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Optimization of Wheat and Barley Production under Changing Climate in Rainfed Pakistan Punjab - A Crop Simulation Modeling Study

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Abstract: Rainfed agriculture is extremely vulnerable to climate change. Climate change is both an opportunity and a potential threat to future agriculture and livestock production globally and in Pakistan particularly. Impacts of climate change will have significant reflections on field practices of wheat growers. The present study is mainly directed to discuss sensitivity of climate change upon the wheat and barley production in rainfed areas of Pakistan Punjab. Field experiments were conducted at Barani Agricultural Research Institute, Chakwal during winter seasons of 2014 and 2015 to study the effects of sowing date and three irrigation levels on grain yield and its attributes of wheat (*Triticum aestivum*) cultivar Chakwal-50 and barley (*Hordeum vulgare*) cultivar Joe-83. Experimental conditions and results obtained from the location were used as a database for calibration (2010, 2012 and 2013) and experiments were performed in 2014-2015 for validation of CERES-wheat and CERES-barley models of DSSAT4.5 package to study the sensitivity of climate change on wheat and barley growth and yield. Results show that by comparing results obtained from CERES-wheat and CERES-barley model and actual observations in the field enabled us to reach very good calibration (anthesis (DAP) RMSE = 3 and 3, NRMSE = 2% and 3%, dstat = 0.84 and 0.783 and r square = 0.98 and 0.75; physiological maturity (DAP) RMSE = 3 and 4, NRMSE = 2 and 3%, d-stat = 0.9 and 0.843, r square = 0.98 and 0.82; grain yield (kg ha^{-1}) RMSE = 173 and 174, NRNSE = 4% and 13%, d-stat = 0.68 and 0.737, r square = 0.75 and 0.99, respectively) and validation (anthesis (DAP) RMSE = 2 and 3, NRMSE = 2% and 3%; physiological maturity (DAP) RMSE = 2 and 3, NRMSE = 1 and 2%; grain yield (kg ha^{-1}) RMSE = 195 and 192, NRNSE = 5% and 24%, respectively) of the model for predicting phonological stages as well as grain yield at different locations using different treatments. Scenario simulations showed that optimum sowing date for wheat and barley was 20-30 November and 25 November to 5 December, respectively, and in case of dry year 30 mm supplemental irrigation could be applied at the time of sowing or 30 DAS.

Key words: Sowing date, crop modeling, wheat, barley.

Climate change is a rapidly unfolding challenge of catastrophic global, regional and national proportions. Pakistan will be affected by the impacts far more adversely than is generally recognized by the policy makers and leaders. Pakistan has continuously witnessed history's worst disasters since 2001. According to the IPCC's fifth Assessment Report (AR5), global surface temperature increase in excess of 1.5°C and keep rising beyond 2100 in all scenarios except the lowest-emission scenario, in which actions are taken to nearly eliminate CO_2 emissions in the second half of the 21st century. In scenarios with higher rates of emissions, warming is likely to exceed 2°C by 2100 and could even exceed 4°C. The temperature increases in both summer and winter are reported higher in northern Pakistan than in southern. Despite the fact that Pakistan has witnessed a number of natural disasters in recent past, the need to study severity and impact of the natural disasters was felt after the devastating flood in 2010 (Yu, Winston *et al.*, 2013). The flood in 2010 had a devastating effect on the lives and livelihoods of millions in the country. The cost of recovery was estimated at USD 8.74-10.85 billion (ADB, WB, and GOP, 2010). Chakwal is located in the Dhanni region of Pothohar Plateau in northern Punjab, which is a semi-arid area with a shortage of irrigation infrastructure and water sources for agriculture. Over 70% of the population engages

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in agriculture, mostly subsistence agriculture dependent on rainfall (Hanif and Ali, 2014). Punjab contributes about 76% to annual food grain production in the country. According to the Punjab Agriculture Department, The Province has 57% of the total cultivated and 69% of the total cropped area of Pakistan. It provides about 83% of cotton, 80% of wheat, 97% fine aromatic rice, 63% of sugarcane and 51% of maize to the national food production. Wheat is a rabi season crop that is grown in the winter period. In Pakistan, sowing of wheat takes place from October to December and harvesting during the months of March to May. Whereas in Punjab, sowing months of wheat are November and December whereas harvesting period is April and May (Rashid and Ayaz, 2015). The temperature increases in Pakistan are expected to be higher than the global average resulting in reduced national agricultural productivity. The minimum and maximum temperatures have increased both in summer and winter seasons almost throughout Pakistan in the recent past (Afzaal *et al.*, 2009). The evidence suggests that an increase of 1°C in mean temperature would reduce wheat yield, a major food staple, by 5-7% in Pakistan (Sivakumar and Stefanski, 2011).

The choice of sowing date is an important crop management option to optimize grain yield in such an environment where the major constraints to wheat grain yield in this region are inadequate rainfall and high temperatures during grain filling at the end of the season (Gomez-Macpherson and Richards, 1995; Radmehr *et al*., 2003; Turner, 2004). In this context, cropping system simulation models that have been evaluated with local experimental data can be valuable tools for extrapolating the short-duration field experimental results to other years and other locations (Mathews *et al*., 2002).

Crop simulation models integrate the interdisciplinary knowledge gained through experimentation and technological innovations in the fields of biological, physical and chemical science relating to agricultural production system (Bannayan *et al*., 2007; Soler *et al*., 2007; Andarzian *et al*., 2008). Therefore, these models can increase understanding and management of the agricultural system in a holistic way. Crop simulation models have been used to investigate the performance of different cultivars at a range of sowing dates in relation to different soil-climate scenarios (Stapper and Harris, 1989; Precetti and Hollington, 1997; Ghaffari *et al*., 2001; Bannayan *et al*., 2003; Heng *et al*., 2007; Bassu *et al*., 2009). The Decision Support System for Agro Technology Transfer (DSSAT4.5) is a comprehensive decision support system (Tsuji *et al*., 1998; Nain and Kersebaum, 2007; Hoogenboom *et al*., 2010) that includes the Cropping System Models CERES-wheat and CERES-barley (Ritchie *et al*., 1998). The CERES-wheat and CERES-barley models can be used to simulate the growth and development of dryland and irrigated wheat and barley across a range of latitudes in northern and southern hemispheres (Jones *et al*., 2003; Hoogenboom *et al*., 2010). The overall goal of this study was: (1) to evaluate the performance of the CERES-wheat and CERES-barley models for simulating growth, development, and grain yield of rainfed wheat and barley crops, and (2) to apply the calibrated CERES-wheat and CERES-barley models to determine optimize sowing dates and supplement irrigation depths for wheat and barley under rainfed conditions in Chakwal, Pakistan region.

Materials and Methods

Experimental site

The study was conducted at Barani Agricultural Research Institute (BARI) located within 72° longitude, 32° latitude and 575 m altitude in the district of Chakwal in Pakistan. The climate of Chakwal is semi-arid sub-tropical and the annual rainfall varies from 500-1000 mm most of which falls during monsoon season in the form of high intensity showers. The area also receives winter showers of lesser intensity during December to February. Experimental site is located in Chakwal district and the total area of the district is 825,578 hectares; 785,795 hectares of which is under cultivation and 39,783 hectares area is covered by the forests. About 8% of the total cultivated land is irrigated by canals, wells and tube-wells (Government of Punjab, 2013). About 70% of the population is engaged in farming or farm-related activities. Groundnut, barley and wheat are the main crops in the district. Sorghum, chickpea, canola, mustard, millet and gram are also grown by the farmers. Vegetables grown in the district include turnip, cauliflower, tomato, okra, onion and carrot. The main fruits are citrus and guava (Government of Punjab, 2009). In this study, two crops were selected - wheat and barley for modeling. Popular wheat and barley varieties of chakwal-50 and Joo-83 were used for model calibration, respectively, because these are high-yielding, drought-tolerant and disease-resistant popular wheat cultivar for rainfed areas of Punjab, Pakistan.

Weather and soil data

The climate data, maximum and minimum temperature (°C), rainfall (mm) and solar radiation (MJ m^{-2} d^{-1}) of last 31 years (1984-2015) were obtained for weather station of Soil & Water Conservation Research Institute (SAWCRI), Chakwal located adjacent to BARI. Data for the years 1984-2000 were in the raw form and contained missing values. The raw data was compiled in MS Excel and missing data were filled using climate data extrapolation software and were again converted to the format compatible to DSSAT modeling software. For the purpose of soil analysis, soil pit to depth of 100 cm was dug and the data of soil was measured (Table 1).

Crop model calibration and validation

Experimental conditions and results obtained from the location BARI were used as a database for calibration and validation of CERES-wheat and CERES-barley models in DSSAT 4.5 software to simulate and predict yield and yield components. The comparison between field-measured and predicted data were done through CERES-wheat and CERES-barley models under DSSAT interface in three steps-retrieval of data (converting data to CERES-wheat and CERES-barley models), validation of data (comparing between predicted and observed data) and running of the DSSAT model provided validation of the crop models. Necessary files were prepared as required. For calibration and evaluation, the simulated dates of anthesis and physiological maturity as well as yield and yield components were compared with the observed data. Different statistical indices were employed, including coefficient of determination (r square), absolute and normalized Root Mean Square Error (RMSE and NRMSE) and index of agreement (d-index).

The RMSE expressed in percent was calculated according to Loague and Green (1991) with Eq. (2).

Absolute RMSE equation is:

$$\text{RMSE} = \left[\sum_{i=1}^{n} \frac{(P_i - O_i)^2}{n}\right]^{0.5} \quad ...(1)$$

$$\text{RMSE} = \left[\sum_{i=1}^{n} \frac{(P_i - O_i)^2}{n}\right]^{0.5} \times \frac{100}{M} \quad ...(2)$$

where, P_i and O_i refer to simulated and observed values for the studied variables, respectively, e.g. days from sowing to anthesis, days from anthesis to physiological maturity and grain yield. M is the mean of the observed variable. Normalized RMSE gives a measure (%) of the relative difference of simulated versus observed data. The simulation is considered excellent when normalized RMSE is less than 10%, good if the normalized RMSE is greater than 10% but less than 20%, fair if normalized RMSE is greater than 20% but less than 30%, and poor if the normalized RMSE is greater than 30% (Jamieson *et al.*, 1991).

The index of agreement (d) proposed by Willmott *et al.* (1985) was calculated using Eq. (3). According to the d-statistic, the closer the index value is to one, the better the agreement between the two variables that are being compared and vice versa.

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|\acute{P}_i| + |\acute{O}_i|)^2}\right] \quad ...(3)$$

Table 1. Soil properties of experimental site

Soil depth (cm)	Saturated hydraulic conductivity (cm h^{-1})	Bulk density (g cm^{-3})	Organic carbon (%)	Clay (%)	Silt (%)	Nitrogen (%)	pH in water
18	0.75	1.52	0.45	6	16	0.04	9.1
61	0.60	1.70	0.35	14	8	0.02	9.1
98	0.80	1.60	0.20	6	20	0.02	8.9
151	0.83	1.39	0.02	8	22	0.02	8.9
198	0.80	1.42	0.02	10	6	0.02	8.9

Previous three years (2010, 2012 and 2013) data for wheat and barley were collected from the experimental site including following parameters: planting date, emergence date, anthesis date, row spacing, plant height, planting method, plant population at seeding, plant population at emergence, planting depth, maturity date, harvesting date, and yield.

Future climate scenarios

An analysis of the effect of different sowing dates and supplement irrigation on yield of wheat and barley were conducted using long-term 30 year historic (1984-2014) daily weather data of BARI. Six different sowing dates for wheat and barley (20 Oct, 30 Oct, 10 Nov, 20 Nov, 30 Nov and 10 Dec) and (15 Oct, 25 Oct, 5 Nov, 15 Nov, 25 Nov and 5 Dec) were simulated using the seasonal analysis tool of DSSAT Version 4.5 under rainfed and supplementally-irrigated conditions.

Results and Discussion

Calibration and validation of CERES-wheat and CERES-barley models

Results obtained from experimental field studies were used as indicators to test performance of CERES-wheat and CERES-barley models. Good agreement was observed between field-recorded values and values predicted by the models. The growth and development modules of the CERES models use different sets of species, ecotype and cultivar coefficients [(P1V, P1D, P5, G1, and G2, G3 and PHINT (Table 2)], which define the phenology and crop growth in time domain. The CERES-Wheat model was calibrated for Chakwal 50 cultivar and CERES-barley model for Joe-83 cultivar. For calibration, the cultivar coefficients were obtained sequentially, starting with the phenological development parameters related to flowering and maturity dates (P1V, P1D, P5 and PHINT) followed by the crop growth parameters related with kernel filling rate and kernel numbers per plant (G1, G2 and G3) (Hunt and Boot, 1998; Hunt *et al*., 1993). Although, GENCALC tool within DSSAT (Hunt and Pararajasingham, 1994) does this type of adjustment automatically and, therefore, uses the observations of phenological events from one or several experiments from a range of environments, we chose the manual approach because there were relatively few experimental data per cultivar, impeding the identification of optimal parameter values by such a mathematical algorithm. Godwin *et al*. (1989) suggest that such a manual, iterative approach usually reaches reasonable estimates of the genetic coefficients. The DSSAT models were calibrated by using the crop data of 2010, 2012 and 2013 (Table 3 and 4) and validated using the crop data of 2014 (Table 5).

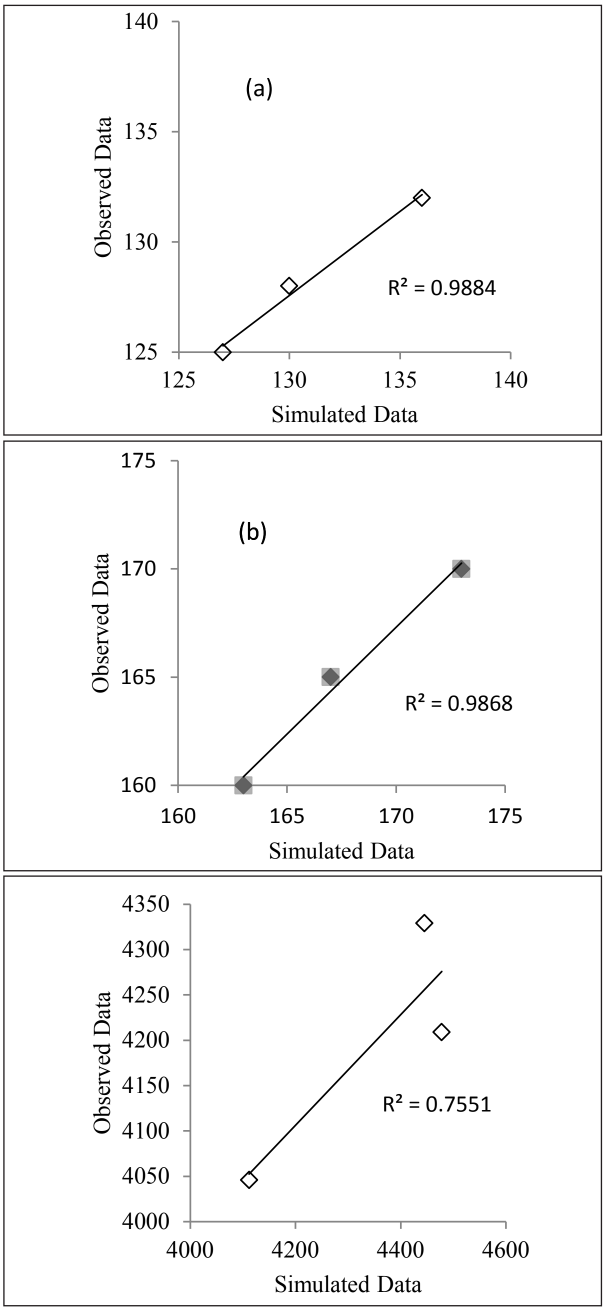


Fig. 1. Comparison between predicted and measured days after sowing to anthesis (a) and to maturity (b) and grain yield (kg ha⁻¹) (c) of wheat.

Table 2. Cultivar coefficients for Chakwal 50 and Joe-83 cultivar

Cultivar coefficients	Wheat (cv. Chakwal-50)	Barley (cv. Joe-83)
P1V	40	12
P1D	55	30
P5	550	625
G1	24	13
G2	26	21
G3	1.3	3
PHINT	70	70

P1V: Days, optimum vernalizing temperature, required for vernalization.
P1D: Photoperiod sensitivity coefficient (% reduction in rate/h near threshold).
P5: Grain filling (excluding lag) period duration (°C d)
G1: Kernel number per unit canopy weight at anthesis (#/g).
G2: Standard kernel size under optimum conditions (mg).
G3: Standard, non-stressed mature tiller weight (including grain) (g dwt).
PHINT: Thermal time between the appearance of leaf tips (°C d).

Phenological stages

The model was able to predict the anthesis date well as shown in Tables 6-9 and Fig. 1 and 2. The values for RMSE, normalized RMSE, index of agreement (d) and r square for anthesis date were 3d (days), 2%, 0.84 and 0.98, respectively. There was, also, a good match between predicted and observed physiological maturity dates. The values for RMSE, normalized RMSE, index of agreement (d) and r square for physiological maturity dates were 3d, 2%, 0.90 and 0.98, respectively. Spring barley was calibrated in the same way as wheat - the difference between the simulated and observed anthesis date as well as physiological maturity date varied between 2 and 3 d; the simulated yield was within 20% of the measured values for each year (r square = 0.99; RMSE = 174 kg ha^{-1}). All of the indices imply that there was a good agreement between simulated and measured durations from sowing to anthesis and from sowing to physiological maturity stages. Based on these results, it can be concluded that the model was very robust in predicting the critical phenological growth stages.

Scenario simulation

Planting dates treatments: An analysis of the effect of different sowing dates and supplement irrigation depths on yield of wheat and barley was conducted using long-term 30 year historic (1984-2014) daily weather data from BARI. Six different sowing dates (20 Oct, 30 Oct, 10 Nov, 20 Nov, 30 Nov and 10 Dec) were simulated using the seasonal analysis (Fig. 3) tool of DSSAT Version 4.5 under rainfed and supplementally-irrigated conditions. This period is the typical sowing window in the region, however, the early and late sowing dates are not suitable to obtain high grain yields, but due to the limitation of the available water, wheat may be sown early and due to delay in harvesting previous crops may be sown at end of the window. Seasonal analysis tool of DSSAT was provided with dates of sowing for rainfed, SI (supplement irrigation) at the time of sowing

Table 3. Wheat crop data used for DSSAT CERES-wheat model calibration

Parameter	Years		
	2010-2011	2012-2013	2013-2014
Planting date	10-Nov-2010	01-Nov-2012	05-Nov-2013
Emergence date	16-Nov-2010	09-Nov-2012	12-Nov-2013
Planting depth (cm)	10	10	10
Planting method	Dry seed	Dry seed	Dry seed
Plant population at seeding (plants m^{-2})	400	400	400
Plant population at emergence (plants m^{-2})	200	200	200
Row spacing (cm)	22.5	22.5	22.5
Anthesis date	15-Mar-2011	11-Mar-2013	14-Mar-2014
Plant height (cm)		97.8	
Maturity date	19-Apr-2011	10-Apr-2013	14-Apr-2014
Harvesting date	30-Apr-2011	24-Apr-2013	28-Nov-2014
Yield (kg ha^{-1})	4209	4329	4046

Table 4. Crop data used for DSSAT calibration for barley crop

Parameter	Year		
	2010-2011	2012-2013	2013-2014
Planting date	29-Oct-2011	04-Nov-2012	01-Nov-2013
Planting depth (cm)	10	10	10
Emergence date	04-Nov-2011	09-Nov-2012	07-Nov-2013
Plant population at seedling (plants m^{-2})	350	350	350
Plant population at emergence (plants m^{-2})	230	230	230
Planting method	Dry seed	Dry seed	Dry seed
Row spacing (cm)	30	30	30
Anthesis date	07-Feb-2011	08-Feb-2013	05-Feb-2014
Plant height (cm)	81.4	73.2	81.4
Tillage date	06-Oct-2011	06-Oct-2012	06-Oct-2013
Tillage implement	Cultivator	Cultivator	Cultivator
Tillage depth (inch)	8 to 12	8 to 12	8 to 12
Harvest area m^{-2}	1	1	1
Harvest method	Manual	Manual	Manual
Maturity date	23-Mar-2011	28-Mar-2013	4-Apr-2014
Harvesting date	22-Apr-2012	20-Apr-2013	23-Apr-2014
Yield (kg ha^{-1})	1480	1190	1250

Table 5. Crop data used for DSSAT validation of wheat and barley crop

Parameters	2014-2015 (wheat)	2014-2015 (barley)
Planting date	14-Nov-14	07-Nov-2014
Emergence date	20-Nov-14	10
Planting depth (cm)	10	12-Nov-2014
Planting method	Dry seed	330
Plant population at seeding (plants m^{-2})	400	200
Plant population at emergence (plants m^{-2})	200	Dry seed
Row spacing (cm)	22.5	30
Anthesis date	20-Mar-15	06-Feb-2014
Plant height (cm)	95	87
Maturity date	22-Apr-14	06-Oct-2014
Harvesting date	07-May-15	Cultivator
Yield (kg ha^{-1})	4100	8 to 12

Table 6. Statistical indices of evaluating the performance of CERES-wheat model in predicting phenological dates and simulating grain yield

Cropping years	Anthesis (DAP)		Physiological maturity (DAP)		Grain yield (kg ha^{-1})	
	Simulated	Measured	Simulated	Measured	Simulated	Measured
2010-2011	127	125	163	160	4478	4209
2012-2013	130	128	167	165	4445	4329
2013-2014	136	132	173	170	4112	4046
Index						
RMSE (day)[a]	3		3		173.0	
NRMSE (%)[b]	2.0		2.0		4.0	
d-stat[c]	0.84		0.90		0.68	
r-square[d]	0.98		0.98		0.75	

Table 7. Statistical indices of evaluating the performance of DSSAT CERES-barley model in predicting phenological dates and simulating grain yield

Cropping years	Anthesis (DAP)		Physiological Maturity (DAP)		Grain yield (kg ha^{-1})	
	Simulated	Measured	Simulated	Measured	Simulated	Measured
2010-2011	103	101	151	145	1704	1480
2012-2013	97	96	146	144	1341	1190
2013-2014	100	96	156	154	1459	1250
Index						
RMSE (day)	3		4		174	
NRMSE (%)	3		3		13	
d-stat	0.78		0.84		0.74	
r-square	0.75		0.82		0.99	

RMSE: Root mean square error.
NRMSE: Normalized root mean square error.
d-stat: Wilmot's index of agreement.
r-square: Coefficient of determination.

Table 8. Statistical indices for evaluating the performance of DSSAT model in predicting phenological dates and grain yield during validation

Cropping years	Anthesis (DAP)		Physiological maturity (DAP)		Grain yield (kg ha^{-1})	
	Simulated	Measured	Simulated	Measured	Simulated	Measured
2014-2015	128	126	161	159	4295	4100
Index						
RMSE (day)[a]	2		2		195	
NRMSE (%)[b]	2		1		5	

[a]RMSE: Root mean square error
[b]NRMSE: Normalized root mean square error

Table 9. Statistical indices of evaluating the performance of DSSAT model in predicting phenological dates and simulating grain yield for evaluation (validation)

Cropping years	Anthesis (DAP)		Physiological maturity (DAP)		Grain yield (kg ha^{-1})	
	Simulated	Measured	Simulated	Measured	Simulated	Measured
2014-2015	91	88	146	143	992	800
Index						
RMSE (day)	3		3		192	
NRMSE (%)	3		2		24	

RMSE: Root mean square error
NRMSE: Normalized root mean square error

and SI (supplement irrigation) 30 DAS. DSSAT model processed the provided information for previous 30 years (Fig. 3).

Model application: determining optimum sowing dates and Supplement irrigation for wheat: The analysis showed a long-term simulated yield ranged from 877 to 6422 kg ha^{-1} depending upon the sowing date. The highest yield was attained for sowing of 10-30 November with supplemental irrigation either at time of sowing or 30 DAS and the lowest yield at sowing on 20 October under rainfed conditions. Delay in sowing date from 20 October to 30 November resulted in yield increase. Grain yield decreased with delay in sowing from 30 November to 10 December (Fig 4). Figure 4 shows yield trend with dates of sowing and supplements irrigations - 1-6 are the 6 sowing dates under rainfed conditions, 7-12 are the 6 sowing dates with 30 mm supplement irrigation at the time of sowing (if initial moisture content in the soil is less for plant germination) and 13-18 are the 6 sowing dates with 30 mm supplement irrigation 30 DAS. It is clearly seen in the graph that the

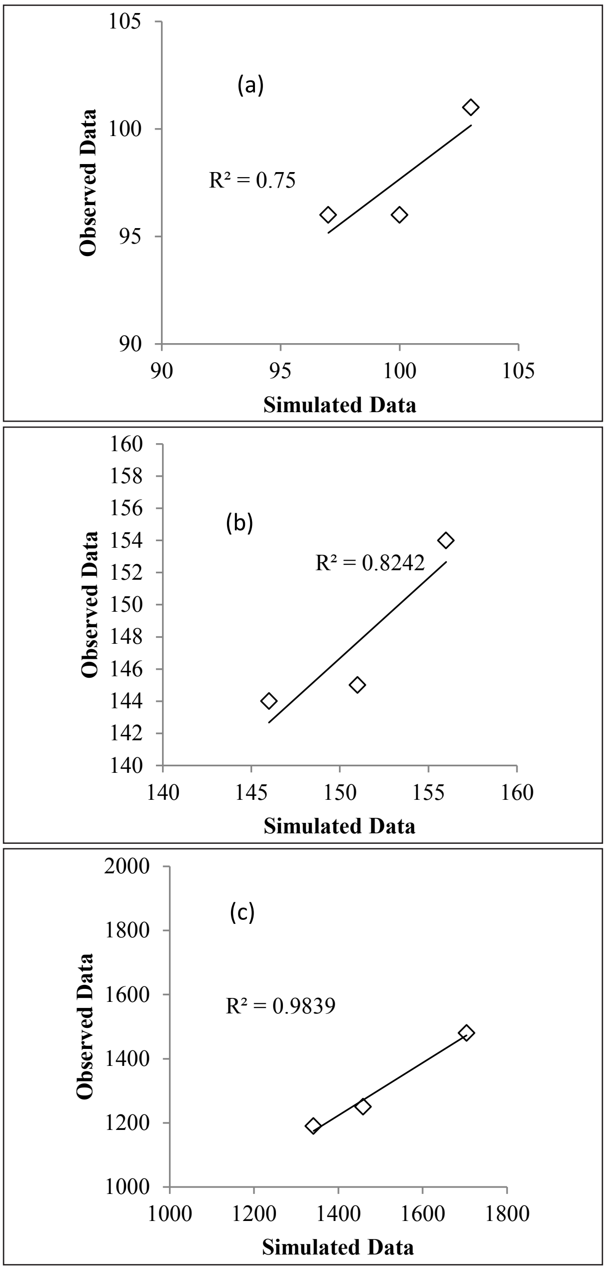


Fig. 2. Comparison between simulated and measured (a) anthesis day, (b) maturity day and (c) yield of barley cv. Joo-83.

highest yield with 50% probability could be attain if sowing date is 10 Nov to 30 Nov.

Effect of auto-irrigation on potential yield of wheat: When DSSAT was run with the condition of auto-irrigation (implying to apply irrigation automatically when there is a stress) with the same planting dates (20 Oct, 30 Oct, 10 Nov, 20 Nov, 30 Nov and 10 Dec), the model predicted following trend (Fig. 5) - the highest yield (6400 kg ha^{-1}) could be attained if wheat was sow on 20 October and if irrigation amount of 315 mm was applied. Potential yield was 6400 kg ha^{-1} with 315 mm supplement irrigation when sow on 20 October and farmer could attain 5000 kg ha^{-1} with 30 mm supplemental irrigation when sown between 20 and 30 November.

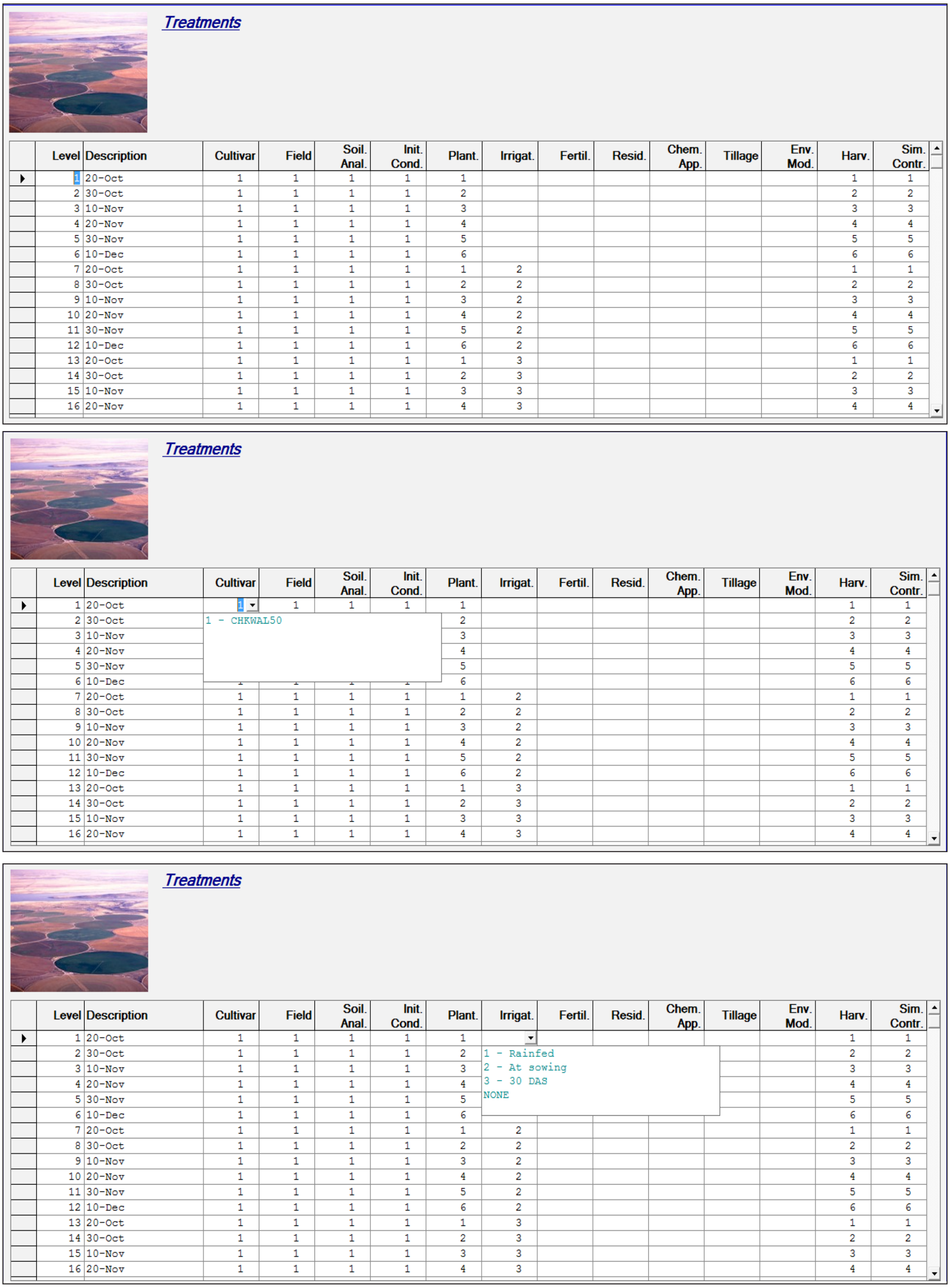
Model application: determining optimum sowing dates and Supplement irrigation for Barley: For barley, same treatments were considered as wheat except the sowing dates (Fig. 6). Sowing dates considered for barley were 15 Oct, 25 Oct, 05 Nov, 15 Nov, 25 Nov and 05 Dec. Higher yield could be attained if barley was sown on 5 December in case of rainfed condition and if there is a 30 mm supplemental irrigation then it should have been applied around 25 Nov at the time of sowing or 30 DAS. In case of auto irrigation scenario, model gave the highest yield with 50% probability on 05 December with 170 mm supplemental irrigation (Fig. 7). But a farmer can have maximum yield of 1200 kg ha^{-1} with 30 mm supplemental irrigation (Fig. 6).

Conclusions

It can be concluded from the obtained results that the CERES-wheat and CERES-barley model were reasonable at simulating crop phenology and grain yields compared with measured data. The normalized RMSE ranged between 2% and 13% for crop parameters which were predicted. The validated CERES-wheat and CERES-barley models were used as a research tool to provide estimates of climatically driven potential yield for different sowing dates in Chakwal, Pakistan conditions. The calibrated models were run using the seasonal analysis option of the DSSAT software to define the optimum sowing window for wheat and barley. Highest grain yields were generally obtained from sowing dates which have suitable equilibrium between anthesis and maturity dates and between grain yield as well. As a result, the simulated optimum sowing window for wheat in this region is between 20 November and 30 November, and 25 November and 05 December. As such models can be used to drive best management options in proportion with environmental conditions. Further model evaluations might also be needed for other cultivars which are released for this region.

Adaptations to Barani rainfed conditions

The analysis of the effects of different sowing dates on wheat and barley was conducted



Treatments

Level	Description	Cultivar	Field	Soil. Anal.	Init. Cond.	Plant.	Irrigat.	Fertil.	Resid.	Chem. App.	Tillage	Env. Mod.	Harv.	Sim. Contr.
1	20-Oct	1	1	1	1	1							1	1
2	30-Oct	1	1	1	1	2							2	2
3	10-Nov	1	1	1	1	3							3	3
4	20-Nov	1	1	1	1	4							4	4
5	30-Nov	1	1	1	1	5							5	5
6	10-Dec	1	1	1	1	6							6	6
7	20-Oct	1	1	1	1	1	2						1	1
8	30-Oct	1	1	1	1	2	2						2	2
9	10-Nov	1	1	1	1	3	2						3	3
10	20-Nov	1	1	1	1	4	2						4	4
11	30-Nov	1	1	1	1	5	2						5	5
12	10-Dec	1	1	1	1	6	2						6	6
13	20-Oct	1	1	1	1	1	3						1	1
14	30-Oct	1	1	1	1	2	3						2	2
15	10-Nov	1	1	1	1	3	3						3	3
16	20-Nov	1	1	1	1	4	3						4	4

Treatments

Level	Description	Cultivar	Field	Soil. Anal.	Init. Cond.	Plant.	Irrigat.	Fertil.	Resid.	Chem. App.	Tillage	Env. Mod.	Harv.	Sim. Contr.
1	20-Oct	1	1	1	1	1							1	1
2	30-Oct	1 - CHKWAL50				2							2	2
3	10-Nov					3							3	3
4	20-Nov					4							4	4
5	30-Nov					5							5	5
6	10-Dec					6							6	6
7	20-Oct	1	1	1	1	1	2						1	1
8	30-Oct	1	1	1	1	2	2						2	2
9	10-Nov	1	1	1	1	3	2						3	3
10	20-Nov	1	1	1	1	4	2						4	4
11	30-Nov	1	1	1	1	5	2						5	5
12	10-Dec	1	1	1	1	6	2						6	6
13	20-Oct	1	1	1	1	1	3						1	1
14	30-Oct	1	1	1	1	2	3						2	2
15	10-Nov	1	1	1	1	3	3						3	3
16	20-Nov	1	1	1	1	4	3						4	4

Treatments

Level	Description	Cultivar	Field	Soil. Anal.	Init. Cond.	Plant.	Irrigat.	Fertil.	Resid.	Chem. App.	Tillage	Env. Mod.	Harv.	Sim. Contr.
1	20-Oct	1	1	1	1	1							1	1
2	30-Oct	1	1	1	1	2	1 - Rainfed						2	2
3	10-Nov	1	1	1	1	3	2 - At sowing						3	3
4	20-Nov	1	1	1	1	4	3 - 30 DAS						4	4
5	30-Nov	1	1	1	1	5	NONE						5	5
6	10-Dec	1	1	1	1	6							6	6
7	20-Oct	1	1	1	1	1	2						1	1
8	30-Oct	1	1	1	1	2	2						2	2
9	10-Nov	1	1	1	1	3	2						3	3
10	20-Nov	1	1	1	1	4	2						4	4
11	30-Nov	1	1	1	1	5	2						5	5
12	10-Dec	1	1	1	1	6	2						6	6
13	20-Oct	1	1	1	1	1	3						1	1
14	30-Oct	1	1	1	1	2	3						2	2
15	10-Nov	1	1	1	1	3	3						3	3
16	20-Nov	1	1	1	1	4	3						4	4

Fig. 3. Scenario simulation window of seasonal analysis tool of DSSAT.

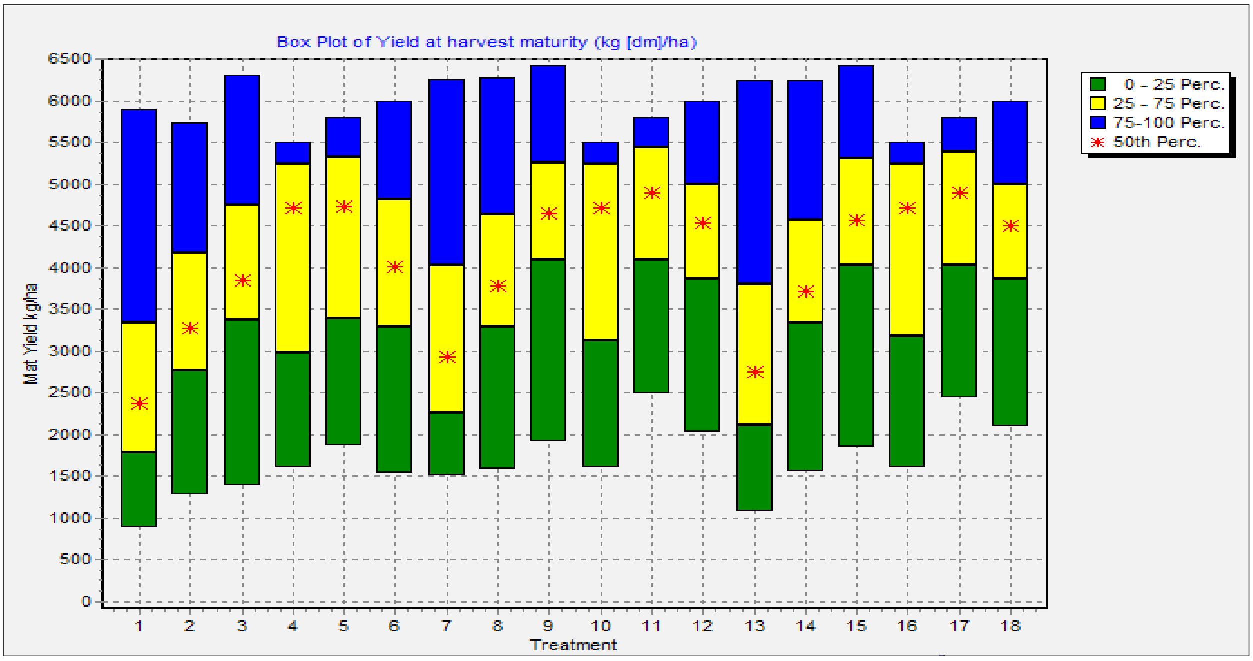
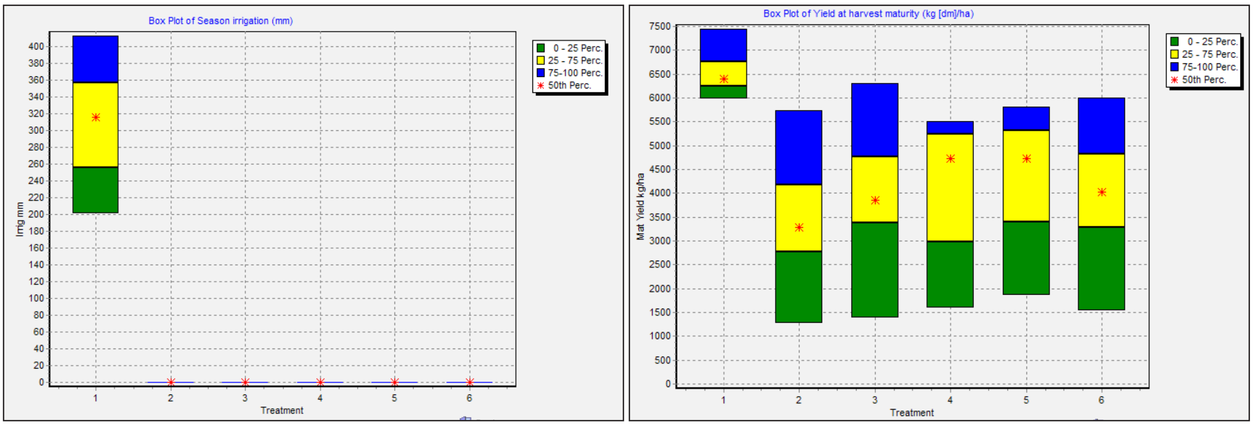


Fig. 4. Box graph showing increase or decrease in maturity yield kg ha^{-1} *(* in the boxes represent the 50*th *percentile (probability)). Treatments 1-6 are rainfed, 7-12 are under supplemental irrigation at sowing and 13-18 are under supplemental irrigation at 30 DAS.*



(a) (b)

Fig. 5. (a) Irrigation amount (b) potential yield of wheat as predicted by DSSAT.

based on 30 years of historical weather data from the BARI, Chakwal location

Shift of sowing time of crops (wheat and barley)

- In case of rainfed conditions, the best sowing date of wheat could be 20-30 November to have higher yields
- If the summer is wetter than normal, the best sowing date of wheat could be 20-30 November and if drier than normal, applying 30 mm of supplemental irrigation 30 DAS and planting wheat on 30 November can produce higher yield of wheat
- In case of rainfed conditions, the best sowing date of barley could be 05 December to have higher yields

Apply supplemental irrigation

- In case of drier than normal year, applying 30 mm of supplemental irrigation either at the time of sowing or 30 DAS and sowing wheat on 30 November and barley on 25 November can give good yield. In case of wetter than

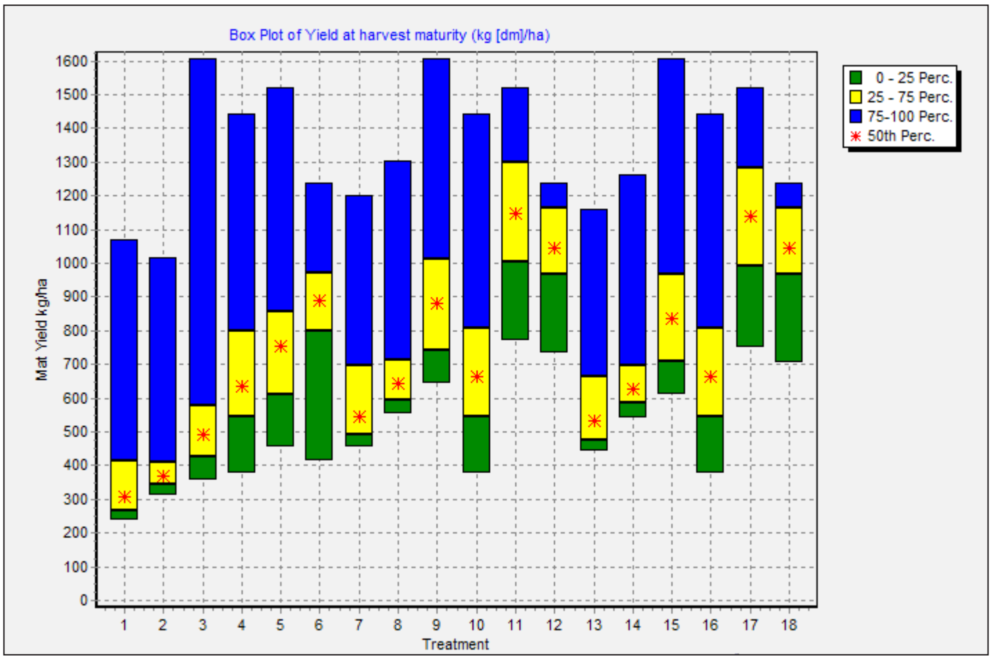


Fig. 6. Box graph showing increase or decrease in maturity yield (kg ha^{-1}) of barley. (in the boxes represent the 50th percentile (probability)). Treatment 1-6 are rainfed, 7-12 are under supplemental irrigation at sowing, and 13-18 are under supplemental irrigation at 30 DAS.*

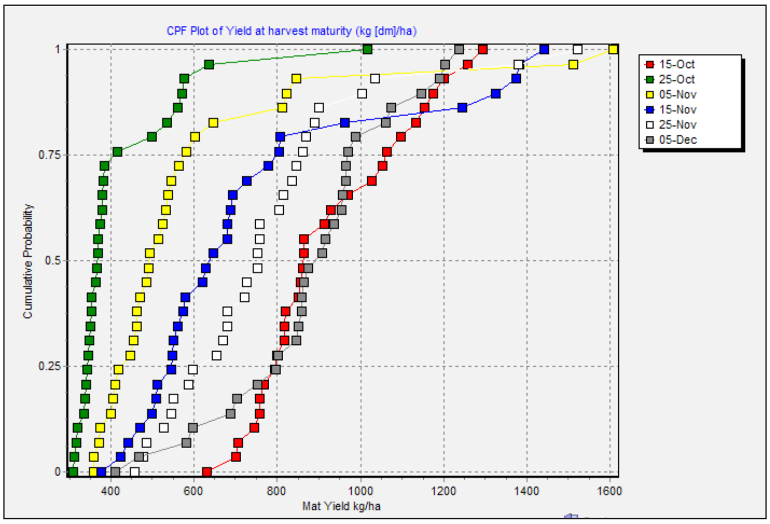


Fig. 7. Potential yield of barley with auto-irrigation scenario at 25%, 50% and 70% probability.

normal year, supplemental irrigation is not recommended but sowing wheat on 20 Nov and barley on 30 Nov or 05 Dec will be beneficial to crop production (Dry year means if the rainfall is less than 200 mm, normal year if rainfall is 500-600 mm and wet year means if rainfall is above 1000 mm. This wet, medium and dry category is based on last 30 year rainfall data set).

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