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Productivity evaluation of wheat varieties under modern irrigation using AquaCrop software

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Highlights
- Study the yield of two types of wheat farmed using rainwater and supplementary irrigation.
- Evaluating the performance of sprinkler irrigation systems based on the AquaCrop model.
- Field data simulation using the AquaCrop model.

Abstract: All field investigations were carried out in the Northern Gezira irrigation project, located in Nineveh Governorate, Iraq. The aim was to evaluate the productivity of the 'Barcelona' and 'Iba'a' wheat varieties. The assessment process was performed from two perspectives: field data analysis and simulation using AquaCrop software. The evaluation focused on product efficiency and rationalisation of irrigation water, and the identification of a suitable irrigation system. The complementary irrigation was applied by giving a total irrigation water depth of 234 mm to the 'Iba'a' wheat variety where the seed productivity was about 4,400 kg·ha^{-1}. Nevertheless, the 'Barcelona' variety achieved a significantly higher yield of 7,200 kg·ha^{-1} under the same irrigation conditions, indicating its superior performance. Moreover, the analytical data was agreed with the field study where the simulation results showed that the 'Iba'a' variety productivity was 4,596 kg·ha^{-1}, while the 'Barcelona' variety achieved 7,340 kg·ha^{-1}. It was also shown that the value of water use efficiency for the 'Iba'a' variety wheat crop was equal to 1.108 kg·m^{-3}, while for the 'Barcelona' wheat variety it became equal to 1.813 kg·m^{-3}.

Keywords: AquaCrop model, irrigation scheduling, sprinkler irrigation, water use efficiency, wheat yield

INTRODUCTION

Iraq's climate is semi-arid as it faces great challenges due to limited water resources. Rainfall is less than the water required for crops. Therefore, obtaining better food production in large quantities using less water is the main goal for agriculture. However, the economy of water use makes it possible to cultivate numerous areas of arable land, thereby increasing agricultural production (Oweis and Hachum, 2006; Hameed and Mohammad, 2024).

Recently, deficit irrigation is an agricultural water management strategy in which less water is applied than the crop's full evapotranspiration needs, aiming to enhance water use efficiency while maintaining acceptable yields. This approach is particularly suitable for water-scarce regions like Iraq, as it involves supplying water at specific growth stages where plants can tolerate mild water stress, while ensuring adequate irrigation during critical phases such as flowering and grain filling. Although this method may result in a slight reduction in yield, it significantly improves water conservation and agricultural sustainability by allowing larger areas to be irrigated with the same water resources. In this context, modern irrigation approaches, such as drip irrigation and sprinkler irrigation, help mitigate these challenges. These methods, including deficit irrigation, are considered among the new field systems applied to increase the efficiency of water used for irrigation purposes. Consequently, deficit irrigation is widely used in Iraq for staple crops like wheat and barley in its semi-arid climate, where modern irrigation techniques further enhance efficiency and productivity (Hameed and Salim, 2022). Accordingly, it has become necessary to evaluate modern irrigation techniques relying on site-specific data, such as climate, soil characteristics, types of crops, planting dates, irrigation, and harvesting (Papadopoulos, Metochis and Chimonidou, 2005; Hachum and Abd, 2008).

Sandhu and Irmak (2019) evaluated the performance of the AquaCrop model in simulating growth and productivity of maize under different water stress conditions and over a period of six years from 2005 to 2010. In Nebraska City, the United States, the AquaCrop was calibrated and validated under different irrigation scenarios, including rainfed conditions, full irrigation, and deficit irrigation (50%, 60%, 75%).

AquaCrop is a computational model developed to predict crop productivity and water consumption by analysing interactions between evapotranspiration, canopy cover, and yield. Central to its framework is the concept of water productivity – the measure of crop output relative to the unit of water used – which supports the optimisation of water use in agriculture. The model employs canopy cover, indicating the percentage of soil shaded by plant foliage, as a key parameter to estimate a crop's capacity to absorb sunlight for photosynthesis. By evaluating water stress during pivotal growth phases, AquaCrop dynamically modifies projections of crop development and yield. It integrates a streamlined soil-water balance equation to monitor moisture levels and stimulate water accessibility. Furthermore, the model computes yield response to water, assessing how variations in water supply across growth stages influence harvest outcomes.

This combination of features enables AquaCrop to generate accurate forecasts of agricultural performance under diverse irrigation strategies, proving particularly valuable in arid or water-limited environments. Following calibration, the model successfully generated daily canopy cover simulations for the years 2009 and 2010. In addition, the biomass was estimated according to the stages of corn growth. The simulation results for 2010 were better than those for 2009. Moreover, the performance of the model decreased significantly in water stress conditions. While crop evapotranspiration and evaporation were analysed numerically and showed agreement in some cases, simulating biomass and soil water proved challenging - particularly during years of low rainfall and high evaporation (Sandhu and Irmak, 2019).

Al-Kaisi, Berrada, and Stack (1997) explained that the relationship between production and the amount of water consumed is complex, as crop productivity depends on the amount of irrigation water and the timing of its application. They collected field information on the optimal irrigation programming and the time of water application to ensure the highest productivity and the efficiency of irrigation.

Several studies have relied on AquaCrop software to improve the efficiency of water use in agriculture. Sheet, Gazal, and Sheet (2019) stated that the AquaCrop model is considered as an efficient tool for estimating crop productivity. Field investigations were conducted in the experimental farm of the Agriculture College in Abu Ghraib, Baghdad, during seasons of sunflower growth in 2009 and 2010. The model is calibrated using 2009 data where good productivity was obtained with determination coefficient (R^2) equal to 0.95. The calibrated model was validated using 2010 data, and the value of R^2 was 0.85, where the field and simulated results showed good agreement (Sheet, Gazal and Sheet, 2019). Terán-Chaves, García-Prats and Polo-Murcia (2022) also demonstrated that the overall performance of AquaCrop in simulating canopy cover, biomass, and soil water content confirmed the model's reliability and the consistency between field and simulated data.

Version 3.0 of the FAO AquaCrop model was tested by Araya *et al.* (2010) using independent climate datasets during the 2006, 2008 and 2009 crop seasons at the Mekelle site in North of Ethiopia. The model was found to be valid for simulating barley biomass and grain yield under different sowing dates at the study site. The researchers proved the ability of AquaCrop to evaluate the optimal planting time. Moreover, the model indicated that more biomass and grain yield could be obtained from a relatively larger barley field under moderate stress conditions (deficit-irrigation) (Araya *et al.*, 2010).

The main aim of this study includes the use the AquaCrop software to simulate wheat crop productivity in Northern Jazera irrigation project under rainfed conditions and supplemental irrigation based on the field data.

MATERIALS AND METHODS

IRRIGATION METHOD

The study evaluates rainfed agriculture (reliance on seasonal rainfall) and supplementary irrigation (applied to compensate for rainfall deficits) as two water management strategies. Supplementary irrigation aligns with the principles of adaptive water use, ensuring that crop water demands are met during critical growth stages.

Sprinkler irrigation systems, including linear moving devices, were selected for their theoretical efficiency in achieving uniform water distribution and their adaptability to variable field conditions.

Crop selection and agronomic principles. Wheat was selected as the crop for this study due to its status as a staple winter crop in semi-arid regions and its sensitivity to water availability. The varieties 'Iba'a' and 'Barcelona' were chosen to compare drought tolerance and yield performance under contrasting water regimes. Crop rotation practices, e.g. barley, maize, and vegetables, were implemented based on principles of diversification to optimise soil health and improve water-use efficiency.

Water management theory. Irrigation scheduling was guided by the integration of climatic data (e.g. rainfall variability) and crop phenological stages to optimise water allocation.

Infrastructure resilience and climate adaptation strategies, e.g. rehabilitation of canals and the upgrading of pumps, reflect theoretical priorities for sustaining agricultural productivity in conflict-affected and climate-vulnerable regions.

METHODOLOGICAL FRAMEWORK

Study site. Field investigations were conducted at the Northern Al-Jazira Irrigation Project, located in Rabi'a district, Nineveh Governorate, Iraq. This site represents a rehabilitated agricultural hub that plays a critical role in regional food security.

Experimental design: (1) crops and irrigation – two wheat varieties ('Iba'a', 'Barcelona') were cultivated under: (a) rainfed conditions relying solely on natural rainfall, (b) supplementary irrigation – applied via linear moving sprinkler systems during water deficit periods; (2) cultivation timeline: seeding began on the first of December. Irrigation was applied on interruptions in rainfall or when soil moisture fell below critical thresholds.

Infrastructure and operations: (1) irrigation network – a centralised system supplies water to wheat fields and other crops such as barley, maize, and vegetables. Post-conflict restoration efforts have ensured the operational reliability of canals and pumps; (2) rehabilitation efforts – included repair of pumping stations, dredging of canals, and the modernization of sprinkler systems, all aimed at enhancing water-use efficiency.

Water allocation strategy. Priority was given to wheat during critical growth stages such as flowering and grain filling, while other crops received water based on seasonal availability and agronomic calendars.

Data collection. Productivity metrics, including yield and water efficiency, for wheat were evaluated under both irrigation regimes. These results were further contextualised within the broader objectives of the project, including multi-crop sustainability.

INTEGRATION OF THEORY AND PRACTICE

The Northern Al-Jazira project serves as a practical application of theoretical water management principles, such as adaptive irrigation and infrastructure resilience, through its rehabilitated framework. This enables a comparative analysis of crop performance under diverse hydrological conditions. This approach ensures scalability of findings to similar semi-arid agro-ecosystems.

This structure clearly distinguishes foundational theories (e.g. irrigation science, crop physiology) from their applied frameworks, including site-specific implementation, infrastructure development, and experimental protocols.

WATER USE EFFICIENCY

Water use efficiency (*WUE*), or water productivity, is defined as the ratio of production, crop yield, to water consumption (Doorenbos and Pruitt, 1977; Doorenbos *et al.*, 1980; Kharrou *et al.*, 2011; Pascale de *et al.*, 2011).

$$WUE = \frac{Y}{W.C.} \tag{1}$$

where: WUE = water use efficiency (kg·m^{-3}), Y = yield (kg·ha^{-1}), $W.C.$ = water consumption (mm).

SIMULATION OF SPRINKLER SYSTEMS PERFORMANCE AND PRODUCTIVITY USING AQUACROP SOFTWARE

Evaluating crop responses to water deficit periods and their impact on productivity is a very complex process. To address this, empirical production criteria – adopted by the Food and Agriculture Organization for Irrigation – were used as the most effective tool for evaluating crop performance under reduced water availability (Mkhabela and Bullock, 2012; Steduto *et al.*, 2012).

Since 1979, the main challenges in this study have involved the collection of climate data, crop production records, soil characteristics, and irrigation management practices. These datasets, obtained from the Northern Al-Jazera Irrigation Project, were analysed numerically using the AquaCrop package, as shown below (Al-Lami, Al-Rawi and Ati, 2023; Saad *et al.*, 2023).

CLIMATE

The climate data required by the AquaCrop model include daily minimum and maximum air temperature, daily precipitation, reference evapotranspiration (ET_o), and average annual CO_2 concentration. Daily evapotranspiration was estimated using ET_o calculator, a secondary tool provided within the AquaCrop package. This program determines daily evapotranspiration based on climatic inputs such as minimum and maximum temperatures, mean relative humidity, wind speed (Raes, 2009; Alexandru and Popescu, 2020; Mansour, Gaballah and Nofal, 2020; Raes *et al.*, 2023b).

THE CROP

The data entered into the program included the planting date for wheat varieties, 'Iba'a' and 'Barcelona', which was set as the first of December. An initial seeding rate of 200 kg·ha^{-1} was used for the 'Iba'a' variety and 140 kg·ha^{-1} for the 'Barcelona' variety. Additionally, a total fertiliser application of 200 kg·ha^{-1} was applied in two stages. In the first stage, seeds and fertiliser were applied simultaneously at planting. In the next step, the fertiliser was spread at the beginning of April. The wheat growth cycle was 183 days, during which the maximum root depth reached about 90 cm (Fig. 1).

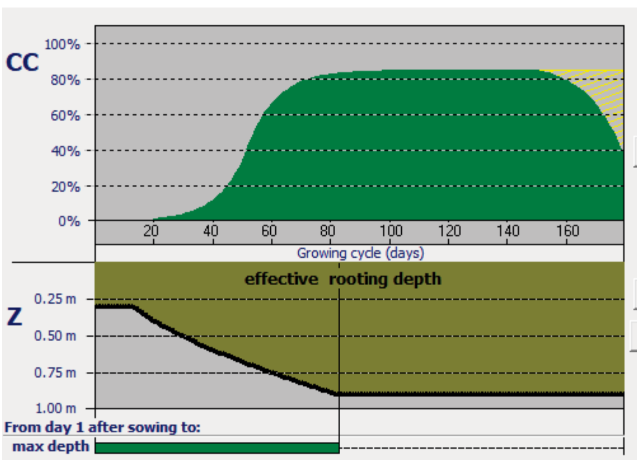

Fig. 1. Effective root depth of a wheat crop; source: own elaboration

The green canopy cover (*CC*) refers to the portion of the soil surface covered by plants. It ranges from 0% at the sowing stage, when no canopy cover is present, to about 100% at mid-season, when a full canopy cover is reached and the soil surface is completely shaded by the canopy, as shown in Figure 2 (Bello and Walker, 2017; Salman, 2021; Raes *et al.*, 2023a).

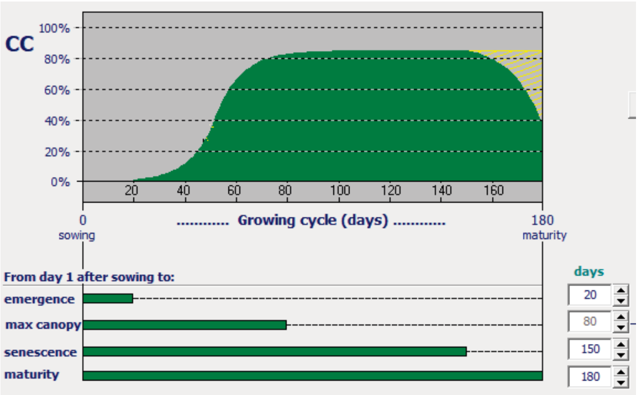

Fig. 2. Canopy development; source: own elaboration

IRRIGATION EVENT MANAGEMMENT

The AquaCrop software simulates crop yield under rainfed irrigation conditions using a climate data file that relies on daily recorded precipitation during the study season. In addition, the model can simulate supplementary and full irrigation scenarios by incorporating datasets that specify dates, number of irrigations events, and corresponding irrigation water depths (Tab. 1).

RESULTS AND DISCUSSION

PRODUCTIVITY INFORMATION

All field investigation results shown in Table 2 indicate a significant increase in yield with greater water application through the sprinkler irrigation system for both 'Iba'a' and 'Barcelona' wheat varieties. This statement aligns with conclusions of Al Najafi and Mahdi (2009). During the study season, a seed rate of 200 kg·ha^{-1} for the 'Iba'a' variety under supplementary irrigation resulted in a crop yield of 4,400 kg·ha^{-1}. Meanwhile, 'Barcelona' variety achieved a higher yield of 7,200 kg·ha^{-1} using only 140 kg·ha^{-1} of seeds, indicating its superior productivity, as highlighted by Ali, Baker and Al-Douri (2022). Furthermore, the spike of the 'Barcelona' variety was greater than that of the 'Iba'a' variety, as shown in Photo 1.

Table 2. Yield of two varieties of wheat according to irrigation rates

Wheat variety	Irrigation type	Water used (mm)	Production yield (kg·ha^{-1})	Water use efficiency (kg·m^{-3})
'Iba'a'	rainfed irrigation	163	360	0.220
	supplemen-tal irrigation	397 (163 + 234)	4,400	1.108
'Barcelona'	rainfed irrigation	163	360	0.220
	supplemen-tal irrigation	397 (163 + 234)	7,200	1.813

Source: own study.

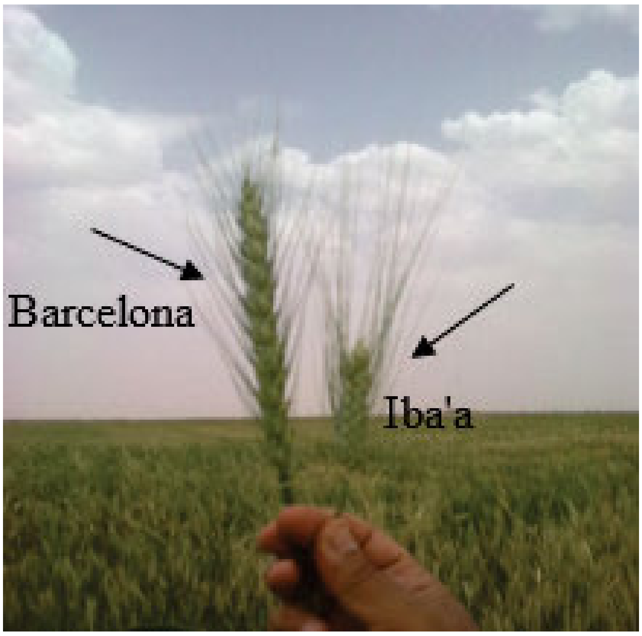

Photo 1. The difference in the shape of the spike between 'Barcelona' and 'Iba'a' wheat (phot.: *A.I. Hameed*)

WATER USE EFFICIENCY OF RAINFED IRRIGATION (WUE_R) FOR 'IBA'A' AND 'BARCELONA' WHEAT VARIETIES

The production yield was 360 kg·ha^{-1} and 163 mm was used for the fully rainfed irrigation. Hence, the water use efficiency is 0.22 kg·m^{-3}, as shown below.

$$WUE_R = 360/163 = 0.22\ \mathrm{kg \cdot m^{-3}}$$

Table 1. Programming the irrigation dates for 'Barcelona' and 'Iba'a' wheat varieties

Parameter	Date of irrigation (day)									
	Dec 16	Jan 8	Feb 8	Mar 20	Apr 2	Apr 10	Apr 20	May 1	May 8	May 12
Depth of irrigation water added (mm)	23	23	31	21	12	23	23	23	23	32
Accumulative depth of irrigation water added (mm)	23	46	77	98	110	133	156	179	202	234

Source: own elaboration.

WATER USE EFFICIENCY OF SUPPLEMENTAL IRRIGATION ($WUE_{(IRR+R)}$) FOR THE 'IBA'A' WHEAT VARIETY

In the study season, ten supplementary irrigation events of 234 mm, as shown in Table 1, resulted in the production of about 4,400 kg·ha^{-1} (Tab. 2). Accordingly, efficiency of water use was 1.108 kg·m^{-3}, as shown below.

$$WUE_{(\mathrm{Irr+R})} = \frac{4,400}{10,000} : \frac{163+234}{1,000} = 1.108 \text{ kg} \cdot \text{m}^{-3}$$

A comparison of water use efficiency shows that under monsoon rainfall alone (163 mm), the wheat crop achieved a productivity of 0.22 kg·m^{-3}. In contrast, with supplementary irrigation of 397 mm, the water productivity for the 'Iba'a' variety increased to 1.108 kg·m^{-3}. This indicates an increase of about 402.2% in the water productivity.

WATER USE EFFICIENCY OF SUPPLEMENTAL IRRIGATION FOR 'BARCELONA' WHEAT VARIETY

Apart from seasonal rain, the depth of irrigation water was 234 mm. The productivity of the 'Barcelona' wheat variety reached 7,200 kg·ha^{-1}, so the water use efficiency was 1.813 kg·m^{-3}.

$$WUE_{(\mathrm{Irr+R})} = \frac{7,200}{10,000} : \frac{163+234}{1,000} = 1.813 \text{ kg} \cdot \text{m}^{-3}$$

The response of the 'Barcelona' wheat variety to the supplementary irrigation resulted in an increase in water productivity efficiency of about 722.3%. Supplementary irrigation had a significantly increased productivity efficiency for both varieties. These findings are consistent with the results reported by Agary *et al.* (2002) and Al Najafi and Mahdi (2009). The simulated productivity values for the 'Iba'a' and 'Barcelona' wheat varieties are presented in Table 3.

Table 3. Simulation of the productivity of 'Iba'a' and 'Barcelona' wheat varieties

Parameter	'Iba'a' wheat variety	'Barcelona' wheat variety
Simulation yield (kg·ha^{-1})	4,596	7,340
Actual yield (kg·ha^{-1})	4,400	7,200
Biomass yield (kg·ha^{-1})	10,450	15,574
Comparison with simulation	results closely aligned with field data	close convergence between actual and simulated results
References supporting results	Mansour, Gaballah and Nofal (2020), Wellens *et al.* (2022)	Kanda, Senzanje and Mabhaudhi (2021)

Source: own study.

CONCLUSIONS

In this study, field investigations supported by analytical simulations using the AquaCrop software were performed to assess the efficiency of the sprinkler irrigation system, both with and without supplementary irrigation. Two wheat varieties, 'Iba'a' and 'Barcelona', were evaluated.

This study demonstrated the unreliability of rainfed irrigation in ensuring stable crop productivity due to seasonal fluctuations in rainfall. During the selected season, the daily precipitation recorded in the region was 163 mm, resulting in a low wheat productivity of about 360 kg·ha^{-1}.

Regarding of the complementary irrigation, a total irrigation water depth of 234 mm was applied to the 'Iba'a' variety, resulting in a productivity was approximately 4,400 kg·ha^{-1}. In contrast, the 'Barcelona' variety achieved a significantly higher yield of 7,200 kg·ha^{-1} compared to the 'Iba'a' variety. Its advantage lies in the higher productivity, especially with the irrigation applied in April. The results demonstrate that the 'Barcelona' variety is more responsive to irrigation conditions during this month.

In contrast, the 'Iba'a' variety does not show such a positive response to irrigation applied in April, which may limit its overall productivity. This highlights the importance of selecting wheat varieties that are better aligned with specific irrigation schedules and local environmental conditions.

Thus, while the 'Barcelona' variety offers higher yields and better adaptation to April irrigation, the 'Iba'a' variety may require modified irrigation strategies or more favourable environmental conditions to match or exceed 'Barcelona' variety productivity.

Moreover, the study showed a strong convergence between the productivity estimates generated by the AquaCrop model and the corresponding values observed in the field.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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