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Development and Evaluation of Irrigation Management Strategies for Higher Yield and Water Productivity of Wheat: A Simulation Modelling Approach

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Abstract: In the present study, CERES-wheat model was calibrated and validated for predicting growth and yield of wheat by using three years of experimental data (2016-17, 2017-18 and 2019-20) under different irrigation treatments. Further the model was run with twenty years of weather data (2000-01 to 2019-20) with optimum management practices under different irrigation scenarios for developing the irrigation management strategies for obtaining higher grain yield and irrigation water productivity (IWP) under dry, wet and normal rainfall conditions. The results indicated that the model slightly overestimated the maximum leaf area index (LAI) and consequently the grain yield in water stress condition; however, overall, model could excellently simulate anthesis and maturity with RMSE<4 days, RMSEn<10% and d>0.90, as well as grain yield (RMSE= 163-204 kg/ha, RMSEn =3-6%, d = 0.93-0.98) for three, four and five irrigations from CRI to jointing, CRI to anthesis and CRI to dough stage, respectively. The IWP was increased with the decrease in number of irrigations. The maximum yield was obtained when the four irrigations applied from CRI to Anthesis under all-weather years (Dry, wet and normal), but it was as par with the three irrigations applied at CRI, Tillering and Jointing or CRI, Tillering and Anthesis stage for wet years. Under three irrigations scenario the maximum yield of 5050-5302 kg/ha and irrigation water productivity (IWP) of 33.7-35.3 kg/ha-mm was noticed when three irrigations applied at CRI, Tillering and Jointing followed by at CRI, Tillering, Anthesis stage and CRI, Jointing and Anthesis stage and under wet year no difference was noticed in yield and IWP whether three irrigations were applied at CRI, Tillering and Jointing or CRI, Tillering and Anthesis stage and under two irrigations scenario, the maximum grain yield as well as IWP was obtained when applied at CRI and Tillering followed by CRI and Jointing stage.

Keywords: Wheat, CERES-wheat, Irrigations, Grain yield, Irrigation water productivity (IWP)

Wheat is one of the major cereal crops in India which plays a very important role for national and global food security. In semi-arid and arid regions where water is the main constraint for the growth and yield of wheat, deficit irrigation at certain specific growth stages can reduce the adverse effects of water stress without compromising the yield (Sun et al 2006). This will also improve the irrigation water productivity (WP) as well as the overall productivity of crop (Attia et al 2016). Deficit irrigation is defined as the application of irrigation water less than the full ET requirement of the crop. Therefore, determining the critical growth stages based on climatic conditions for applying the limited water available for irrigation is important to reduce the impact of water stress on growth and yield of wheat crop. In the fields, however, conducting long term experiments and testing different management scenarios is difficult because it is time consuming and also labour intensive process. CERES-wheat model is very robust in simulating the critical phenological growth stages and yield of different cultivars of wheat under different crop management and environmental conditions (Mahdi and Mizanul 2018, Koushik and Mahdi 2019). The irrigation management strategies (such as amount, depth and frequency) under different soils, climates and management conditions can be developed by using the well calibrated and validated crop model (Chen et al 2018) to obtain higher irrigation water productivity (IWP) and optimum grain yield (Abd El Baki et al 2018).

The objectives of the current research were to: calibrate and validate a CERES-Wheat model for simulating grain yield and phenology of wheat under different levels of irrigation and sowing date and evaluate irrigation management strategies for obtaining higher yield and water productivity.

MATERIAL AND METHODS

Experimental details and data collection*:* Field experiments were conducted during *Rabi* season of 2016-17 and 2017-18, 2019-20 on a sandy loam soil at the research farm of Water Technology Centre, ICAR-Indian Agricultural Research Institute (IARI), New Delhi (28°38'23" N, 77°09'27" E). Wheat cultivar HD-2967 was sown on a split plot design under three sowing dates as the main plot treatments and 5 irrigation regimes levels as subplot treatments within each main plot. The dates of sowing were: D_1-15th November, D_2 –30th November and D_3 –15th December. The irrigation regimes were: I_1 –CRI, I_2 –CRI and TL, I_3 –CRI, TL and JO, I_4–CRI, TL, JO and FL, I_5– CRI, TL, JO, FL and DS (CRI=Crown Root Initiation, TL- Tillering, JO-Jointing, FL-Flowering and DS- Dough Stage). The recommended dose of Nitrogen (N), phosphorus (P) and potassium (K) were applied at the rate of 120, 60 and 40 kg ha^{-1}. Total dose of P and K and half dose of N were applied as basal doses and remaining N doses were top dressed at tillering and booting stages in equal amounts.

Crop growth and yield attributes such as phenological stages, tillers/m^2, plant population, dry matter partitioning, biomass, grain yield etc. were collected following the standard procedures and methods. Leaf area index (LAI) at different growth stages were measured by using Canopy Analyser (LP-80). The profile wise data of soil parameters required for the model were taken from Ajdary et al (2007). The weather parameters *viz.* daily solar radiation, maximum and minimum air temperature, and rainfall during the growing seasons were taken from the agro meteorological observatory of ICAR-IARI, New Delhi.

DSSAT CERES-Wheat: The DSSAT CERES-Wheat model (Jones et al 2003) is radiation use efficiency (RUE) based model which simulates growth, development and yield of the crop; based on light interception and environmental stresses; soil water balance; and soil N balance. The model describes the progress through the crop life cycle using degree-day accumulation. Input requirements for CERES-Wheat include site information (e.g. latitude, longitude, elevation etc), daily weather (e.g. solar radiation, maximum and minimum air temperature and rainfall), soil conditions (physical and chemical characteristics of soil profile), plant characteristics, and crop management (e.g. sowing date, depth and method; plant population; irrigation and fertilizer management, dates, method, depth and amount; tillage; harvest schedule etc.).

Calibration and validation of model: The growth and yield data of wheat crop collected during *Rabi* season of the year 2016-17 from the treatment combination of 15th November sowing date and full irrigation (5 irrigations) were used for model calibration. Treatment with full irrigation and optimum sowing time could meet the ET demand throughout the growing season without any shortage of water. Other information used for calibration were daily weather parameters, soil and crop management data. From model calibration process, the genetic coefficients of the wheat cultivar HD 2967 were derived using the Generalised Likelihood Uncertainty Estimator (GLUE) coefficients estimator module of DSSAT 4.6. An iterative approach was used to obtain reasonable genetic coefficients through trial-and-error procedure until the simulated and measured values matched or was within predefined error limits. The calibrated model was validated by using the independent data set of remaining treatments of *Rabi* season of the year 2016-17 and all treatments data of *Rabi* season of the year 2017-18. Thereafter the model performance was also evaluated using independent data set of 2019-20. The model performance was assessed by using normalised root mean square error (RMSEn) and index of agreement (d) (Wilmot 1982) between the observed and simulated values of growth and yield parameters by using the following equation:

$$RMSE_n = \frac{RMSE \times 100}{\overline{O}}$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{\sum_{i=1}^{n} (\left|S_i^{'}\right| + O_i^{'})^2} \right], 0 \leq d \leq 1$$

Where, *n*= number of observations, *Si*= simulated value for the ith measurement, *Oi*=observed value for the *i*th measurement, O= the overall mean of observed values, $S_i^{'} = S_i - \overline{O}, O_i^{'} = O_i - \overline{O}$ and RMSE=root mean square error which is calculated using the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n}}$$

A high value for the Wilmot's *d*-index approaching one and a low value for RMSEn approaching zero indicate a good fit between the simulated and observed values. According to Liu et al (2013), d values < 0.70, 0.71 – 0.80, 0.81 – 0.90 and > 0.91 indicated poor, moderate, good, and excellent agreements, respectively. According to Soler et al (2007), RMSEn values < 10%, 10 – 20%, 20 – 30%, and > 30% indicate good, moderate, fair, and poor performance, respectively.

Model simulation setup and irrigation scenarios*:* Simulations were carried out using 20 years (2000/2001–2019/2020) of historical weather data from ICAR-IARI, New Delhi with 15th November sowing date, which is the optimum sowing date for the variety HD-2967 (Bisht et al 2019). Three irrigation scenarios were generated for development of irrigation strategies based on the availability of irrigation water or number of irrigations at different stages (Table 1). It includes four irrigations applied at [CRI (C)+Tillering (T) +Jointing (J) +Anthesis (A)]; three irrigations applied at [CRI (C)+Tillering (T) +Jointing (J), CRI (C)+Tillering (T) +Anthesis (A) and CRI (C)+ Jointing (J) +Anthesis (A)] and two irrigations at [CRI (C)+Tillering (T), CRI (C)+Jointing (J) and CRI (C)+Anthesis (A)}. The yield and water productivity were compared under three irrigation scenarios and based on the analysis the best irrigation management strategies were developed for wheat. The irrigation water productivity (IWP) was calculated by using the following formula:

$$IWP\ (kg/ha\text{-}mm) = \frac{Grain\ Yield\ (GY)\ (kg/ha)}{Total\ Irrigation\ applied\ (I)\ (mm)}$$

RESULTS AND DISCUSSION

Calibration of CERES-Wheat model: The seven genetic coefficients *viz.* P1V, PID, P5, G1, G2, G3 and PHINT of wheat cultivar HD 2967 were derived by GLUE estimator (Table 2). The models provided very satisfactory estimates for the germination, anthesis, physiological maturing date, yield and biomass and LAI. Calibrated results are presented in Table 3.

Validation of CERES-Wheat Model

Anthesis date and physiological maturity: Statistical indices derived for evaluating the performance of CERES-Wheat model in simulating the days to anthesis (DAS), days to physiological maturity (DAS), maximum leaf area index (LAI) and grain yield (kg/ha) are presented in Table 4. The maximum number of days to anthesis as well as physiological maturity were observed with five irrigations (I_5) and the minimum number of days were observed for reduced irrigation frequency as it was found in I_1 (when irrigation was applied at CRI stage only). CERES-wheat model also showed an overestimation in respect of phenology of wheat. The statistical results for evaluation of anthesis and physiological maturity dates were excellent with a RMSE less than 4 days for I_3, I_4 and I_5 with d value >0.90. Dar et al (2017). Malik and Dechmi (2019) reported RMSE values lower than 4 days in terms of the time to anthesis and physiological maturity. However moderate agreements were observed under lower irrigation regimes *i.e.,* one and two irrigation levels with d value ranged from 0.71 to 0.73. Moreover, the deviation percentage between observed and simulated value was observed to be higher in moisture stressed conditions, while, least variation was found with five irrigations (I_5).

Maximum LAI and Grain Yield: The higher value of maximum LAI (5.3 to 5.4) was observed for non-stressed conditions while the lower values were observed under water stressed conditions. The grain yield increased with increase in number of irrigations from I_1 (irrigation at CRI only) to I_5 (irrigation from CRI to dough stage). Although there was an increase in grain yield with increase in irrigation, irrigation

Table 3. Calibration results for CERES-wheat

Parameters	Simulated	Observed
Anthesis date (DAS)	109	109
Physiological maturity date (DAS)	145	144
Grain yield (kg ha^{-1})	5086	5033
Biomass at harvest (kg ha^{-1})	15894	17795
Maximum LAI (m^2/m^2)	5.5	5.8

Table 1. Different irrigation scenarios

Irrigation scenario	No of available irrigations	Stages	Irrigation amount (mm)
1	4	CRI (C)+Tillering (T) +Jointing (J) +Anthesis (A)	200 (50 mm at each stage)
2	3	CRI (C)+Tillering (T) +Jointing (J)	150 (50 mm at each stage)
		CRI (C)+Tillering (T) +Anthesis (A)	150 (50 mm at each stage)
		CRI (C)+ Jointing (J) +Anthesis (A)	150 (50 mm at each stage)
3	2	CRI (C)+Tillering (T)	100 (50mm at each stage)
		CRI (C)+Jointing (J)	100 (50 mm at each stage)
		CRI (C)+Anthesis (A)	100 (50 mm at each stage)

Table 2. Genetic crop coefficients fitted for wheat cultivar HD 2967

Parameters	Description	Calculated values
P1V	Days at optimum vernalizing temperature required to complete vernalization	11.9
P1D	Percentage reduction in development rate in a photoperiod 10 h shorter than the optimum relative that optimum	94.26
P5	Grain filling (excluding lag) period duration (GDD)	520.9
G1	Kernel number per unit canopy weight at anthesis (g1)	16.45
G2	Standard kernel size under optimum condition (mg)	39.95
G3	Standard non-stressed dry weight (total, including grain) of a single tiller at maturity (g)	1.82
PHINT	Phyllochron interval (GDD)	95.78

beyond I_4 did not increase the maximum LAI and grain yield significantly (Table 4). The model overestimated the maximum LAI for stressed treatment with normalised RMSE (RMSEn) value of >20% and index of agreement of <0.7 between the measured and simulated value. However, moderate value was found for non-stressed treatment with RMSEn value between 10-20%. There was strong agreement between the simulated and observed grain yield (kg/ha) for I_3(RMSE=204 kg/ha, RMSEn =6.3% and d=0.93), I_4(RMSE= 239.2 kg/ha, RMSEn =5.41% and d= 0.97) and I_5 (RMSE=162.9 kg/ha, RMSEn= 3.47% and d=0.98). Malik and Dechmi, (2019) reported that the DSSAT model performed well in simulating grain yield with the RMSE less than 587 kg ha^{-1}and d-statistic higher than 0.7. However relatively moderate agreement was noticed for I_1 and I_2 with RMSEn value of 19.8% and 18.9%, respectively and d value of 0.70 and 0.77, respectively (Table 4). Mehrabi and Sepaskhah (2019) also reported the model overestimated slightly the maximum leaf area index (LAI) and consequently biomass and yield in water stress condition.

Evaluation of limited irrigation strategies to improve grain yield and IWP of wheat: Model was run using Weather data from 2000-2019 with optimum sowing date (S1) under different irrigation scenarios. Percentage of deviation in average rainfall above 19% was considered as wet year, between -19% and 19% as normal year, and below -19% as dry year (as per IMD criteria). Rainfall analysis indicated that among twenty years, nine years were dry, seven years were wet and four years were normal. The, the maximum yield was obtained under four irrigations scenarios i.e. when irrigation was applied at four stages namely, CRI (C), Tillering (T), Jointing (J) and Anthesis (A). But the irrigation water productivity (IWP) was lowest in this scenario (Table 5). Wang et al. (2012) also reported that IWP decreased in non-

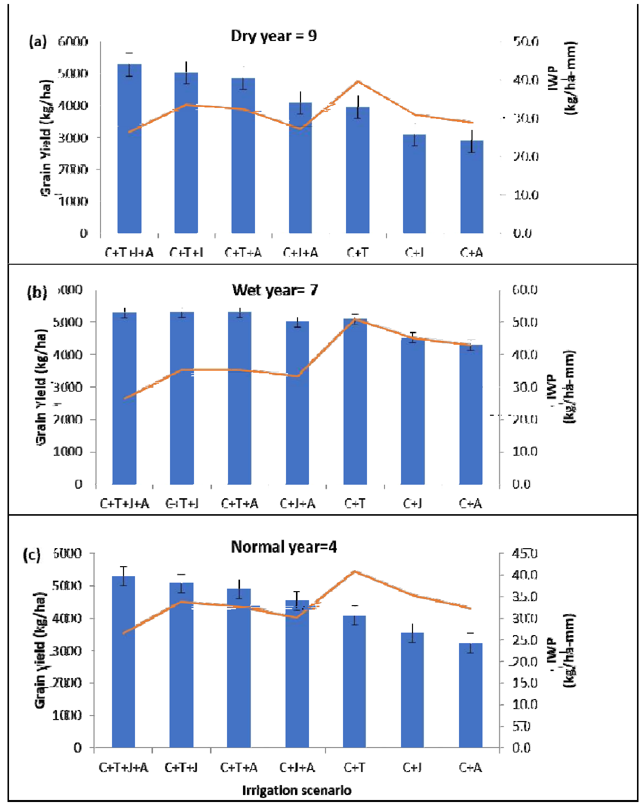

Fig. 1. Grain yield and water productivity of wheat for (a) dry year (b) wet year and (c) normal year under different irrigation scenarios

Table 4. Statistical indices derived forevaluation of CERES-wheat model for predicting the days to anthesis (DAS), days to physiological maturity (DAS), Maximum (LAI) and grain yield (kg/ha) of wheat cultivar HD-2967 (n=9)

Treatments	Anthesis (DAS)					Physiological maturity (DAS)				
	O_{mean}	S_{mean}	RMSE	RMSEn (%)	d	O_{mean}	S_{mean}	RMSE	RMSEn (%)	d
I_1	90.9	97.9	7.19	7.95	0.72	116.50	126.85	11.13	9.56	0.73
I_2	91.2	98.2	7.38	8.10	0.71	116.50	127.50	11.19	9.56	0.72
I_3	99.0	101.9	3.21	3.27	0.96	120.85	125.15	4.43	3.68	0.95
I_4	101.2	103.7	2.45	2.45	0.97	124.00	127.50	3.46	2.79	0.97
I_5	101.4	103.2	2.08	2.06	0.98	124.85	127.65	3.05	2.45	0.98
	Maximum LAI					Grain Yield (kg ha^{-1})				
Treatments	O_{mean}	S_{mean}	RMSE	RMSEn (%)	d	O_{mean}	S_{mean}	RMSE	RMSEn (%)	d
I_1	2.9	3.8	0.85	29.44	0.52	2034.8	2470.5	451.3	19.80	0.70
I_2	3.2	4.0	0.82	25.27	0.60	2142.9	2594.5	466.2	18.85	0.77
I_3	4.4	4.8	0.63	14.75	0.68	3525.1	3663.5	204.0	6.30	0.93
I_4	5.4	6.0	0.66	12.22	0.76	4473.8	4660.9	239.2	5.41	0.97
I_5	5.3	5.9	0.63	10.98	0.80	4692.6	4798.9	162.9	3.47	0.98

S_{mean}: mean of simulated value, O_{mean}: mean of observed value, n: number of observations, LAI: Leaf Area Index, RMSE: root mean square error, RMSEn (%): normalized root means square error, d: Wilmot's index of agreement.Irrigation treatments: I_1: CRI, I_2: I_1+ Tillering, I_3: I_2+Jointing, I_4: I_3+Anthesis, I_5: I_4+Dough

Table 5. Grain yield (kg ha^{-1}) and irrigation water productivity (IWP) (kg ha^{-1} mm) under different irrigation scenarios

Irrigation	Dry years (9)		Wet year (7)		Normal year (4)	
	Grain yield (kg ha^{-1})	I WP (Kg ha^{-1} mm)	Grain yield (kg ha^{-1})	I WP (Kg ha^{-1} mm)	Grain yield (kg ha^{-1})	I WP (Kg ha^{-1} mm)
C+T+J+A	5288	26.4	5302	26.5	5295	26.5
C+T+J	5050	33.7	5302	35.3	5074	33.8
C+T+A	4878	32.5	5302	35.3	4909	32.7
C+J+A	4100	27.3	5015	33.4	4539	30.3
C+T	3968	39.7	5102	51.0	4091	40.9
C+J	3100	31.0	4515	45.1	3539	35.4
C+A	2891	28.9	4300	43.0	3229	32.3

stressed condition in wheat as compared to mild-stressed because the available soil water during stress conditions was used more effectively as compared to non-stressed conditions. The three irrigations scenario (CRI + Tillering + Jointing) reported the maximum grain yield of 5050 and 5074 kg/ha for dry and normal year conditions, respectively. Similarly, water productivity of 33.7 and 33.8 kg/ha-mm for dry and normal year conditions, respectively was obtained when three irrigations were applied at CRI (C)+ Tillering (T)+ Jointing (J) stage followed by at CRI (C)+Tillering (T)+Anthesis (A) stage and CRI(C)+ Jointing (J)+Anthesis (A) stage. Whereas under wet year there was no difference in grain yield and IWP noticed whether three irrigations applied at CRI (C)+ Tillering (T)+ Jointing (J) stage or CRI (C)+Tillering (T)+Anthesis (A) stage. Grain yield with three irrigations (applied at CRI, tillering and jointing stage or at CRI, tillering and anthesis stage) was similar to that with irrigations at all four stages, during wet years. Under two irrigations scenarios the maximum grain yield as well as IWP was obtained when applied at CRI (C)+ Tillering (T) followed by CRI(C)+Jointing (J) for all the dry, wet and normal year. The minimum grain yield and water productivity was obtained when two irrigations were applied at CRI (C)+Anthesis (A) stage.

CONCLUSION

This study concluded that the model overestimated slightly the maximum leaf area index (LAI) and consequently the grain yield in water stress condition; however, overall, model could excellently simulate anthesis and maturity as well as grain yield. . The study indicates that with the increase in frequency of irrigation the IWP decreased. Under three irrigations scenario the maximum grain yield and IWP was observed when three irrigations applied at CRI, tillering and jointing followed by at CRI, Tillering, anthesis stage for dry and normal years, whereas grain yield and IWP were at par at this stage. In two irrigations scenario, the maximum grain yield as well as IWP was when irrigation applied at CRI and tillering followed by CRI and jointing stage. This study could guide the farmers and agronomists on best and efficient irrigation management in order to achieve the better yield and improve the irrigation use efficiency.

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