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ORIGINAL PAPER

Modelling climate smart rice-wheat production system in the middle Gangetic plains of India

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Abstract
A simulation study based on water balance approach and field experimentation with rice-wheat cropping system was carried out by employing daily rainfall and evaporation (2002–2016) and edaphic data of Experimental Farm of the university, Pusa (25.98°N, 85.67°E, 52 m amsl), Bihar, situated under middle Indo-Gangetic Plains. The aims of the study were to optimize transplanting dates and assess irrigation requirement and water productivity of rice with a view to achieve climate smart rice-wheat production system. The suitability of advancing wheat planting under this cropping system was also evaluated for escaping terminal heat stress during reproductive to maturity period. Under rice-wheat system, late transplanting of rice during *kharif* season (monsoon season, synonymously also called as wet season) and, consequently, late planting of wheat during *rabi* (winter) season tend to reduce grain yield significantly under a set of adverse environmental conditions during flowering to maturity phases of both the crops. The study revealed that rice crop of 150-day duration (seed to seed) could be successfully transplanted early in the *kharif* season during 20–30 June and be harvested by 25 October–5 November with the use of average 404–425-mm irrigation water to achieve potential yield and higher water productivity (1.648–1.731 kg m^{-3} ha^{-1}). Early rice harvesting ensured early completion of wheat planting before 15 November, which helped in escaping terminal high-temperature stress during the reproductive phase. Hence, higher system productivity can be achieved by shifting the planting dates of rice and wheat through optimum utilization of natural resource environment (moisture and thermal regimes) and offsetting the negative impacts of erratic monsoon rains on rice growth and terminal heat stress and hailstorm on subsequent wheat crop.

1 Introduction

The rice-wheat cropping system (RWCS) is a very important food production system around the globe, which accounts for securing the food security to more than 20% of the world's population (Memon et al. 2018). It is a vital life-supporting cropping system in India. Rice and wheat form the backbone of food security, accounting for approximately 58% and 77% of the total area and food grain production in the country, respectively (Panwar et al. 2019; Singh 2011). They together share more than 90% of total cereal consumption in India (Panwar et al. 2019). RWCS occupies an area of about 10.5 million hectares spread over Indo-Gangetic Plains spanning from Punjab in the north-west to West Bengal in the east (Bhatt et al. 2015). The sustainability of RWCS has become a major concern with yield stagnation (Bhatt et al. 2015), soil health deterioration (Mondal et al. 2020), declining underground water table (Sidhu et al. 2019), climate change and environmental issues. With changing climate, rice of this cropping system has become vulnerable to erratic monsoon rainfall during its growing (*kharif*) season, while occurrence of high-temperature stress during reproductive phase of wheat is a major constraint. Under such situation, sustainability and productivity enhancement of RWCS is a prime concern to feed the rapidly increasing population of India (Panwar et al. 2019; UNEP 2008).

Rice in RWCS is mainly cultivated under transplanted condition in middle Gangetic plains during monsoon season (June–September) with occasional supplemental irrigation during dry spell. Hand transplanting of rice seedlings after puddling and subsequent flooding is the traditional method of rice cultivation in the Indo-Gangetic Plains (Mohammad

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et al. 2018). A shallow depth of water (3–5 cm) is maintained throughout the growing period up to physiological maturity. With changing climate, monsoon rainfall which is the major source of water for growing *kharif* rice has become uncertain in recent years and has started posing serious challenges for the rice growers. Thus, climate change and declining water resources are threatening the sustainability of rice production and food security (Ishfaq et al. 2020). In such climatic scenario, the sustainability of profitable rice cultivation in the Indo-Gangetic Plains has been a central focus of attention of the researchers and extension workers. In the middle Gangetic plains, transplanting of rice starts usually with the receipt of monsoon rainfall, i.e. from 15 to 20 June (normal time for onset of monsoon) and continues until the end of August. However, with delayed transplanting, the yield of rice tends to decrease significantly, and it also delays the planting schedule of subsequent wheat crop, because of late harvesting of rice. Rice cultivars which mature in 130–150 days and are transplanted during the period from mid-June to first fortnight of July tend to give better yields as compared to crop transplanted on later dates. The yield response of rice to different transplanting dates gets varied with weather conditions at different growth stages as well as occurrence of insect-pest infestation. The shift of transplanting dates also results in a saving of water. Crop water productivity (real and apparent grain yield per unit of water consumed by crop as evapotranspiration and irrigation water applied, respectively) is more in rice transplanted under lower (end of June) than higher evaporative demand (May end) (Chahal et al. 2007). Studies showed that apparent water productivity of rice can be increased by shifting transplanting dates (Jalota et al. 2009).The evapotranspiration in irrigated rice varies from 400 to 800 mm seasonally (Zwart and Bastiaanssen 2004). Although water productivity of rice in terms of evapotranspiration is similar to that of comparable cereals such as wheat, rice requires more water at the field level than other grain crops because of high seepage and percolation losses from the field (Bouman 2009).

In Bihar like all of middle Gangetic plains, major constraint in getting potential yield of rice is late transplanting (Sattar et al. 2017a) due to delay in obtaining ponded condition to facilitate puddling. The reasons for low yields are due to delays in transplanting for farming operations of sowing/transplanting, weeding, irrigation and water management (Saito and Futakuchi 2009). The first condition for obtaining higher productivity is that transplanting should be completed by optimum time, i.e. by 15 July. If medium to long-duration rice of 130–150 days is transplanted in the month of June, it ensures that it could be harvested by the end of October, giving ample time for field preparation and sowing of next wheat crop, which is the main winter crop extensively grown in Indo-Gangetic Plains. Another option is to grow short-duration rice (100–110 days). However, the cultivation of short-duration rice limits the potential productivity below 5 t per hectare. Hence, efforts have been made to prepone the planting of long-duration rice (135–150 days) by utilizing available rain water and supplemental irrigation with various climate smart interventions, viz. 3 hp. single-phase motor pump, tractor-mounted solar pump and solar-operated pump. Irrigation cost is a major contributor to rice production cost, because the cost of pumping water is very high leading to higher operating cost. In middle Gangetic plains, electricity and diesel pumping sets are commonly used for irrigation in rice fields. The cost tends to escalate during the period of frequent dry spell under erratic and bad monsoon rainfall regime. Moreover, farmers of the region mostly rely on traditional knowledge and experiences to irrigate their crops, which lead to application of excess irrigation water to their crops without any consideration of crop, climate and soil. Under the emerging scenario of erratic monsoon and shortages of water, it is imperative that efficient approaches for higher water use in rice are prioritized (Sidhu et al. 2019; Yadvinder et al. 2014).

After the harvest of rice, the sowing of wheat is done by the farmers under both normal (20 November to 5 December) and late conditions (5–31 December). About 80% of wheat sowing is achieved during the period from 20 November to 5 December. Of late, the vulnerability of growing wheat in this region has increased owing to problem of higher temperatures (terminal heat stress) occurring during late (end of February to March) in the growing season (Sattar et al. 2014). According to Joshi et al. (2007), 13.5 million hectares of wheat area in India experiences heat stress. The role of heat stress in limiting the productivity of wheat in India was first highlighted by Howard (1924) in his statement "Wheat growing in India is a gamble in temperature" (Vijaya Kumar et al. 2015). The terminal heat stress associated with dry westerly wind during reproductive phase of wheat creates serious constraint for growth, resulting in non-setting of grains, which creates panic among the farmers and the policy makers alike. It is a serious climatic constraint for successful wheat cultivation in India, particularly when it occurs during grain filling stage (Sandhu et al. 2016). Pre-anthesis and post-anthesis occurrence of high temperatures and heat tend to make significant impact upon growth and photosynthetic efficiency of wheat crop (Wang et al. 2011). Temperature decides the sowing time of wheat and, consequently, the duration of different phenophases, which ultimately affect crop productivity. Thus, planting of crop after appropriate time tends to reduce grain yield due to terminal heat stress occurring during its reproductive period (Sattar et al. 2020). Higher seasonal temperature during flowering and grain filling periods threaten wheat growth and production (Liu et al. 2020; Rashid et al. 2018). The idea behind early planting of wheat is that the crop can be protected from terminal heat stress as well as hailstorm during flowering to maturity stage of the crop.

Therefore, adoptions of climate smart production technologies for RWCS are essential in the wake of changing climate. In view of this, an attempt has been made in this paper (i) to optimize transplanting dates and assess irrigation requirement and water productivity of rice and also (ii) to evaluate the suitability of advancing wheat planting under this cropping system for achieving sustainable and profitable rice-wheat production system in the middle Gangetic plains of India.

2 Materials and methods

2.1 Location and climate of the area

Pusa, Bihar, is located in the middle Gangetic plains of India. The location map of the study area is given in Fig. 1. The region has sub-humid subtropical monsoon climate. About 85% of annual rainfall occurs during monsoon season, synonymously also called as *kharif* season considering different crop growing seasons. The region experiences four seasons, viz. summer (March–May), monsoon (June–September), post monsoon (October–November) and winter (December–February). The average annual rainfall of the area is about 1230 mm. The month-wise rainfall distribution pattern is given in Fig. 2. The rainfall distribution during *kharif* rice growing season at Pusa presented in Figs. 3 and 4 shows that out of 15 years during the simulation period, 11 years experienced drought of varying intensities. May is the warmest summer month of the year with a daily maximum temperature of 37–41 °C, while coldest winter month is January with daily minimum temperature of 5–8 °C. Although December, January and February are main winter months, temperature decreases significantly from November. Average temperature falls appreciably from 26.9 in October to 21.9 °C in November.

2.2 Soils and cropping system

Soils of the area are mainly young alluvium, calcareous and predominantly sandy loam to loam in texture. Soils are deep having calcium carbonate more than 10%. The water holding capacity varies from moderate to high. It has moderate drainage behaviour. There is a wide variation in nitrogen and available potassium status of these soils. Soil pH varies from 6.5 to 8.4. Rice-wheat is the major cropping system of the area and comprises about 60% of all crops and cropping sequences followed in the region.

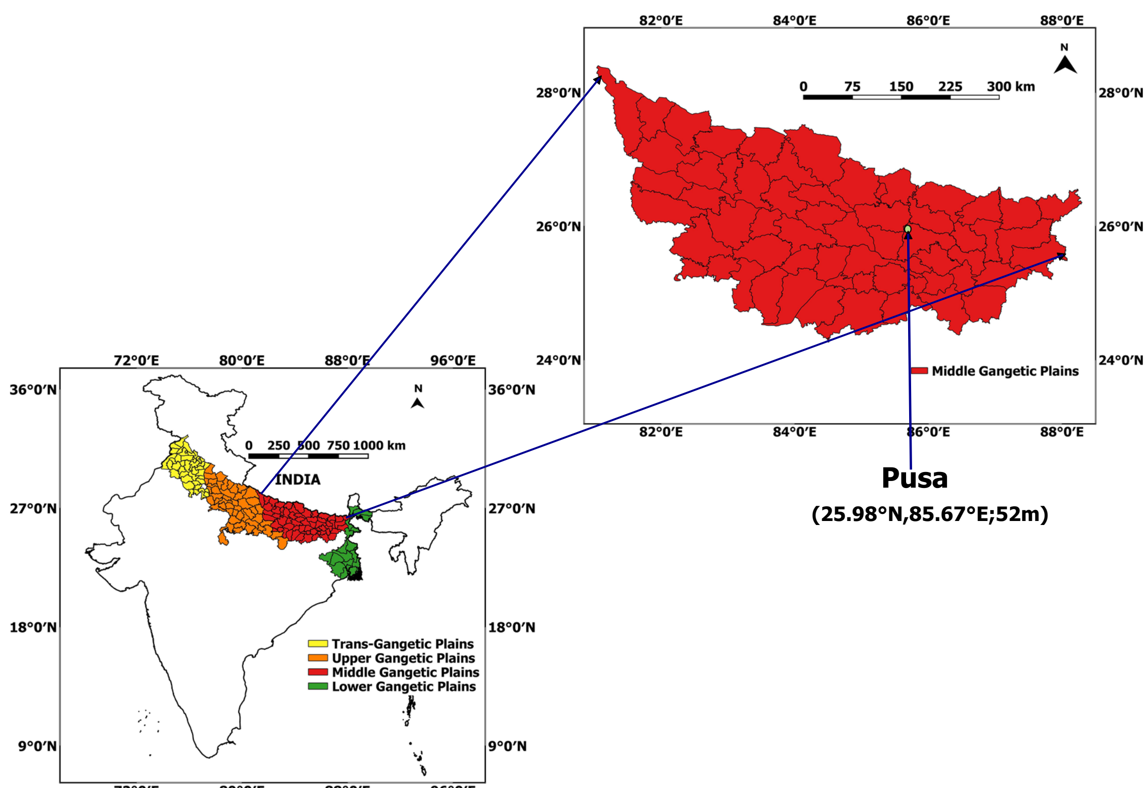


Fig. 1 Location of the study area (Pusa, Bihar, Middle Gangetic Plains)

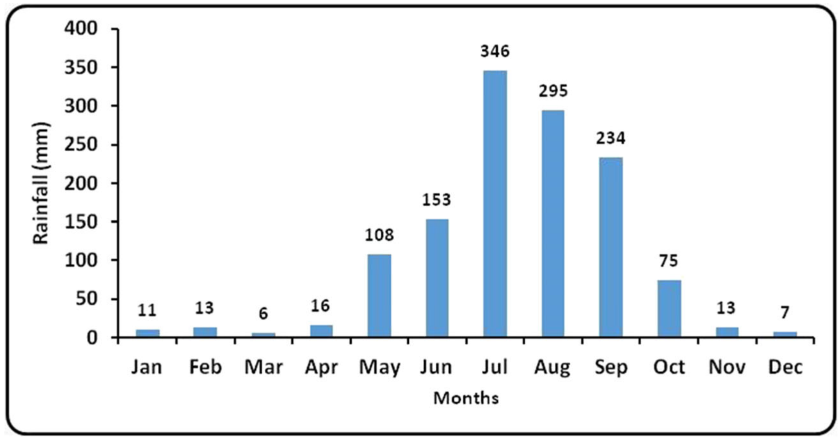


Fig. 2 Distribution pattern of normal monthly rainfall (mm) at Pusa, Bihar (India)

2.3 Formulation and methodologies of simulation

The simulation study related to estimation of irrigation requirement of transplanted *kharif* rice was conducted for loamy soils of the research farm of Dr. Rajendra Prasad Central Agricultural University, Pusa (25.98°N, 85.67°E, 52 m amsl). In this simulation study, rice (varieties *Prabhat*, *Saroj*, *Rajendra Suhasini*, *Rajendra Bhagwati*, *Swarna*) which matures in 110, 120, 130, 135 and 150 days, respectively (seed to seed), has been selected with five transplanting dates starting from 10 June to 10 August at an interval of 10 to 20 days (Table 1). The dates of physiological maturity have been considered 15 days before the date of harvesting. The simulation study has been conducted for the entire growing period of rice transplanted on five different dates, viz. 10 June, 20 June, 30 June, 20 July and 10 August. Total duration of rice has been calculated from 25 days before date of transplanting to date of harvesting as rice seedlings of 25 days old are generally considered suitable for transplanting. The region gets premonsoon showers in May. The normal rainfall of the region for the month of May is about 110 mm. The value of permanent wilting point, field capacity and saturation has been taken as 16, 35 and 50%, respectively, on v/v basis based on actual field observation of paddy soils on research farm. A root zone depth of 75 cm has been considered.

The model has been divided into three phases. First phase of the model deals with pre-transplanting period by factoring soil moisture content 1 day before date of transplanting. Second phase covers the first week after transplanting and irrigation requirement for initial ponding of 5 cm for proper establishment of seedlings. Third phase of the model estimates the irrigation requirement to maintain soil moisture above field capacity for the growing period up to physiological maturity. The simulation starts from the date of puddling for transplanting and continues up to the physiological maturity. In the model simulation, no irrigation was considered during the period from physiological maturity to harvest maturity as this period requires drainage.

The calculation of irrigation requirement for puddling operation for transplanting, for the period 1 week after transplanting and for the period from 1 week of transplanting to physiological maturity, has been done in MS Excel based on the water balance model of Srivastava (2001). In every occasion, 70-mm irrigation was applied when soil moisture

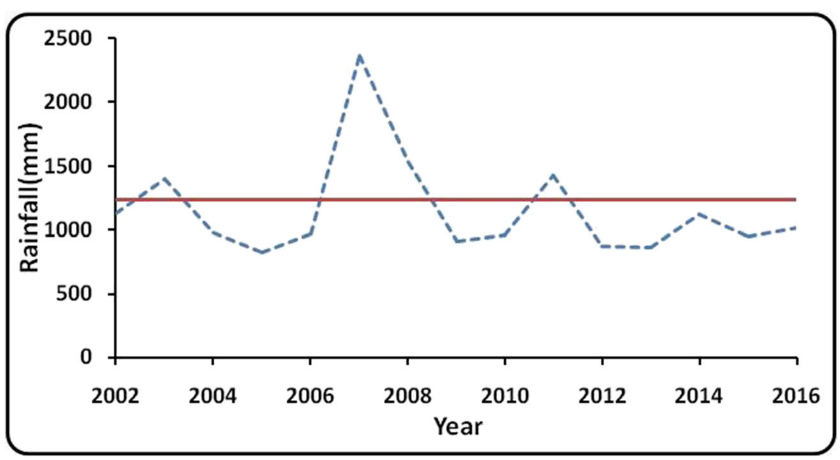


Fig. 3 Variability in annual rainfall (mm) during the simulation period (2002–2016) at Pusa, Bihar (India)

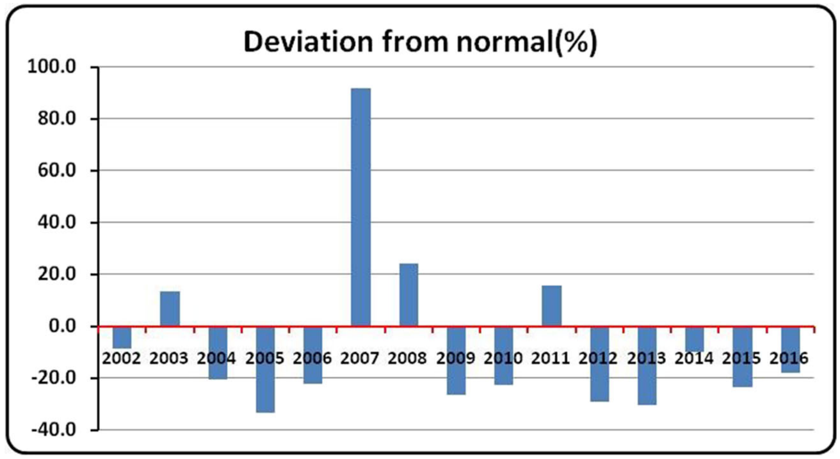


Fig. 4 Anomaly in annual rainfall (mm) from the normal during the simulation period (2002–2016) at Pusa, Bihar (India)

dropped below field capacity. Soil moisture content 1 day before puddling was determined to decide the amount of irrigation required for puddling operation based on equivalent water depth at saturation, accumulated rainfall 5–7 days before transplanting, field capacity, rate of evaporation, permanent wilting point and available water holding capacity. If accumulated rainfall during 5–7 days before puddling exceeds available water holding capacity, soil moisture status on the day of puddling reaches saturation. Hence, no irrigation is required for puddling operation. Crop coefficient, seepage and percolation were taken into account in the model.

2.4 Model for pre-transplanting period

The model for pre-transplanting period is given in Eq.1 and Eq.2.

$$SM_i = SM_{i-1} + P_i - E_i, \text{Subject to SMi} > 0 \quad (1)$$

where P_i and E_i are daily rainfall and evaporation. Initial value of SM (equivalent depth of soil moisture) one day before puddling was worked out.

2.4.1 Irrigation requirement for puddling

$$I_p = \left(30.0 + SAT - SM_{P-1} - P_{P-1} + Eo_{p-1} + SP_{P-1} + Eo_p + SP_p - P_p\right)/\eta, \quad (2)$$

where, I_p is irrigation requirement for puddling, SAT is equivalent water depth at saturation (mm), SM_{P-1} is equivalent depth of soil moisture one day before puddling, P_{P-1} is precipitation one day before transplanting, E_{0p} is evaporation one day before puddling, SP is seepage and percolation (mm), SP_{P-1} is seepage and percolation (mm) one day before puddling and η is irrigation efficiency = conveyance efficiency * application efficiency (Srivastava 2001).

The ponding depth at the time of transplanting has been assumed at 30 mm.

2.5 Water balance for 1 week after transplanting

The evaporation during the period has been assumed to be equal to open pan evaporation as the crop factor (ET_{crop}/E_0)

Table 1 Transplanting schedules employed in the simulation study

S.N.	Nursery sowing	Dates of transplanting	Physiological maturity dates	Harvesting dates	Duration* (days)
1	15 May	10 Jun	30 Sep	15 Oct	150
2	25 May	20 Jun	10 Oct	25 Oct	150
3	5 Jun	30 Jun	20 Oct	5 Nov	150
4	5 Jun	30 Jun	5 Oct	20 Oct	135
5	5 Jun	30 Jun	30 Sep	15 Oct	130
6	25 Jun	20 Jul	10 Oct	25 Oct	120
7.	25 Jun	20 Jul	20 Oct	5 Nov	130
8	15 July	10 Aug	20 Oct	5 Nov	110

*Duration of rice has been calculated from 25 days before date of transplanting to date of harvesting (25 days is the age of nursery seedlings) for initial stages of transplanted rice has been given a value of 1.0 (Michael 1978).

The calculation of irrigation requirement for this period is given in Eq. 3.

$$I_p = (50 - D_{i-1} + E_{oi-1} + SP_{i-1} - P_{i-1})/\eta \quad (3)$$

where I_p is irrigation requirement and D_{i-1} is the depth of ponding on (i-1)th day; here 5-cm ponding depth has been considered.

2.6 Water balance for subsequent period

The irrigation was applied to the crop when soil moisture went below field capacity up to physiological maturity stage. Irrigation was not applied between physiological maturity and maturity during which drainage is necessary for harvesting. The water balance equation (Eq. 4) will be:

$$D_{i=} D_{i-1} - SP_i - E_{0i}\, K_c + P_i \quad (4)$$

where $K_c = ET_{Crop}/E_0$, i.e. crop factor or pan coefficient = 1.0. The phase will occur where the following condition (Eq. 5) is satisfied.

$$D_{i-1} > SP_i + E_{0i}\, K_C - P_i \quad (5)$$

where D_i is depth of ponding and SP = seepage and deep percolation (mm day^{-1}).

If the condition expressed by the equation is not satisfied, the soil will go into moist phase; in that case, the water balance equation (Eq. 6) will be

$$SM_i = SM_{i-1} + Pi - E_{0i}\, K_C - SP_i \quad (6)$$

If the moisture is less than field capacity, irrigation will be applied, and the irrigation (IR) required to bring the submergence to the level of 5 cm is expressed by Eq. 7.

$$IR = (50 + SAT - SM_{i-1} - P_i + E_{oi}Kc)/\eta \quad (7)$$

The seepage and deep percolation (SP) was calculated as given in Eq. 8.

$$SP = 2.0786 + 0.0338D \quad (8)$$

SP: Seepage and deep percolation (mm day^{-1}).
D: Depth of ponding (mm).

2.7 Water productivity

Apparent water productivity of rice was determined as the grain yield per unit of irrigation water applied (Chahal et al. 2007). The potential yields of *kharif* rice under different dates of transplanting have been used.

2.8 Field experiment for model validation

A field experiment on rice was conducted at the University Research Farm, Pusa, during *kharif* season of 2017 and 2018 to test the performance of the model. Rice crop was transplanted on four dates, viz. 5 June, 20 June, 10 July and 30 July, to measure the actual irrigation requirement during the growing period. The experiment was laid out in randomized block design with three replications. Actual irrigation requirements of the crop from transplanting to physiological maturity were estimated using portable Parshall flume (throat width 7.5 cm) for all dates of transplanting considering rainfall, evaporation and percolation during the growing period.

2.9 Field experiments on wheat

Field experiments on crop-weather relationship were conducted under the All India Coordinated Research Project on Agrometeorology at the University research farm, Pusa (25.98°N, 85.67°E, 52 m amsl), Bihar, during five wheat growing seasons (2011–2012 to 2015–2016) to validate the postulate that early planting of wheat would enable the growers to escape terminal heat stress on wheat crop. For wheat crop-weather relationship studies, dominant cultivars were grown with five staggered dates of planting, viz. 15 November, 25 November, 5 December, 15 December and 25 December covering the entire period of expanded sowing window, which is widely practised by the farmers of the region for planting of wheat. Different planting dates during a year exposes the crop to different temperature regimes during its growing season, allowing an understanding of crop responses to temperature without the artificial conditions imposed by controlled environments (Vijaya Kumar et al. 2015). Crop responses to temperature regime vary with variety and phenological stage of the crop (Shpiler and Blum 1986). The experiment was laid out in randomized complete block design with three replications. The crop was raised following recommended package of practices for the area under irrigated conditions by applying fertilizer (nitrogen-phosphorus-potassium at 120–60–40 kg ha^{-1}) to ensure unlimited nutrient and water supply. All P and K and a half dose of N were applied at sowing as basal dose. The remaining half dose of N was top dressed in two equal splits at crown root initiation and boot stages. The crop was kept weed free throughout the growing season. No insect pest appeared on the crop, and no pesticide was applied during the growing period.

The occurrence of phenological events like tillering, flowering, milking, dough and maturity was recorded from each plots, and average dates of these phases were calculated and used for analysis. The daily weather data on maximum temperature (T_{max}) and minimum temperature (T_{min}) for the growing season were collected from the nearby Agrometeorological Observatory, Dr. Rajendra Prasad

Central Agricultural University, Pusa. Optimum weather conditions in terms of mean and ranges of T_{max} and T_{min} during different crop growth phases were worked out based on daily weather observations.

3 Results and discussion

3.1 Simulated irrigation requirements and water productivity of *kharif* rice

Daily simulation of irrigation requirements (IR) for *kharif* rice (main rice growing season during monsoon) with five staggered dates of transplanting, viz. 10 June, 20 June, 30 June, 20 July and 10 August, were made, and the results presented in Table 2 revealed that for a 150-day crop transplanted on 10 June required 348.6 (± 124) mm water for puddling, 84.1(± 41) mm during 1 week after transplanting and 107.3 (± 115) mm for subsequent period until physiological maturity (PM). The total IR for the entire growing period from transplanting to PM was calculated as 541 (± 163) mm. The same crop (150-day duration) when transplanted on 30 June having PM falling on 20 October needed 404.4 (± 204) mm irrigation during the period from transplanting to maturity. The IR of 30 June transplanted crop (150-day duration) for the period during 1 week after transplanting as well as for the whole growing period was much lower compared to 10 June transplanted crop. This may be due to higher evaporation rate during the early growing period of 10 June transplanted crop. On the other hand, a 135-day-long crop transplanted on 30 June with PM on 5 October required 375.4 (± 185) mm irrigation during its entire growing period. Among all the dates of transplanting in the month of June, the lowest simulated IR of 367.1 (± 178) mm was associated with the crop having 130 days duration transplanted on 30 June and matured on 30 September. Other than long-duration varieties of rice having the crop duration of 150 days and transplanted during the month of June, medium duration rice maturing in 130–135 days required irrigation varying between 367.1 (± 178) mm and 375 (± 185) mm. The IR of the crop transplanted on 10 August (late transplanting) was recorded to be the highest (761.4 mm) followed by the crop transplanted on 10 June and having PM coinciding on 30 September (Table 2). The puddling water requirements were almost comparable for the crops having DOT (dates of transplanting)-DoPM (dates of physiological maturity) as 10 June–30 September and 10 August–20 October. It varied between 348.6 (± 124) and 370 (± 28) mm. These values were much higher than crops transplanted on other dates. The variations in simulated IR for puddling, 1 week after puddling, from puddling to DoPM of *kharif* rice transplanted on different dates from 2002 to 2016 have been presented in Fig. 5, which revealed that there was greater inter-annual variability in simulated IR for the crops having DOT-DoPM as 10 June–30 September and 30 June–30 September. Chaves and Oliveira (2004) reported that moderate water deficits are directly linked to a decrease in carbon fixation by the photosynthetic apparatus, primarily due to stomatal closure, whereas Nguyen et al. (2009) linked it to a decrease in leaf elongation. The most important task is to match cultivar's phenology with rain water availability for achieving higher yield with lesser input cost. This can be achieved by planting an adapted cultivar at an appropriate time (Fukai et al. 1998). Planting of crops in appropriate times, according to actual sowing window, is an important factor in crop production (Ati et al. 2002; Hussein 1987; Latham et al. 2000; Sattar et al. 2019). Moreover, delayed planting in

Table 2 Irrigation requirement (mm) of *kharif* rice transplanted on different dates at Pusa, Bihar, based on model simulation (2002–2016)

S. N	DOT-DOPM	Rice duration (days)	Irrigation requirement (IR), mm							
			For puddling		Irrigation up to 1 week		For subsequent period until DOPM		Transplanting to DOPM	
			IR (mm)	Stdev	IR (mm)	Stdev	IR (mm)	Stdev	IR (mm)	Stdev
1	10 Jun–30 Sep	150	348.6	124	84.1	41	107.3	115	541.0	163
2	20 Jun–10 Oct	150	298.0	167	51.0	42	75.0	77	424.7	222
3	30 Jun–30 Sep	130	288.4	144	32.0	37	46.7	57	367.1	178
4	30 Jun–5 Oct	135	288.4	144	32.0	37	54.9	71	375.4	185
5	30 Jun–20 Oct	150	288.4	144	32.0	37	84.0	84	404.4	204
6	20 Jul–10 Oct	120	265.0	138	34.0	39	79.3	74	378.3	150
7	20 Jul–20 Oct	130	256.0	138	35.1	40	93.3	86	393.4	153
8	10 Aug–20 Oct	110	370.0	28	64.7	40	326.7	105	761.4	136

DOT date of transplanting, *DOPM* date of physiological maturity, *Stdev* standard deviation

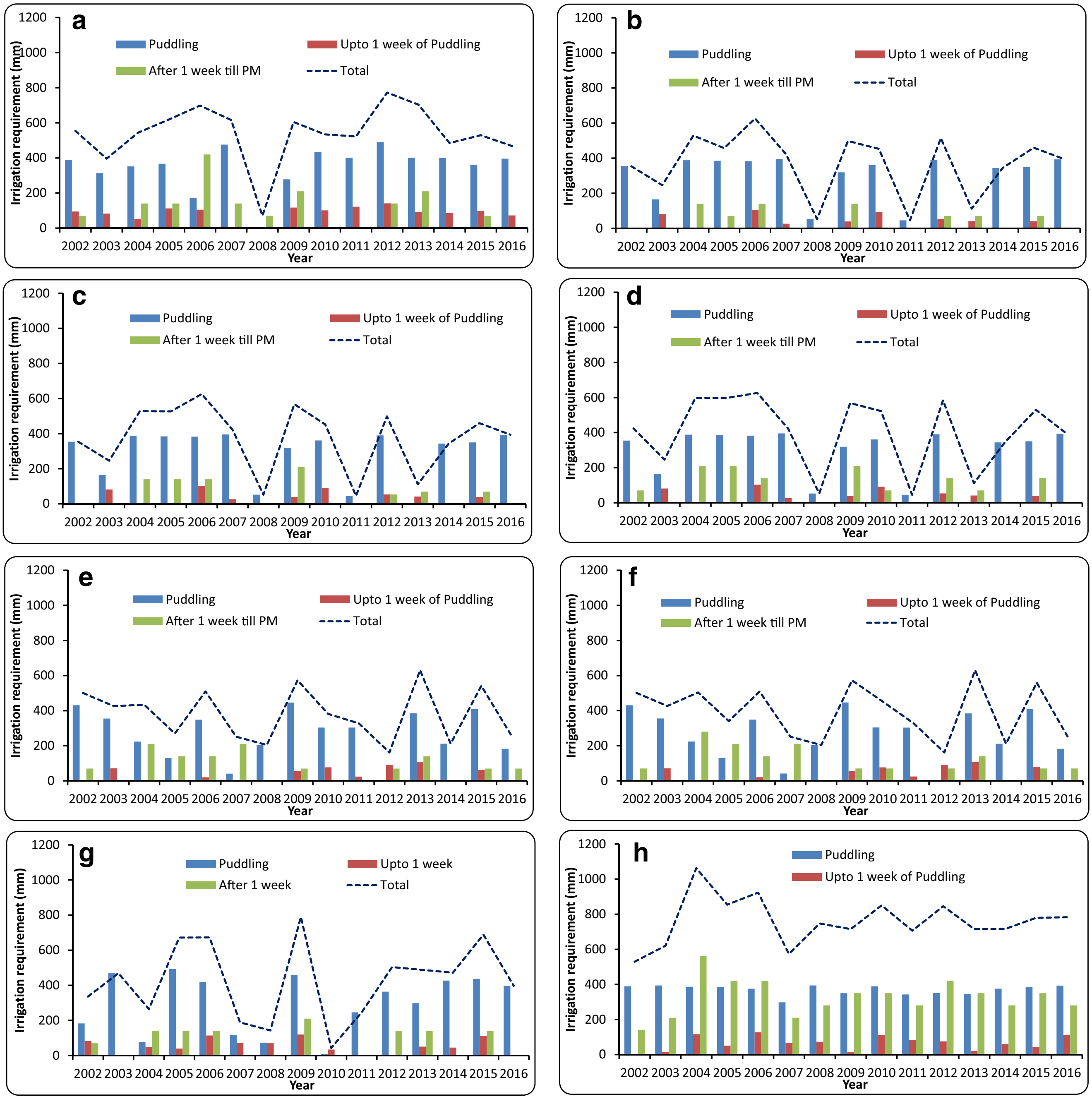


Fig. 5 Variations in simulated irrigation requirements of *kharif* rice transplanted and having physiological maturity on different dates during the period from 2002 to 2016. (**a**) 10 June–30 September, (**b**) 30 June–30 September, (**c**) 30 June–5 October, (**d**) 30 June–20 October, (**e**) 20 July–10 October, (**f**) 20 July–20 October, (g) 20 June–10 October and (**h**) 10 Aug–20 October

an area shorten the length of crop growing period and increases the chances of weed (Stoop et al. 1981; Vaksmann et al. 1992) and pest infestations, leading to significant reduction in crop productivity.

The apparent water productivity of rice transplanted on different dates in the month of June irrespective of crop duration and dates of transplanting ranged from 1.293 to 1.732 kg m^{-3} ha^{-1} (Table 3). Considering long-duration rice of 150 days, the apparent water productivity was observed to be the highest, when the crop was transplanted on 30 June having PM date on 20 October. Rice crop maturing in 130–135 days recorded water productivity of 1.362 to 1.598 kg m^{-3} ha^{-1}, when transplanted on 30 June. The water productivity of late transplanted crop of 110–130 days duration ranged from 0.459 to 1.271 kg m^{-3} ha^{-1} with higher

Table 3 Potential productivity (Kg ha^{-1}) and apparent water productivity (Kg m^{-3} ha^{-1}) of different durations of *kharif* rice grown under different sowing dates

Sl No	DOT-DOPM	Rice duration (days)	IR for one hectare (m^3)	Potential yield (Kg ha^{-1})	Apparent water productivity (Kg m^{-3} ha^{-1})
1	10 Jun–30 Sep	150	5410	7000	1.293
2	20 Jun–10 Oct	150	4247	7000	1.648
3	30 Jun–30 Sep	130	3671	5000	1.362
4	30 Jun–5 Oct	135	3754	6000	1.598
5	30 Jun–20 Oct	150	4040	7000	1.732
6	20 Jul–10 Oct	120	3783	4000	1.057
7	20 Jul–20 Oct	130	3934	5000	1.271
8	10 Aug–20 Oct	110	7614	3500	0.459

value recorded for the crop transplanted on 20 July having PM date on 20 October. The lowest water productivity was observed for the crop transplanted on 10 August and maturing on 20 October due to lower potential productivity and comparatively higher IR. Considering all durations of rice, the highest water productivity of 1.732 kg m^{-3} ha^{-1} was recorded in case of 150-day long-duration crop transplanted on 30 June having PM coinciding with 20 October. Apparent water productivity of rice was significantly influenced by change in time of transplanting (Brar et al. 2012). Tuong et al. (2005) reported average water productivity of 0.41 kg grain m^{-3} water for rice with respect to water input (irrigation plus rainfall). Under water saving regime, an increase in water productivity to 0.8–1.0 kg grain m^{-3} has been reported (Beldar et al. 2004; Kato et al. 2009). The range of water productivity of rice was observed to be about 0.6–1.6 kg m^{-3} (Zwart and Bastiaanssen 2004). The higher water productivity of 30 June transplanted rice of 150-day duration in comparison to 10 June transplanted one may be attributed to the fact that enough rainwater was available to make the soil moisture favourable during plant growth and development, which reduced the necessity of applying higher amount of irrigation. The water productivity decreased with decrease in crop duration when transplanting was delayed beyond 30 June. If a farmer intends to grow long-duration rice cultivar keeping in view the potential yield and lesser irrigation requirement, he needs to raise the crop transplanted on 30 June, which would mature by 20 October. This implied that if the crop is scientifically managed, it will lead to twofold benefits, viz. higher yield, realized with lesser amount of irrigation and higher water productivity. Based on water use and water productivity, the study revealed that farmers should opt for 150-day rice crop with sowing window around 30 June and PM on 20 October, which ensured higher grain yield. The 150-day crop transplanted on 30 June having PM on 20 October although gives highest yield (7000 kg ha^{-1}) and highest water productivity (1.732 kg m^3 ha^{-1}) provides lesser turn-around time of 5–7 days for land preparation and early sowing of the next wheat crop. The same crop (150 days) when transplanted on 20 June and harvested on 25 October (PM date on 10 October) recorded water productivity of 1.648 kg m^3 ha^{-1}. It gives higher turn-around time (10–15 days) to the farmers than the crop transplanted on 30 June having PM on 20 October. Thus, considering the criteria such as grain yield, water productivity and turn-around time for field preparation and planting of next crop, i.e. wheat, farmers should transplant it by 20 June having PM date on 10 October, allowing him to harvest the crop by 25 October. This ensured ample time-space to finish wheat sowing much early before 10–15 November. The more early the wheat is sown before 15 November, the greater is the chance that it will escape terminal heat stress.

Moreover, lesser yield of rice due to delayed transplanting beyond 20 July was attributed to higher percentage of chaffy grains in the panicle (Anon 2016). The formation of chaffy grains coincided with the setting of lower air temperature ($T_{max} < 32.5$ °C and $T_{min} < 23.0$ °C) during 50% flowering and dough stage of rice crop (Sattar et al. 2017a). Venkataraman and Krishnan (1992) observed that lower temperature renders the opening of flowers irregular and the filling of panicle inadequate. Maximum temperature required for germination of pollens is 33–34 °C (Grist 1986). Sattar et al. (2017a) observed decreasing grain yield of irrigated rice with delayed transplanting due to temperature variation and reduced sunshine duration. Daily bright sunshine hours (BSH) of 7 to 8 h during flowering phase led to enhanced grain yield; however, BSH of less than 7 h resulted in decline of grain yield. De Datta (1981) observed that the yield of rice may decrease with delayed transplanting due to low solar radiation, probably because of the use of photosensitive variety. Reduced radiation affected the crop yield in photosensitive and short-duration varieties at 3–4 weeks before heading, when the mutual shading by the fully developed leaves was maximum (Stansel 1967). The weather factors affecting rice yield may be temperature, affecting pollen germination and rainfall damaging or washing of pollens during flowering to anthesis period.

About 60% of rice crop in the region is grown under rainfed condition during *kharif* (monsoon) season (Sattar

Table 4 Comparative analysis of dry spells in consecutive 20-year periods at Pusa, Bihar

Number of dry spell of different intensity during different months of *kharif* season

Year	June			July			August			September		
	5–7 Days	8–10 Days	11–15 Days	5–7 Days	8–10 Days	11–15 Days	5–7 Days	8–10 Days	11–15 Days	5–7 Days	8–10 Days	11–15 Days
1977–1996	22	7	9	11	1	0	6	3	1	17	3	2
1997–2016	15	5	9	13	2	1	18	8	0	18	6	6

and Khan 2016). Nowadays, cultivation of rainfed rice in the region is constrained with the regime of increased frequency of dry spell during its growing season (Table 4). The occurrence of drought and frequent dry spell during growing season of *kharif* rice is bound to affect yield of the crop (Sattar and Khan 2016). While evaluating crop production potential under rainfed condition in Bihar, India, Sattar and Khan (2016) observed greater crop production potential with higher length of growing period and availability of sufficient moisture for the crop. Significant negative correlations of dry spell with rainfall and soil moisture impacting productivity were also observed. The data presented in Table 4 reveals that the month of June has become wetter during the recent period (1997–2016) compared to the period of 1977–1996. Taking advantage of wetter June in the recent period, seedlings could be prepared early in the season for advancing the date of rice transplanting due to greater availability of wet condition facilitated by pre-monsoon showers. Once the crop is established, even reduced rainfall activity as shown by increasingly drier condition in July and August in recent times would allow the crop to survive with the provision of supplemental irrigation. This also supports our postulate that early transplanting of rice during 20–30 June would help reduce the irrigation requirement of the crop, and thus it can save precious water, which is increasingly becoming scarce under changed climatic condition. Chahal et al. (2007) while working on rice in Punjab, India, observed that with the shifting of transplanting dates of rice from higher (mid-May) to lower (end of June onwards) evaporative demand, there was an increase in grain yield of rice, while there is a reduction in evapotranspiration and irrigation water applied.

As adaptation options, climate smart water saving interventions such as direct seeded rice, alternate wetting and drying irrigation system in rice, low water requiring cultivars, shifting planting time, aerobic rice system, system of rice intensification, crop residue management, smart irrigation scheduling and cropping system optimization are being advocated by the researches, extension workers and policy makers for the farmers to enhance resilience of the crop to climate change. The results presented in the article give an overview of the attempt for smart irrigation scheduling in rice and optimization of RWCS by shifting sowing window for sustainable production based on climate, soil and crop information.

3.2 Validation of the model used in IR calculation and development of irrigation software

To test the performance of the model used in this paper for estimation of IR of rice based on climate, soil and crop coefficient, we validated the model for rice crop grown during *kharif* season of 2017 and 2018. Using the model, simulated IR for the crop grown during 2017 and 2018 was worked out (Table 5). It was observed that total simulated IR for the crop

Table 5 Simulated and actual irrigation requirement (mm) of *kharif* rice transplanted on different dates in 2017 and 2018

S. N.	DOT-DOPM	Rice duration (days)	Simulated irrigation requirement (mm)						Total actual irrigation requirement (mm)		Error (%)	
			Puddling		For subsequent period		Total					
			2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
1	5 Jun–10 Oct	127	316.3	410.2	245.3	261.6	561.6	671.6	526.8	619.5	6.6	8.4
2	20 June–27 Oct	129	295.7	318.4	277.3	289.0	563.0	607.0	510.6	655.4	10.2	7.4
3	10 Jul–16 Nov	130	95.3	193.3	360.0	271.6	455.3	464.6	484.4	494.7	1.4	6.0
4	30 July–8 Dec	131	310.0	132.5	422.3	300.0	732.3	432.0	747.4	458.0	2.0	5.7

DOT date of transplanting, *DOPM* date of physiological maturity

grown during 2017 varied from 455.3 to 732.3 mm, while actual IR were found to vary from 484.4 to 747.4 mm. The model predicated IR within 1.4 to 10.2% of actual irrigation amount. On the other hand, model simulated IR varying from 432.0 to 671.6 mm for different dates of transplanting during 2018 against the actual IR of 458.0–655.4 mm. Error percentages between simulated and actual irrigation for the crop grown during 2018 varied from 5.7 to 8.4 among different dates of transplanting. The variation in IR depended on date of transplanting and availability of rainwater during the crop growing period.

Using the data used in the model, an irrigation software entitled "Climate Smart Irrigation Software for *Kharif* Rice" was developed with a view to calculate precise amount of irrigation and decide the actual date of irrigation for *kharif* rice. The application of right quantity of water for irrigation is essential for enhancing the water use efficiency in the crop, and also it prevents its excess use or loss. Another thing is that the farmers of the region do not have any reliable and effective technique for deciding the actual date of irrigation. This user-friendly software has been designed to give practical solution in this direction. The software consists of three modules, viz. (i) calculation of irrigation requirement for puddling operation, (ii) calculation of irrigation requirement for the period of 1 week after transplanting and (iii) calculation of irrigation requirement for the period from 1 week after puddling until physiological maturity. To run the software, the user should have information on field capacity, permanent wilting point, available water holding capacity and seepage and percolation rate of the farm soil as primary requirements. Only two meteorological parameters, viz. daily rainfall and evaporation rate of a location, are required for estimation of irrigation requirement and deciding the actual date of irrigation.

3.3 Climatic suitability for early planting of wheat

The early transplanted rice would enable the farmers of the region to have their fields vacated for early planting of wheat. Results of field experiments on crop-weather relationship revealed that a wheat crop planted early by 15 November would ensure completion of its most sensitive flowering phase by 15 February, beyond which increase in day temperature above 25 °C accompanied by dry westerly winds tend to interfere with pollination of wheat crop, thereby adversely affecting the grain setting (Sattar et al. 2017b). Hence, if wheat planting is finished well before 15 November, there is higher possibility that the sensitive phases of reproductive and maturity period would escape terminal high temperatures (Fig. 6). To corroborate this fact, plots of average air temperature recorded during 50% flowering to milking, 50% flowering to physiological maturity of wheat crop across different dates of planting, viz. 15 November, 25 November, 5 December, 15 December and

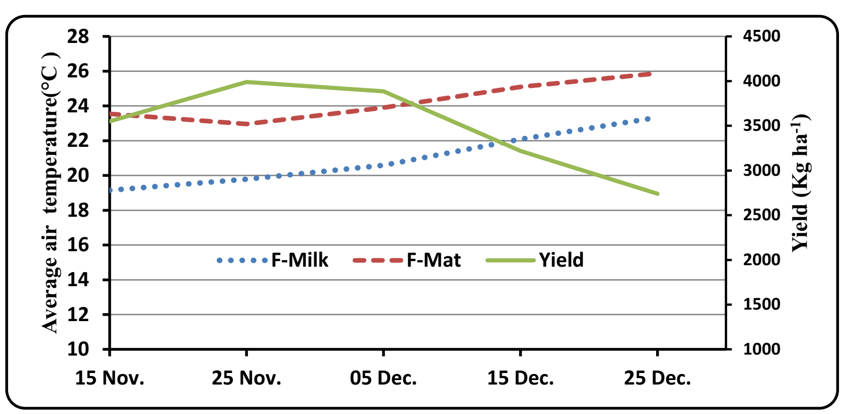
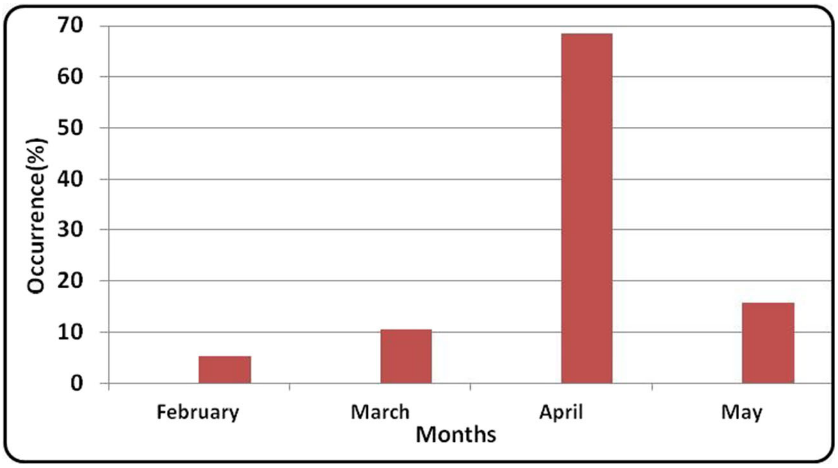


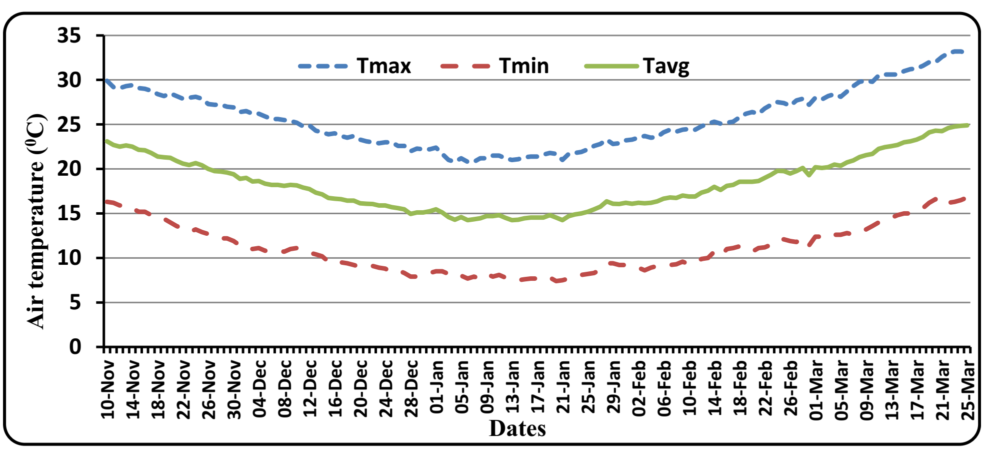
Fig. 6 Effect of average air temperature during flowering to milking (F-Milk), flowering to maturity (F-Mat) stages on grain yield of wheat crop planted on different dates at Pusa, Bihar (India)

Fig. 7 Occurrence of hailstorm(%) in different months at Pusa, Bihar (India) (database 2001–2020)



25 December, for five wheat growing seasons (2011–2012 to 2015–2016) against grain yield demonstrated that with delayed planting, sensitive phases of the crop experience higher air temperature, which led to reduction in grain yield (Fig. 6). Considering grain yield vis a vis temperature regime during flowering to maturity stage, the most viable recommendation for the farmers of the region would be to finish wheat planting before 15 November. Early harvesting of rice by 25 October (PM date on 10 October) facilitated early wheat planting before 10–15 November and thus helped avoid terminal heat stress on wheat during flowering to maturity phase. It also ensured that a wheat crop of 135–140-day duration if planted around 5–10 November could be harvested in the last week of March. Early harvesting of wheat in March also helped escape hailstorm damage on wheat in April as the probability of occurrence of hailstorm in the month of April in the region is almost 70% (Fig. 7). The anthesis-time management by manipulating planting dates of crops at different times could be an adaptation strategy for optimum yield under changing climate (Richards 2006; Sattar et al. 2020). The study further implied that advancing the sowing of wheat could prove a boon for millions of farmers in the regions in escaping terminal heat stress induced by high temperature and thereby realizing higher grain yield of wheat (Fig. 6). The daily normal maximum, minimum and average air temperatures have also been presented to bring an idea of prevailing temperature regime in the region during wheat growing season (Fig. 8), which shows that there is a tendency of T_{max} and T_{min} to shoot up above 25 °C and 12 °C, respectively, from 20 February onwards surpassing the critical thresholds for obtaining optimum wheat productivity (> 4500 kg ha^{-1}). Nathaniel et al. (2012) considered shifting of sowing date as one of the adaptive options under climate change condition. Liu et al. (2020) observed that changing growing season start date is a potential way to enhance resilience to climate change. One minor problem related to early planting of wheat could be the prevalence of initial higher temperature during sowing time of wheat, which might affect seed germination. The average maximum temperature during 1–15 November in the region prevails between 29.2 and 30.1 °C, while minimum temperature varies from 15.2 to 16 °C. Average temperature during this period (1–15 November) is found to vary from 22.0 to 23.1 °C. Such

Fig. 8 Variation in daily normal maximum temperature (T_{max}), normal minimum temperature (T_{min}) and average temperature (T_{av}) during wheat growing season at Pusa, Bihar (India)



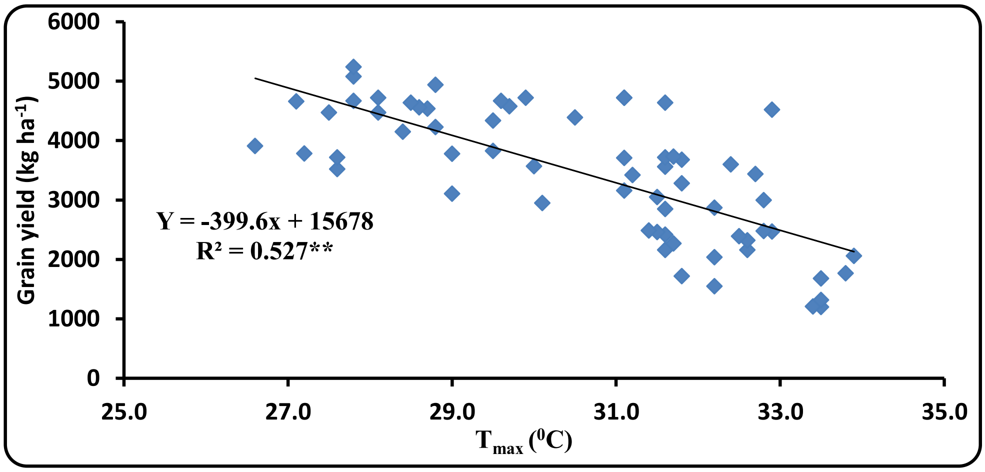


Fig. 9 Effect of maximum temperature (T_{max}) during flowering to maturity phase of wheat crop on grain yield

variation of temperature is within optimum threshold limit for wheat sowing and germination (Luo 2011; Porter and Gawith 1999). Moreover, early sowing of wheat before 15 November does not appear to be a constraint with adoption of cultivar such as HD 2967 by the farmers, which can tolerate comparatively higher temperature during germination. On the other hand, with delayed sowing, sensitive phases of the crop experienced higher air temperatures, which led to reduction in grain yield (Sattar et al. 2017b). Critical thresholds identified for the crop revealed that during 50% flowering to milking stage, maximum temperature and minimum temperature above 24.6 °C and 11.6 °C, respectively, reduced grain yield sharply below 4500 kg ha^{-1}. Significant reduction in grain yield was observed beyond a day temperature of 26.9 °C. An increase of T_{max} from 29.2 to 32.1 °C during flowering to physiological maturity curtails the wheat production drastically. Grain yield declines by 399 kg ha^{-1} per 1 °C rise in T_{max} during 50% flowering to physiological maturity stage (Fig. 9). A few days of temperature above threshold values, if coincided with anthesis, can significantly reduce grain yield, affecting subsequent reproductive processes (Wheeler et al. 2000).

4 Conclusions

The findings of the study could be immensely useful in developing climate smart rice-wheat production system in the middle Gangetic plains of India. It revealed that rice transplanting can be advanced to realize the potential yield of the crop with higher water productivity. Early transplanting of rice facilitated early wheat sowing, thereby reducing the negative impact of terminal heat stress on its growth and yield. Simultaneously, it also reduced the higher chances of hailstorm damage in April (70%) on matured wheat crop, as early planting ensured its harvesting in the last week of March. A set of combinations with respect to transplanting dates and duration of rice followed by early planting of wheat before 15 November would enable the farmers of the region to harness greater economic benefits and environmental services from adopting such climate smart vibrant RWCS. Early transplanting of rice during 20–30 June appeared to be the best option for the farmers following RWCS. The anthesis-time management by manipulating sowing window of wheat would lead to an effective solution for tackling the problem of terminal heat stress on wheat, which tends to curtail wheat productivity in this region of the Indo-Gangetic Plains. This would enhance the resilience of life-supporting rice-wheat production system to climatic change. The study highlighted a bright prospect for millions of farmers following RWCS in vast areas of Indo-Gangetic Plains, particularly Bihar and eastern Uttar Pradesh. Moreover, climate smart irrigation software developed for *kharif* rice based on the model used in this study would help researchers and farmers to optimize water use in rice under water stressed environment.

Authors' contributions All authors equally contributed to the study conception, design and construction of the manuscript. Authors of the manuscript approved the final manuscript.

Data availability Data and materials as well as software used in the manuscript comply with transparency and field standards.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Anon (2016) Annual Progress Report, All India Coordinated Research Project on Agrometeorology, DRPCAU, Pusa, Bihar centre, pp 58

Ati OF, Stigter CJ, Oladipo EO (2002) A comparison of methods to determine the onset of growing season in northern Nigeria. J Climatol 22:731–742

Beldar P, Bouman BAM, Cabangon R, Quilang EJP, Spiertz JHJ, Tuong TP(2004) Effect of water saving irrigation on rice yield and water use in typical lowland condition in Asia. Agric Water Manag 65: 193–210

Bhatt R, Kukal SS, Arora S, Busari MA, Yadav M (2015) Sustainability issues on rice-wheat cropping system. Int Soil Water Conserv Res. https://doi.org/10.1016/j.iswcr.2015.12.001

Bouman BAM (2009) How much water does rice issue. Rice Today 6:38

Brar SK, Brar AS, Vashist KK, Neerja S, Buttar GS (2012) Transplanting time and seedling age affect water productivity, rice yield and quality in north-west India. Agric Water Manag 115:217–222

Chahal GBS, Sood A, Jalota SK, Chaoudhury BU, Sharma PK (2007) Yield, evapotranspiration and water productivity of rice (Oryza sativa L.)–wheat (Triticum aestivum L.) system in Punjab (India) as influenced by transplanting date of rice and weather parameters. Agric Water Manag 88:14–22

Chaves MM, Oliveira MM (2004) Mechanisms underlying plant resilience to water deficits: prospects for water-saving agriculture. J Exp Bot 55:2365–2384

De Datta SK (1981) Climate effects on rice production. In: Principles and practices of rice production. Wiley, New York, pp 9–40

Fukai S, Sittisuang P, Chanphengsay M (1998) Increasing production of rainfed lowland rice in drought prone environments- a case study in Thailand and Laos, plant prod. Sci 1(1):75–82

Grist DH (1986) Characteristics of the plant in rice. Longman, London/ New York, pp 69–98

Howard A (1924) Crop production in India: a critical survey of its problems. Oxford University Press, Oxford

Hussein J (1987) Agro-climatological analysis of growing season in natural regions II, IV and V of Zimbabwe. In: proceedings of the workshop 'cropping in the semi-arid areas of Zimbabwe', sponsored by German Agency for Technical Cooperation (held in Harare). Zimbabwe, 24–28 August 1987

Ishfaq M, Muhammad F, Usman Z, Saddam H, Nadeem A, Ahmad N, Ahmad AS (2020) Alternate wetting and drying: a water-saving and ecofriendly rice production system. Agric Water Manag 241: 106363

Jalota SK, Singh KB, Chahal GBS, Gupta RK, Somshubhra C, Anil S, Ray SS, Panigrahy S (2009) Integrated effect of transplanting date, cultivar and irrigation on yield, water saving and water productivity of rice (Oryza sativa L.) in Indian Punjab: field and simulation study. Agric Water Manag 96:1096–1104

Joshi AK, Mishra B, Chatrath R, Ortiz Ferrara G, Singh RP (2007) Wheat improvement in India: present status, emerging challenges, and future prospects. Euphytica 157:431–446

Kato Y, Okami M, Katsura K (2009) Yield potential and water use efficiency of aerobic rice (Oryza sativa L.) in Japan. Field Crop Res 113:328–334

Latham B, Murungweni M, Wood F, Rook M, Matare K (2000) The farmer (www.thefarmer.co.zw). The African farming news magazine. Morden farm. Publ. Trust 70(1):11–21

Liu C, Wang L, Le Cock K, Chang C, Li Z, Chen F, Liu Y, Wu L (2020) Climate change and environmental impacts on and adaptation strategies for production in wheat-rice rotations in southern China. Agric For Meteorol 292-293:108136. https://doi.org/10.1016/j.agrformet.2020.108136

Luo Q (2011) Temperature thresholds and crop production: a review. Climate Change 109:583–598

Memon MS, Guo J, Tagar AA, Perveen N, Ji C, Memon SA, Memon N (2018) The effects of tillage and straw incorporation on soil organic carbon status, rice crop productivity, and sustainability in the rice-wheat cropping system of eastern China. Sustainability 10(4):961

Michael AM (1978) Irrigation theory and practices. Vikas Publishing House, New Delhi, p 521

Mohammad A, Susama S, Das TK, Man S, Ranjan B, Anchal D, Manoj K, Sharma VK, Neeta D, Mukesh K (2018) Water balance in direct-seeded rice under conservation agriculture in north-western Indo-Gangetic Plains of India. Irrig Sci 36:381–393

Mondal S, Kumar NS, Haris AA, Mishra JS, Joydeep M, Rao KK, Bhatt BP (2020) Effect of conservation tillage and rice-based cropping systems on soil aggregation characteristics and carbon dynamics in Eastern Indo-Gangetic Plain. Paddy Water Environ 18:573–586. https://doi.org/10.1007/s10333-020-00802-x

Nathaniel DM, James SG, Matt J, Deepak KR, Navin R, Jonathan AF (2012) Closing yield gaps through nutrient and water management. Nature 490:254–257

Nguyen HT, Fischer KS, Fukai S (2009) Physiological responses to various water saving systems in rice. Field Crop Res 112:189–198

Panwar AS, Shamim M, Babu S, Ravishankar N, Prusty AS, Alam NM, Singh DK, Bindhu JS, Kaur J, Dashora LN, Latheef Pasha MD, Chaterjee S, Sanjay MT, Desai LJ (2019) Enhancement in productivity, nutrients use efficiency, and economics of rice-wheat cropping systems in India through farmer's participatory approach. Sustainability 11:122. https://doi.org/10.3390/su11010122

Porter JR, Gawith M (1999) Temperatures and the growth and development of wheat: a review. Eur J Agron 10:23–36

Rashid MA, Andersen MN, Wollenweber B, Zhang X, Olesen JE (2018) Acclimation to higher VPD and temperature minimized negative effects on assimilation and grain yield of wheat. Agric For Meteorol 248:119–129

Richards RA (2006) Physiological traits used in the breeding of new cultivars for water-scarce environments. Agric Water Manag 80: 197–211

Saito K, Futakuchi K (2009) Performance of diverse upland rice cultivars in low and high fertility conditions in West Africa. Field Crop Res 111:243–250

Sandhu SS, Prabhjyot K, Padmakar T, Patel SR, Rajinder P, Solanki NS, Ramesh K, Singh CB, Dubey AP, Rao VUM (2016) Effect of intra-seasonal temperature on wheat at different locations of India: a study using CERES-wheat model, J. Agrometeorol 18(2):222–223

Sattar A, Khan SA (2016) Evaluation of crop production potential using long term simulated soil moisture in drought prone region of Bihar. Indian J Soil Cons 44(3):256–265

Sattar A, Manish K, Khan SA, Pandey IB (2014) Calibration and validation of DSSAT 4.5 model for wheat in North-West Bihar. J Agrometeorol 16:180–185

Sattar A, Manish K, Mithilesh K, Vijaya Kumar P (2016) Agrometeorology of rice in Bihar state of India. RPCAU, Pusa (Samastipur), p 47

Sattar A, Manish K, Vijaya Kumar P, Khan SA (2017a) Crop weather relation in *kharif* rice for North-west Alluvial Plain Zone of Bihar. J Agrometorol 19(1):71–74

Sattar A, Kumar Manish, Kumar Sumant, Kumar Mithilesh (2017b) "Assessing crop weather relation in wheat for enhanced crop productivity in north Bihar" paper presented in the International Symposium "Stress Resilient Wheat in the Regime of Climate Change" held at DRPCAU, Pusa during 22–24 April, 2017

Sattar A, Khan SA, Saon B, Nanda MK (2019) Assessing sowing window and water availability of rainfed crops in eastern Indian state of Bihar for climate smart agricultural production. Theor Appl Climatol 137:2321–2334. https://doi.org/10.1007/s00704-018-2741-9

Sattar A, Gulab S, Singh Shruti V, Mahesh K, Vijaya Kumar P, Bal SK (2020) Evaluating temperature thresholds and optimizing sowing dates of wheat in Bihar. J Agrometeorol 22(2):158–164

Shpiler L, Blum A (1986) Differential reaction of wheat cultivars to hot environments. Euphytica 35:483–492

Sidhu HS, Jat ML, Yadvinder S, Kaur SR, Naveen G, Parvinder S, Pankaj S, Jat HS, Bruno G (2019) Sub-surface drip fertigation with conservation agriculture in a rice-wheat system: a breakthrough for addressing water and nitrogen use efficiency. Agric Water Manag 216(1):273–283

Singh M (2011) Yield gap and production constraints in rice-wheat system: scenario from eastern Uttar Pradesh. Bangladesh J Agric Res 36(5):623–632

Srivastava RC (2001) Methodology for design of water harvesting system for high rainfall areas. Agric Water Manag 47:37–57

Stansel JW (1967) Rice grain yields and stages of plant growth as influenced by weather conditions. Texas Agricultural Experiment Station (Progress Report P.R. 462)

Stoop WA, Pattanayak CM, Matlon PJ, Root WR (1981) A strategy to raise the productivity of subsistence farming systems in the West African semi-arid tropics. In: Proceedings Sorghum in the Eighties. ICRISAT, Patancheru, pp 519–526

Tuong T, Bouman BAM, Mortimer M (2005) More rice, less water—integrated approaches for increasing water productivity in irrigated rice-based systems in Asia. Plant Prod Sci 8:231–241

UNEP (2008) Fresh water under threat, South Asia, vulnerability assessment of freshwater resources to environmental change. Nairobi, Kenya, United Nations Environment Program

Vaksmann M, Traore SB, Niangado O (1992) Le photoperiodisme des sorghos africains. Agric Dev 9:13–18

Venkataraman S, Krishnan A (1992) Crops and weather. Indian Council of Agricultural Research, New Delhi, p 586

Vijaya Kumar P, Rao VUM, Bhavani O, Dubey AP, Singh CB, Venkateswarlu B (2015) Sensitive growth stages and temperature thresholds in wheat (Triticum aestivum L.) for index-based crop insurance in the Indo-Gangetic Plains of India. J Agric Sci:1–13. https://doi.org/10.1017/S0021859615000209

Wang X, Cai J, Jiang D, Liu F, Dai T, Cao V (2011) Pre-anthesis high-temperature acclimation alleviates damage to the flag leaf caused by post-anthesis heat stress in wheat. J Plant Physiol 168(6):585–593

Wheeler TR, Craufurd PQ, Ellis RH, Porter JR, Vara Prasad PV (2000) Temperature variability and the annual yield of crops. Agric Ecosyst Environ 82:159–167

Yadvinder S, Kukal SS, Jat NL, Sidhu HS (2014) Improving water productivity of wheat-based cropping systems in South Asia for sustained productivity. Adv Agron 127:157–258

Zwart SJ, Bastiaanssen WGM (2004) Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agric Water Manag 69:115–133