of ETo and CO ₂ during yield formation (%WP*)	100
The maximum air temperature above which pollination starts to fail (heat stress) (°C)	35.0
The minimum air temperature below which pollination starts to fail (cold stress) (°C)	5.0
The excess of potential fruits (%)	100
The canopy growth coefficient (CGC): increase in CC (fraction soil cover per day)	0.1241
The maximum canopy cover (CCx) in fraction soil cover	0.8
The canopy decline coefficient (CDC): decrease in CC (in fraction per day)	0.07697
The soil surface covered an individual seedling at 90% emerged (cm ²)	1.5
The crop coefficient when the canopy is complete but prior to senescence (Kcb,x)	1.10
The maximum root water extraction (m ³ water/m ³ soil day) in top quarter of root zone	0.019
The maximum root water extraction (m ³ water/m ³ soil day) in bottom quarter of root zone	0.006
The effect of CC in reducing soil evaporation in late season stage	50
The soil, water depletion factor for pollination (p – pol) – upper threshold	0.55
The shape factor for water stress coefficient for canopy expansion (0.0 = straight line)	3.0

Sources: Vanuytrecht et al. (2015), Hellal et al. (2019) and Mansour et al. (2019).

Table 2: Effect of the irrigation systems, wheat cultivars and algae on the observed and simulated water productivity

Irrigation	Varieties	Grain yield (kg/fed)			Water		Measured WP (kg/m ³)			Simulated by AquacropWP (kg/m ³)		
		Algae			Applied (m ³)		Algae			Algae		
		Cont.	1.5 g/l	Mean			Cont.	1.5 g/l	Mean	Cont.	1.5 g/l	Mean
Drip	G-9	2,415.00	2,988.00	2,701.50	1,200	2.01	2.49	2.25	3.39	4.19	3.79	
	M-1	1,762.50	2,935.50	2,349.00	1,200	1.47	2.45	1.96	2.47	4.12	3.30	
	Mean	2,088.75	2,961.75	2,525.25	1,200.00	1.74	2.47	2.10	2.93	4.15	3.54	
Sprinkler	G-9	1,417.50	1,987.50	1,702.50	1,200	1.18	1.66	1.42	1.99	2.79	2.39	
	M-1	1,404.00	1,750.50	1,576.50	1,200	1.17	1.46	1.31	1.97	2.46	2.21	
	Mean	1,410.75	1,869.00	1,639.50	1,200.00	1.18	1.56	1.37	1.98	2.62	2.30	
Mean for varieties	G-9	1,582.50	2,343.00	1,963.50	1,200	1.32	1.95	1.64	2.22	3.29	2.75	
	M-1	1,749.00	2,415.00	2,082.00	1,200	1.46	2.01	1.74	2.45	3.39	2.92	
Mean		1,665.75	2,379.00	2,022.75	1,200.00	1.39	1.98	1.69	2.34	3.34	2.84	
LSD at 5% for												
Irrigation (I)		12.47			0.58				0.09			
Varieties (V)		14.58			0.47				0.08			
Algae (A)		11.12			0.85				0.02			
Model (M)		12.35			0.58				0.07			
I * V		15.22			0.25				0.05			
I * A		22.11			NS				NS			
V * A		21.57			NS				NS			
I * V * A		24.24			NS				NS

Figure 5: The effect of irrigation systems, wheat varieties and algae on observed and simulated water productivity.

The LSD 0.05% values in Table 2 show significant differences between all values of the four factors (irrigation system, wheat varieties, applied algae and Aquacrop model). Interactions between factors showed significant differences under wheat grain yield, but no significant differences were found under observed or simulated WP by the Aquacrop model.

Regarding the relationship between the observed values and the values of the Aquacrop simulation model as shown in Table 2 and Figure 5, it can be noticed that in the two wheat varieties, the WP after the Aquacrop model under both irrigation systems with algae, the WP simulated by the Aquacrop model under both studied conditions were higher than the cases observed. These results are consistent with those reported by Steduto *et al.* (2009), Hsiao *et al.* (2009) and Raes *et al.* (2009).

In the relationship between the observed values and the simulated model values as shown in Figure 5, it can be seen that in all Egyptian varieties, the WP of the Aquacrop model was reduced without stress. The highest value was obtained when cultivating G-9 variety as compared to M-1 variety. These results are consistent with those of Steduto *et al.* (2009), Hsiao *et al.* (2009) and Raes *et al.* (2009).

One of the advantages of the drip irrigation system is adding algae solution to plants through the drip irrigation network, which is known as chemical irrigation. It works for an optimal distribution process of adding nutrients and dissolved fertilizers in irrigation water in an easy way and without additional costs (Mansour *et al.* 2015a–b).

5 Conclusion

The field research work was conducted in two seasons at the Research and Production station of the National Research

Centre, at Nubaria, Beheira Governorate, NRC, Egypt, to assess by the Aquacrop model the WP of wheat varieties derived from Egypt, under different irrigation systems, with and without the application of algae at 1.5 g/l concentration. The required meteorological data for the evaluation of Aquacrop model are everyday values of minimum and maximum air temperatures and reference crop evapotranspiration (ET₀). The study showed the clear convergence of all data resulting from the use of the Aquacrop simulation program for the WP values with the corresponding quantities that were actually observed in the field for two successful seasons on wheat varieties from Egypt, Gemmeza-9 (G-9) and Misr-1 (M-1), and compared the simulated data with the Aquacrop model to the observed WP. Based on these results, it will be possible to recommend using the Aquacrop simulation program for different wheat varieties in the future to predict the water unit productivity in these semi-arid areas, especially under different irrigation systems. The use of this program is based on the input of the most important (climate, plant, soil, and water) data. Therefore, it is possible to predict the outputs for the production data of the water unit, which will help in finding suitable scenarios in case of climatic changes, water or nutrition shortage or changes in soil characteristics.

Conflict of interest: The authors declare no conflicts of interest.

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