SOIL SCIENCE ANNUAL
2024, 75(3), 195823

https://doi.org/10.37501/soilsa/195823

Optimizing wheat yield and water use efficiency using AquaCrop model calibration and validation in various irrigation and tillage systems under climate change

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Received: 2024-07-22
Accepted: 2024-11-11
Published online: 2024-11-11
Associated editor: Jacek Antonkiewicz

Keywords:

AquaCrop
Biomass
Water productivity
Tillage system
Climate change
Soil water use efficiency

Abstract

Modeling achievable yield under water-limiting environments is an imperative goal in arid, semi-arid, and drought-prone locations. This study aimed to calibrate the AquaCrop model simulation based on experience gained at al-Hashimiya District, 20 km east of Babylon, Iraq. Wheat (*Triticum aestivum)* in 2016–2017 and 2017–2018 was grown using deficit irrigation systems (surface and sprinkler irrigation) and different tillage methods (deep, moderate, and zero tillage). A simulation was conducted on the systems, using climate data for a period of 10 years and specific data on the study area, crops grown, and irrigation types. Then, statistical analysis was conducted with the root-mean-square error (RMSE), which refers to compatibility between the results and predictions of the measured values. For 2016–2017 and 2017–2018, RMSE values were 0.764 and 0.643 for biomass, 0.473 and 0.419 for dry matter, 0.141 and 0.154 for water productivity, and 1.59 and 0.946 for harvest index. The R^2 values were 0.917 and 0.956 for dry matter, 0.982 and 0.946 for biomass, 0.869 and 0.849 for harvest index, and 0.923 and 0.943 for water productivity from 2016–2017 and 2017–2018. Mean bias error (MBE) and mean absolute error (MAE) were also derived with comparable results. The model results indicated that there is an explicit agreement with the simulated values of the wheat crop. The AquaCrop model can be used to estimate water productivity, dry matter, and biomass to improve agricultural water management and as an input into future research of alternate forms of irrigation.

1. Introduction

Severe water scarcity is currently a major concern in all dry and semi-arid regions of the world, exacerbated by the increasing water consumption of rapidly growing urban populations. It is imperative that agriculture, which consumes about 80%–90% of the world's freshwater, improve its water efficiency and productivity (Waller and Yitayew, 2015). The prime influences on tilling are the land and harvest. Therefore the environment is a vector with a wide impact. It is impossible to envisage the effects of tillage on the soil since the extraction method can affect its chemical, biological, and physical characteristics (Kheir et al., 2021). Unlike in favorable environments, tillage activities in dry and semi-dry climates aim to improve soil water intake and management capacity while decreasing natural material evaporation decay, mitigating erosion, and providing weed control (Sato et al., 2020). Strategic options for improving water use in the agricultural sector include investment in high-efficiency irrigation techniques, including the development of irrigation systems, improved water conservation and productivity, and the promotion of non-traditional water resources, such as saltwater desalination and the use of wastewater after treatment (Khaliq et al., 2022; Hussain et al., 2022).

The AquaCrop model estimates soil water content by simulating the soil's water balance using selected input data. It simulates vegetable growth and crop maturity based on soil water content, climate data, and known crop features (Wang et al., 2018). Biomass production is directly derived from the maximum transpiration of crops using water productivity, and the yield is calculated by multiplying biomass production with the harvest index. The simulation is conducted for specific periods or degrees of crop growth days (FAO, 2017). According to Toumi et al. (2016), the AquaCrop model was used to simulate canopy cover (CC), actual evapotranspiration (ETcact), total soil water content (TWC), and grain yield (GY) for winter wheat grown under surface irrigation in Marrakech, Morocco, during the 2002–2003 and 2003–2004 seasons, with mean bias error (MBE) values ranging from 4.6 to 20.23. The study also employed root mean square error (RMSE) criteria to measure the consistency between actual field values and AquaCrop-simulated values. It concluded that the AquaCrop model is a potentially useful tool for planning irrigation schedules in arid and semi-arid regions (Liu et al., 2020; Hussain et al., 2023). To optimize model results, parameters and coding are calibrated against observable results. Validation, on the other hand, ensures the model operates accurately against independent evidence without changing software parameters or code (Nain et al., 2007; Salazar et al., 2009; Jaafar et al., 2020; Ali et al., 2021).

Under water-limiting circumstances, the FAO AquaCrop model forecasts crop production, water demand, and water usage performance (Raes et al., 2009; FAO, 2016; Hassan et al., 2020; Akol et al., 2021; Hassan et al., 2023). This model was evaluated in various environmental conditions for maize (Hsiao et al., 2009; Farahan et al., 2009), cotton (García-Vila et al., 2009; Todorovic et al., 2009), and sunflower (Geerts et al., 2009; Silungwe et al., 2018; Jafaar et al., 2022; Jafaar et al., 2023). Each of these previous studies showed that, under complete and water-deficit irrigation and conditions of stressed soil productivity, the model could correctly predict the crop biomass and yield, in addition to soil water dynamics. Raes et al. (2009) studied 187 papers from peer-reviewed journals, conferences, and reports that discussed UPSs (upgrading strategies) appropriate for grains and biophysical models to assist in selecting UPS in semi-arid regions. This study found that four UPSs are the most suitable: bound hills, small fertilization, different seeding dates, and field dispersion (Ahmed et al., 2022). The Decision Support System for Agrotechnology Transfer DSSAT, the Agricultural Production Systems Simulator (APSIM) software, and AquaCrop models adequately emulate these UPSs (Mubeen et al., 2021; Huang et al., 2022). This work provides a system for UPS crops and models in semi-arid regions that scientists and planners could employ. These models are rarely used by planners and economists, irrigation and farm managers, consulting engineers, or water user associations. The FAO Water Unit established the model, AquaCrop (Steduto et al., 2009; Doorenbos et al.,1980), which resulted from the revision of FAO's Irrigation and Drainage Paper No. 33 on water yield response (Andarzian et al., 2011). This model, which predicts the yield response to water for many herbaceous crops, is comprehensible, practitioner-oriented, and aims to be robust, balanced, accurate, and simple (Garofalo et al., 2019). It uses a relatively limited number of explicit and largely intuitive parameters and input variables, which require precise methods for their determination. The AquaCrop model has been parameterized and evaluated on many crops, for example, wheat (Mkhabela and Bullock, 2012; Stričević et al., 2011), sugar beet (Hussein et al., 2011), quinoa (Silungwe et al., 2018), maize (Heng et al., 2009; Farahani et al., 2009), cotton (García-Vila et al., 2009; Todorovic et al., 2009; Katerji et al., 2013), and sunflower (Geerts et al., 2009) in different conditions.

Previous studies have found that, under complete irrigation and fertility conditions, the AquaCrop model correctly simulates crop biomass (B) and grain yield (GY), real evapotranspiration (ETcact), canopy cover (CC), and soil water quality dynamics. However, the model has certain drawbacks in predicting ETcact and soil moisture when there is an extreme stress situation (Farahani et al., 2009; Jaddoa et al., 2013; Mohammed et al., 2019; Mohammed et al., 2022). García-Vila et al., (2009) also found that AquaCrop appeared to underestimate cotton calculations by ETcact under different water regimes. AquaCrop simulates salinity and soil water content using simple soil and weather details, in addition to simulating crop yield. The significance to agriculture of having sufficient surface water and suitable salinity levels cannot be overemphasized. AquaCrop determines the water balance for the studied soil profile by the root system and uses evaporation, transpiration, runoff, erosion, internal drainage, deep percolation, and capillary rise from shallow groundwater.

Soil moisture refers to the quantity of water contained in the pores of the soil and on the surface of its particles in relation to their mass. Completely devoid of moisture. Soil moisture is intricately linked to soil processes that affect plant development and root elongation, ultimately influencing crop output by aiding in the absorption of nutrients and promoting ventilation (Mane et al., 2024). Predicting the moisture distribution in vertical and horizontal distance with time is an important factor in developing a suitable vision for the irrigation process, as the Aquacrop program performs a water balance under the influence of several factors, which are internal drainage, deep retardation, surface runoff, and evaporation transpiration (Mkhabela and Bullock, 2012). In a study conducted by Tommi et al. (2016) to test the ability of the AquaCrop model to simulate the water content in the soil, it was found that all locations of the soil moisture distribution were close to the measured values, as the values of MBE were good, as were both NSE and RMSE.

The main objectives of this reseach are as follows:

a) employing and assessing the AquaCrop model in a simulation of water consumption in the environments of the study area in Iraq, aiming to reinforce water productivity and maintain the water balance of the wheat crop.
b) using the AquaCrop model to simulate the impacts of using different irrigation and tillage systems.

2. Materials and methods

2.1. Experimental site

A field investigation was carried out at a private farm in the al-Hashimiya district, Babylon Governorate, Republic of Iraq, during the growing seasons of 2016–2017 and 2017–2018 (Fig. 1). The farm is situated on flat land approximately 25.2 meters above sea level, with alluvial soil that has a silty clay loam texture, classified as Typic Torrifuvent (Mohammed and Suliman, 2023). This region has a subtropical climate, with an average temperature of 25.6°C. The average annual rainfall is about 135 mm, while evaporation exceeds 2122 mm. The average wind speed is 3.8 m/sec, and the relative humidity is 38%. Table 1 provides the physical and chemical properties of the soil in the study area. The study aimed to investigate and evaluate the impact of three interrelated factors—irrigation system, tillage system, and seeding rates—on wheat growth attributes, grain yield, consumptive water use, and water use efficiency (WUE).

Fig. 1. Study area location map

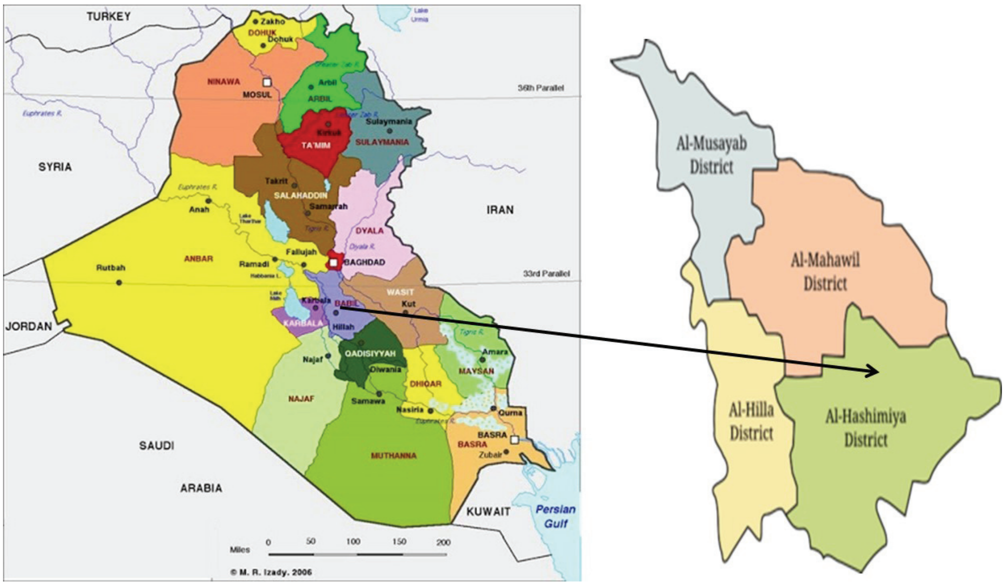

Table 1
Selected chemical and physical properties of experimental soil

Characteristics	Units	Value
EC	dS m^{-1}	2.34
PH		7.31
Sand	%	16
Silt		49
Clay		35
Textural Class		Silty Clay Loam
Ca	meq L^{-1}	12.41
Mg		5.60
Na		3.86
K		1.55
HCO_3		2.89
CL		14.15
SO_4		7.87
Organic Matter	%	1.50
Bulk Density	g cm^{-3}	1.38
Particle Density		2.65
Hydraulic Conductivity	cm h^{-1}	0.72

2.2. Land preparation

The experimental site was prepared using three types of tillage: zero tillage (T0), minimum tillage to a depth of 15 cm (T1), and deep tillage up to 30 cm (T2). Moldboard and chisel tillers were utilized for conventional and deep tillage, respectively. The land was then leveled and divided into plots measuring 4 × 5 meters. A 1-meter strip was left between blocks and plots to control horizontal water movement. For sprinkler irrigation (I1), the irrigation system was installed with main tubes placed 10 meters apart between rows and sprinklers. For surface irrigation (I2), 2-inch diameter plastic tubes with a gauge meter were used to measure water supplied to each plot. A distance of 3 meters was maintained between the two irrigation systems to prevent interaction between sprinkler and surface irrigation water.

2.3. Irrigation water supply

Irrigation was performed after 50% of the available water was depleted. The amount of water supplied was determined by measuring soil moisture content before irrigation. From sowing until the end of the vegetative growth phase, irrigation was based on moisture depletion in the 0–10 cm soil layer. During flowering, irrigation depth increased to 10–20 cm, and further increased to 20–30 cm until the end of physiological maturity to achieve moisture content near field capacity. The soil's permanent wilting point and field capacity were estimated using a pressure plate apparatus, and accessible water content was calculated using equation (1)

$$d = (f.c - pwp/100)*BD*soil\ depth \quad (1)$$

using Equation (1). where d = available water depth (%), f.c = field capacity, pwp = permanent wilting point, B = bulk density, d = soil depth (cm).

Precipitation Intensity: the water balance formula of equation (2) was used as a direct method for calculating the actual water consumption of the wheat crop (Robertson et al., 1994).

cm. Therefore, the equation becomes:

$$ETa = I + C \quad (2)$$

Water use efficiency: the efficiency of field water use was calculated according to the following equation (AOAC)

$$WUEf = \frac{Y}{WA} \quad (3)$$

where WUE_f = efficient use of field water (kg m^{-3}); *Y* = grain yield (kg); and *WA* = amount of water added in the irrigation process (m^3 $season^{-1}$).

2.4. Studied characters

2.4.1. Grain yield

An area of 1.2 m^2 was harvested from each plot (four rows in the middle with 2 m length). Grains were separated from straw, weighed, and translated to t ha^{-1} at 14% moisture content of grains (Baldini et al., 1999).

2.4.2. Biological yield

The biological yield was determined from the same four rows (grains + straws) and then translated to t ha^{-1}.

2.4.3. Harvest Index (HI)

Harvest index (HI) was calculated from the following equation (Nash et al., 1970):

$$HI\ (\%) = \frac{GY}{BY} \times 100 \quad (4)$$

where GY = grain yield (t ha^{-1}). BY = biological yield and includes all parts of the plant above the soil surface (t ha^{-1}).

2.5. AquaCrop model

The calibration of the AquaCrop model was performed by running the model after providing the required data as follows:

1. Insert climate data (field measurements).
2. Insert soil data (field measurements).
3. Insert crop data (check the proportionality between the growing season period and climate data for the same simulation).
4. Insert irrigation data (full irrigation–no water stress).
5. Insert field management data (if any).
6. Run the simulation (without any water or fertile stress) and check whether the simulated biomass and production agree with the actual biomass and production measures.
7. Adjust crop inputs (planting date, plant phases, and growth period).
8. Run the simulation again with modified crop inputs.
9. Calibrate the crop in water deficit and poor fertilization conditions after the calibration of the optimal environment is completed.

Four statistical indicators were used to evaluate the compatibility quality between measured values and the simulation produced by the AquaCrop model. These values were biomass (B), water productivity (WP), crop production of grains (Y), and harvest index. The statistical indicators are (Willmott et al., 1982; Iqbal et al., 2014):

1. Coefficient of Determination (R^2)

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(oi - si)^2}{\sum_{i=1}^{n} oi - o_{avg})^2} \quad (6)$$

2. Men Bios Error (MBE)

$$MBE = \frac{\sum_{i=1}^{n}(si - oi)}{n} \quad (7)$$

3. Mean Absolute Error (MAE)

$$MAE = \frac{\sum|oi - si|}{n} \quad (8)$$

4. Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{\sum(si - oi)^2}{n}} \quad (9)$$

3. Results and discussion

3.1. Effect of irrigation methods and tillage systems on actual wheat production

The simulation results produced by the AquaCrop model indicated that the production of simulated wheat grains was in good agreement with actual wheat production. As shown in Table 2, for 2016–2017, the simulated production of wheat grains under sprinkler irrigation (I_1) was 4.57, 4.98, and 4.68 t ha^{-1} for zero tillage (T_0), minimum tillage (T_1), and deep tillage (T_2), respectively; simulated production under surface irrigation (I_2) was 3.89, 4.61, and 4.49 t ha^{-1}, respectively. This compares to measured production in the 2016–2017 season of 4.10, 4.54, and 4.32 t ha^{-1} (I_1) and 3.54, 4.00, and 3.94 t ha^{-1} (I_2), for T_0, T_1, and T_2, respectively. As shown in Table 3, for 2017–2018, simulated production under sprinkler irrigation (I_1) was 4.33, 4.70, and 4.59 t ha^{-1}, for the T_0, T_1, and T_2 treatments, respectively (Fig. 2). This compares to measured production in the 2017–2018 season under sprinkler irrigation (I_1) of 3.95, 4.37, and 4.15 t ha^{-1}, for the T_0, T_1, and T_2 treatments, respectively (Fig. 3). As shown

Table 2
Some input parameters for the AquaCrop model

	Input Parameters	Value
1	The maximum temperature set for growth	30
2	Expected maximum flag leaf area index	5
3	Coefficient of shading for total solar radiation	0.59
4	Crop coefficient value at full coverage	1.25
5	The average daily temperature that limits early growth	10
6	Modulus of transpiration curve gradient efficiency	0.45
7	The transpiration efficiency when the water vapour pressure is deficient	5.5
8	The depth of the maximum roots	0.5
9	Available soil water for plants	50%
10	Number of Plants per Hectare	2000000
11	Harvest Index	40%
12	Base temperature (°C)	10
13	Possible increase (%) in HI due to water stress before flowering	42%
14	Soil water content at SAT	0.41
15	Soil water content at FC	0.33
16	Soil water content at PWP	0.14
17	planting methods	seeding
18	sand particular	160
19	silt particular	490
20	clay particular	350
21	Texture	SiClL
22	Hydrluic Conductivity	0.72
23	Degree Days: from sowing to emergence	45
24	Degree Days: from sowing to max. canopy	95
25	Degree Days: from sowing to flowering	138
26	Degree Days: from sowing to senescence	145
27	Degree Days: from sowing to maturity	160
28	Maximum canopy cover (CCx) in fraction soil cover	90%

Table 3
Irrigation and tillage treatments, simulated and measured values, and statistical indicators for biomass, dry yield, harvest index, and water productivity for the 2016–2017 season

		Biomass (t ha^{-1})		Dry yield (t ha^{-1})		Harvest Index		Water Productivity (kg m^{-3})	
Treatments		Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured
I_1	**T_0**	10.45	9.7	4.57	4.10	44	42.1	1.11	1.05
	T_1	11.33	10.6	4.98	4.54	45	42.8	1.22	1.16
	T_2	10.83	10.1	4.68	4.32	44	42.5	1.18	1.10
I_2	**T_0**	9.28	8.6	3.89	3.54	42	41.1	0.93	0.76
	T_1	10.56	9.7	4.61	4.00	43	41.1	1.07	0.86
	T_2	10.42	9.6	4.49	3.94	41	40.8	1.02	0.84
R^2		0.991		0.917		0.869		0.923	
R		0.995		0.958		0.932		0.961	
MBE		−0.762		−0.463		−1.433		−0.127	
MAE		0.762		0.463		1.433		0.127	
RMSE		0.764		0.473		1.59		0.141	

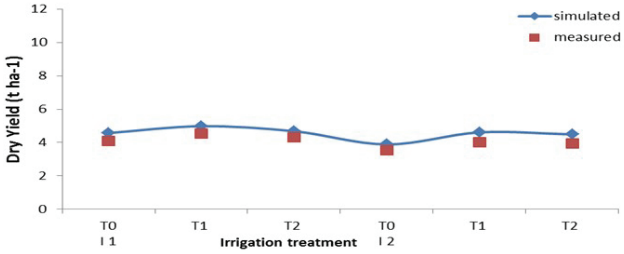

Fig. 2. Dry yield (t ha^{-1}), 2016–2017 season

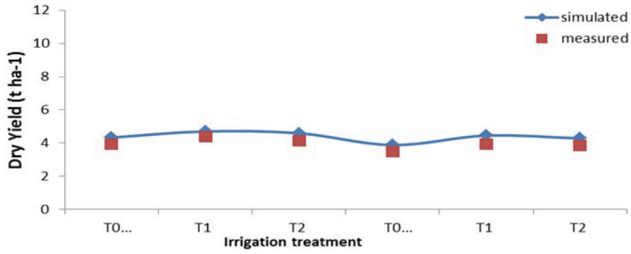

Fig. 3. Dry yield (t ha^{-1}), 2017–2018 season

Table 4

Irrigation and tillage treatments, simulated and measured values, and statistical indicators for biomass, dry yield, harvest index, and water productivity for the 2017–2018 season

		Biomass (t ha^{-1})		Dry yield (t ha^{-1})		Harvest Index		Water Productivity (kg m^{-3})	
Treatments		Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured
I_1	T_0	9.62	9.16	4.33	3.95	44	43.19	1.09	1.01
	T_1	10.81	10.08	4.70	4.37	45	43.35	1.18	1.12
	T_2	10.03	9.63	4.59	4.15	44	43.10	1.17	1.06
I_2	T_0	8.86	8.08	3.88	3.47	43	42.87	0.91	0.72
	T_1	9.91	9.19	4.45	3.93	44	42.95	1.03	0.82
	T_2	9.68	9.01	4.28	3.87	43	42.75	1.00	0.80
R^2		0.946		0.956		0.849		0.943	
R		0.972		0.978		0.922		0.971	
MBE		−0.627		−0.415		−0.798		−0.142	
MAE		0.627		0.415		0.798		0.142	
RMSE		0.643		0.419		0.946		0.154	

in Tables 3 and 4, for the 2016–2017 and 2017–2018 seasons, respectively, statistical indicators were as follows: RMSE, 0.473 and 0.419; R^2, 0.917 and 0.956; R, 0.958 and 0.978; MBE, −0.463 and −0.415; and MAE, 0.463 and 0.415.

The simulation model results for biomass were similar to the measured values. For the 2016–2017 season, measured biomass was 9.7, 10.6, and 10.1 t ha^{-1} for T_0, T_1, and T_2, respectively, using a sprinkler irrigation system, and 8.6, 9.7, and 9.6 t ha^{-1}, respectively, using surface irrigation (Fig. 4). By comparison, the AquaCrop simulation values for sprinkler irrigation for the 2016–2017 season were 10.83, 11.33, and 10.45 t ha^{-1} for T_0, T_1, and T_2, respectively, and for surface irrigation were 9.28, 10.56, and 9.28 t ha^{-1}, respectively. For the 2017–2018 season, measured biomass was 9.16, 10.08, and 9.63 t ha^{-1} for T_0, T_1, and T_2, respectively, using a sprinkler irrigation system, and 8.08, 9.19, and 9.01 t ha^{-1}, respectively, using surface irrigation (Fig. 5). By comparison, the AquaCrop simulation values for sprinkler irrigation for the 2016–2017 season were 9.63, 10.81, and 10.30 t ha^{-1} for T_0, T_1, and T_2, respectively, and for surface irrigation were 8.86, 9.91, and 9.68 t ha^{-1}, respectively. The statistical indicators for the two seasons, respectively, were as follows: RMSE, 0.764 and 0.643; R^2, 0.991 and 0.946; R, 0.995 and 0.972; MBE, −0.762 and −0.627; and MAE, 0.762 and 0.627.

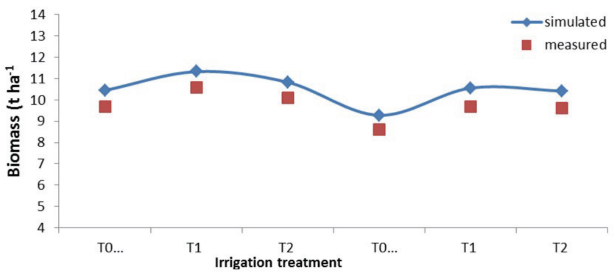

Fig. 4. Biomass (t h^{-1}), 2016–2017 season

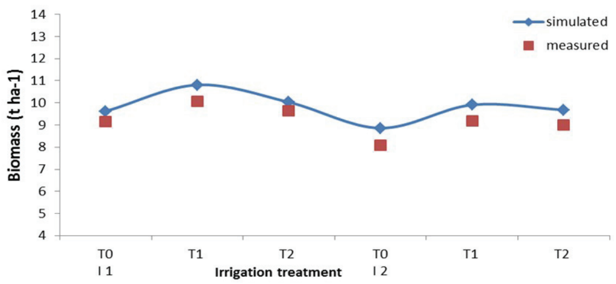

Fig. 5. Biomass (t h^{-1}), 2017–2018 season

The water productivity of wheat also recorded a decent agreement between the measured and the simulated values. For the 2016–2017 season, measured water productivity was 1.05, 1.16, and 1.10 kg m^{-3} for T_0, T_1, and T_2, respectively, using a sprinkler irrigation system, and 0.76, 0.86, and 0.84 kg m^{-3}, respectively, using surface irrigation. By comparison, the AquaCrop simulation values for sprinkler irrigation for the 2016–2017 season were 1.11, 1.22, and 1.18 kg m^{-3} for T_0, T_1, and T_2, respectively, and for surface irrigation were 0.93, 1.07, and 1.02 kg m^{-3}, respectively (Fig. 6). For the 2017–2018 season, measured water productivity was 1.01, 1.12, and 1.06 kg m^{-3} for T_0, T_1, and T_2, respectively, using a sprinkler irrigation system, and 0.72, 0.82, and 0.80 kg m^{-3}, respectively, using surface irrigation (Fig. 7). By comparison, the AquaCrop simulation values for sprinkler irrigation for the 2016–2017 season were 1.09, 1.18, and 1.17 kg m^{-3} for T_0, T_1, and T_2, respectively, and for surface irrigation were 0.91, 1.03, and 1.00 kg m^{-3}, respectively. The statistical indicators for the two seasons, respectively, were as follows: RMSE, 0.141 and 0.154; R^2, 0.923 and 0.943; R, 0.961 and 0.971; MBE, −0.127 and −0.142; and MAE, 0.127 and 0.142.

The simulation model also showed a significant convergence in the harvest index values between the measured values and the simulation. For the 2016–2017 season, the measured harvest index was 42.1, 42.8, and 42.5 for T_0, T_1, and T_2, respectively, using a sprinkler irrigation system, and 41.1, 41.1, and 40.8, respectively, using surface irrigation (Fig. 8). By comparison, the AquaCrop simulation values for sprinkler irrigation for the 2016–2017 season were 44, 45, and 44 for T_0, T_1, and T_2, respectively, and for surface irrigation were 42, 43, and 41, respectively. For the 2017–2018 season, the measured harvest index was 43.19, 43.35, and 43.10 for T_0, T_1, and T_2, respectively, using a sprinkler irrigation system, and 42.87, 42.95, and 42.75, respectively, using surface irrigation (Fig. 9). By comparison, the AquaCrop simulation values for sprinkler irrigation for the 2016–2017 season were 44, 45, and 44 for T_0, T_1, and T_2, respectively, and for surface irrigation were 43, 44, and 43, respectively. The statistical indicators for the two seasons, respectively, were as follows: RMSE, 1.59 and 0.946; R^2, 0.869 and 0.849; R, 0.932 and 0.922; MBE, −1.433 and −0.798; and MAE, 1.433 and 0.798.

These results are consistent with those of a previous evaluation of the AquaCrop wheat model (Rodriguez et al., 2019; Ali et al., 2013), which found RMSE = 0.58 kg/ha and R^2 = 0.85, thus demonstrating a good simulation. Kuschel-Otárola et al. (2020) found RMSE = 0.240, 0.420 t ha^{-1} in 2003–2004 and 2004–2005, respectively. Mkhabela and Bullock (2012) found RMSE = 0.27 t ha^{-1} and R^2 = 0.95 for wheat production. The results agree with previous results from using a field experiment to assess the AquaCrop model for different coefficients of irrigation on the wheat crop (Ghoochanian et al., 2019; Salemi et al., 2011). The AquaCrop model was able to simulate the water content in the soil accurately from the root area. In addition, good simulations of the mass of the crop were found, with RMSC less than 10%. These studies found the highest grain crop can be achieved by applying four stages: evolution stage, the level of aboveground leafy growth, flowering level, and maturity and harvesting. Our results were also consistent with Zeleke et al. (2019). Salemi et al. (2011) conducted a field experiment in eastern Iran to estimate the AquaCrop model, with variables consisting of three levels of salinity of irrigation water, two types of wheat, and four levels of irrigation water quantity. The model was calibrated, and its validity was verified using the statistical standards RMSC, CRM, and R^2. The results showed good agreement for both water

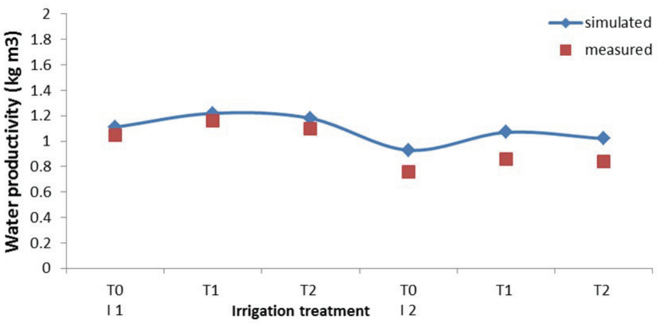

Fig. 6. Water productivity (kg m^{-3}), 2016–2017 season

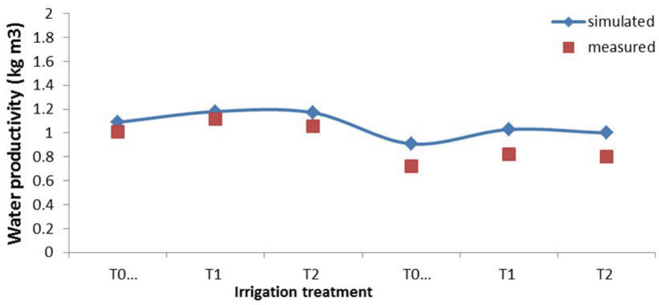

Fig. 7. Water productivity (kg m^{-3}), 2017–2018 season

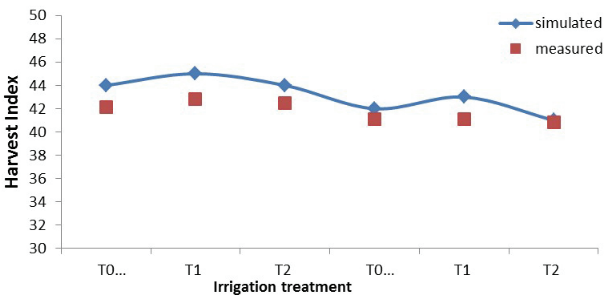

Fig. 8. Harvest index, 2016–2017 season

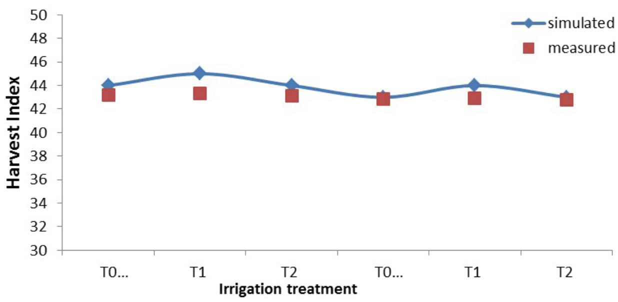

Fig. 9. Harvest index, 2017–2018 season

productivity and the harvest index between the measured and simulated values performed by the AquaCrop model.

3.2. Effect of irrigation methods and tillage systems on soil moisture distribution

Understanding the effects of different irrigation methods and tillage systems on soil moisture distribution is crucial for optimizing WUE and crop productivity. This discussion explores how these parameters influence volumetric moisture content in the soil during the flowering period of the wheat crop. The findings indicate that the choice of irrigation method and tillage system significantly affects soil moisture distribution. Sprinkler irrigation tends to keep the moisture confined to the root zone, potentially improving WUE by reducing deep percolation losses. In contrast, surface irrigation allows for deeper moisture penetration, which might be beneficial in regions where deeper soil moisture is required for crop sustainability during dry periods but can also lead to water inefficiency. The interaction between tillage systems and irrigation methods further influences moisture distribution. Conservation tillage seems to complement sprinkler irrigation by maintaining higher moisture levels in the root zone, whereas conventional tillage might enhance deeper infiltration under surface irrigation. These insights are critical for developing irrigation and tillage management strategies that optimize water use, enhance soil moisture distribution, and ultimately improve crop yield and sustainability. Future studies should focus on long-term impacts, variations under different soil types, and the economic implications of these practices to provide comprehensive guidelines for farmers. The The Fig. 10 shows the effect of the parameters of the two irrigation methods and the tillage system on the values of moisture distribution in the flowering period of the wheat crop, as the volumetric humidity was estimated 24 hours after the end of irrigation, as the measurement was done on two horizontal and vertical axes. It was found that the volumetric moisture content in the sprinkler irrigation treatment was limited to the root zone and did not extend to greater depths, while we note that in the irrigation irrigation process it goes to depths outside the root zone, as shown. It is also clear that zero tillage is superior to the medium

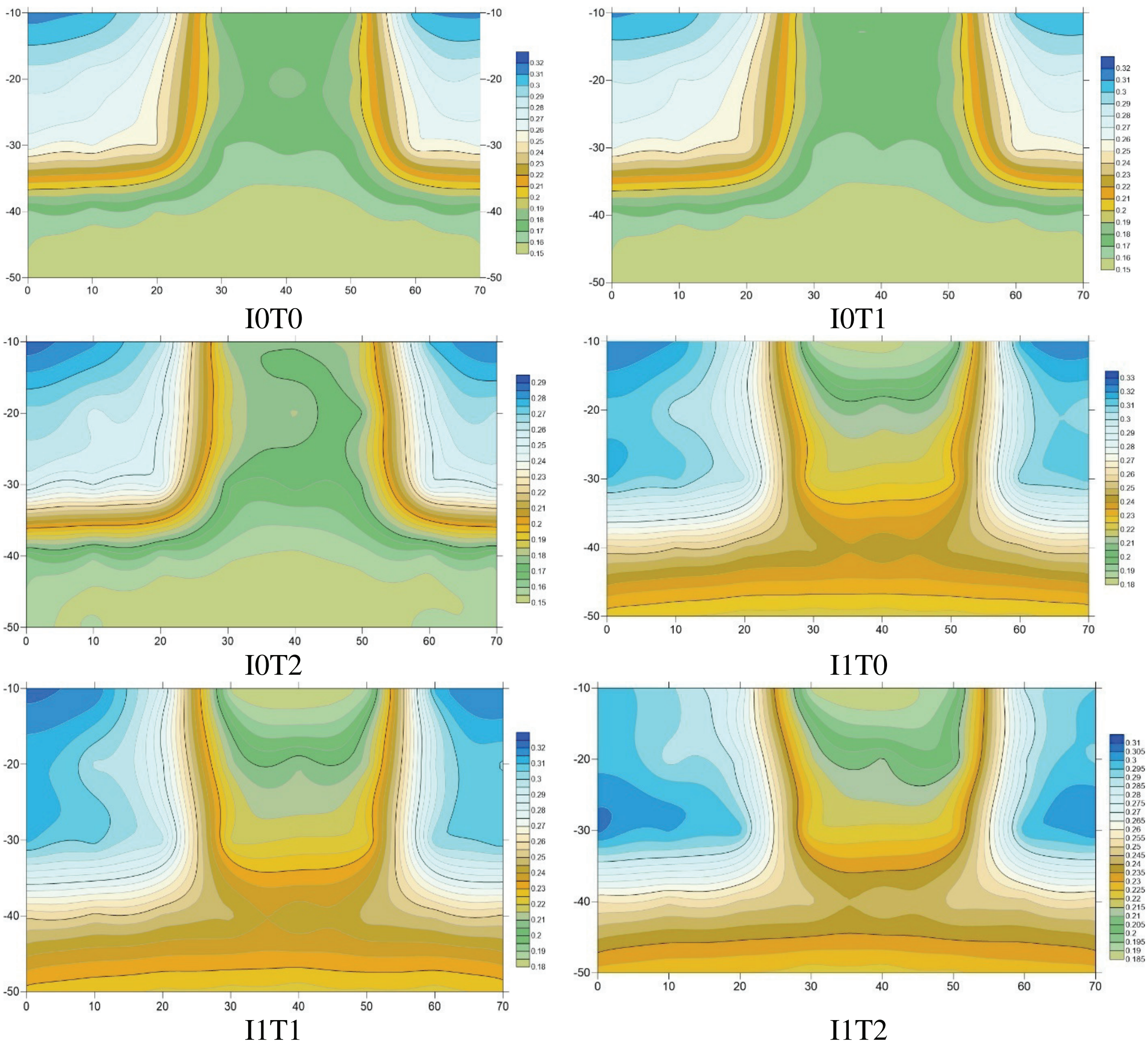

Fig. 10. Water content distribution in soil

tillage treatment, which in turn is superior to traditional tillage. The reason for this is due to the role of zero tillage in increasing the soil's capacity to retain water by improving its physical characteristics and reducing high porosity through tillage, unlike traditional (deep) tillage, which works to break down the soil structure and reduce porosity. The moisture content of the soil decreases with depth, but it moves in a way that makes it go outside the root zone. This is due to the fact that most of the irrigation water moves under the influence of terrestrial gravitational forces, so the moisture content decreases (Borodyhev and Lytor, 2020; Lin et al., 2018).

Sprinkler irrigation involves applying water in a manner similar to natural rainfall. It typically results in a uniform distribution of water over the soil surface. However, observations indicate that under sprinkler irrigation, the volumetric moisture content remains confined to the root zone of the wheat crop. This suggests that the water application does not penetrate deeply into the soil, maintaining higher moisture levels within the upper soil layers where the roots are actively absorbing water. The rapid decline in moisture content beyond the root zone implies that sprinkler irrigation might be more efficient in terms of water use, as it minimizes deep percolation losses. Surface irrigation, on the other hand, involves distributing water across the soil surface, allowing it to infiltrate and move laterally and vertically. This method has been observed to result in moisture distribution extending beyond the root zone. The deeper penetration of water can be attributed to the prolonged exposure of the soil to the water, allowing for more significant infiltration. While this can ensure that deeper soil layers are also moistened, it might lead to inefficient water use, as water moves beyond the reach of the root system, potentially contributing to groundwater recharge or loss through deep percolation. Moisture distribution in the soil is crucial for crop growth, as it determines the availability of water to plant roots throughout various growth stages. Uniform moisture ensures optimal nutrient uptake, reducing stress and promoting consistent development. Poor moisture distribution can lead to waterlogging or drought stress, negatively impacting yield. Efficient moisture management enhances WUE, crucial for sustainable agriculture, especially under changing climate conditions. Tillage practices can significantly influence soil structure, porosity, and the movement of water through the soil profile. Conventional tillage tends to disturb the soil structure more than conservation tillage, leading to different patterns of moisture distribution. Conventional tillage, which involves plowing and turning over the soil, can create a more homogenous soil profile with less resistance to water movement. This might facilitate deeper water infiltration under surface irrigation, contributing to the observed extension of moisture beyond the root zone. However, it can also lead to faster drying of the soil surface under sprinkler irrigation due to increased evaporation from the disturbed soil surface. Conservation tillage, which minimally disturbs the soil, helps in maintaining soil structure and organic matter. This practice often results in improved water retention within the root zone, especially under sprinkler irrigation, due to the presence of mulch and organic residues on the surface. These residues reduce evaporation and enhance infiltration rates, keeping the moisture content higher within the upper soil layers (Jin et al., 2018). Irrigation generally has more influence on moisture distribution than plowing. While plowing can affect soil structure and water infiltration rates, the amount, timing, and method of irrigation directly control how water is distributed within the soil profile. Proper irrigation can ensure that moisture reaches the root zone uniformly, while plowing primarily influences how well the soil can retain and distribute this moisture. So, irrigation practices are the primary factor in managing soil moisture distribution.

4. Conclusions

This study aims to simulate the AquaCrop model in a water consumption environment in Iraq to reinforce water productivity and maintain the water balance of the wheat crop. Also, the AquaCrop model was used to simulate the impacts of using different irrigation and tillage systems in the study region. The study results identified that the AquaCrop model has been improved according to the FAO Irrigation and Drainage guidelines to replace the previous, manual procedures for estimating water productivity, thus saving the effort and time of specialists in the agriculture and water resources sectors. One significant advantage of the model is its relatively small number of inputs (e.g., climate, crop, soil, and irrigation water data), with which the model considers the most tremendous amount of information affecting the irrigation process and crop production. The model requires accurate input data and choices within the model. Despite the existence of files prepared in advance by the FAO, inaccuracies in the model can lead to illogical or exaggerated results. It should be noted that the model may overstate values in dry and semi-dry conditions, especially with summer crops. While both irrigation and tillage practices significantly impact on crop yield and soil moisture distribution, irrigation plays a more direct and immediate role in controlling moisture availability to plants. Effective irrigation management can optimize WUE and ensure consistent moisture distribution, which is critical for maximizing crop performance, especially under water-limited conditions. Users must provide complete data to reach the correct understanding and conclusions about the yield being simulated. The AquaCrop model can help estimate water productivity, dry matter, and biomass to improve agricultural water management and provide input into future research of alternate forms of irrigation.

Authors' note

The authors declares that there is no conflict of interest regarding the publication of this article.

Author Contributions

Alaa M. Akol – Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – original draft. **Diaa F. Hassan** – Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – original draft.

Rafal J. Mohammed – Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – original draft. **Zaid A.Z A. AlJanaby** – Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing – review & editing. **Mahdi Abdu Kadium Abed** – Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing – review & editing. **Sajjad Hussain** – Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing – review & editing. **Nadine Nassif** – Conceptualization, Investigation, Methodology, Supervision, Visualization. **Khudhair Abbas Jaddoa** – Supervision, Visualization. **Hiba Kalaf Razzaq** – Supervision, Visualization. All authors read and approved the final manuscript.

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