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Irrigation management strategies for winter wheat using AquaCrop model

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Abstract

Many regions of the world face the challenge to ensure high yield with limited water supply. This calls for utilization of available water in an efficient and sustainable manner. Quantitative models can assist in management decision and planning purposes. The FAO's newly developed crop-water model, AquaCrop, which simulates yield in response to water, has been calibrated for winter wheat and subsequently used to simulate yield under different sowing dates, irrigation frequencies, and irrigation sequences using 10 years daily weather data. The simulation results suggest that "2 irrigation frequency" is the most water-efficient schedule for wheat under the prevailing climatic and soil conditions. The results also indicate decreasing yield trend under late sowing. The normal/recommended sequence of irrigation performed better than the seven-days shifting from the normal. The results will help to formulate irrigation management plan based on the resource availability (water, and land availability from previous crop).

Introduction

By 2030, the world economy is projected to double and the world population to increase by $1/3^{rd}$ (Gurria 2009). To feed these people, crop production should be increased by 33%. The agricultural sector needs particular attention, as it accounts for about 70% of water use worldwide. In addition, competition for water resources by domestic, industrial, and agricultural uses – or between users and environmental needs are increasing. Another era on water resource is the pollution of water from agricultural fields, domestic use and industrial areas. Climate change is expected to worsen the situation of water availability (both in temporal and spatial scale). To fulfill the demand of agricultural sector, overexploitation of groundwater has been occurred in many parts of the world.

In Bangladesh, a substantial amount of rainfall occurs, but this is seasonal and concentrated during few months of the year (summer months, May to September), leaving the other months dry. The source of irrigation water for dry-season cropping is groundwater. Excessive use of groundwater is seriously threatening the sustainability of groundwater and, consequently the agricultural systems that rely on it. Considering the above facts, sustainable use of water resources and sustain the crop productivity under limited and variable water availability are clearly urgent. Strategic options for achieving sustainable agriculture in the country include improving water productivity in crop production, cultivation of low water-demanding crops, and adoption of water saving irrigation scheduling. Wheat, a low water demanding crop, shows a promising alternate option of rice (a high water demanding crop) cultivation during dry, winter period (Ali et al. 2007).

For wheat cultivation in Bangladesh, recommended irrigation schedule (time and amount) is available for optimum sowing date. The recommended sowing date often has to shift due to land availability from previous crop (as multiple crops are grown in a year) and climatic calamities. Besides, optimum irrigation time/interval often cannot be materialized due to unavailability of irrigation water. Thus, the recommended irrigation schedule becomes questionable and uncertain in producing desired yield under diverse conditions. Simulation models capable of quantifying the effects of water on yield can be a worthy tool for evaluating different irrigation management options. The AquaCrop model, developed by FAO, is a water-driven simulation model to simulate the yield of field crops. AquaCrop has been validated and tested on barley (Arya et al. 2010), teff (*Eragrostis tef*) (Aaraya et al. 2010), potato (Patel et al. 2010), maize (Heng et al. 2009), cotton (Farahani et al. 2009; Garcia-Vila et al. 2009), quinoa (Geerts et al. 2009), and wheat (Andarzian et al. 2011).

In this study, we calibrated the AquaCrop model for winter wheat crop, and used the calibrated model to simulate wheat yield under different sowing dates, irrigation frequencies, and irrigation sequences; with a view to help develop better irrigation management plan under the above mentioned diverse situations.

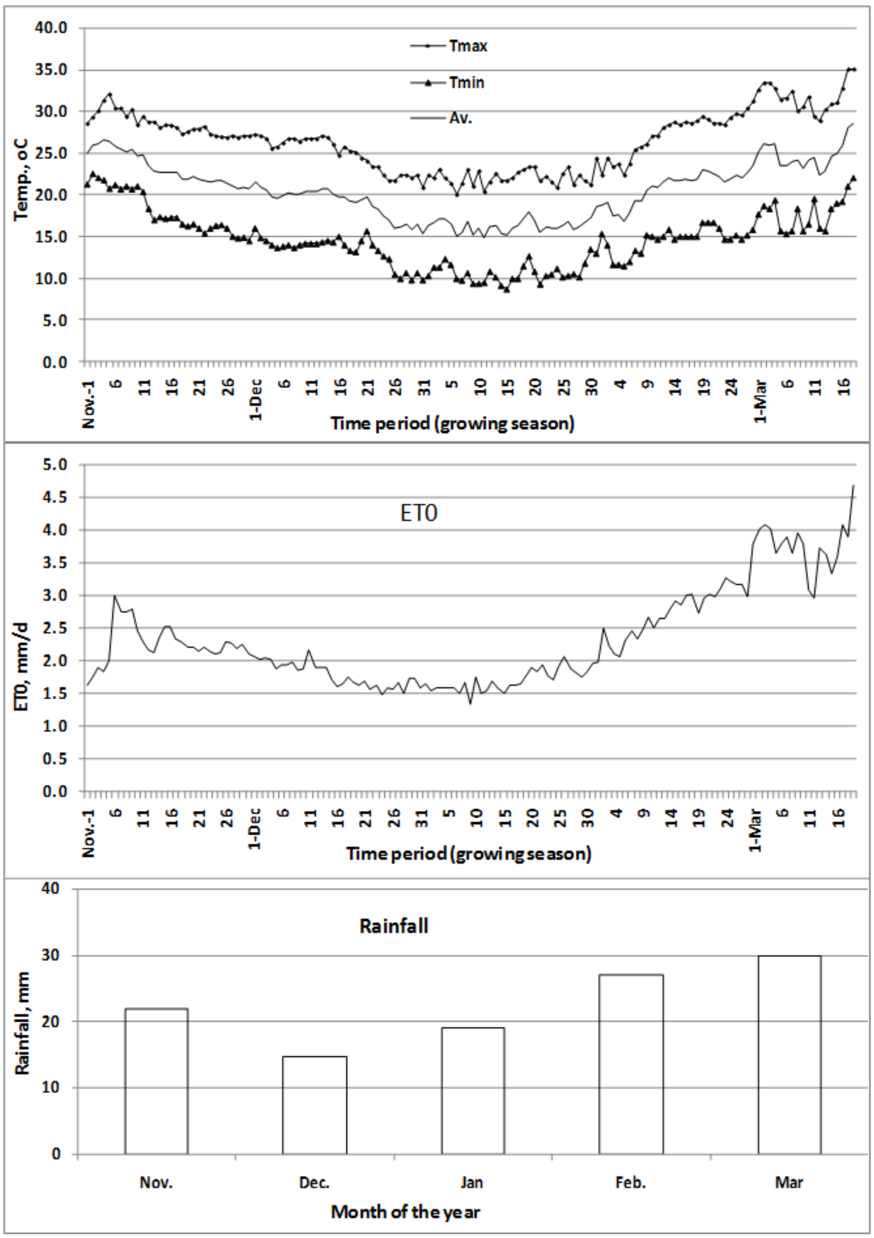

Figure 1. Long-term average temperature, ET0, and rainfall for the wheat growing period.

Materials and methods

About the model AquaCrop

AquaCrop version 3.1 was used in this study. It was developed by the Land and Water Division of FAO. AquaCrop predicts biomass production through simulation of crop green foliage. From biomass, grain yield is predicted using harvest index. Detail principles, methods, and capabilities of AquaCrop can be found in Raes et al. (2010) and Steduto et al. (2009).

Field experimental

Field experiment was conducted for three consecutive years (2002-03, 2003-04 and 2004-05) at the experimental farm of Bangladesh Institute of Nuclear Agriculture (BINA), Ishurdi, Bangladesh (co-ordinates are: latitude 24^0 06′ N, longitude 89^0 01′ E). The climate of the region falls under humid sub-tropic having summer dominant rainfall. Long-term average temperature, reference evapotranspiration, and rainfall pattern of the experimental site are depicted in Fig.1. The wheat growing period, November to March, is characterized by dry-winter. Experimental details have been well documented elsewhere (Ali 2008; Ali et al. 2007). Here, only a brief description is given.
The field soil texture was silty loam. The field capacity and wilting point of the field soil were 45% and 19% (by volume), respectively. The wheat cultivar was a semi-dwarf variety (average height is 88 cm). It is a 120-130 days cereal crop and suits the prevailing climate of winter season. Details of irrigation treatments are given in Table 1. The experimental design was a randomized complete block (RCB), with four replications.

Table 1. Details of irrigation treatments

Treatment	Irrigation at growth phase †			
	CRI	Jointing to shooting	Booting to heading	Flowering to soft dough
T_1	0	0	0	0
T_2	1	1	1	1
T_3	0	1	1	1
T_4	1	0	1	1
T_5	1	1	0	1
T_6	1	1	1	0
T_7	1	0	1	0
T_8	0	1	0	1
T_9‡	1	1	1	1

† '1' indicates one irrigation at this stage, and '0' indicates no irrigation (deficit).
‡ in addition to irrigation at each stage, irrigation was given when total available moisture within the root zone dropped below 50 %.

Soil moisture was measured in one replication by gravimetric method and/or neutron moisture meter. Access tubes were installed at the center of the plots. Measurements were taken at soil depths of 15, 30, 45, 60, 75, and 90 cm at sowing, at every growth stage, and at physiological maturity. Soil moisture measured by gravimetric method (weight basis) was converted into volumetric proportion by multiplying with bulk density. Irrigation water was applied in the unit plots using hose pipe by calibrating the rate with large bucket of known volume.
Evapotranspiration (ET) was calculated using the general water balance equation (as there was no runoff):

$$ET = I + P \pm \Delta W \quad \textbf{(1)}$$

Where, ET is crop evapotranspiration, I is irrigation water applied, P is effective rainfall, ΔW is change in soil moisture storage in the soil profile.

The grain and straw yield were adjusted to 12 % moisture using the following equation:

$$Y_{adj} = Y_i \times \frac{100+m_T}{100+m_i} \quad \textbf{(2)}$$

Where, m_i the initial moisture content, Y_i the initial yield (at m_i moisture content), m_T the targeted moisture content (here, 12 %), and Y_{adj} the adjusted yield (at m_T % moisture content).

Calibration of AquaCrop

The experimental data of the year 2002-03 was used to calibrate AquaCrop model. The calibration was performed against grain and biomass yield, and ET; for both well watered and water deficit conditions. Climatic data files were prepared with measured data except the CO_2 concentration, which was taken as the default value of AquaCrop (Manua Loa Observatory records in Hawai, USA). Average value of three years calculated harvest index (HI) and crop coefficient (K_c) were used (and kept constant) in calibration process. The Model was run keeping the measured/observed data constant. Other crop, soil and growth parameters were initially gauged from literature value adjusting with crop cultivar and climatic condition. The parameter values were changed systematically realizing their practical range, literature value, suggested conservative parameters, and local conditions (crop characteristics, crop duration, soil and climatic condition). Special care was taken to the sensitive and moderately sensitive parameters of AquaCrop as noted by Greets et al. (2009).

Validation/Evaluation of AquaCrop

Independent data sets (for the year 2003-04 & 2004-05) were used to evaluate the performance of AquaCrop model. All the calibrated parameters (along with average HI and K_c values) were used in simulation process. The weather, irrigation, and initial condition of the particular years were used as input for simulation purpose. In evaluation of simulated output, graphical and statistical comparisons were made. The following statistics were used to indicate overall model performance: Mean bias or error (ME), mean absolute error (MAE), root mean square error (RMSE), and relative error (RE) (Loague and Green, 1991).

Simulation study

After calibration and validation/evaluation of the AquaCrop model, it was used to simulate yield for different irrigation treatments under different sowing dates and irrigation sequences.

Weather input data

Average of ten years daily weather data were used as input to calculate reference evapotranspiration and other input file for model run, which is fairly representative of the area. The data were collected from meteorological department, which is 1.5 km apart from the field side. For rainfall file in AquaCrop, long-term (30 years) monthly total rainfall was used, as the monthly rainfall is more representative than the daily values (which are erratic and uneven).

Irrigation options

Yields are simulated under different irrigation frequencies and sequences for different sowing dates (Table 2). Irrigation frequency options are: 2 and 3 irrigations; irrigation sequences are: normal/ recommended sequence, and 7 days shifting (late) from the normal date; sowing dates are: 7, 15, and 23 November.

Table 2. Treatment combinations for simulation study

Sowing date	Irrigation frequency	Irrigation sequence (days after sowing)	Combination	Treatment name
D1: Nov.7	N1 – 2 nos	S1: 19, 52	D1-N1-S1	T1
		S2: 26, 60	D1-N1-S2	T2
	N2 – 3 nos	S3: 19, 39, 56	D1-N2-S3	T3
		S4 : 26, 44, 64	D1-N1-S4	T4
D2: Nov.15	N1 – 2 nos	S1: 22, 62	D2-N1-S1	T5
		S2: 29, 69	D2-N1-S2	T6
	N2 – 3 nos	S3: 22, 45, 65	D2-N2-S3	T7
		S4: 29, 52, 72	D2-N1-S4	T8
D3: Nov.23	N1 – 2 nos	S1: 22, 62	D3-N1-S1	T9
		S2: 29, 70	D3-N1-S2	T10
	N2 – 3 nos	S3: 22, 46, 66	D3-N2-S3	T11
		S4: 29, 53, 74	D3-N1-S4	T12

Irrigation frequencies are based on the general recommendation for deficit irrigation in wheat. In case of irrigation sequences, the 1stsequence (S1) is based on the average degree-days (GDD) (which correspond to general recommendation of irrigation interval for different frequencies) for normal sowing date, which is 15 November. The degree-day is chosen for fixing sequence because, due to change in sowing date, the accumulation of thermal unit will vary accordingly (Ali et al. 2004). For each sequence, the GDD is translated again into Julian day (in terms of days after sowing) for implementation/ preparation of irrigation file for model run.

The GDD is calculated following Nuttonson (1955):

$$GDD = \sum_{i=m}^{n} (T_A - T_B)\, \Delta t \quad \textbf{(3)}$$

where, T_A is the average of daily maximum (T_{max}) and minimum (T_{min}) air temperature, T_B is a base temperature below which development is assumed to cease, *m* is date of sowing, *n* is target date up to which we want to calculate GDD, and Δt is the time step in days. The T_B for the entire period (from sowing to maturity) is considered as 5^0C (Ali et al. 2004).

After preparing the input files (according to the treatments mentioned in Table 2), the model AquaCrop was run to obtain the simulated output.

Results and Discussions

Calibration of AquaCrop

Figure 2 presents the visual goodness of fit of the model calibration at full irrigation (4 nos.) and deficit irrigation (2 nos). The coefficient of determination, index of agreement, relative error, and root mean squared error were 0.99, 0.994, 7.4%, and 0.45, respectively; which indicates that the model fitted the observed data set very well. Calibrated parameters of crop growth, morphology, and other soil & management aspects are tabulated in Table 3.

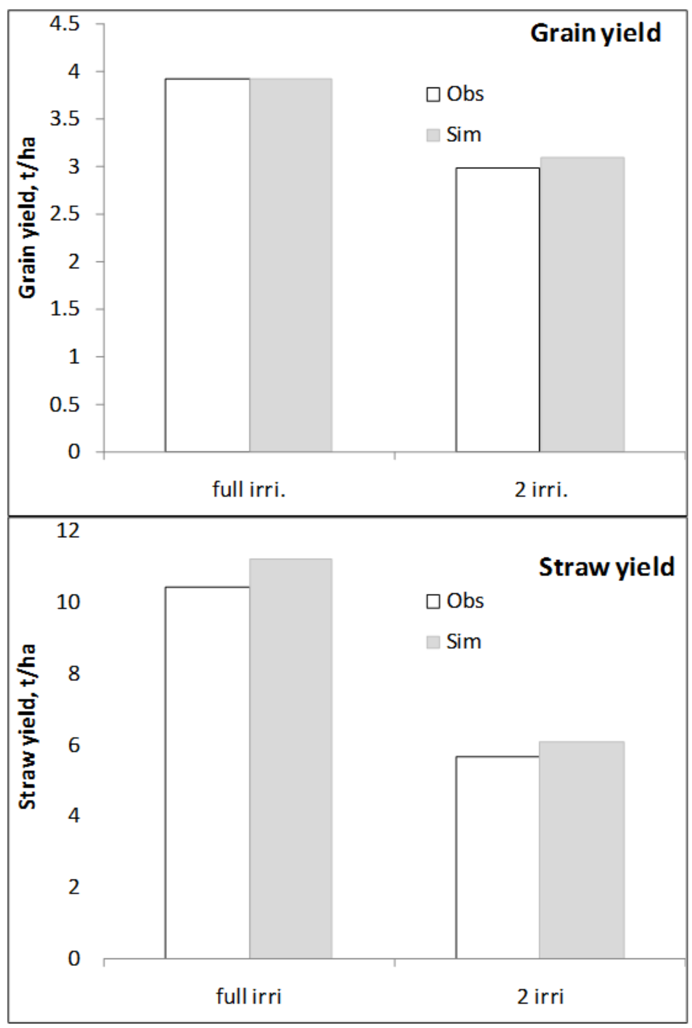

Figure 2. Observed and simulated yield and biomass in calibration process.

Table 3. Calibrated soil and crop parameters for wheat.

Parameters		Value	Way of determination *
Growth and morphology	Initial canopy cover, %	1.2	E
	Maximum canopy cover, %	98	E
	Canopy expansion, %/day	14.4	E
	Canopy decline coefficient , %/day	10.7	E
	Shape factor for stress coefficient for canopy expansion	1.7	E
	P_upper threshold for canopy/leaf expansion	0.10	E
	P_lower threshold for canopy/leaf expansion	0.45	E
	P_upper threshold for stomatal closer	0.55	E
	Shape factor for stomatal closure	0.2	E
	P_upper for pollination	0.65	E
	P_upper threshold for canopy senescense	0.5	
	Shape factor for stress coefficient for canopy senescense	0.4	E
	Maximum effective rooting depth, m	0.60	F
	Shape factor for root expansion (-)	1.7	E
	Maximum evapotranspiration crop coefficient (Kc)	1.1	F
	Decline in crop coefficient as a result of ageing (% per day)	0.01	E
	Time to reach full canopy (d)	54	F
	Time to reach maximum root depth (d)	67	F
	Time to reach senescence (d)	87	E
	Base temperature (0C)	5	L
	Cut-off temperature (0C)	35	L
Production	Normalized crop water productivity – before anthesis (WP), g.m-2	16	E
	Normalized crop water productivity – after anthesis (as of % WP)	30	E
	Harvest index (%)	35	F
Soil & Management parameter	Soil water content at saturation (% vol)	49	F
	Field capacity(FC) (% vol)	45	F
	Permanent wilting point (PWP) (% vol)	19	F
	Ksat (mm/d)	150	L
	Height of soil bund (m)	0.15	F
	Effect of mulches on reduction of soil evaporation (%)	0 (No mulch)	F

* F= Field observed/measured data; E= calibrated; L= comparing with the literature, adapted for the crop cultivar and/or local condition (soil/climatic).

Validation/evaluation of AquaCrop

The simulated grain yield and biomass (for the year 2003-04 and 2004-05) are depicted in Fig.3(a) and 3(b). The data points except the simulated output for extreme water-deficit treatments (no irrigation, and only one irrigation) are close to the 1:1 line, which indicates reasonable prediction of grain and biomass yield.

The statistical indicators of the simulation outputs are summarized in Table 4. The positive and negative values in mean bias and relative error indicate error in positive direction (increasing trend) and negative direction (decreasing trend), respectively. Mean error, mean absolute error, root mean square error, and relative error are reasonable, which indicate that the model can simulate yield with acceptable accuracy.

Table 4. Statistical indicators for model performance

Statistical/ performance indicators*	Grain yield		Biomass yield	
	Year 2003-04	Year 2004-05	Year 2003-04	Year 2004-05
Mean bias (t/ha)	-0.087	0.193	-0.193	0.123
Mean absolute bias (t/ha)	0.175	0.391	0.525	0.371
RMSE (t/ha)	0.240	0.420	0.747	0.413
RE (%)	6.27	12.98	7.39	4.02

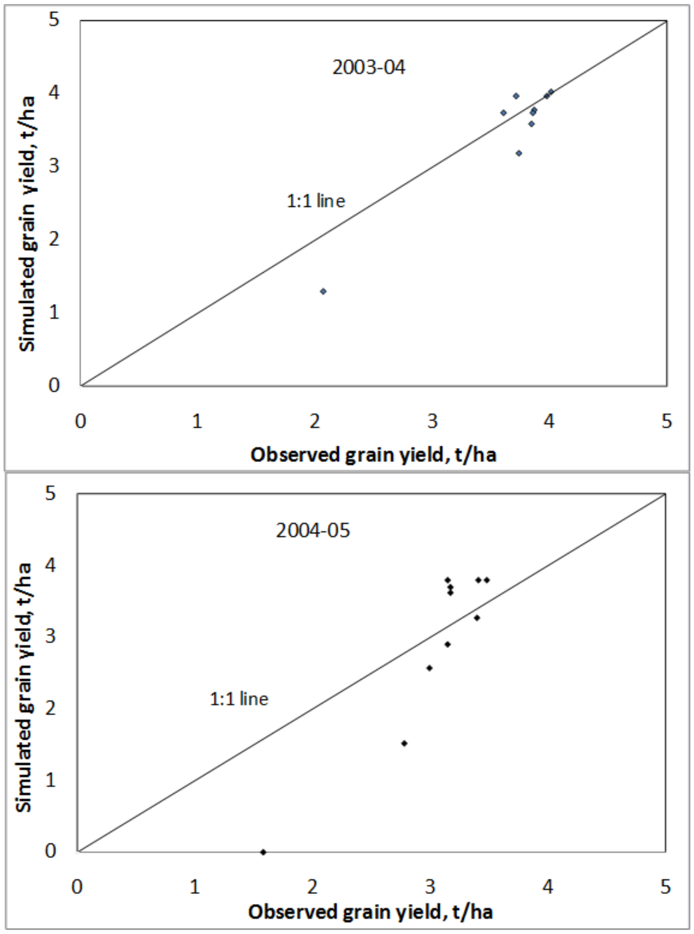

Figure 3. (a) Observed versus simulated grain yield during validation process.

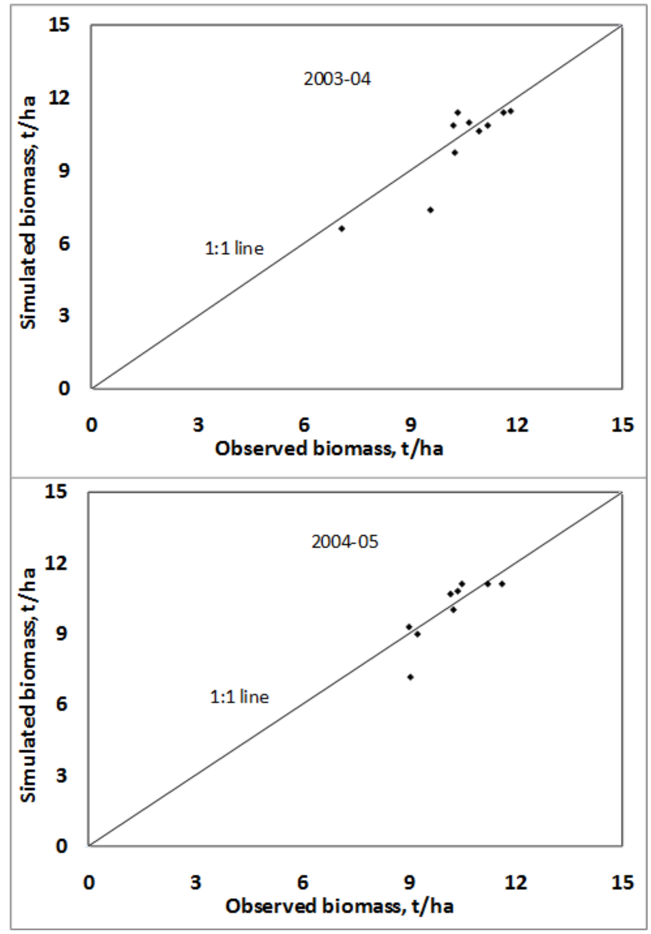

Figure 3. (b) Observed versus simulated biomass during validation process.

Table 5. Simulated yield, water productivity, and water balance* under different simulation treatments/combinations.

DOS	Irri. Sequence	Treatment	Grain yield,t/h	Biomass yield,t/h	Infiltrated water,mm	E, mm	T, mm	WP, Y/ET	WP, Bio/ET
2 irrigation frequency									
Nov.7	S1	T1	3.37	9.89	205.3	87.5	152.9	1.51	4.44
	S2	T2	3.33	9.72	205.3	84.6	151.5	1.53	4.44
Nov.15	S1	T5	3.27	9.59	207.6	79.6	165.1	1.39	4.07
	S2	T6	3.24	9.43	207.6	76.1	164.9	1.40	4.07
Nov.23	S1	T9	3.12	9.31	207.7	76.1	172.6	1.32	3.90
	S2	T10	3.11	9.11	207.7	72.6	171.9	1.33	3.88
3 irrigation frequency									
Nov.7	S3	T3	3.78	10.88	255.3	87.3	170.0	1.57	4.53
	S4	T4	3.74	10.71	255.3	84.5	168.5	1.59	4.55
Nov.15	S3	T7	3.70	10.66	257.6	79.3	185.7	1.45	4.17
	S4	T8	3.65	10.46	257.6	76.0	184.7	1.45	4.16
Nov.23	S3	T11	3.56	10.28	257.7	75.9	193.3	1.37	3.96
	S4	T12	3.52	10.10	257.7	72.4	192.9	1.37	3.95

Note: DOS = date of sowing; Infiltrated water = irrigation + rainfall; E = evaporation; T = transpiration; WP = water productivity (expressed in Kg/m^3); Y=grain yield; ET= evapotranspiration; Bio = biomass

* No drainage from the treatments.

Simulation results under different perspectives

Simulated grain & biomass yield, water-balance components, and the water productivity (WP) are summarized in Table 5. The results showed that the simulated yield and the WP are affected by the irrigation frequency (2 or 3 nos), sequence/timing of irrigation (at normal/recommended days or 7 days shifting from normal), and the sowing dates (7, 15 or 23 Nov.).

Comparison within 2 irrigation frequencies

Within the two irrigation frequency combinations, the irrigation sequence/timing S1 produced higher grain and biomass yield compared to sequence S2 in all sowing dates. The November 7 sowing (SD1) produced the highest followed by November 15 sowing (SD2), and the November 23 the lowest.

Comparison within 3 irrigation frequencies

Within the three irrigation frequency combinations, similar trends of those of the two frequencies are also observed. Within a particular irrigation frequency, the difference between the effects of sequences of irrigation is small.

Sowing dates

In different sowing dates, the simulated grain & biomass yield and the WP were affected differently. For both irrigation frequencies, the Nov.7 sowing performed the best and the Nov.23 sowing the worst. This may be due to the shortening of growing period and heat stress at the later stage (Figure 1). A shortening in growing cycle can reduce the potential time for biomass accumulation.

The differences among simulated yields under different scenarios/treatments (combination of irrigation frequency, irrigation sequence, and sowing dates) are small, which may be due to combined effect (or interactions) of temperature or heat stress, solar radiation, rainfall (generated due to variation of sowing date), differential effect of water stress and consequent osmotic adjustment or adaptation (generated from irrigation sequence), and irrigation amount (generated from different frequency).

Water balance

In case of water balance components, transpiration (T) is more affected by irrigation frequency compared to evaporation (E). Within a particular irrigation frequency (2 or 3), the amount of transpiration increases with the late sowing dates (SD1 to SD3) coupled with decreases of evaporation. This may be due to the higher temperature at the later part of the wheat growing period (Fig.1.). Within the two sequences, the T & E varied a little. The water productivity of grain yield (Y/ET, kg/m^3 of water) and biomass yield followed the similar trend of grain yield and biomass yield, respectively (because of direct functional relationship with WP).

The amount of irrigation water under the simulated treatments and the corresponding irrigation water productivity (IWP) are presented in Table 6. The IWP shows similar trend as that of WP (based on ET). The IWP of 2 irrigation frequency combinations is higher than those of 3 irrigation frequencies (for all cases).

Table 6. Irrigation amount and irrigation water productivity (IWP) under different simulation treatments/combinations.

Date of sowing	Irrigation sequence	Treat-ment	Grain yield(t/h)	Irrigation amount(mm)	IWP
2 irrigation frequency					
Nov.7	S1	T1	3.37	100	33.70
	S2	T2	3.34	100	33.37
Nov.15	S1	T5	3.27	100	32.72
	S2	T6	3.24	100	32.38
Nov.23	S1	T9	3.16	100	31.58
	S2	T10	3.11	100	31.14
3 irrigation frequency					
Nov.7	S3	T3	3.78	150	25.17
	S4	T4	3.74	150	24.94
Nov.15	S3	T7	3.70	150	24.67
	S4	T8	3.65	150	24.33
Nov.23	S3	T11	3.56	150	23.71
	S4	T12	3.52	150	23.44

Discussion

During simulation, initial soil moisture at upper 3 layers (0.30 m each) was taken as 35%, 36%, and 38% (by volume), respectively (i.e. favored soil moisture, close to field capacity – 45%). In practice, if the soil moisture is low (e.g. <28%), post-sowing irrigation may be needed for proper germination and/or crop establishment.

The simulation study demonstrates that "2 irrigation frequency" is the most water-efficient schedule for wheat under the prevailing climatic and soil conditions (Table 4, 5). Among the sowing dates, the Nov.23

sowing produced the lowest yield for all irrigation frequencies and sequences. Among the sequences, the sequence S1 for 2 frequencies and sequence S2 for 3 frequencies performed better. So, these two sequences should be used, depending on 2 or 3 irrigation frequency, along with Nov.7 sowing is the first preference and Nov.15 sowing is the second preference.

The time of sowing of wheat seed depends on the freeness/ availability of the land from previous crop, soil moisture status or irrigation water availability, and the availability of the farm resources (such as labour, farm machinery, seed, etc.). Based on the availability of the resource, the farmers have to decide regarding sowing date or irrigation frequency or sequence. Thus, the results of the present study will help to formulate management plan for higher yield and water efficiency.

Summary and Conclusion

The FAO model "AquaCrop" was calibrated by matching observed yield and biomass data, and then validated with independent data sets. Subsequently, the calibrated model was used to simulate grain yield for different sowing dates, irrigation frequencies, and irrigation sequences with a view to develop appropriate irrigation management strategy for wheat. The simulation study shows a clear decreasing yield trend for winter wheat under late sowing. 'Two irrigation frequency' demonstrates water-efficient production, and the normal/recommended irrigation sequence performed better than the alternate sequence. The results will help to select appropriate irrigation management option for the prevailing conditions of weather and farm resources.

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References

Ali M.H., 2008. Deficit irrigation for wheat cultivation under limited water supply condition. PhD Dissertation, Dept. of Irrigation & Water Management, Bangladesh Agricultural University, Mymensingh, Bangladesh.

Ali M. H., Hoque M.R., Hassan A. A., Khair M.A., 2007. Effects of deficit irrigation on wheat yield, water productivity and economic return. Agric. Water Manage. 92, 151- 161.

Andarziana B., Bannayanb M., Steduto P., Mazraeha H., Baratid M.E., Baratie M.A., Rahnama A., 2011. Validation and testing of the AquaCrop model under full and deficit irrigated wheat production in Iran. Agric. Water Manage. 100, 1-8.

Araya A., Habtub S., Hadguc K. M., Kebedea A., Dejened T., 2010. Test of AquaCrop model in simulating biomass and yield of water deficient and irrigated barley (Hordeumvulgare). Agric. Water Manage. 97, 1838–1846.

Araya A., Keesstra S.D., Stroosnijder L., 2010. Simulating yield response to water of Teff (Eragrostistef) with FAO's AquaCrop.model. Field Crops Res. 116, 196–204.

Farahani H.J., Izzi G., Oweis T.Y., 2009. Parameterization and evaluation of the AquaCrop model for full and deficit irrigated cotton. Agron. J. 101(3), 469-476.

García-Vila M., Fereres E., Mateos L. , Orgaz F., Steduto P., 2009. Deficit Irrigation Optimization of Cotton with AquaCrop.Agron. J. 101(3), 478-487.

Geerts S., Raes D., Garcia M., Miranda R., Cusicanqui J. A., Taboada C., Mendoza J., Huanca R., Mamani A., Condori O., Mamani J., Morales B., Osco V., Steduto P., 2009. Simulating Yield Response of Quinoa to Water Availability with AquaCrop. Agron. J. 101(3), 499-508.

Gurria A., 2009. Sustainably managing water: challenges and responses. Water International, 34(4), 396-401.

Heng L. K. , Hsiao T., Evett S., Howell T., Steduto P., 2010. Validating the FAO AquaCrop Model for Irrigated and Water Deficient Field Maize. Agron. J. 101(3), 488-498.

Hsiao T.C., Heng L.K., Steduto P., Rojas-Lara B., Raes D., Fereres E., 2009. AquaCrop - The FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. Agron.J. 101(3), 101- 448.

Loague K., Green R. E., 1991. Statistical and graphical methods for evaluating solute transport models: Overview and application. J. Contam. Hydrol. 7, 51-73.

Nuttonson, M.Y., 1955.Wheat climate relationship and use of phenology in ascertaining the thermal and photothermal requirements of wheat.American Institute of crop ecology, Washington DC, pp. 388.

Patel N., Kumar P., Singh N., 2010. Performance evaluation of AquaCrop in simulating potato yield under varying water availability conditions.www.rid.go.th/thaicid/_6_activity/Technical-Session/Subthem2/2.16-Neelam-p-P_kumar-Neetu_S.pdf, accessed on 23/12/2010.

Raes D., Steduto P., Hsiao T.C., Fereres E., 2010. AquaCrop, Version 3.1 – Reference Manual, FAO, Land and Water Division, Rome, Italy.

Steduto P., Hsiao T.C. , Raes D., Fereres E., 2009. AquaCrop - The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agron. J. 101(3), 101- 426.