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Full Length Research Paper

Optimizing Deficit Irrigation Strategies for Winter Wheat Using the AquaCrop Model in Arid Environments

Hamidreza Salemi[1]*, Mohd Amin Mohd Soom[2], Teang Shui Lee[1], Sayed Farhad Mousavi[3], Arman Ganji[4] and Mohd Kamil Yusoff[5]

[1]Department of Biological and Agricultural Engineering, University Putra Malaysia, 43400 UPM Serdang, Kuala Lumpur, Malaysia.
[2]Smart Farming Technology Laboratory, ITMA and Department of Biological and Agricultural Engineering, University Putra Malaysia, 43400 UPM Serdang, Malaysia.
[3]Department of Agriculture Isfahan University of Technology, Isfahan, Iran.
[4]Shiraz University, Shiraz, Iran.
[5]Department of Environmental Sciences, University Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.

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Simulation models that clarify the effects of water on crop yield, are useful tools for improving farm-level water management and optimizing water use efficiency. The main purpose of deficit irrigation is high water productivity with less water supply to plants. In this research, the potential of AquaCrop model in deficit irrigation practice for winter wheat, the main agronomic crop in Gavkhuni river basin, Isfahan province, Iran, was studied. The results of reliability indices such as RMSE, d, E, CRM and deviation percent were 2.31 to 5.63, 0.97 to 1.00, 93 to 99, -0.15 to 0.016 and -0.70 to 12.00% respectively, and showed that, the model overestimated the simulated parameters compared with field data. This difference was more obvious in deficit irrigation treatments. The model provided excellent simulations of canopy cover, grain yield and water productivity. Considering only drought stress and neglecting other stresses such as salinity is the most important limitation of AquaCrop model. In this study, water productivity for the studied crop was in the range of 0.91 to 1.49 kg m^{-3} and its maximum value was in 40% deficit irrigation treatment. A second-order, yield-water function, obtained in this study is recommended for winter wheat crop. Also, the sensitivity analysis of AquaCrop model was carried out for winter wheat in this arid area in central Iran.

Key words: Deficit irrigation, Winter wheat, grain yield, water productivity, AquaCrop model.

INTRODUCTION

Producing enough food in Iran to better feed the people and generate adequate income for the farmers is a great challenge. This challenge is likely to intensify, with a population that is projected to increase to 100 million in 2030. Irrigation accounts for about 72% of global and 90% of developing-countries water withdrawals (93.5% in Iran); but water availability for irrigation may have to be reduced in many regions, in favor of rapidly increasing water uses for industry, drinking and environmental purposes. With growing irrigation-water demand to produce more food, and increasing competition across water-using sectors, Iran faces a challenge to produce more food with less water. This goal will be met only if appropriate strategies are sought for water savings and for more efficient water uses in agriculture. One important strategy is to better manage the water and increase the productivity of water (Molden, 2006).

In the year 2000, Iran was the largest wheat importer from the international market. The amounts of imported wheat were 3.53, 6.16, and 6.58 million tons for 1998, 1999, and 2000, respectively, and the amounts of imported cereals were 5.18, 8.44, and 9.93 million tons (IAS, 2001). In 2005 however, the country became self-sufficient in wheat production. This could have not been attained without putting much pressure on groundwater withdrawal and substituting cultivation of wheat for other cereals. Part of the needed water was supplied through building of numerous new dams, better water management, better cultivation practices, and other managements at the field level (JCE, 2006).

Unfortunately, this self-sufficiency was not sustainable and did not last long, and in 2008 had to import wheat again. Improvements in water resources management are being sought and implemented in Iran, including transformation in the structure of the national economic system and demand-supply mechanism for water (Ardekanian, 2005).

In spite of all the efforts to mitigate the problem of water scarcity, reasonable management and judicious utilization of available water still needs more plans and actions (Roohani, 2006). Sun et al. (2006) reported that WP of winter wheat in North China Plain ranged from 0.97 to 1.83 kg m^{-3}. The WP of higher-stressed irrigation treatment was the highest, and the lowest WP occurred in the full irrigation treatment. In the central part of Iran, maximum WP for Pishtaz wheat cultivar was found to be 1.54 kg m^{-3} that was acquired from 60% DI (Salemi et al., 2005). Zwart and Bastiaanssen (2004) based on a review of 84 literature sources, reported that the range of WP of wheat was very large (0.6 to 1.7 kg m^{-3}) and offered new water management practices, such as DI, with 20 to 40% less water application. Oweis et al. (2004) believe that, there is a need to look for an optimum combination of production per hectare and production per m^3 of irrigation water, to obtain "more food with less water". Deficit irrigation helps at stabilizing crop yields and obtaining maximum WP rather than maximum yields (Zhang et al., 2005). Another study in North China Plain demonstrated that, reduction of irrigation water volumes should be done according to the water resources availability with respect to minimized yield losses from soil water deficits (Li et al., 2005).

Many sophisticated crop-growth models, based on physiological processes, have been developed and applied in water management projects with varying degrees of success. Many of these models however, have not yet been tested under DI in arid conditions in GRB. Some widely acceptable cereal models are hybrid models, such as CERES (Gabele, 2002), and DSSAT that simulate the growth of crops under water-limited conditions (Setiyono, 2007). CROPWAT model, as an appropriate tool for irrigation planning, is another example; but due to improper simulations of evapotranspiration, the crop yield reductions estimated by this model should be taken with caution (Cavero et al., 2000). Nearly, all these models are complicated, demanding advanced skills for their calibration and operation and need large number of parameters (Heng et al., 2009). To address these concerns and in trying to achieve an optimum balance between accuracy, simplicity and robustness, a new crop simulation model named AquaCrop has been developed by FAO (Steduto et al., 2009; Raes et al., 2009a).

To date, no study on simulation of the effects of deficit irrigation on wheat with AquaCrop has been reported in the literature. Therefore, some of the previous researches that have applied AquaCrop for other crops are presented as follows. Farahani et al. (2009) and Garcia-Vila et al. (2009) investigated AquaCrop model for cotton under full and deficit irrigation regimes in Syria and Spain. They showed that the key parameters such as normalized water productivity, canopy cover and total biomass, for calibration must be tested under different climate, soil, cultivars, irrigation methods and field management. Geerts et al. (2009), Heng et al. (2009), Todorovic et al. (2009), and Hsiao et al. (2009) applied AquaCrop model to evaluate the effect of changes in the quantity of irrigation water for quinoa, corn, sunflower and maize, respectively. All researches explored that, the AquaCrop model is a new model for scenario analysis that provides a good balance between robustness and output precision.

Traditional analyses of irrigation methods and the efficiency of agriculture can mislead planners and policy makers, especially where water availability at the river basin level becomes the primary constraint to agricultural production. Modern analyses place greater emphasis on getting more value-added and welfare derived from the use of each drop of water. Therefore, all levels in a river basin such as plant, field, system and basin levels are vital in improving WP. Inadequate water supplies, especially in arid and semi-arid regions, often lead to GY well below potential levels. Scheduling and determination of irrigation water amounts are important problems, considering restricted water resources and increasing concern about agricultural productivity. This work investigates the earlier stated issue.

The main objective of the present study was to evaluate AquaCrop model, to simulate winter wheat growth under full and deficit irrigation at a major irrigation scheme in GRB, central Iran. The main features of the model area: 1) CC simulation, 2) wheat GY simulation, 3) B simulation, and 4) WP estimation. This paper also presents calibration and validation of the AquaCrop model for simulation of essential parameters, and provides a local CWPF.

*Corresponding author. E-mail: hr_salemiuk@yahoo.com. Tel: 00983114392537. Fax: 00983117757022.

Abbreviations: B, Biomass; **DI**, deficit irrigation; **CWPFs**, crop water production functions; **CC**, canopy cover; **CGC**, canopy growth coefficient; **CDC**, canopy decline coefficient; **DAS**, days after sowing; **ETa**, actual evapotranspiration; **ETc**, crop evapotranspiration; **Ea**, soil moisture evaporation; **FC**, field capacity; **GRB**, Gavkhuni river basin; **GY**, grain yield; **HI**, harvest index; **HI_0**, reference harvest index; **LAI**, leaf area index; **N**, nitrogen; **PWP**, permanent wilting point; **SA**, sensitivity analysis; **S_C**, sensitivity coefficient; **SWC**, soil water content; **T_{max}**, maximum temperature; **TAW**, total available water; **Tr**, crop transpiration; **TDR**, time domain reflectometry; **WP**, water productivity.

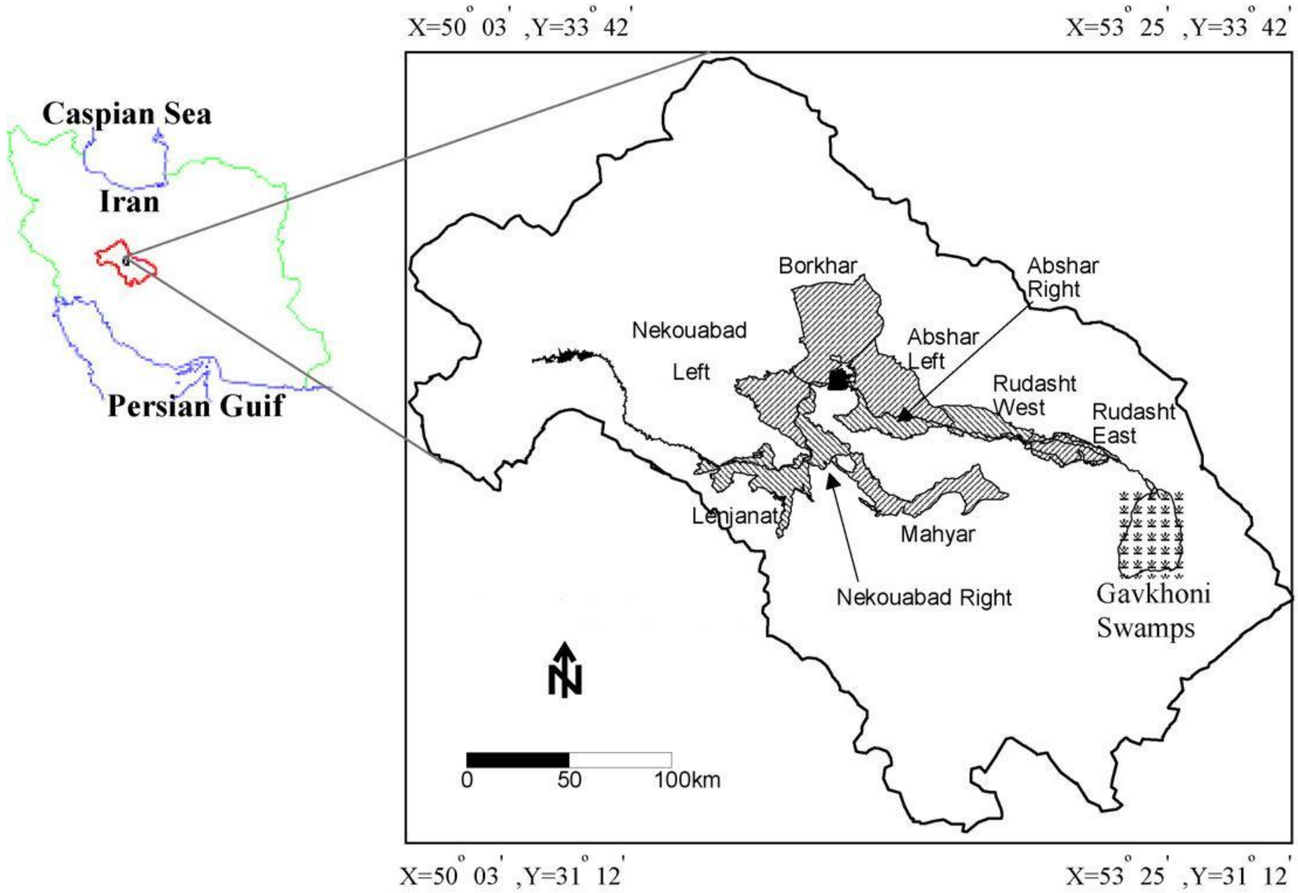

Figure 1. Location of study area and major irrigation networks in the GRB, Isfahan, Iran.

MATERIALS AND METHODS

Study area

The GRB is located in central Iran and has an arid and semi-arid climate. Annual average rainfall within the basin is about 130 mm, most of which occur in the winter. Annual potential evapotranspiration is 1500 mm. It is almost impossible to have any economical agriculture without reliable irrigation in this region. About 180,000 ha of the land is under irrigation and the main crops are wheat, maize, barley, vegetables and rice. Most irrigation practices takes place in 9 major irrigation networks within the basin (Figure 1). The Nekuabad irrigation network consisting of left and right bank schemes is the most important one. Further details can be found in Salemi and Murray-Rust (2002).

Experimental data analysis and treatments details

In order to illustrate the impacts of water deficit on yield and some agronomic characteristics of wheat, a study was conducted as randomized complete blocks design with a split plot layout and three replications during three years in Kabutarabad Agricultural Research Station, Isfahan. Three levels of irrigation including: 60, 80 and 100% of water requirement (ETc) were considered as the main plots and six wheat cultivars (Pishtaz, Shiraz, M-73-18, Marvdasht, Mahdavi and Back-cross Roshan) as subplots. In this study, Pishtaz cultivar was used as recommended cultivar for dry regions.

AquaCrop model

From the outset, the study had as a specific objective, the utilization of DI and to support this with extensive use of the new crop model. AquaCrop is the crop growth model developed by FAO to segregate the ETa into Tr and non-beneficial soil evaporation Ea. Detailed description of the model was given by Steduto et al. (2009). One of the important key features of AquaCrop is the simulation of green CC instead of LAI. The impact of water deficit is expected to be accounted for by the variation of the green LAI. This variable is critical in plant modeling (Duchemin et al., 2008). Since the model uses canopy ground cover instead of LAI, the CC was monitored at the field. In AquaCrop, the inputs were saved in climate, crop, soil, management (irrigation) and initial soil water condition files (Raes et al., 2009a). Those model parameters that do not change with time such as normalized WP, HI_0, CDC and Tr were named conservative (nearly constant). The location and cultivar-dependent parameters, as well as weather data, irrigation schedule, and planting density were referred to as user parameters.

Agronomic practices

Winter wheat cultivar Pishtaz was sown by hand at the beginning of November and harvested in mid-June of the following year. The seed rate was 400 seed m^{-2}, with a row spacing of 0.75 m. The first irrigation was by furrow method, implemented one day after seeding. Seeds emergence was observed about 5 days later. The type and amount of the required fertilizers was determined from analysis of soil samples (Malakouti, 1999). The N application was 250, 200 and 300 kg ha^{-1} of N (urea at 46% N) for each year divided into installments (10 days before planting, 30 days after planting, and every 30 days until the last irrigation). The P_2O_5 (phosphate ammonium and super-phosphate triple) application to soil was 200, 100 and 50 kg ha^{-1} during the 3 years, respectively. At this stage, cultivation was done to mix the fertilizers with top soil manually. Pests and weeds were controlled, following the recommendations given by Isfahan Pest Management Department. At harvest, the final total grain yield per plot was determined.

Irrigation application

The amount of evapotranspiration for irrigation scheduling was determined by using crop coefficient (Kc), ETo from measured daily open Class A pan data, and pan coefficient values from FAO 24 (Doorenbos and Pruitt, 1977). Irrigation water requirement was calculated as the difference between ETc = Kc×ETo and effective rainfall. In this study, pan evaporation and rainfall data collected from Kabutarabad meteorological station, located at the Agricultural Research Center, were used for calculating irrigation water depth. It should be noted that, all FAO standards and the corresponding commitments in data recording and meteorological station design were considered and as a result, pan-based ETo values had enough accuracy to be used in this type of study (Salemi et al., 2005). The irrigation schedule was timed to meet the crop water requirements. Depth of irrigation water and consequently the volume of water were applied by siphons at a 10-day interval. The irrigation amount equaled the previous 10-day evapotranspiration (ETc) from the crop. Then, considering the discharge of the irrigation siphons, the appropriate irrigation time for each treatment was determined. During the experiment, yearly evaporation was accounted as 728.4, 563 and 521 mm, and the rainfall depth was 117.4, 48 and 120 mm in years 2001 to 2002, 2002 to 2003 and 2003 to 2004, respectively. Normal annual rainfall within the Kabutarabad area is about 115 mm. Over the 3 years, SWC was measured every 10 days for all the treatments. The TDR Waveguides (Model 6050 X1, Santa Barbara, USA) was used several times during the growing season to measure the SWC in the root zone. The TDR Waveguides (Model 6050 X1, Santa Barbara, USA) was calibrated before the experiment, using gravimetric method on soil samples from the respective depths. There were 9 different irrigation applications that were imposed in approximately 11-day intervals from 2 days after planting until 10 days prior to harvest (totally about 200 days). Total average water applied during the whole growing season in irrigation treatments (fully irrigated T1 and deficit irrigated T2-T3) was 674.8, 540.4, and 404.7 mm, respectively.

Model input data

The local inputs such as weather data, irrigation schedule, and sowing density were obtained from corresponding Iranian organizations. In order to run the model, cultivar-specific parameters such as plant density, GY, B, HI_0, effective rooting depth, flowering and maturity time, CC and crop germination were collected and SWC was measured. Canopy cover was measured at every 15 to 20 days interval, using a grid system. Grain yield and rooting depth were determined by removing a 1×1 m frame of wheat spike in one replication. Before cutting, the plants at the ground level, the time to emergence, maximum canopy cover, start of senescence and maturity were recorded. Plants were randomly selected from different plots of the treatments for measuring the yield contributing parameters (that is, plant height, plant population, number of spikes per m^2, 1000- kernel weight, weight of biological yield, and number of grains per spike). Soil physical characteristics [soil texture (silty clay loam), soil salinity (4.2 dS/m), salinity of water (2.2 dS/m), soil moisture at saturation (45%), FC (32%), PWP (16%), bulk density (1.45 mg cm^{-3}) and saturated hydraulic conductivity (K_{sat}= 400 mm day^{-1})] at field site were measured in the Isfahan Soil and Water Laboratory. The soil water content in the root zone was recorded throughout the season.

Estimation of ET_o

The ETo was accounted with the use of ETo calculator (Version 3, January 2009; Raes et al., 2009b). The ETo calculator uses Penman-Monteith equation for calculation of evapotranspiration. The inputs for the calculator [maximum air temperature (T_{max}), minimum air temperature (T_{min}), maximum relative humidity (RH_{max}), minimum relative humidity (RH_{min}), sunshine hours (n/N) and wind speed at a height of 2 m (u_2) based on long-term weather data (1979 to 2007)] were collected at Kabutarabad-Isfahan station. In this study, the Penman-Monteith approach was utilized for ETo computation. This method is the most general and widely used equation for calculating daily reference ET, that is recommended by FAO (Allen et al., 1998). In the study area, the ETo can rise to 13.6 mm day^{-1} in summer time (Figure 2).

Sensitivity analysis

Before applying a model, it is necessary to have some familiarity with its behavior and sensitivity to input parameters. Sensitivity analysis helps to recognize the parameters that have significant impact on model output (Cao and Petzold, 2006). SA, developed in late 1990, is almost a new method for recognition of mathematical and computer models' operation under the variations in input parameters. If variations in the values of input parameters have minor effect on model predictions, it could be concluded that input data have insignificant effect on the results and therefore the errors of their field measurements are negligible.

The inputs for SA in the present research are: agronomic, soil, meteorology, and irrigation management data. First, AquaCrop model was run with these data and the results were considered as the "basic outputs". In the next runs of the model, in each step, one of the inputs was changed and the rest of the inputs were kept constant. In this regard, Abbasi (2007) states that selection of percent change in the inputs is somewhat arbitrary (in the range of 25, 50, 75%, etc.) and it depends on limits of parameters, sensitivity of the model to different parameters, and convergence rate of the model. In the SA, a selection of 14 crop parameters, five agronomic parameters (crop coefficient for transpiration, CGC, WP, time to canopy senescence, root deepening), initial soil water content, initial soil conditions, irrigation management, and climate were considered. The interval of variation of the inputs was chosen from - 50 to +50% of its median value. After changing the values of input parameters, the model outputs were compared with the "basic outputs" using the following relationship (McCuen, 1973):

$$S_c = \frac{\frac{w}{\bar{w}}}{\frac{p}{\bar{p}}} \qquad (1)$$

where S_c is sensitivity coefficient, w is output difference before and after changing the input value, $\bar{W}$ is mean of outputs, p input

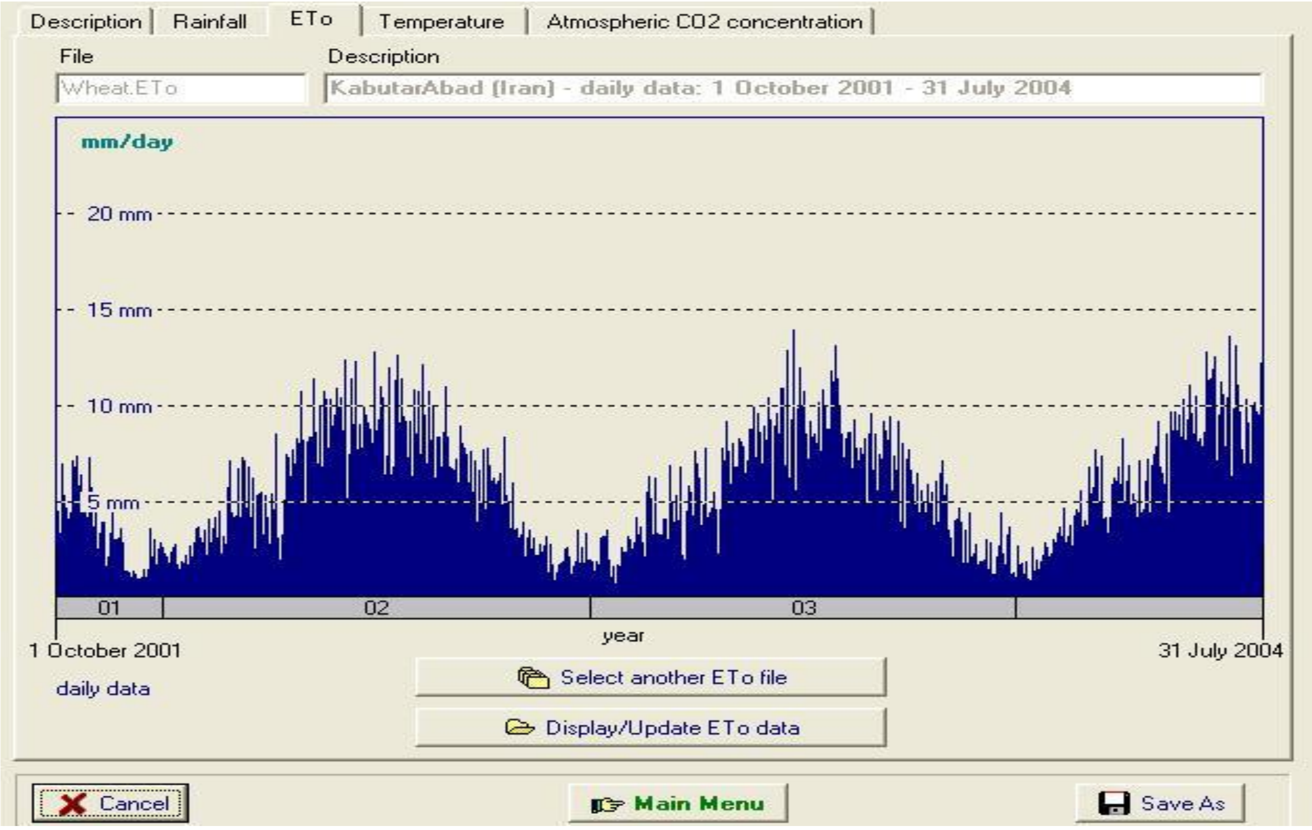

Figure 2. ETo computed from daily meteorological data using the PM equation (2001 to 2004).

difference, and $\bar{P}$ is mean of inputs. Generally, SA is employed before calibration stage.

Model calibration

To calibrate the model, results of a research project carried out in 2001 to 2004 were used (Salemi et al., 2005). Output data from this project, and meteorological data of Kabutarabad synoptic station, were calibration inputs for the model. The model simulated GY, B, WP and CC of wheat, considering that SWC was variable. Part of the monitored field data (full irrigation treatment) was used for calibration of the model, while the remaining data (T2 and T3) served to validate the model (Todorovic et al., 2009). For each of the simulation runs, the weather data, soil characteristics, irrigation depths, CC development, sowing date, and planting density were entered as input. The cultivars' data, local plant density, estimated maximum rooting depth, and time of crop development were used for model calibration. Assuming and changing conservative parameters during crop growth in the simulation of Kabutarabad data set carried out with respect to the AquaCrop reference manual (Raes et al., 2009b). The crop parameters used in this study are presented in Table 1.

Model evaluation

The AquaCrop model was evaluated against the experimental data set of 2001 to 2004 growing season. The GY, B, WP and CC were simulated for different treatments (T2 and T3) using the calibrated model. To evaluate the goodness of fit between observed GY, B WP, and CC and simulated outputs, the statistical indicators such as coefficient of determination (R^2), efficiency (E), root mean squared error (RMSE), compatibility (d), coefficient of residuals (CRM), and deviation percent were used to compare simulated and measured values of the parameters (Nash and Sutcliff, 1970). The E, d and CRM are defined as:

$$E = 1 - \frac{\sum_{i=1}^{n}(M_i - S_i)^2}{\sum_{i=1}^{n}(M_i - \bar{M})^2} \quad (2)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}\left(\left|S_i - \bar{M}\right| + \left|M_i - \bar{M}\right|\right)^2} \quad (3)$$

$$CRM = \frac{\sum_{i=1}^{n} M_i - \sum_{i=1}^{n} S_i}{\sum_{i=1}^{n} M_i} \quad (4)$$

Where S_i is simulated and M_i is measured value. R^2 shows the discrepancy of simulated and measured values and E shows efficiency of the model in simulation of the parameters. The index of agreement is a measure of relative error in model estimates. It is a dimensionless number and ranges from 0 to 1.0, where 0 describes complete disagreement and 1.0 indicates that the estimated

Table 1. AquaCrop model parameters for winter wheat simulation for 3 years in GRB.

Parameter	Value	Units
Number of plants per ha	2000000	-
Time to reach max canopy cover	170 (1971)	Day (GDD)
Initial canopy cover (CC_0)	4.8	%
Maximum canopy cover (CC_X)	90	%
Canopy growth coefficient (CGC)	10.2	%/Day (GDD)
Canopy decline coefficient (CDC)	5.1	%/Day (GDD)
Time to start senescence	190 (2080)	Day (GDD)
Time to reach flowering	160 (1752)	Day (GDD)
Length of flowering stage	7 (77)	Day (GDD)
Time from sowing to emergence	15 (165)	Day (GDD)
Time from sowing to reach maturity	210 (2300)	Day (GDD)
Minimum effective root depth	0.10	m
Maximum effective root depth	0.30	m
Time from sowing to maximum root depth	175	Day (GDD)
Building up of HI	64	Day (GDD)
Reference harvest index (HI_0)	45	%
Normalized water productivity	15	gr/m^2
Irrigation management	DI levels	%
Initial soil water content	DI levels	%
Hydraulic conductivity	300	mm/day
Tmax	daily data	°C
Rain	daily data	mm

andobserved values are identical. CRM presents model tendency to over-estimate or under-estimate measured values of parameters.

RESULTS AND DISCUSSION

Results of the field experiment (Salemi et al., 2005) showed that, irrigation treatments had significant effect on grain yield (P≤ 0.01) and DI decreased CC_{max}. The maximum WP was 1.54 kg m^{-3} that was acquired from ETc of 60%. Pishtaz wheat cultivar was found to be tolerant to water stress. Field data from the experiment were used to validate the performance of the AquaCrop model. In crop simulation models, calibration is necessary to estimate the model parameter values for different crops, cultivars and ecosystems. Model calibration helps in reducing the parameter uncertainty. However, when the number of parameters in a model is large, the calibration process becomes complex. In such cases, sensitivity analysis helps in recognizing the parameters that have significant impact on model output (Cao and Petzold, 2006). More description about the sensitivity analysis are presented subsequently.

Sensitivity analysis

The inputs were organized in five classes according to their relative influence on the simulated B and GY (Table 2). Classes were selected as high, moderate and low, if the model response to changes in inputs was higher than 15%, between 15 and 2%, or smaller than 2%, respectively (Geerts et al., 2009). The results showed that, the most sensitive agronomic parameters in AquaCrop model are time to senescence and the 60% full irrigation, followed by the root deepening, irrigation management (full irrigation), CC, WP, T_{max} and CGC. It should be noted here that, over-estimation of the beginning of the maturity causes less error in yield prediction than under-estimation of this phenomenon. The model showed less sensitivity to initial soil moisture content in full irrigation and the 80% full irrigation treatments, K_{sat} and rainfall. The sensitivity of the model to the depth of irrigation water was different in different irrigation treatments. Model's sensitivity increased with decreasing irrigation depth. In general, model outputs were highly sensitive to the depth of irrigation water, initial soil moisture content in water-stressed treatments, and time of maturity.

Assessing and evaluating irrigation strategies

Comparison of the simulation results with data of field experiments allowed the study of the AquaCrop model's performance under drought and farming conditions. By using the calibrated AquaCrop model, winter wheat

Table 2. The sensitivity coefficient (S_c) of AquaCrop for winter wheat to calibrate the model.

Input parameter		S_c (+50%)	S_c (-50%)	Sensitivity level
Agronomic parameters	Crop coefficient for transpiration	0.47	1.08	2%< S_c<15% Moderate
	CGC	0.87	0.59	2< S_c <15 Moderate
	Crop WP	0.99	0.43	2< S_c <15 Moderate
	Time to canopy senescence , DAS	0.33	3.20	S_c >15% (High)
	Root deepening	0.39	0.87	2%< S_c <15 Moderate
Initial soil water content	Full irrigation	0.05	0.10	S_c <2% (Low)
	80% full irrigation	0.00	0.22	S_c <2% (Low)
	60% full irrigation	0.00	1.50	S_c >15% (High)
Initial soil condition	Hydraulic conductivity	0.008	0.01	S_c <2% (Low)
Irrigation management	(TAW) full irrigation	0.31	0.75	2%< S_c <15% Moderate
	80% full irrigation	0.10	0.61	2%< S_c <15% Moderate
	60% full irrigation	0.02	1.09	Sc>15% (High)
Climate	T_{max}	0.01	0.57	2%< S_c<15% Moderate
Climate	Rain	0.01	0.13	S_c <2% (Low)

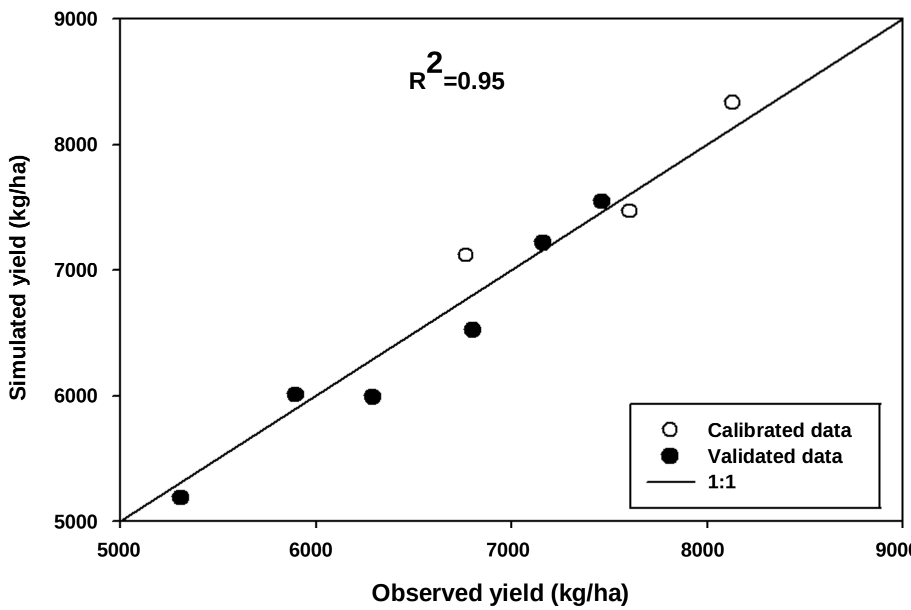

Figure 3. Simulated vs. observed values of winter wheat grain yield- two data sets used for model calibration and validation.

irrigated area can be managed under optimized irrigation programming and water-saving practices. The model was validated on the treatments T2-T3 in 2001 to 2004 including regulated DI conditions. The following crop growth parameters were analyzed: CC, GY, harvestable B, and WP, indicating the ratio between GY at harvest and the water requirement. According to the research results, R^2 values were 0.95, 0.96 and 0.94 for model calibration and validation (Figures 3 to 5) 0.91, 0.89, and 0.90 for simulated values of CC in fully irrigated, 80% ETc and 60% ETc treatments (Figure 6), and 0.90 for CWPFs (Figure 7), respectively.

This index shows good correlation between simulated and measured crop parameters and CWPFs for three years of the experiment. For calibration process, the E values for CC (100%), CC (80%), CC (60%), GY, B and

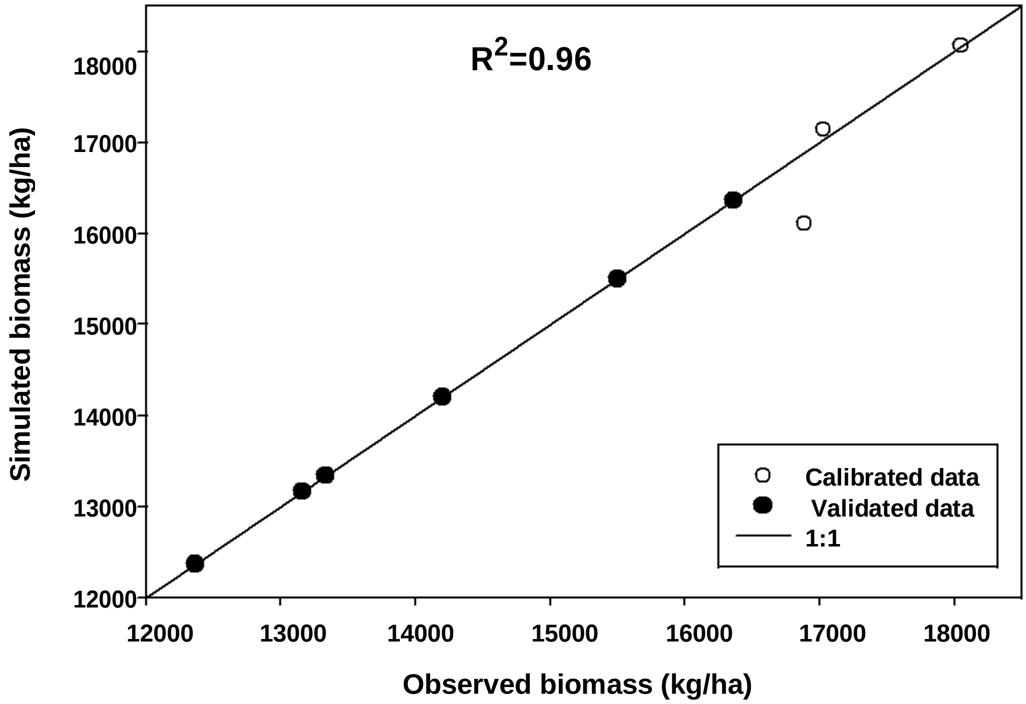

Figure 4. Simulated vs. observed values of winter wheat biomass- two data sets used for model calibration and validation.

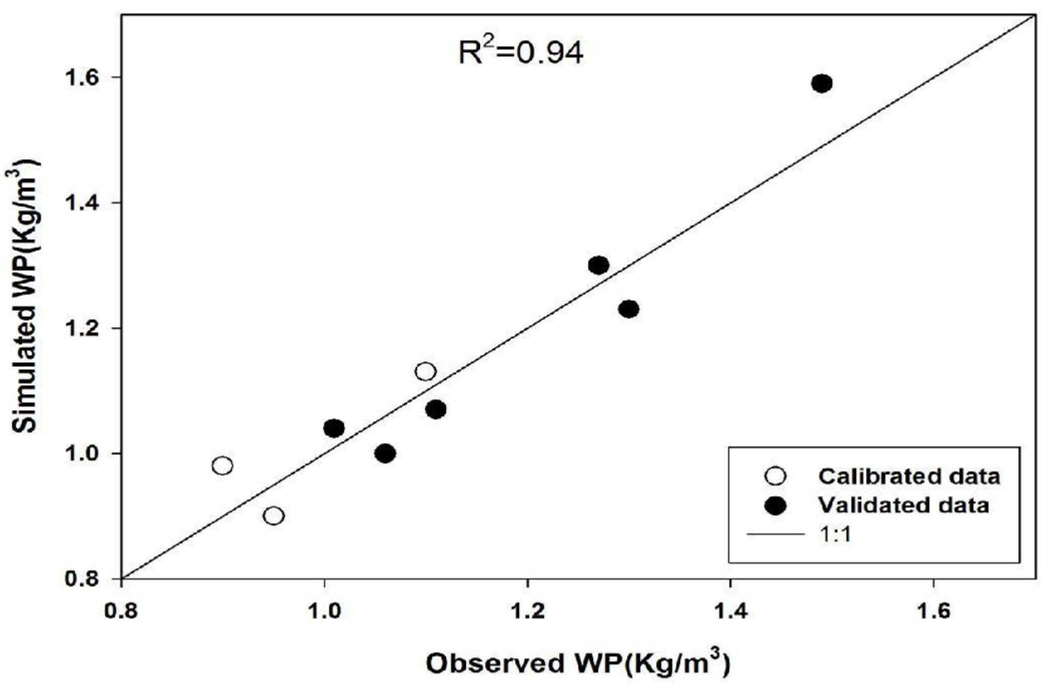

Figure 5. Simulated vs. observed values of winter wheat WP- second and third years used for model validation.

WP were 0.98, 0.94, 0.92, 0.90, 0.99 and 0.94, respectively, whereas the corresponding values for validation process were 0.98, 0.95, 0.93, 0.97, 0.99 and 0.96, respectively. The highest and lowest model efficiency was for B and CC (60%). Low value of efficiency for CC (60%) was due to high irrigation water

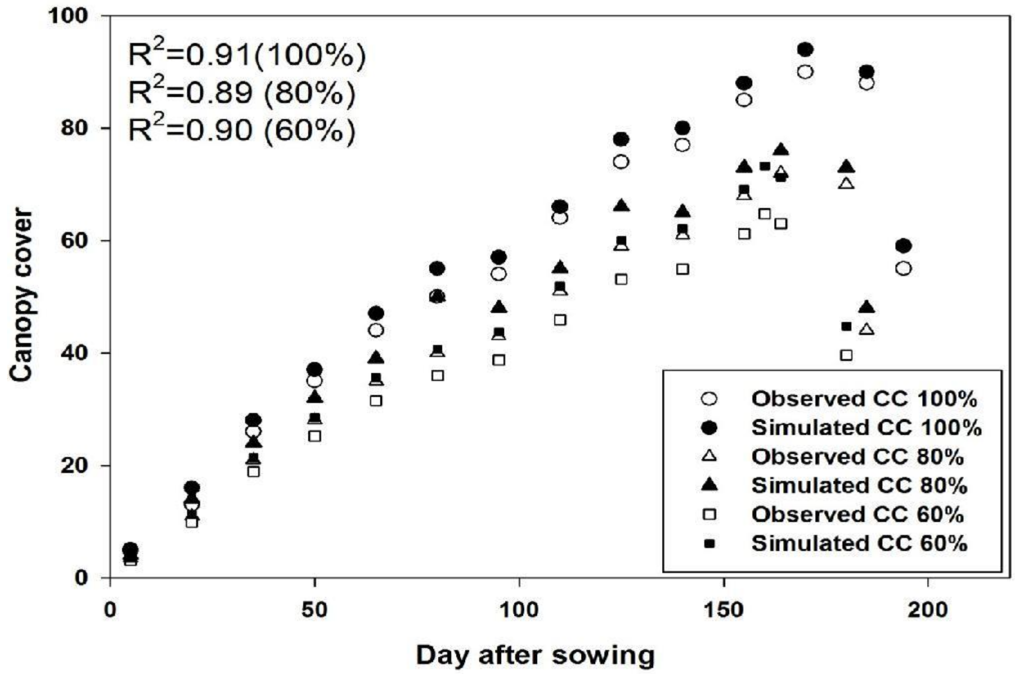

Figure 6. Comparison between simulated and measured values of CC in fully irrigated, 80% Etc and 60% treatments.

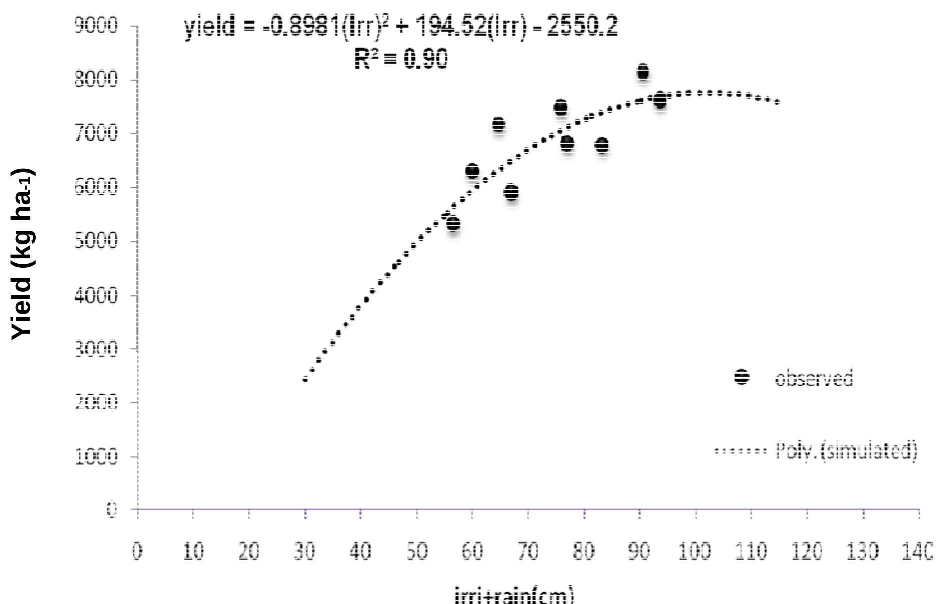

Figure 7. Local grain yield-water-production function.

stresses. The simulated yield was reduced with decreasing irrigation water depth. The model simulated GY and CC fairly well, when irrigation treatment changed from 60 to 100%. The lowest RMSE was for B, which is a good sign of model simulation. The higher RMSE values belonged to CC (60%) (Tables 3 and 4). CRM value is - 0.13 and -0.15 for CC (60%) in calibration and validation processes respectively. The negative CRM shows that, the model over-estimated CC in most cases. Positive values of CRM for B and WP shows that, the model under-estimates this parameter. The next indicator is compatibility index (d) which was 0.96 to 1.0 for the four evaluated parameters. This index shows good correlation between irrigation water deficit and reduction of simulated

Table 3. Statistical indices derived for evaluating the performance of the model in simulating GY, B, WP and CC for calibration.

Statistical Index	E	RMSE (%)	d	CRM	Deviation (%)
GY	0.90	3.48	0.98	0.02	1.90
B	0.99	2.63	0.96	-0.03	1.40
WP	0.94	3.83	1	0.048	1.82
CC (100%)	0.98	3.10	0.98	-0.06	7.0
CC (80%)	0.94	4.80	0.98	-0.10	10.0
CC (60%)	0.92	5.63	0.99	-0.13	11.0

Table 4. Statistical indices derived for evaluating the performance of the model in simulating GY, B, WP and CC for validation.

Statistical index	E	RMSE (%)	d	CRM	Deviation (%)
GY	0.97	2.87	0.99	-0.015	-1.35
B	0.99	2.39	0.97	0.016	-1.42
WP	0.96	2.31	1	-0.031	-0.70
CC (100%)	0.98	3.10	0.99	-0.06	6.50
CC (80%)	0.95	4.80	0.98	-0.10	10.0
CC (60%)	0.93	5.63	0.98	-0.15	12.0

wheat GY. The deviation index shows that, the model over-estimated CC by 6.5, 10, and 12%, under-estimated GY by 1.35%, B by 1.42 and WP by 0.7 respectively. All these values show very good simulations by the model in the study region. Therefore, with regard to the results of sensitivity analysis, calibration, validation and evaluation of the AquaCrop model, it could be concluded that this model simulates satisfactorily GY, B, WP, and CC very well for the non-water-stress treatments of winter wheat crop in the central region of Iran.

In an experiment in East Africa, barley showed slightly lower performance under mild water deficit condition compared to full irrigation condition (Araya et al., 2010). This result is similar to our results. Results of simulation of canopy development of wheat compared with observed CC follow the same trend in all treatments. The model overestimates the development of CC for Pishtaz wheat cultivar. Correct simulation of CC is central to AquaCrop performance, as it affects the rate of Tr and consequently B accumulation (Farahani et al., 2009). The mean of CC data for 3 years showed that, the measured canopy decline was slightly steeper than the simulated one for all irrigation treatments. In the DI treatments, both simulated and calibrated CC dropped fast, indicating the shorter crop cycle due to early senescence. Both full irrigation and DI treatments achieved their maximum canopy development around 170 DAS and began to decline around 190 DAS (Figure 6). The results also showed that with an increase in irrigation water amount, the GY and B were increased and WP was decreased.

Although irrigation is an essential measure in this arid area, and capable of decreasing the water stress, but the WP decreased with increasing irrigation amount for all three years. This is not consistent with the findings of Hedge (1987), who found that irrigation significantly increased WP of crops. In this study, WP for wheat was in the range of 0.91 to 1.49 kg m^{-3} and its maximum value was 40% DI. Li et al. (2005) reported WP values for winter wheat between 0.93 and 1.51 kg m^{-3} and Wang et al. (2001) found that, it was between 0.70 and 1.30 kg m^{-3} in the north of China. Heng et al. (2009) showed that, AquaCrop predicts yield very well under full irrigation water supply or a moderate stress, which is similar to the results of the present study. Besides, in AquaCrop, the improvement of WP resulted by maximizing Tr consumption, relative to E. The separation of ETa into E and Tr avoids the confounding effect of the non-productive consumptive use of water (E) (Raes et al., 2009b). The reasons for the difference among the amounts of irrigation in the three seasons were soil water storage and rainfall.

Thus, an irrigation strategy can be developed according to the rainfall and soil water storage by the model. Since the rainfall in 2002 to 2003 (a total of 48 mm) was less than the long-term average (115 mm), the crop may have suffered from water stress during a long dry period (mid-March to early June). However, improvement by straw mulching and no-till for winter wheat to reduce soil evaporation was being considered in this region (Hemmat and Taki, 2001). Some researchers reported the effects of different tillage practices on conserving soil water (Ghazavi, 2004; Hajabbasi and Hemmat, 2000). Considering the serious water shortage conditions in GRB, irrigation might be further increased to prevent the rapidly falling groundwater levels. This experiment showed that, even under optimized irrigation scheduling and water-saving practices, winter wheat still requires a large amount of irrigation water. Therefore, reducing winter wheat cropping area might be an option. Moghaddasi et al. (2009) proposed to reduce irrigated area to deal with water scarcity in GRB through virtual water import.

Crop-water-production functions

CWPFs show the rate of transformation of production functions to yield. The mathematical functions of ETc and yield that better fit the production obtained with the water volume received are second-degree polynomials (Mao et al., 2003). It is noted that there is no CWPF universally applicable to all crops, growing seasons and climatic zones. There is therefore the need to establish the CWPFs using AquaCrop model. The coefficient of determination of the regressed equation was 0.90, which shows good correlation between applied water and yield. The good relationship obtained in this study between crop performance and seasonal irrigation water demonstrates that, accurate estimates of water requirement on a seasonal basis can be valuable in irrigation management decisions and scheduling.

This second-order production function is recommended for the region (Figure 7). It is noted that due to severe water resources limitations in the entire study area, it is necessary to consider deficit irrigation by means of simply cutting allocations on a reasonable basis. This approach has been traditionally applied in the management of irrigation schemes. Therefore, in the derived CWPF, there is no consideration for sensitivity of different growth stages of the wheat crop to water stress. The maximum yield (7700 kg ha^{-1}) was obtained when the optimal gross irrigation water depth was 90 cm (average of three seasons). Dry and hot winds in May and June, accelerated the maturity of wheat plants and may have reduced HI and seed weight. This might be one of the reasons that well-watered winter wheat did not produce maximum yield (potential yield for Pishtaz cultivar is reported 9 to 10 ton ha^{-1} for the study area). Another important reason is that winter wheat responds differently to water stress at different growing stages.

Conclusions

In this study, AquaCrop model was used to simulate wheat yield and yield component responses to deficit irrigation in arid Gavkhuni river basin, central Iran. A field experiment was conducted for three growing seasons. It seems that the calibrated AquaCrop model has performed well under water stress conditions to predict winter wheat yield. Generally, crop yield depends on many factors, including soil fertility, amount and time of fertilizer application, and soil and water salinity. These parameters are not dealt with in AquaCrop, and therefore, this model is not recommendable under saline conditions.

For sustainable agriculture in the study area, monitoring of soil moisture and salinity is necessary for better management of irrigation water. In this respect, with all the beneficial aspects of AquaCrop model, some adjustments should be added to it for soil and water salinity problems. One important application of AquaCrop would be to compare the attainable against actual yield in a field or a region, and to identify the constraints in crop production and water productivity. Therefore, further studies are needed to evaluate the crop yield responses to water stress during different crop growth stages in GRB.

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