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Modelling effects of water stress on the productivity of irrigated wheat (Triticum Aestivum L.) in a semiarid condition of Northeastern Nigeria

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Abstract

Lake Chad region is currently experiencing trending issues. Climate change is among the major influencers of these issues that require inevitable consideration for a sustainable ecosystem. Various crop models have been developed and employed in various environmental conditions and management practices, which are cheaper and easier than field experiments. Therefore, crop models could be used to simulate various water management strategies and suggest suitable options. In this work, the FAO AquaCrop model has been evaluated to simulate deficit irrigation (DI) scenarios for wheat crops using data generated from a field experiment. The model simulated grain yield (GY), biomass yield (BMY), biomass production (BMP) and canopy cover (CC) adequately during its calibration and validation. However, its performance in simulating water productivity (WP) and actual crop evapotranspiration (ET_a) was low with average r^2, NRMSE, model efficiency (EF) and Willmot Index of agreement (d) of 0.58, 11.0 %, -1.40 and 0.69 respectively. The study of DI scenarios using the model revealed that the application of DI throughout the growth stages of the crop could significantly affect GY and WP. The highest GY and WP of 5.3 t/ha and 1.50 kg/m^3 were respectively obtained at the application of full irrigation (T100). Increasing DI beyond 20 % depressed both GY and WP significantly. However, increasing the irrigation interval from seven to ten days did not affect GY, thereby improving WP from 1.28 kg/m^3 to 1.38 kg/m^3. Therefore, applying an 80 % irrigation requirement throughout the wheat growing season at 10-day intervals could save 25 % of irrigation water, a valuable strategy to improve irrigation water use without significant yield reduction. Furthermore, irrigation-related scientists and managers can use the validated model to decide the current and future irrigation water management for similar wheat varieties in similar environmental conditions.

Keywords:
AquaCrop model;
Deficit irrigation;
Irrigated wheat;
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INTRODUCTION

Climate change and variability will likely pressure water demand and create physical and economic water scarcity in Africa [1]. The Sub-Saharan African (SSA) countries are the most vulnerable to devastating impacts of climate change due to their geographical location, population growth, urbanization, low income earning, low technological and institutional capacity to adapt to the climate change, as well as their huge reliance on water and agriculture, which are highly influenced by climate [1]. Agriculture, a major consumer of fresh water, is the major source of livelihood for about 60 % of the people residing in the Lake Chad Basin. Population growth necessitated agricultural expansion in the region, doubling the initial agricultural water demand from 13 million cubic meters in 1960 to 26 million cubic meters in 1990 [2]. Therefore, irrigation costs and increased water scarcity call for developing strategies that maximize water use efficiency.

Analyses of climate change impacts consistently show that the yields of cereal crops may decrease by as much as 10 % by the middle of this century in semiarid West Africa due to a decrease in the length of the growing season, temperature rise, unprecedented rainfall characteristics and water scarcity [3]. Wheat (*Triticum aestivum L.*) is among the most important cereal crops in the world, which is cultivated largely due to its tolerance to various climatic and edaphic conditions. Globally, about 33 million ha of the world's wheat-cultivated lands are facing drought damage [4]. It is anticipated that due to climate change, water and heat stress will be the major limitations for wheat production, even in irrigated environments [5]. Farmers in the semiarid region of Borno state in northeastern Nigeria face the challenge of water stress during crop cultivation, especially when cultivating the wheat crop. This is due to the drying of streams or ponded water used for irrigation, necessitating groundwater, which is economically not feasible for the financially-incapacitated farmers. Promising wheat production techniques that would conserve water and energy could be useful in promoting local crop production.

Previous studies suggested that much of the losses in crop yields can be reduced by employing adaptation measures such as crop models [3]. The literature contains data on DI and uses models as promising alternatives for water scarcity adaptation. However, there is a dearth of such information in sub-Saharan African countries [6].

It was extensively reported that deficit irrigation significantly affects wheat growth, yield and its components [7, 8, 9, 10]. For many crops, research on DI produced different outcomes worldwide [7][8]. Therefore, effectively implementing this technique requires precise knowledge of its effects on a particular cultivar under local environmental conditions. Using crop models and simulation of crop responses to environmental challenges such as water scarcity, contamination, and uncertainties caused by climate change and variability is an indispensable and efficient means of identifying their impacts and proposing best management practices.

Among the existing models, the FAO AquaCrop is a physically-based water-driven model that has evolved from yield response to water to normalized water productivity. The model focuses its simulation on attainable crop biomass and yield in response to water availability. It is a powerful modeling tool for developing various irrigation strategies and rain-fed systems subjected to soil types and environmental conditions [11]. Researchers around the world widely confirmed the accuracy of the model in simulating crop productivity of different crops in various types of the environment [12]. However, despite the importance of wheat in the semiarid northeastern Nigeria, the model has not been evaluated for the crop in the region.

Several researchers have noted that crop model calibration is essentially site-specific, and simulation performance should be assessed using different field management, climate, crop, and soil to constantly provide suggestions for improving the accuracy and applicability of models [13]. A localized crop model would aid in assessing competing management alternatives and possible constraints to improve crop productivity. Models are often localized by subjecting them to calibration techniques, and they are validated to appraise the scale of applicability of the calibrated model in a particular region in achieving specified objectives.

This work will provide information on the deficit irrigation strategy that could be adopted to advance wheat production in the study area. Specifically, the outcome of this research will constitute a body of knowledge that farmers could use to plan for their expected returns and irrigation project managers, consultants, engineers and agronomists to increase crop water productivity through optimal water management decisions. The objectives of this work are thus to evaluate the FAO AquaCrop model using irrigated wheat based on water stress conditions for Borno state and environs; and apply the validated model to evaluate the impacts of deficit irrigation on the productivity of wheat.

MATERIALS AND METHOD

Study Location

The experiment was conducted at the Research Farm of the Lake Chad Research Institute, Maiduguri, Borno state, Nigeria. The site is located between latitude 11°51'40" and longitude 13°13'37", 341 m above mean sea level, as presented in Figure 1. The climate of Maiduguri is generally semiarid with tropical grassland vegetation. The mean monthly minimum temperature is lowest (13.5° C) during the period of strongest and most constant northeast winds (Harmattan) in December and January; and highest (24.7^{o} C) in April. The mean monthly maximum temperature is highest (40.3^{o} C) before and during the onset of the rains in April, and the lowest (30.8^{o} C) during the peak rained August [14]. The area is characterized by a short wet season (June-October) and a long dry season (November-May) with a mean annual rainfall of 625 mm. The major water source in the area is the Ngadda River, which is a tributary to Lake Chad. The river flows through Maiduguri Metropolitan Council (MMC) and Jere local government area. Table 1 illustrates the average daily monthly climatic data of the location.

The experimental site's soil physical properties, including textural class, bulk density, saturated hydraulic conductivity and moisture content at saturation, field capacity and permanent wilting point, were determined in a laboratory at the Department of Soil Science, University of Maiduguri.

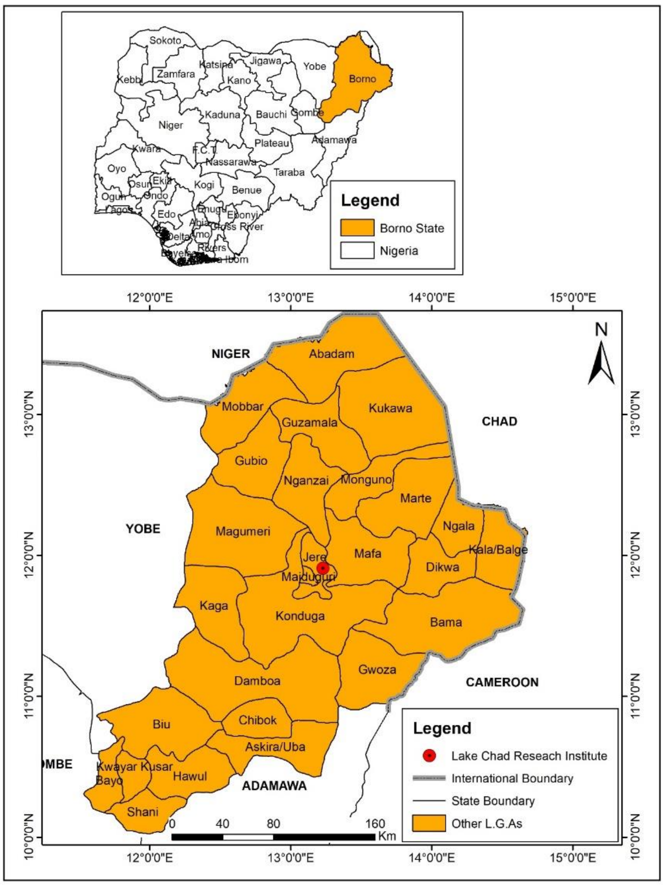

Figure 1: Map of the Study Area

Table 1. Monthly Average Climatic Variables of the Study Area

Months	Min. Temp. (°C)	Max. Temp. (°C)	Relative Humidity (%)	Wind Speed (m/s)	Sunshine Duration (Hours)
January	13.4	32.7	32.0	1.2	7.8
February	17.8	35.2	25.0	1.3	8.6
March	20.8	37.8	20.7	1.6	9.7
April	24.7	40.3	28.3	1.6	9.9
May	26.1	39.3	41.8	1.6	9.1
June	24.6	36.6	55.6	1.6	8.3
July	23.1	32.2	71.2	1.5	7.6
August	22.0	30.8	80.2	1.3	6.9
September	22.4	32.7	71.9	1.5	8.4
October	22.4	35.2	55.9	1.4	8.3
November	16.8	36.0	36.0	0.9	7.7
December	13.3	33.0	34.0	0.9	7.7

Source: Nigerian Meteorological Agency, Maiduguri.

Soil samples were collected from the experimental field at an incremental depth of 30 cm from the soil surface to 150 cm depth. Particle size distribution was analyzed using the hydrometer method, and the textural class was determined based on the sand, silt and clay percentage. The soil bulk density of the undisturbed sample was determined as the ratio of the oven dried soil mass to the core sampler volume. The soil moisture content at saturation, field capacity and permanent wilting point were determined using pressure plates at 0, 0.3 and 15 bars, respectively.

Treatments and Experimental Design

The experiment was based on irrigation treatment of 100 % gross irrigation requirement (I_g) as the control and deficit irrigation treatments of 80, 60 and 40 % I_g, each only at vegetative, flowering or yield formation growth stages, making a total of ten (10) treatments as presented in Table 2. The treatments were laid in a randomized complete block design (RCBD) with three (3) replications, making 30 plots. The size of each plot (basin) was 3 x 4 m and was separated by 0.5 m. The buffer zone between replications/blocks was 1 m. A gross field size of 40 x 15 m (0.06 ha) was used during the field experiment.

Management Practices

REYNA 28 is a variety of wheat crops selected and adapted in the ecology by the Lake Chad Research Institute (LCRI). The variety has outstanding characteristics of medium maturity (90-95 days), heat tolerance, good yielding (5-5.5 t/h) and baking quality.

Table 2. Description of Treatments

Treatments	Description
Treatment 1	Full irrigation; 100 % of I_g throughout the growing season
Treatment 2	Irrigation at 80 % I_g during the vegetative stage only
Treatment 3	Irrigation at 60 % I_g during the vegetative stage only
Treatment 4	Irrigation at 40 % I_g during the vegetative stage only
Treatment 5	Irrigation at 80 % I_g during flowering only
Treatment 6	Irrigation at 60 % I_g during flowering only
Treatment 7	Irrigation at 40 % I_g during flowering only
Treatment 8	Irrigation at 80 % I_g during yield formation only
Treatment 9	Irrigation at 60 % I_g during yield formation only
Treatment 10	Irrigation at 40 % I_g during yield formation only

The lengths of the crop's establishment, vegetative, flowering and yield formation stages were 14, 30, 14 and 37 days, respectively. The variety, originated from the International Centre for Agricultural Research in Dry Areas (ICARDA), Sudan, was well adapted to Northern Nigeria's irrigated conditions [14]. The experimental treatments were imposed two weeks after planting to allow proper establishment. All other agronomic activities, such as weeding, fertilizer application and harvesting were kept the same for all treatments. NPK (20:10:10) was applied in each plot at planting, at the rate of 400 kg/ha and at four (4) weeks after planting at the rate of 200 kg/ha as recommended by LCRI. Weeding was done manually at two weeks intervals, and no incidence of birds, rodents, pests and disease was observed.

Irrigation Scheduling and Irrigation Water Application

Basin irrigation with size 3 x 4 m was adopted during the field experiment. Crop water requirement and irrigation requirements were determined using the FAO-CROPWAT 8.0 Software based on climatic, environmental and crop characteristics. The climate and soil data used in the software are presented in Table 1 and Table 3, respectively. For the crop input requirement, default crop parameters such as crop coefficients, rooting depth and critical depletion were adopted from the software except for the crop growth stages, which are mostly cultivar specific. They were substituted with 15, 25, 35 and 20 days for initial, developmental, mid-season and late season growth stages, respectively, as recommended by LCRI. The software generated net irrigation depths of the control treatment (100 % I_g), then calculated gross irrigation depths as the ratio of net irrigation to application efficiency inputted as 65 % [15]. Weekly (7-days) irrigation interval was used throughout the growing period, which gave 100 % irrigation scheduling efficiency from the software. LCRI recommended seven (7) days of irrigation interval for the region's sandy loam and medium textured soils. Irrigation depths of the DI treatments at each irrigation were calculated as their corresponding percentage of the control treatment (T1). Table 3 shows the irrigation schedule for the season.

Water was conveyed into the experimental plots from the field channels using pair of 4.6 cm diameter calibrated PVC pipes installed in each basin to give free orifice flow. The calibration resulted in an average coefficient of discharge (C_d) of the PVC pipe to be 0.68.

Table 3. Physical Properties of the soil at the

Properties/ Layers	**0-30cm**	**30-60cm**	**60-90cm**	**90-120cm**	**120-150cm**
Textural Class	Sandy loam	Sandy clay loam	Sandy loam	Sandy clay loam	Sandy clay loam
SAT (g/g)	0.325	0.428	0.394	0.444	0.444
FC (g/g)	0.257	0.104	0.085	0.104	0.118
PWP (g/g)	0.027	0.055	0.051	0.066	0.077
Bulk Density (g/cm^3)	1.63	1.46	1.70	1.56	1.52
Ksat (mm/day)	1200	269	1200	273	342

Pairs of 30 cm meter rule were used as gauges at the pipe's inlet to determine the water's height (head) above the inlets. Then, water discharge through the pipe was calculated using the orifice equation as expressed in (1).

$$Q = AC_d\sqrt{2gH} \quad (1)$$

A = cross sectional area of orifice (m^2); g = acceleration due to gravity (9.81 m/s^2); H = height of water above the orifice (m).

The time of flow into each plot was based on the depth of water applied into the plot at an irrigation (i.e. I_g= gross irrigation depth). Having known the plot size (A) and the flow rate into the plot (Q), irrigation time was calculated using (2). A stopwatch was used to monitor the time of water application.

$$t = \frac{I_g * A}{Q} \quad (2)$$

Determination of Crop Phenological Data

Physical observations determined phenological parameters such as days to emergence, days to maximum canopy cover, days to maturity, etc.

Determination of Canopy Cover (CC)

LAI was estimated using the method reported by Jin et al. [16] by multiplying the plant population by leaf area per plant (3).

$$LAI = 0.75 * \rho * \left(\frac{\sum_{i=1}^{m}\sum_{i=1}^{n}(Lij * Bij)}{m}\right) \quad (3)$$

Where ρ is plant density, m is the number of measured plants, Lij is leaf length (cm), Bij is the maximum leaf width (cm), and n is the number of leaves of the nth plant. Five plants were randomly selected from each plot for this measurement.

LAI was converted to canopy cover (CC) in % using the empirical relationship between CC and LAI for wheat crops using (4) [17].

$$CC = 94.00\left[1 - \exp^{(-0.43 * LAI)}\right]^{0.52} \quad (4)$$

Determination of Dry Matter Production (DMP)

The dry matter production (DMP) was determined using a method described by Jin et al. [16]. Five (5) representative plants were randomly cut from a 0.25 m^2 area of each plot. Samples stayed in a well-ventilated oven for 48 hours at 65 °C [18], and final dry weights (DW) were recorded. CC and DMP were determined three times once at each of the vegetative, flowering and yield formation growth stages.

Determination of Actual Crop Evapotranspiration (ET_a)

Soil moisture content in each plot was monitored throughout the growing season before and two days after irrigation using calibrated gypsum blocks. The blocks were installed at 15 cm, 45 cm and 75 cm depths to represent 0-30, 30-60 and 60-90 cm soil layers. The actual crop evapotranspiration (ET_a) was estimated using the soil moisture depletion method with the expression given in Equation 5 [19]. Evapotranspiration of each growth stage was calculated as the summation of daily ET_a for that particular period whereas seasonal evapotranspiration was the summation of daily ET_a for the entire growing season.

$$ET_a = \frac{\sum_{i=1}^{n}(GMC_{1i} - GMC_{2i}) * A_i * D_i}{t} \quad (5)$$

Where ET_a is average daily evapotranspiration between successful soil moisture sampling periods (mm/day), (GMC_{1i}-GMC_{2i}) is soil moisture deficit between two measurement dates in ith soil layer, A_i is specific gravity of ith layer, D_i is depth of ith layer (mm), n is number of soil layer sampled and t is number of days between successful soil moisture content sampling.

Determination of Biomass Yield (BMY) and Grain Yield (GY)

Harvesting was done manually when the crop reached maturity. An area of 1 m^2 from center of each plot was selected to represent the harvestable yields of each treatment as described by Memon et al. [8]. Samples were harvested from ground surface in each plot and tagged, and then sun-dried for one week. The dried samples were weighed using electric balance to record BMY (consisting both grain yield and straw yield). Samples were manually threshed, winnowed and cleaned, and then the GY was also weighed using electric balance at the standard gravimetric moisture content (13.5 %) [8].

Determination of Crop Water Productivity (WP)

Crop water productivity was determined as the ratio of grain yield to seasonal actual crop evapotranspiration as presented in (6).

$$WP = \frac{GY}{ET_a} \quad (6)$$

Running AquaCrop Model

AquaCrop version 6.1 was used in the study. The model has four sub model components: (i) the climate; (ii) the crop; (iii) the soil and (iv) the management. The soil, climate and irrigation scheduling data used in running the model are presented in Table 1, Table 2 and Table 3, respectively. Default conservative crop parameters were adopted from the model whereas cultivar or user specific crop parameters were generated from the field experiment conducted.

Model Calibration

Sensitivity analysis of the model output variables to the model input parameters was performed prior to the calibration process to distinguish the model's sensitive parameters from the insensitive parameters. The common practice of calibration is to run the model starting with estimated or default model's parameter values and then compare the output with the measured experimental/field data, then adjust and run the simulation and compare again. This was done repeatedly until the simulation result closely agreed with the experimental data. The identified sensitive model input parameters were considered for these iterations. But for sound calibration, it is necessary to include data from DI treatments [11]. Therefore, the calibration was carried out using field data of the fully irrigated treatment (T1) and some DI treatments (T4, T7 and T10). The parameters considered for evaluation during the calibration were canopy cover (CC), dry matter production (DMP), grain yield (GY) and biomass yield (BMY). After several adjustments, the final values of the model parameters at which the simulation outputs had the highest correlation with the field data for CC, DMP, BMY and GY were adopted as the input data of the model.

Model Validation

Validation of the model was done using independent data sets to attest the calibration done initially. The remaining six (6) treatments that were not used during the calibration were utilized in validating the model. These treatments were: T2, T3, T5, T6, T8 and T9. Canopy cover development (CC), dry matter production (DMP), biomass yield (BMY), grain yield (GY), water productivity (WP) and actual evapotranspiration (ET_a) were the variables assessed as references during the validation.

Data Analysis

A combination of several statistical indices is necessary to sufficiently assess the performance of a model [20] because each indicator has its strength and weakness. Equations 7 through 11 were the statistical indices used in evaluating the performance of the model. In the equations, Oi and Pi are the observations (measured field data) and predictions (simulation data), respectively and their averages and n are the number of observations.

1- Coefficient of determination (r^2):

$$r^2 = \left[\frac{\Sigma(Oi-\bar{O})(Pi-\bar{P})}{\sqrt{\Sigma(Oi-\bar{O})^2\,\Sigma(Pi-\bar{P})^2}}\right]^2 \quad (7)$$

2 - Root mean square error (RMSE):

$$RMSE = \sqrt{\frac{\Sigma(Pi-Oi)^2}{n}} \quad (8)$$

3 - Normalized root mean square error (NRMSE):

$$NRMSE = \frac{1}{\bar{O}}\sqrt{\frac{\Sigma(Pi-Oi)^2}{n}} * 100 \quad (9)$$

4- Nash-Sutcliffe model efficiency coefficient (EF):

$$EF = 1 - \frac{\Sigma(Pi-Oi)^2}{\Sigma(Oi-\bar{O})^2} \quad (10)$$

5 - Willmott's index of agreement (d):

$$d = 1 - \frac{\Sigma(Pi-Oi)^2}{\Sigma(|Pi-\bar{O}|+|Oi-\bar{O}|)^2} \quad (11)$$

Scenario study of deficit irrigation scheduling using AquaCrop Model

The validated model was applied to analyze the effects of some deficit irrigation strategies on wheat grain yield and water productivity. Application of 80, 70, 60, 50 and 40 % gross irrigation requirement throughout the crop growth cycle at 7-days and 10-days irrigation intervals were the scenarios studied. The results were statistically analyzed using analysis of variance (ANOVA) to determine the effects of the DI and irrigation intervals on the productivity of the wheat crop in the study area. Difference between means were compared using least significant difference (LSD) at 5 % level of significance.

RESULTS AND DISCUSSION

Physical Properties of the Soil in the Study Area

The analysis revealed that the texture of the soil is sandy loam to sandy clay loam, which becomes more clayey towards the eastern direction. The gravimetric soil moisture content of the top most layer at saturation (SAT), field capacity (FC) and permanent wilting point (PWP) were 0.325, 0.257 and 0.027, respectively. Likewise, the saturated hydraulic conductivity (K_{sat}) was found to be 1200 mm/day. The bulk densities of the sandy loam and sandy clay loam layers average 1.67 and 1.50 g/m3, respectively. Table 3 presents the physical properties of the soil for the site.

Irrigation Scheduling

The amount of weekly gross irrigation depth and the seasonal irrigation water applied for the treatments is presented in Table 4. Seasonal irrigation water applied for treatment is the total sum of all its weekly gross depths. All treatments received the same amount of weekly gross irrigation depths of 33.7 and 12.1 mm at the first two irrigations, respectively, to allow the proper establishment of the crop. The crop received four irrigations during the vegetative and yield formation stages, while two irrigations were applied during the flowering stage. The seasonal depth of gross irrigation water applied for the crop in T1 (non-deficit condition) was 477.10 mm.

Model Calibration

Table 5 presents the adopted input parameters for the calibrated model and Table 6 presents the calibration performance indices of the model in simulating GY and BMY. During the calibration process, most of the conservative parameters such as base temperature (T_{base}), upper temperature (T_{upper}), initial canopy cover (cc_o), crop dormancy linked with flowering, and shape factor describe root-zone expansion. The crop coefficient (K_{cTrx}), normalized water productivity (WP*) and temperatures for cold and heat stresses were adopted from the model's default values. However, some conservative parameters were adjusted within their ranges available in Raes et al. [21]. These parameters include: CGC (9.5-13.5 %), CDC (9 % by default) and possible increase of HI.

The variations of some conservative parameters within small limits for different cultivars of the same crop were also reported by Steduto et al. [11]. The non-conservative parameters, which include cultivar specific and management related parameters observed from the field experiment were also within their ranges given in the reference manual. The cultivar specific parameters include HI_o (45 to 50 %) and crop phenological data such as days to emergence and days to maturity with ranges of 5 to 13 days and 90 to 118 days, respectively. Depending on the environment and field management CC_x, Z_n and Z_x were also calibrated within their given ranges, as described in Raes et al. [21]. The model indicated simplicity and robustness because most parameters were set to their default values after the calibration as it was widely reported for several crops in the literature [22].

The model performance was good in simulating GY with r^2, RMSE, NRMSE, EF and d values of 0.96, 0.29 t/ha, 6.60 %, 0.88 and 0.97 respectively. Also, the performance indices of BMY shows that the model simulated BMY adequately. Similar indices values were reported by Beltran et al. [23] but with higher NRMSE of 11.46 %.

Table 7 presents the calibration performance of the model in simulating CC and DMP. It was observed that the model predicted CC reliably throughout the growth stages with the best prediction occurred during the vegetative stage of the wheat, with r^2, RMSE, NRMSE, EF and d values of 0.99, 1.24 %, 3.03 %, 0.96 and 0.99, respectively.

Table 4. Weekly Gross Irrigation Depths and Seasonal Irrigation Water Applied (SIWA) for the Treatments

Treatments	**Weekly Gross Irrigation Depths (mm)**												**SIWA (mm)**
	Establishment		Vegetative				Flowering		Yield Formation				Total
	1	2	3	4	5	6	7	8	9	10	11	12	
T1	33.7	12.1	17.0	23.3	30.6	42.0	46.4	49.7	52.9	54.3	56.0	59.1	477.1
T2	33.7	12.1	13.6	18.6	24.5	33.6	46.4	49.7	52.9	54.3	56	59.1	454.5
T3	33.7	12.1	10.2	14.0	18.4	25.2	46.4	49.7	52.9	54.3	56	59.1	431.9
T4	33.7	12.1	6.8	9.3	12.2	16.8	46.4	49.7	52.9	54.3	56	59.1	409.4
T5	33.7	12.1	17.0	23.3	30.6	42.0	37.1	39.8	52.9	54.3	56	59.1	457.9
T6	33.7	12.1	17.0	23.3	30.6	42.0	27.8	29.8	52.9	54.3	56	59.1	438.7
T7	33.7	12.1	17.0	23.3	30.6	42.0	18.6	19.9	52.9	54.3	56	59.1	419.4
T8	33.7	12.1	17.0	23.3	30.6	42.0	46.4	49.7	42.3	43.4	44.8	47.3	432.6
T9	33.7	12.1	17.0	23.3	30.6	42.0	46.4	49.7	31.7	32.6	33.6	35.5	388.2
T10	33.7	12.1	17.0	23.3	30.6	42.0	46.4	49.7	21.2	21.7	22.4	23.6	343.7

Table 5. Crop Input Parameters for Aqua crop

Symbol	Description and unit	Values
T_{base}	Base temperature (°C)	0
T_{upper}	Upper temperature (°C)	26.0
ccs	Soil surface covered by individual seedling at 90% emergence (cm^2/plant)	1.5
cc_o	Initial canopy cover (%)	4.86
	Number of plants per hectare	3240000
	Time from sowing to emergence (days)	7
CGC	Canopy growth coefficient (%) (fraction per day)	13.3
C_x	Maximum canopy cover (%) (function of plant density)	90
	Time from sowing to start of senescence (days)	75
CDC	Canopy decline coefficient (%) (fraction per day)	13.2
	Time from sowing to maturity (days)	90
	Time from sowing to flowering (days)	45
	Length of flowering stage (days)	15
	Crop determinacy linked with flowering	Yes
Z_n	Minimum effective rooting depth (m)	0.30
Z_x	Maximum effective rooting depth (m)	0.75
	Shape factor describing root zone expansion	1.5
K_{cTrx}	Crop coefficient when canopy is complete but prior to senescence	1.10
WP*	Water productivity normalized for ET_o and CO_2 (gram/m^2)	15
	Water productivity normalized for ET_o and CO_2 during yield formation (% of WP*)	100
HI_o	Reference harvest index (%)	47
	Possible increase % of HI due to water stress before flowering	Moderate
	Allowable maximum increase (%) of specified HI	10
P_{exp_upper}	Soil water depletion threshold for canopy expansion-Upper (fraction of TAW)	0.25
P_{exp_lower}	Soil water depletion threshold for canopy expansion-Lower (fraction of TAW)	0.5
	Shape factor for water stress coefficient for canopy expansion	2
P_{sto}	Soil water depletion threshold for stomatal control-Upper (fraction of TAW)	0.5
	Shape factor for water stress coefficient for stomatal control	2
P_{sen}	Soil water depletion threshold for canopy senescence-Upper (fraction of TAW)	0.45
	Shape factor for water stress coefficient for canopy senescence	2.5
P_{pol}	Soil water depletion threshold for failure of pollination-Upper (fraction of TAW)	0.80
	Minimum air temperature below which pollination starts to fail (cold stress) (°C)	5
	Maximum air temperature below which pollination starts to fail (heat stress) (°C)	35

GDD = Growing degree day; TAW= Total available water

Table 6. Model Performance in Simulating GY, And BMY during Calibration

	r^2	RMSE	NRMSE	EF	d
GY (t/ha)	0.96	0.29	6.60	0.88	0.97
BMY (t/ha)	0.97	0.40	3.54	0.94	0.98

Table 7. Model Performance in Simulating CC and DMP during Calibration

		r^2	RMSE	NRMSE	EF	d
CC	Vegetative	0.99	1.24	3.03	0.96	0.99
	Flowering	0.98	5.00	7.66	0.88	0.97
	Yield Formation	0.94	6.76	9.83	0.68	0.94
DMP	Vegetative	0.86	0.09	9.90	0.37	0.82
	Flowering	0.98	0.09	3.12	0.98	0.99
	Yield Formation	0.93	0.38	8.95	0.80	0.95

This is in line with Kale et al. [22] where r^2= 0.99, RMSE= 5.6 %, EF= 0.90, d= 0.98 but with higher average NRMSE of 10.9 %.

The simulation of DMP was also adequate in all the three growth stages considered, with the best performance occurring during the flowering growth stage with r^2, RMSE, NRMSE, EF and d values of 0.98, 0.09 t/ha, 3.12 %, 0.98 and 0.99 respectively.

AquaCrop model was calibrated and found to sufficiently predict wheat crop's GY, BMY and CC with similar statistical indices using wheat by Beltran et al. [23], Kale et al. [22] and Zhai et al. [24]. Similarly, the findings of Umesh et al. [20] and Guo et al. [13], using maize and millet, respectively, were also in line with current work.

Model Validation

Table 8 presents the performance of the AquaCrop model in simulating GY, BMY and WP during the validation. The model performance was high in simulating GY with r^2 greater than 0.8, small RMSE, NRMSE of 5.03 %, a good model efficiency ($0.6 \leq EF \leq 0.79$) and d value greater than 0.9. Good agreement between simulated and field measured BMY was observed during the model validation. The r^2 value indicated moderate model performance ($0.7 \geq r^2 \leq 0.79$) in simulating the BMY. However, small RMSE, NRMSE (<5), EF ($0.6 \leq EF \leq 0.79$) and d (>0.9) showed that the model performance was very good. During the simulation of WP, the evaluation resulted in negative EF value of -3.31, which showed poor agreement (-10≤EF≤0) between the field measured and simulated WP. From the table, the statistical indices show that the model's performance in simulating WP was low. The performance of the model in simulating CC, DMP and ET_a during validation is presented in Table 9.

The model gave best CC simulation at the vegetative growth stage with r^2 value of 0.92, RMSE of 1.56 %, NRMSE of 3.64 %, model efficiency of 0.68 and d value of 0.95. All the indicators showed that the model predicted CC with very high precision. The next stage in term of fitness of the model is the flowering stage, the model also simulated CC at this stage adequately but with higher RMSE of 7.32 % and NRMSE of 10.77 % compared to the vegetative stage. The least agreement was observed at the yield formation stage and this might be due to some flaws in the manual measurement of the leaf area of the partially yellowed leaves as an indication of the beginning of senescence. The model simulation of CC can also be assumed to be good at the yield formation stage.

Using wheat crop, similar results of CC validation were reported by Jin et al. [16] and Kale et al. [22]. The former got r^2= 0.89-0.97 and RMSE= 3.18-7.19 % and the latter got r^2= 0.96, RMSE= 6.2-7.1 %, NRMSE= 13.9 % but higher EF and d values were reported. The manner in which the model simulated CC was also observed by Oiganji et al. [6] and Kale et al. [22].

Table 8. Model Performance in Simulating GY, BMY and WP during Validation

	r^2	RMSE	NRMSE	EF	d
GY (t/ha)	0.81	0.24	5.03	0.61	0.92
BMY (t/ha)	0.73	0.40	4.34	0.73	0.92
WP (kg/m^3)	0.63	0.15	9.47	-3.31	0.60

Table 9. Model Performance in Simulating CC, DMP and ET_a during Validation

		r^2	RMSE	NRMSE	EF	d
CC	Vegetative	0.92	1.56	3.64	0.68	0.95
	Flowering	0.94	7.32	10.77	0.36	0.82
	Yield Formation	0.82	9.63	13.73	-0.88	0.64
DMP	Vegetative	0.64	0.12	12.67	0.33	0.56
	Flowering	0.56	0.24	8.70	0.40	0.85
	Yield Formation	0.74	0.41	8.78	0.54	0.86
ET_a	Vegetative	0.51	0.43	11.43	0.43	0.84
	Flowering	0.50	0.47	10.82	-0.67	0.68
	Yield Formation	0.56	0.61	14.64	0.47	0.78

The agreement between field observation and the model simulation was closer from vegetative to the flowering stage than after flowering to senescence.

Table 9 shows that the best model's prediction for DMP was observed at the yield formation stage, followed by the flowering stage and lastly the vegetative stage. The r^2 and EF ranges between 0.7 to 0.79 and 0.4 to 0.59, respectively, which implies the model performed moderately in predicting DMP. Small RMSE, NRMSE between 6 to 15 and d greater than 0.8 showed a good agreement between field observation and the model simulation of the DMP. The table shows that the statistical indicators of the flowering stage resemble that of the yield formation stage. The simulation was moderate poor at the vegetative stage with r^2 of 0.64, EF value of 0.33 and d value of 0.56.

In simulating ET_a, the best model performance was at the vegetative stage followed by the yield formation and then the flowering stage. From the table, r^2 values of 0.51, 0.50 and 0.56 were observed at vegetative, flowering and yield formation stages respectively; these are considered moderate for a model performance. Low model efficiencies of 0.43, -0.67 and 0.47 were observed at the vegetative, flowering and the yield formation stages respectively. It can be deduced that the model performance in simulating ET_a was moderate poor.

Conclusively, the FAO AquaCrop model validation showed that the model simulations of the considered parameters were very good except for WP and ET_a. This could had been caused by the low sensitivity of the gypsum blocks used in determining soil water content as was also observed by Oiganji et al. [6]. Owing to the low performance of the model in simulating ET_a, the simulation of WP was also affected. The better performance of the model in simulating GY, BMY, CC and DMP than ET_a and WP can be corroborated by Guo et al. [13] Greaves and Wang [25] and Mousavizadeh et al. [26]. The cause of some deviations is attributed to the failure of the model in considering the great soil heterogeneity of field [27]. Guo et al. [13] recommended that the model requires further improvement in estimating WP which based on ET simulation. Better techniques should also be adopted in determining ET_a and CC to minimize the errors observed in this work. Using soil moisture probe and high-resolution cameras could be more reliable than gypsum blocks and manual measurement of leaf area, respectively.

Scenario study of deficit irrigation scheduling using AquaCrop Model

The validated model was used to simulate some deficit irrigation scenarios. Table 10 presents the effects of deficit irrigation at seven (7) and ten (10) days irrigation frequencies on GY and WP of the wheat crop. The result showed that applying DI throughout the wheat's growth period significantly affected the crop's yield and water productivity, as observed in many works [10, 28, 29].

The highest grain yield was observed at T100 (5.3 t/ha), which is statistically the same as T80 (5.12 t/ha) whereas the lowest grain yield was observed at T40 (2.82 t/ha). A similar value of 5.20 t/ha at non deficit conditions was also obtained by Ouda et al. [9]. The table shows that GY of all treatments is statistically at par with one another except in T100 and T80, which is similar to the results of Saad et al. [10] and Asmamaw et al. [28]. Yield reductions of 3, 12, 26, 48 and 74 % were observed at T80, T70, T60, T50 and T40 respectively. Imposing a water deficit of 20 % resulted in GY loss of 3 % which is consistent, thus reasonable amount of water can be saved without significant yield reduction.

The highest WP observed was at T100 (1.50 kg/m^3) which is statistically similar with T80 (1.48 kg/m^3) and the lowest WP was achieved at T40 (1.09 kg/m^3).

The analysis showed that there is significant difference among all the levels of irrigation application except between T100 and T80. This implied that WP was maintained under mild stress, but it decreased significantly under moderate and severe stresses, as was also reported by Rady et al. [29] and Zhao et al. [30].

Table 10. Impacts of Deficit Irrigation and Irrigation Interval on Yield and Water Productivity of Wheat

Treatments/ Factors	**Yield (t/ha)**	**WP (kg/m^3)**
Irrigation Amount (IA)		
T100	5.30^{a}	1.50^{a}
T80	5.12^{a}	1.48^{a}
T70	4.70^{b}	1.40^{b}
T60	4.10^{c}	1.30^{c}
T50	3.33^{d}	1.20^{d}
T40	2.82^{e}	1.09^{e}
LSD	0.22	0.06
Irrigation Interval (II)		
7 days	4.18	1.28^{b}
10 days	4.27	1.38^{a}
LSD	NS	0.04
Interaction		
IA x II	NS	NS

Means followed by different letters in a column differ significantly and those followed by the same letter are not significantly different at $p<0.05$ level of significance; NS= not significant.

Contrasting results were reported by Memon et al. [8] and Jalil et al. [31] where highest WP were achieved at the most stressed treatments due to higher drop in ET than in GY in response to the water deficits imposed. Imposing water deficit of above 20 % significantly caused drops in GY and WP of the wheat crop. Therefore, application of water deficit beyond this level will not be a promising or optimization strategy for the wheat crop in the area.

The result showed that increasing irrigation interval from seven days to ten days had no significant effect on GY, as observed by EL-Hwary and Yagoub [32]. Although, at 14, 21 and 28 days irrigation intervals, significant effects were observed by EL-Hwary and Yagoub [32] and Baloch et al. [33]. Ten (10) days irrigation interval resulted WP of 1.38 kg/m^3 which is statistically higher than that of 7-days irrigation interval (1.28 kg/m^3) and this is also in line with EL-Hwary and Yagoub [32]. Therefore, increasing irrigation interval from seven (7) to ten (10) days-maintained GY and improved the WP of the crop. The interaction of irrigation amount (IA) and irrigation interval (II) showed insignificant differences in both GY and WP. It can be deduced that the application of 80 % gross irrigation at ten days intervals are a promising strategy that will optimize irrigation water management while maintaining the potential yield of the wheat crop. Zhao et al. [30] stated that mild stress suits wheat crops in arid areas.

CONCLUSION

The FAO AquaCrop was observed to be user-friendly and easily calibrated. It reliably simulated wheat crop development and production. However, a poor agreement was observed between the simulations and field observations of ET_a and WP with r^2=0.50, RMSE=0.47 mm/day, NRMSE= 10.82 %, EF= -0.67 and d= 0.68 for ET_a during the flowering stage. This might be due to the inferiority of the gypsum blocks used in monitoring the experimental plots' soil moisture, which is the basis for determinations of ET_a and WP. Applying deficit irrigation throughout the growth stages of the wheat variety using the validated model affected the grain yield significantly and the WP of the crop at water stresses above 20 %. Increasing the irrigation interval from seven (7) to ten (10) days improved the WP of the crop by 8 %. Therefore, applying an 80 % irrigation requirement throughout the wheat growing season at 10-day intervals could save 25 % of irrigation water, a valuable strategy that will improve irrigation water use without significant yield reduction. The validated model can be used by irrigation managers, consultants, extension workers, agronomists and scientists in generating and evaluating various irrigation schedules for a similar wheat variety and under similar environmental conditions. The model should be validated using other wheat varieties and under different environmental conditions. A more reliable approach should be employed in determining crop evapotranspiration instead of using locally constructed gypsum blocks.

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