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Stochastic analysis of rainfall and its application in appropriate planning and management for Eastern India agriculture

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Abstract

Rainfall analysis is essential for agricultural crop planning and water resources management, especially under water scarcity conditions. The 36 years (1977–2013) of rainfall data for Kharagpur were analyzed for characterization of different seasonal events. The Weibull's formula predicted the probability of mean onset on 23rd standard meteorological weeks (SMW) (3rd–9th June) and withdrawal on 43rd SMW (21st–27th October). There was 80–83% probability of a wet week [P(W)] occurring within 25th–35th SMW. The first order Markov chain process shows the conditional probability of one wet week preceded by another wet week [P(W/W)] varied between 0 and 86%; whereas, dry week preceded by another dry week [P(D/D)] varied in the range of 70 to 100%. The stochastic analysis of successive wet or dry weeks formulates the adaptation strategies to avoid the possible effect of wet or dry spell during cropping seasons. The wet spell analysis suggests rainwater harvesting to control soil erosion and maximization of water use efficiency. The probability of getting consecutive wet [P(W/W)] and dry days [P(D/D)] were varied in the range of 40%–70% and 50%–90%, respectively. The probability of getting different magnitude of rainfall (10 to 40 mm) during the monsoon weeks (25th–39th week) were found to be more than 50% probability level, which suggest for harvesting of excess runoff water for future supplemental irrigation.

Keywords: Conditional probability; Markov chain model; Onset and withdrawal of monsoon; Supplemental irrigation (modified); Weibull's distribution

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Introduction

Water is a prime natural resource and a precious national asset. Therefore, planning, management and development of water resources need to be governed by national perspectives. The spatial and temporal availability of water is highly uneven. Precipitation is mainly confined within three or four months in the year and varies from 10 cm in the western parts of Rajasthan to over 1,000 cm at Cherrapunji in Meghalaya. Therefore, floods and drought affect vast areas of the country, transcending state boundaries. Moreover, dealing with drought and water scarcity has become an urgent policy objective, to be guided by the principles of conservation, protection of water quality, sustainability and equitable access. Long-term rainfall data are very useful for making decisions about agriculture water management and crop planning for drought-prone areas (Valipour, 2012). Indian agriculture is predominantly influenced by rainfall, specifically by the south-west monsoon rainfall (June–October) (Mandal *et al.*, 2013). Under a climate variability scenario, the rainfall distribution pattern has become erratic and unpredictable; subsequently increasing the probability of occurrence of a long dry spell or drought-like situation in the country. Sharma *et al.* (2010) reported that India stands first among the countries that practice rainfed agriculture both in terms of extent (86 M ha) and value of production. Ghildyal (1989) reported in his study that, in Eastern India, more than 70% of the net cultivated area is under rainfed farming with lowland rice as the principal rainy season crop with productivity of 1,586 kg ha^{-1} as compared to the country's average productivity of 1,921 kg ha^{-1} (Mandal *et al.*, 2013). But, it contributes only about 50% compared to irrigated ecosystems. There are many constraints that are associated with the small production of rainfed lowland rice of the region. The most important factor is the scarcity of available irrigation water during the cropping season (Panigrahi *et al.*, 2002). The ever increasing demand for the available water in various sectors other than agriculture, namely urbanization, industrialization, etc., is causing a reduction in the share of available water for agriculture farming. It is likely to also become a major constraint for other crops in the near future, under changing climatic conditions.

Therefore, sustainable development is needed in agricultural systems, in terms of proper water management, to increase water use efficiency under rainfed ecosystems and meet the increasing food demand. Kothari *et al.* (2007) revealed that harvesting of rainwater can be utilized as life-saving irrigation during severe moisture stress and also to raise the post-monsoon crops. This will also help in increasing the cropping intensity and net returns from the cultivated lands. Therefore, detailed knowledge of rainfall distribution may help in determining the appropriate planning of different agricultural operations and designing water harvesting structures to meet irrigation water requirements (Prakash & Rao, 1986). Previously many researchers have attempted to characterize rainfall in terms of its variability and probability distribution for sustainable crop planning (Rana & Thakur, 1998; Mohanty *et al.*, 2000). The study of the likelihood of onset and withdrawal of monsoon determines the crop planning, deciding cropping pattern and choice of suitable crop varieties throughout the year. It also helps in developing an efficient rainwater management strategy for improving crop productivity per unit of available water (Das *et al.*, 1998).

West Bengal, an important farming state of Eastern India, has about 70% of the population engaged in agricultural activities and contributes 50% into the state's economy (Panigrahi *et al.*, 2010). The agricultural production depends on the management of natural resources, especially rainwater that needs to be utilized properly to obtain sustainable crop production and food security for future generations (Kar & Singh, 2002). Therefore the scientific study of the magnitude and distribution of rainfall, both in space and time, will help in crop planning, making the best use of the rainfall pattern of an area to stabilize the crop production (Shetty *et al*., 2000). The stochastic analysis of consecutive dry and wet spells of a zone can also help to prepare crop planning, improve productivity and cropping intensity, and develop agricultural operations during and after the cropping season. The Markov chain probability model has been used by several researchers for finding out the long-term frequency behavior of wet and dry spells (Victor & Sastry, 1979) as well as for stochastic analysis of daily precipitation (Stern, 1982). The Markov chain model was also used to study the probability of dry and wet spells in the shortest period, i.e. a week, to demonstrate its utility in agricultural planning (Pandarinath, 1991; Dash & Senapati, 1992). The dry spell analyses have practical utility in contingency crop planning against drought. Like the stochastic analysis of rainfall, the forward and backward accumulation of rainfall data to determine the onset and withdrawal of monsoon also helps in crop planning. Delay in the onset of monsoon results in late sowing of rainy season crops, whereas pre-monsoon showers help in the land preparation and planting of wet season crops. Similarly, early withdrawal of rains causes a reduction in yield due to severe moisture stress at the critical growth stages like grain formation and seed development (Dixit *et al*., 2005). The annual and seasonal analysis of rainfall will provide a general idea about the rainfall pattern of the region, whereas the weekly analysis of rainfall will be of much use as far as agricultural planning is concerned (Mandal *et al*., 2013). Keeping all the scenarios in mind the following objectives were set for the study:

1. To analyze rainfall pattern, forewarning of onset and withdrawal of rainy season.
2. To investigate the initial, conditional probability and consecutive dry and wet spells by using the Markov chain model and to determine appropriate management practices in terms of supplementary irrigation for rice under weather variability conditions.

Materials and methods

Study area

The study was carried out for the Kharagpur subdivision of West Medinipur district of West Bengal, India. Kharagpur is located at 22.33°N latitude and 87.33°E longitude with an elevation of 48 m above the mean sea level (Figure 1). The study area has a sub-humid, sub-tropical climate, and it comes under the red and lateritic zone with an average temperature of 30°C and total annual rainfall of around 1,300 mm (1,665 mm last 30 years' average). The 36 years of mean rainfall has been represented in Figure 2.

The data set and estimation of effective rainfall

Rainfall data for 36 years (1977–2013) for this location were collected and analyzed season wise (winter, pre-monsoon, monsoon and post-monsoon). Weather data for 2009 were not considered for the analysis as the data set was incomplete. All the weather data were monitored by the Automatic Weather Station installed at the farm of the Agricultural and Food Engineering Department, Indian Institute of Technology Kharagpur. The monthly effective rainfall was calculated using Equations (1) and (2)

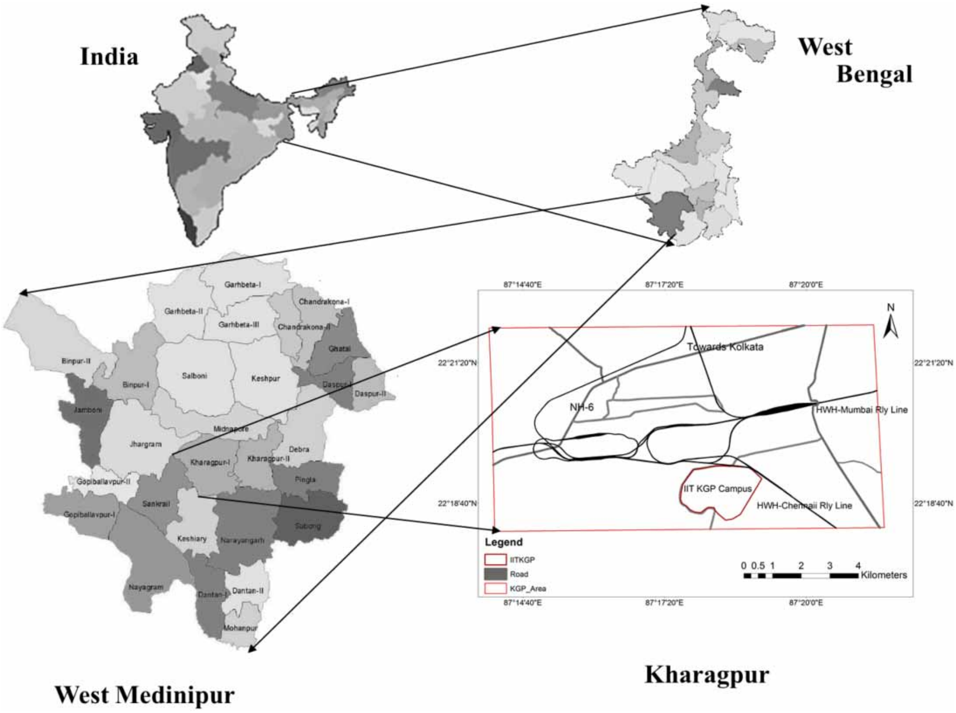

Fig. 1. Geographical representation of the study area (Kharagpur).

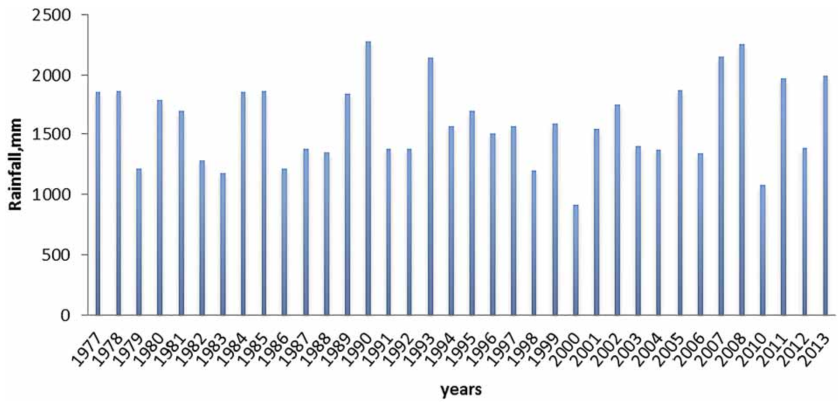

Fig. 2. Distribution of mean rainfall at Kharagpur for the period 1977 to 2013.

following the USDA Soil Conservation Service method. This method is being widely used in India for calculation of monthly effective rainfall (Sharma *et al.*, 2010).

$$P_e = \frac{P_t}{125}(125 - 0.2P_t)(\text{when}\, P_t < 250\text{mm}) \tag{1}$$

$$P_e = 125 + 0.1P_t(\text{when}\, P_t > 250\text{mm}) \tag{2}$$

where P_e = monthly effective rainfall (mm) and P_t = total monthly rainfall (mm).

Computation of onset and withdrawal of rainy season

The standard meteorological weeks (SMW) for the 36 years were taken into consideration. For computation of onset and withdrawal weeks of the rainy season, weekly rainfall data for the 36 years were used and forward and backward accumulation methods were used. In this process weekly rainfall was summed by forward accumulation ($21 + \ldots + 52$ weeks) until a certain amount of rainfall was accumulated. Seventy-five millimetres of rainfall accumulation has been considered as the onset time. The onset of the monsoon is essential during the growing seasons of dry-seeded crops and also for the land preparation for rainy season crops (Babu & Lakshminarayana, 1997; Panigrahi *et al*., 2002). The withdrawal of the rainy season was determined by backward accumulation of rainfall ($48 + 47 + 46 + \ldots + 30$ weeks) data. Twenty millimetres of rainfall accumulation was chosen for the end of the rainy season. The percent probability (P) of each rank was calculated by arranging them in ascending order and by selecting highest rank allotted for a particular week. The following Weibull's formula has been used for calculating percent probability:

$$P = \frac{m}{N+1} \times 100 \tag{3}$$

where m is the rank number and N is the number of years of data used. The weekly mean, maximum, minimum, standard deviation, coefficient of variation and percentage contribution to annual rainfall were also computed and tabulated.

State and order of Markov chain model

First order Markov chain. Defining $P(\text{w/w})$ as the probability of a wet day on day i given a wet day on day $i-1$, and $P(\text{w/d})$ as the probability of a wet day on day i given a dry day on day $i-1$, then $P(\text{d/w}) = 1-P(\text{w/w})$ is the probability of a dry day given a wet day on day $i-1$ and $P(\text{d/d}) = 1-P(\text{w/d})$ is the probability of a dry day given a dry day on day $i-1$. These transition probabilities are calculated for each month at each location of interest. Daily values of these probabilities are interpolated using previous years' data.

Second order Markov chain. With the second order Markov chain model, the probability of rain on a given day is conditioned on the wet or dry status of the previous days. A wet day is defined as a day with 0.01 inches of rainfall or more.

Let P_i (w/ww) be the probability of a wet day on a day i given a wet day on the day $i-1$ and $i-2$, P_i (w/dw) be the probability of a wet day on a day i given a dry day on the day $i-1$ and a wet day on the day $i-2$, P_i (w/wd) be the probability of a wet day on a day i given a wet day on the day $i-1$ and a dry day on the day $i-2$, and P_i (w/dd) be the probability of a wet day on a day i given a dry day on the day $i-1$ and $i-2$.

Then,

$$P_i\left(\frac{d}{ww}\right) = 1 – P_i\left(\frac{w}{ww}\right) \tag{4.1}$$

$$P_i\left(\frac{d}{dw}\right) = 1 – P_i\left(\frac{w}{dw}\right) \tag{4.2}$$

$$P_i\left(\frac{d}{wd}\right) = 1 – P_i\left(\frac{w}{wd}\right) \tag{4.3}$$

$$P_i\left(\frac{d}{dd}\right) = 1 – P_i\left(\frac{w}{dd}\right) \tag{4.4}$$

The transition probabilities are fully defined given P_i (w/ww), P_i (w/dw), P_i (w/wd) and P_i (w/dd).

Markov chain probability model for dry and wet spell analyses

In this study, weekly rainfall values have been computed from daily values and were used for initial, conditional and consecutive dry and wet spell analysis based on the Markov chain probability model as described by Pandarinath (1991). In this method, 20 mm or more rainfall in a week is considered as a wet week and is otherwise dry, as the previous researchers (Pandarinath, 1991; Dash & Senapati, 1992) also used 20 mm as the threshold value. Initial, conditional probabilities and consecutive dry and wet spell analysis for 52 SMWs were made using Equations (4)–(13). The successive dry and wet day analysis was carried out with the help of daily and weekly total rainfall for summer and monsoon season using the Excel logical function that counts the total number of successive wet and dry days.

The probabilities of successive wet and dry days were also determined following the first order Markov chain process. An initial and conditional probability of total weekly rainfall at different threshold limits (10, 20, 30, 40, 50, 60, 70 mm) was computed. The successive dry and wet day analysis was carried out with the help of daily and weekly total rainfall for monsoon season from the 21st to 48th weeks using the Excel logical function which counts the total number of successive wet and dry days. The probability of successive wet and dry days was then determined. The results of the stochastic analysis were separated on a yearly and weekly basis. The same rainfall data were also taken for determining the assurance level of rainfall in a particular week and in a particular year.

Initial probability

$$P(\mathrm{D}) = \frac{F(\mathrm{D})}{N} \tag{5}$$

$$P(\mathrm{W}) = \frac{F(\mathrm{W})}{N} \tag{6}$$

where P(D) = probability of the week being dry, F(D) = frequency of dry weeks, P(W) = probability of the week being wet, F(W) = frequency of wet weeks, and N = total number of years of data being used.

Conditional probabilities

$$P(\mathrm{DD}) = \frac{F(\mathrm{DD})}{F(\mathrm{D})} \tag{7}$$

$$P(\mathrm{WW}) = \frac{F(\mathrm{WW})}{F(\mathrm{W})} \tag{8}$$

$$P(\mathrm{WD}) = 1 – P(\mathrm{DD}) \tag{9}$$

$$P(\mathrm{DW}) = 1 – P(\mathrm{WW}) \tag{10}$$

where P(DD) = probability of a week being dry preceded by another dry week, F(DD) = frequency of dry week preceded by another dry week, P(WW) = probability of a week being wet preceded by another wet week, F(WW) = frequency of a wet week preceded by another wet week, P(WD) = probability of a wet week preceded by a dry week, and P(DW) = probability of a dry week preceded by a wet week.

Consecutive dry and wet week probabilities

$$P(2\mathrm{D}) = P(\mathrm{DW}_1) \times P(\mathrm{DDW}_2) \tag{11}$$

$$P(3\mathrm{D}) = P(\mathrm{DW}_1) \times P(\mathrm{DDW}_2) \times P(\mathrm{DDW}_3) \tag{12}$$

$$P(2\mathrm{W}) = P(\mathrm{WW}_1) \times P(\mathrm{WWW}_2) \tag{13}$$

$$P(3\mathrm{W}) = P(\mathrm{WW}_1) \times P(\mathrm{WWW}_2) \times P(\mathrm{WWW}_3) \tag{14}$$

where P(2D) = probability of two consecutive dry weeks starting with the first week of monsoon month, $P(\mathrm{DW}_1)$ = probability of the first week being dry, $P(\mathrm{DDW}_2)$ = probability of the second week being dry, given the preceding week being dry, P(3D) = probability of three consecutive dry weeks starting with the first week of monsoon month, $P(\mathrm{DDW}_3)$ = probability of the third week being dry, given the preceding week being dry, P(2W) = probability of two consecutive dry weeks starting with the first week of monsoon month, $P(\mathrm{WW}_1)$ = probability of the first week being wet, $P(\mathrm{WWW}_2)$ = probability of the second week being wet, given the preceding week being wet, P(3W) = probability of three consecutive wet weeks starting with the first week of monsoon month, and $P(\mathrm{WWW}_3)$ = probability of the third week being wet, given the preceding week being wet.

Results

Statistical analysis of long-term rainfall data

Descriptive statistics for the long-term rainfall data for Kharagpur has been presented in Table 1. The rainfall data can be assessed from their values of skewness and kurtosis. The result shows that the data are evenly distributed over the mean of the density function.

Table 1. Descriptive statistics of the rainfall data for Kharagpur for the period 1977–2013.

Year	Minimum	Maximum	Mean	Std. deviation	Skewness	Kurtosis
1977	0.00	255.60	35.79	56.26	2.43	6.68
1978	0.00	354.80	35.90	69.14	3.30	11.51
1979	0.00	240.60	23.46	45.22	2.93	10.41
1980	0.00	205.70	34.48	53.14	1.81	2.62
1981	0.00	148.50	32.79	38.28	1.26	1.04
1982	0.00	149.00	24.63	37.05	1.95	3.43
1983	0.00	121.20	22.75	28.39	1.57	2.30
1984	0.00	255.60	35.79	56.26	2.43	6.68
1985	0.00	354.80	35.90	69.14	3.30	11.51
1986	0.00	240.60	23.46	45.22	2.93	10.41
1987	0.00	222.60	26.61	41.96	2.76	9.60
1988	0.00	154.00	25.95	35.29	1.50	2.13
1989	0.00	248.10	35.50	62.16	2.10	3.72
1990	0.00	225.70	43.83	59.60	1.73	2.59
1991	0.00	268.50	26.55	44.87	3.48	16.20
1992	0.00	219.50	26.60	44.34	2.56	7.70
1993	0.00	294.20	41.30	64.15	2.15	4.75
1994	0.00	175.40	30.25	43.31	1.71	2.39
1995	0.00	160.20	32.72	44.17	1.46	1.16
1996	0.00	235.40	28.96	51.84	2.34	5.37
1997	0.00	194.60	30.34	40.71	1.93	4.43
1998	0.00	123.70	23.16	30.78	1.78	2.64
1999	0.00	241.60	30.75	49.07	2.26	6.34
2000	0.00	141.00	17.59	32.78	2.57	6.54
2001	0.00	119.90	29.79	38.33	1.16	0.05
2002	0.00	263.70	33.70	52.99	2.40	6.69
2003	0.00	157.20	26.99	41.19	1.75	2.34
2004	0.00	161.00	26.44	37.72	1.54	2.03
2005	0.00	258.60	36.00	58.78	2.16	4.51
2006	0.00	163.30	25.92	45.86	1.98	3.00
2007	0.00	533.90	41.46	89.31	3.86	18.27
2008	0.00	766.70	43.48	108.77	5.98	39.96
2010	0.00	144.00	20.78	28.90	2.04	5.51
2011	0.00	567.70	37.98	88.46	4.69	26.03
2012	0.00	128.00	26.68	31.35	1.41	1.58
2013	0.00	338.00	38.44	65.86	2.50	7.67

Long-term annual rainfall, effective rainfall analysis

The cumulative annual rainfall of Kharagpur region over 36 years ranged from 186.7 to 13,045.0 mm with an average of 1,954.9 mm over 36 years. If rainfall received in a year was equal to or more than the average rainfall plus one standard deviation for 36 years of rainfall (i.e. $1{,}954.9 + 1{,}593.37 = 2{,}114.2$ mm), it was considered as an excess rainfall year (Sharma & Kumar, 2003). On four occasions (1990, 1993, 2007 and 2013), this region received rainfall of more than 2,114.2 mm; these years were considered as excess rainfall years. Only 9% of the total years of analyses under this study received rainfall of more than 2,114.2 mm for this region. It can also be observed that in most of the cases (91%) the total annual rainfall was below 2,114.2 mm, which were considered as deficit rainfall years. Monthly average and effective rainfall of Kharagpur region for 36 years are presented in Figure 3. It is revealed that mean rainfall of July (420.79 mm) was the highest and it contributed 22% to the average annual rainfall (which was 1,954.82 mm). August rainfall was slightly lower than July rainfall (i.e. 18% of average annual rainfall). Average rainfall was moderate in the month of December.

Analyses of rainfall for onset and withdrawal of monsoon season

The weekly rainfall data analysis indicated that the monsoon starts effectively from the 23rd SMW (3rd–9th June) and remains active up to the 43rd SMW (21st–27th October). Therefore, the mean length of the rainy season was found to be 21 weeks (147 days). The earliest and delayed week of onset of the rainy season was the 21st SMW (21st–27th May) and the 26th SMW (24th–30th June), respectively. Similarly, the earliest and delayed week of cessation of the rainy season was the 38th SMW (16th–22nd September) and the 48th SMW (25th November–1st December), respectively. The longest and shortest length of the rainy season coincided with 28 and 13 weeks, respectively. The probabilities of onset and withdrawal of the rainy season were calculated by using Weibull's formula and results are presented in Figure 4. The results reveal that there is an 84.84% chance that the onset and withdrawal of the rainy season will occur during the 25th and 48th SMW, respectively.

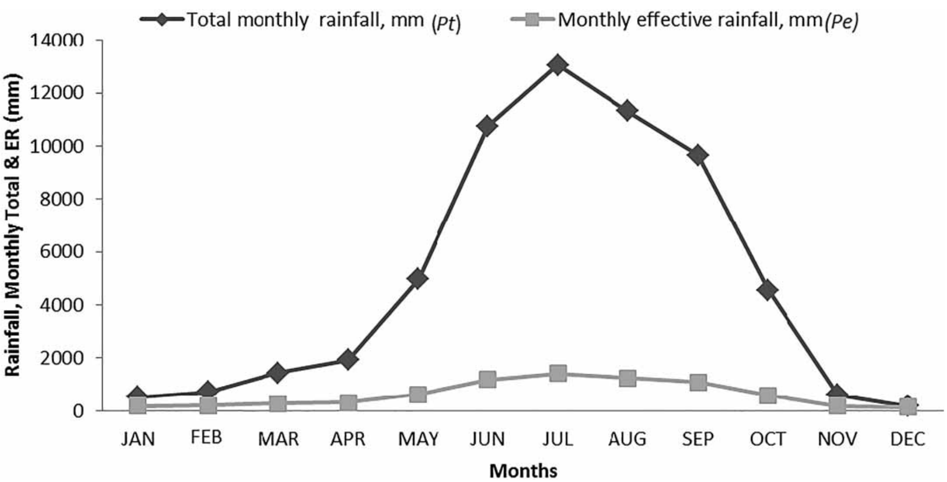

Fig. 3. Long-term average monthly rainfall and effective rainfall for Kharagpur (ER: effective rainfall).

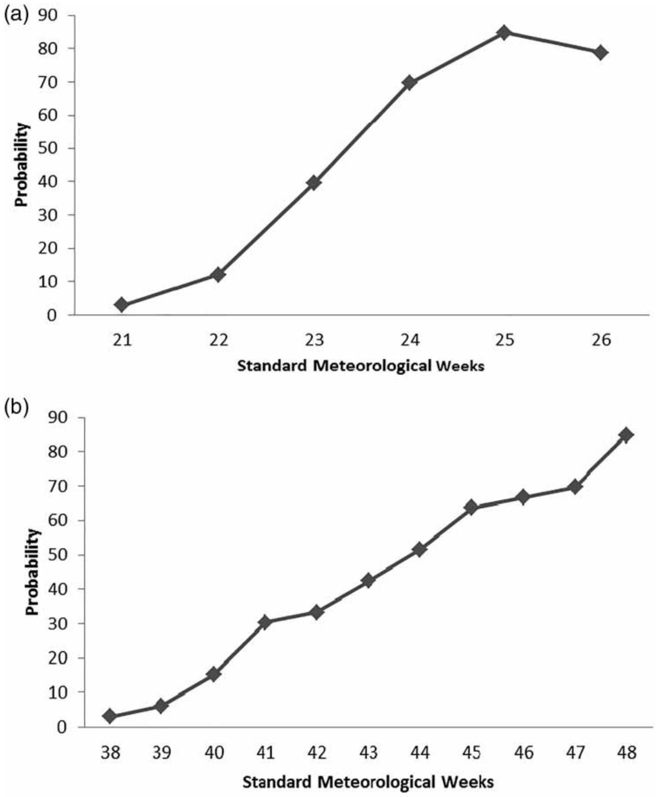

Fig. 4. Probability of (a) onset and (b) withdrawal of rainy season at Kharagpur.

Markov chain model

Conditional probability analysis (dry and wet weeks). Results of the initial and conditional probabilities of dry and wet weeks are presented in Figures 5 and 6 for the 52 standard meteorological weeks. The results reveal that the probability of occurrence of a dry week was high up to the end of the 22nd SMW. The range of probability of occurrence of a dry week from the 1st to 20th SMW was from 72 to 94%. The probability of occurrence of a dry week preceded by another dry week [*P(*D/D*)*] and that of a dry week preceded by a wet week [*P(*D/W*)*] vary from 70% to 100% and 50% to 100%, respectively, during the 1st–20th SMW period. Similar results of initial and conditional probabilities of dry and wet days and consecutive dry and wet days of Khorram Abad and Zahedan synoptic stations have been reported by Shahraki *et al*. (2013). However, from the 25th to 35th SMW the probability of both *P*(D) and *P*(DD) are low. The probability that these weeks (25th to 35th SMW) remain wet [*P*(W)] varies from 80 to 83%. The conditional probability of a wet week preceded by another wet week [*P(*W/W*)*] varies from 0 to 86%. The chances of occurrence of dry spells were again high from the 41st SMW to the end of the year.

The analyses of consecutive dry and wet spells (Figures 7 and 8) reveal that there was a 26–89% chance that two consecutive dry weeks [*P*(2D)] will occur within the first 20 weeks of the year. Similarly, the probability of occurrence of three consecutive dry weeks [*P*(3D)] varied from 0–79% in the

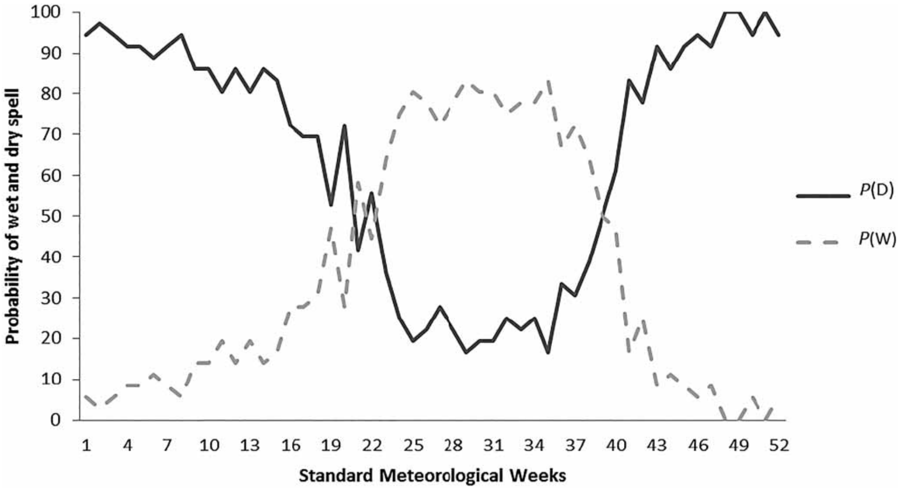

Fig. 5. Probability of wet spell and dry spell at Kharagpur over 36 years (1977–2013).

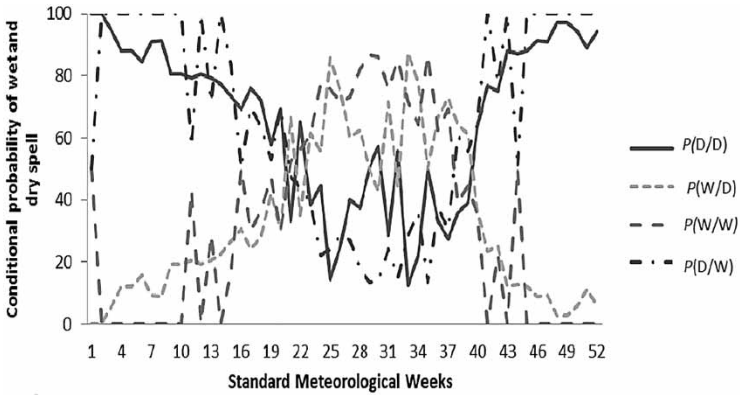

Fig. 6. Conditional probability of wet spell and dry spell at Kharagpur over 36 years (1977–2013).

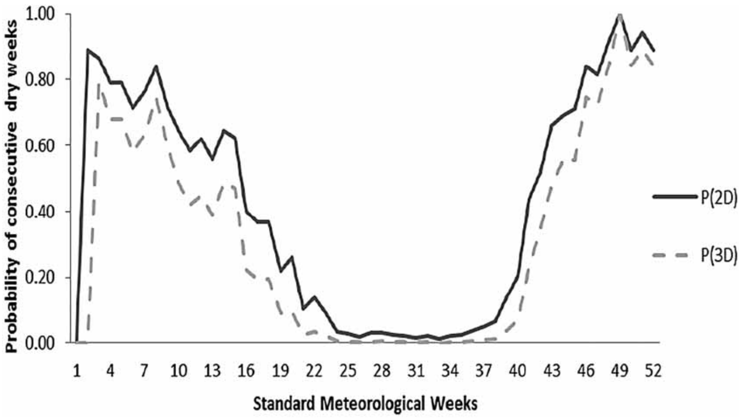

Fig. 7. Markov's chain probability showing standard meteorological weeks of consecutive dry spells for different probability levels at Kharagpur.

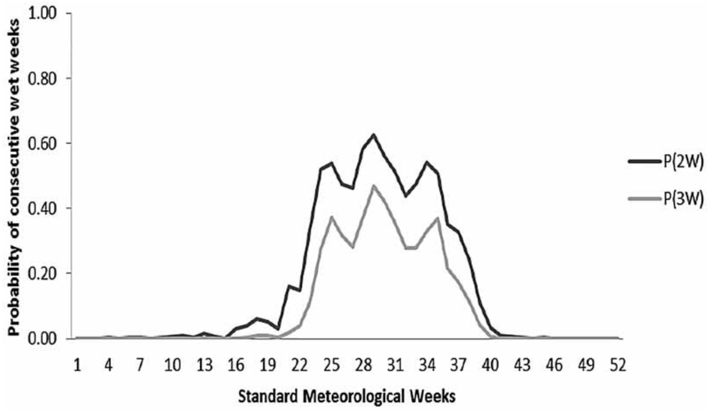

Fig. 8. Markov's chain probability showing standard meteorological weeks of consecutive wet spells for different probability levels at Kharagpur.

first 20 weeks of the year. The corresponding values of two and three consecutive wet weeks [i.e. *P*(2W) and *P*(3W)] from the 1st to 20th SMW were very low with values 0% and 0% to 3%, respectively. From the 21st to 40th SMW, the chances of occurrence of two and three consecutive dry weeks are only within 10% to 20% and 0% to 7%, respectively. Conversely, there were chances of 1% to 63% and 0% to 47% that the weeks from the 21st to 40th SMW will be getting sufficient rain with two and three consecutive wet weeks, respectively. This study reveals that the last 12 weeks of the year (41st to 52nd weeks) may remain under stress on an average, as there was an 85% chance of occurrence of two consecutive dry weeks. The corresponding value for three consecutive dry weeks during the period was 75%.

Conditional probability analysis (dry and wet days). Conditional probability analysis of weather data for 36 years (1977–2013) was carried out with reference to summer and monsoon rainfall. The probability of getting two consecutive wet days [*P*(w/w)] during the summer was noted to vary between 10–70%, whereas the probability of getting a dry day followed by a wet day [*P*(d/w)] varied between 30–90%. The probability of getting a dry day followed by a dry day [*P*(d/d)] varied between 60–90% and the probability of getting a wet day followed by a dry day ranged between 10–40% (Figure 9(a)) during the summer season. These results will be useful for providing supplemental irrigation to summer crops and also to analyze the effect on crop growth. The results of the monsoon data show that the probability of getting two consecutive wet days [*P*(w/w)] varied between 40–70%, whereas the probability of getting a dry day followed by a wet day [*P*(d/w)] varied in the range of 30–60%, as shown in Figure 9(b). It can also be seen that the probability of getting dry followed by dry days [*P*(d/d)] as well as wet days followed by dry days [*P*(w/d)] were in the range of 50%–90% and 10%–40%, respectively.

Stochastic analysis of successive wet and dry days during summer and monsoon seasons

Successive wet days. The stochastic analysis of successive wet and dry days has been shown in Figures 10 and 11(a) and 11(b). The analysis of successive wet days over 33 years during summer and monsoon

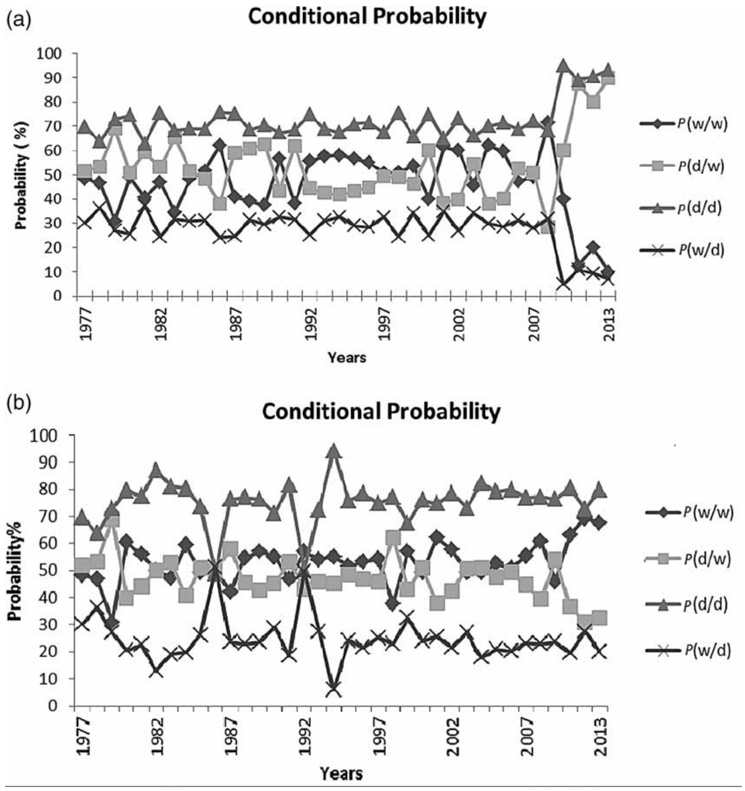

Fig. 9. Conditional probability of getting rainfall during (a) summer and (b) monsoon seasons (1977–2013).

season reveals that the probability of occurrence of two successive wet days was between 0–25% and 5–30% during both the seasons. However, the probability of three, four and five successive wet days varied in a lower range (Figure 10(a) and 10(b)). These results indicate that supplemental irrigation was needed to maintain proper soil moisture at critical growth stages during the summer crop season and also stagnant water was needed in the case of rainfed rice.

Successive dry days. The probability of occurrence of two successive dry days varied between 40–80% during the summer season and 30–60% during monsoon season, as shown in Figure 11(a) and 11(b). The probability of occurrence of four successive dry days was found to be less as compared to others. These results indicate that to sustain higher yield of summer crop as well as rainfed rice, supplemental irrigation is needed to avoid stress during critical growth stages.

Stochastic analysis of annual and seasonal rainfall

The results of stochastic analysis of annual and seasonal (monsoon) rainfall are shown in Figures 12 and 13. The probability of having weekly rainfall magnitude of more than 10 mm ranges between 0 and 100% with the highest probability of 100% during the 48th standard meteorological week. It was observed that the probability of occurrence of more than 20 mm weekly rainfall ranges between 20

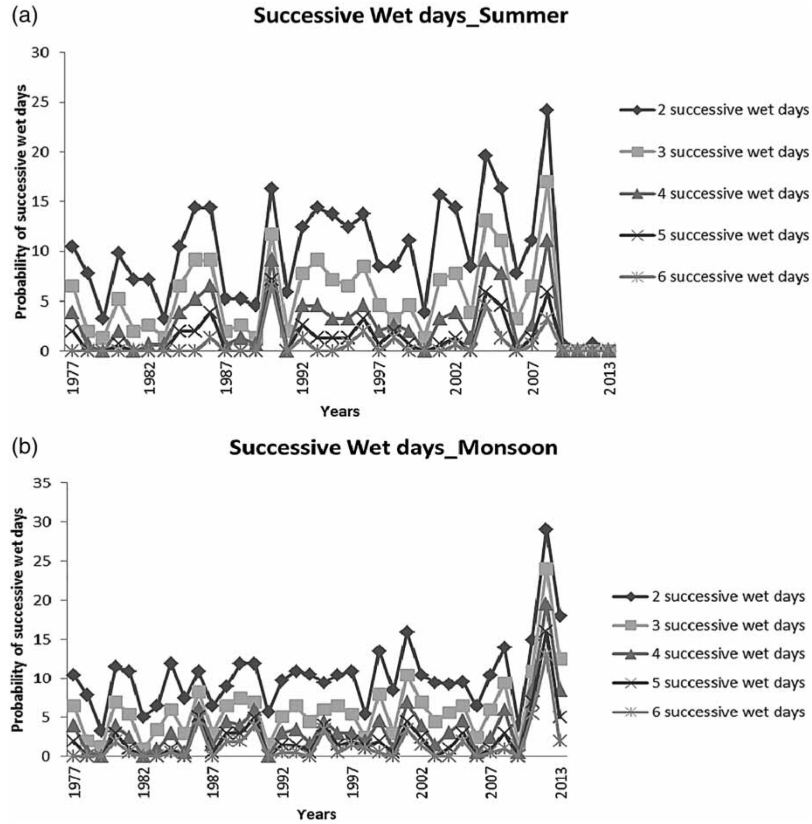

Fig. 10. Probability of getting successive wet days during (a) summer and (b) monsoon seasons (1977–2013).

and 95%, whereas the probability of having at least 30 mm weekly rainfall was 0–80% throughout the monsoon week over 36 years. Similarly, the probability of having 50, 60 and 70 mm weekly rainfall was 25 to 65% (Figure 12). The stochastic analysis of occurrence of yearly total rainfall during monsoon weeks (21st to 48th week) has also been carried out. The probability of getting more than 10 mm rainfall ranged between 65 and 85%, whereas the probability of getting more than 20 mm rainfall ranged between 80 and 95% throughout the crop season, as shown in Figure 12. The probabilities of getting more than 30, 40, 50, 60 and 70 mm rainfall ranged between 40 and 50% (Figure 13).

Discussion

Rainfall analyses, crop planning and management

Effective rainfall is the fraction of the total rainfall that is received on the cropped area, during a specific period to meet the potential transpiration requirements in the cropped area (Bos *et al*., 2009). Most of the rainfall received during monsoons is lost due to surface runoff, deep percolation and evaporation. In the case of rainfall of high intensity, only a part of the rain enters and is stored in the root

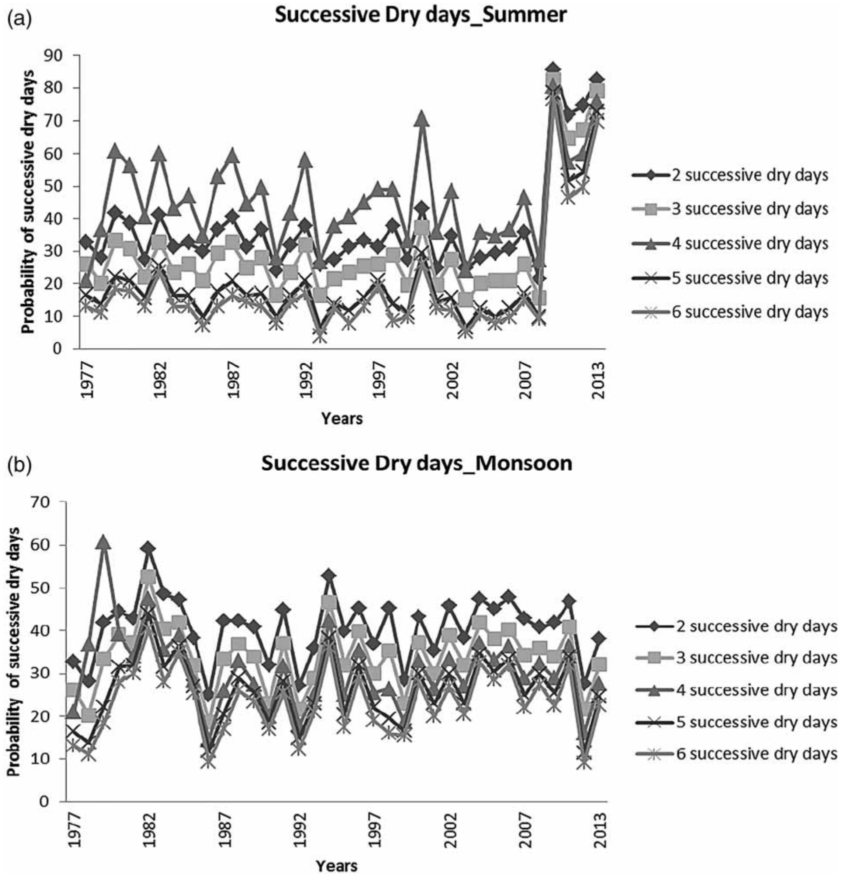

Fig. 11. Probability of getting successive dry days during (a) summer and (b) monsoon seasons (1977–2013).

zone. Therefore the quantity of effective rainfall during the rainy season is low. The study of Panigrahi *et al.* (2002) reveals that the occurrence of effective monsoon rainfall in Eastern India is highly fluctuating and is ranging from 21st May to 25th July, whereas rainfall distribution during winter and pre-monsoon season, that is for about 5 months, is much less. Therefore, it is essential for the farming community to have a rainwater storage reservoir, so that they can store the rainwater in the pond and use it as supplemental or life-saving irrigation to post-monsoon crops. Crop selection during the post-monsoon and winter season can also be made based on the availability of stored water in the reservoir.

For rainfed agriculture, rainfall is the only source of water. Deficiencies of rainfall during the crop growing season can cause a drought/dry spell situation. A severe drought or dry spell during the critical growth stages of crops enhances the reduction of crop yield. Therefore, detailed analysis of rainfall data for the study area can be useful for agricultural planning, to reduce the yield reduction during drought or dry spell conditions. According to the analysis of onset of monsoon season, the mean onset of the rainy season was found to be the 23rd SMW (3rd–9th June). The probability of a wet week was more than 60% and average weekly rainfall was more than 59 mm. So, the sowing or land preparation operations can be taken up during this time. Sowing operations at the 23rd SMW helps for good germination of

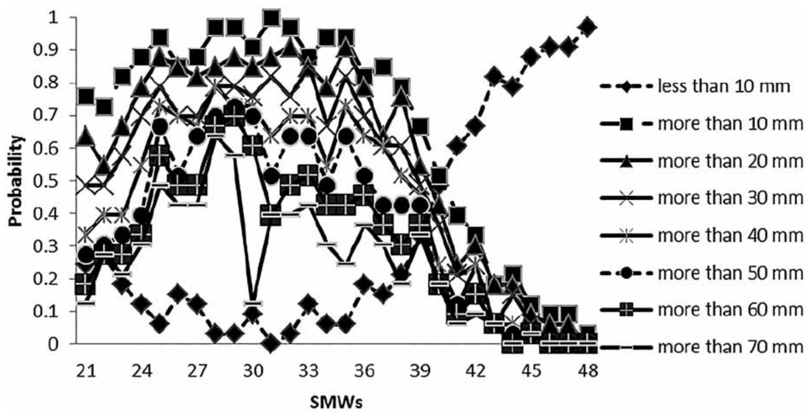

Fig. 12. Probability of exceedance of weekly monsoon rainfall at different magnitudes (1977–2013).

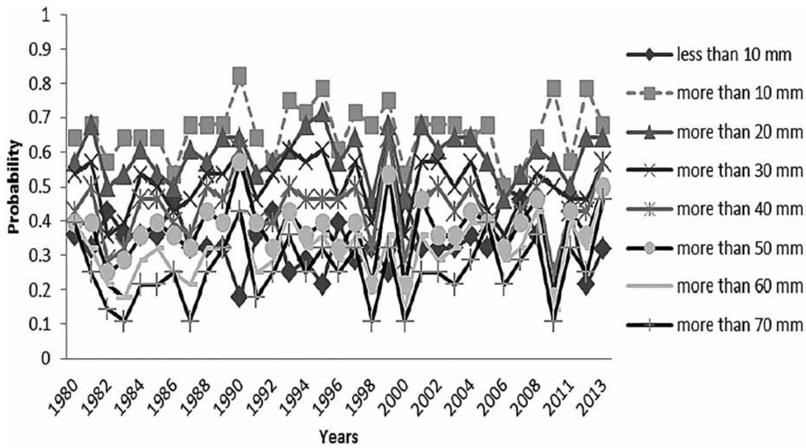

Fig. 13. Probability of exceedance of yearly monsoon rainfall at different magnitudes (1977–2013).

seeds and avoids moisture stress during the germination period of 25th–27th SMW. In the case of delayed start of the rainy season the sowing operations can be taken up by the 26th SMW (24th June–30th June) at the latest, but further delay in sowing cause very low productivity. The analysis also revealed that the mean length of the rainy season at Kharagpur was 21 weeks (i.e. 147 days) during the Kharif season (monsoon). Therefore, long-duration rice of 130–140 days duration can effectively utilize the entire monsoon rain and the crop can be harvested well before the withdrawal of monsoon. This will minimize the chance of moisture stress during the critical growth stages and thus improve the yield. Short duration and low water-requiring crops like groundnut, pigeon pea, maize, green gram, soybean, etc., can be taken up as high value alternative cash crops after the harvest of short duration rice (100–110 days). Growing of these short duration crops like cereals, pulses and oilseeds helps to properly utilize the residual soil moisture and fertilizers and will provide a quality product within a very short period of time. Cultivation of short duration pulses and oilseed crops, like groundnut, after rice cultivation will effectively utilize the residual soil moisture and improve the soil quality and health by adding atmospheric nitrogen into the soil through the root nodules. According to Mandal *et al*. (2005, 2006) by saving limited irrigation water we can explore the potential benefits of irrigation and nutrient interaction.

The results of the study show that the mean date of withdrawal of monsoon was found to be during the 43rd week (21st–27th October). Withdrawal of monsoon can vary from the 36th week (16th–22nd September) to the 48th week (25th November–1st December). But, rainfall received after the 43rd week is reduced, so delayed sowing of rice crop, after July or the beginning of August, may cause water stress during the critical growth stages during the grain filling stage. On the other hand, high value *rabi* crops can be grown during the 40th–43rd SMW (1st–28th October) with the residual soil moisture, to get a good crop stand at the initial growing stages without supplementary irrigation. This will increase the water use efficiency (Mandal *et al*., 2013) and give real economic return.

The conditional probability analysis of weekly rainfall contributes significantly during the 25th–36th SMW with high consecutive wet week probability during the 24th–37th SMW. Similarly, the probability of getting different magnitudes of rainfall during the monsoon weeks (25th–39th week), i.e. more than 10, 20, 30, and 40 mm rainfall is greater than 50%. This results hints at the benefit of harvesting excess runoff water for future supplemental irrigations. However, the probability of getting more than 10 mm rainfall was around 60%, which suggests use of supplemental irrigation to avoid moisture stress during the cropping season. High consecutive dry week probabilities after the 42nd SMW, indicate the need for supplementary irrigations and moisture conservation practices, like mulching, etc., that will help in reducing soil evaporation and conserve moisture in top layers of the soil. It is clear from the analysis that, since the probability of occurrence of a wet week was more than 45% during the 20th–22nd SMW and average weekly rainfall ranged from 19.24 to 37.5 mm, this pre-monsoon rain can be utilized for summer ploughing and initial seed bed preparations. The above study also shows that an average rainfall of 358.1 mm was obtained in the month of June. Therefore, the sowing operation of different rainy season crops and nursery bed preparation for rice can be carried out in the month of June with the commencement of southwest monsoon. In the month of July the observed rainfall was 420.79 mm. Therefore, rice transplanting can be performed by utilizing this vast amount of rainfall during this month. The transplanting of rice in the first week of July will have additional advantages of assured irrigation through rain during the critical growing periods in the months of August and September. Paddy can also be substituted with low water-requiring, high value cash crops through sole or intercropping, to increase the rainwater use efficiency productivity and improve soil health. In these intercropping practices under upland situations, water does not stagnate in the field. Thus, weed management should be appropriate for a clean crop stand. Since the rainfall after October was uncertain and erratic, sowing of high value crops without supplementary irrigation is not advisable. Since the probability of occurrence of a wet week was more than 30% during the 19th–21st SMW (7th–27th May) and average weekly rainfall ranged from 24.1 to 40.7 mm, the pre-monsoon rain can be utilized for summer ploughing and seed bed preparations.

The detailed analysis of conditional probability of getting consecutive wet or dry days [P (w/w)] or [P(d/d)] during the summer suggested providing supplemental irrigation to summer crops to ensure a stress-free situation during the different critical growth stages of the crop plants. The results of conditional probability during the monsoon precipitation show that the probability of getting consecutive wet or dry days [P(w/w)]/ [P(d/d)] varied between 40%–70%, and 50%–90%, respectively. Therefore, rainy season crops may get more consecutive dry days that may hamper the growth stages and require frequent watering through supplemental irrigation to meet the water demand. The stochastic analysis results show that the probability of getting two successive dry days during summer and monsoon months was more than 80% and 40%, respectively. This may cause the dry period to coincide with a sensitive stage in crop growth, leading to reduction of yields (Oldeman & Frere, 1982). Therefore, to avoid this yield reduction, supplemental irrigation can be applied despite the fact that erratic rainfall may occur on the irrigated land.

Conclusions

Total annual rainfall of the study area ranged from 186.7 to 13,045.0 mm (average of 1977 to 2013 rainfall data) with an annual average of 1,945.82 mm. The normal southwest monsoon, which delivers about 75.7% of annual rainfall, extends from June to September, and is the main season (rainy season) for cultivation of rainfed crops; the other seasons viz. pre-monsoon (March–May), post-monsoon (October–December) and winter season (January–February) contribute only 10.8, 10.4 and 3.1% of the total annual rainfall. Effective rainfall during monsoon season causes water loss through runoff, deep percolation and evaporation. Due to the high intensity of monsoon rainfall, a tiny portion of the water can enter into the root zone and most of the rainwater drains out from the upper soil surface. This estimated loss of water influences greatly in reducing the crop water use efficiency during the later half of the crop growing period. Therefore, construction of properly designed rainwater harvesting structures can harvest local runoff flow and store it in reservoirs to use further as supplementary irrigation during dry spells. The above-mentioned strategy can improve the productivity of crops and water in the rainy season in high rainfall regions. The stochastic analyses of rainfall using the Markov chain model develops the knowledge of the probability of getting consecutive dry and wet weeks or dry and wet days during the cropping season, which can formulate the mitigation strategies to avoid the possible effect of dry or wet spells on crop planning and management. The study of conditional probability of successive wet and dry weeks or days suggests harvesting of rainwater and supplemental irrigation during the dry spells between the cropping seasons. Effective soil conservation practices, namely mulching and other moisture conservation practices, can also be helpful in increasing the water use efficiency by reducing soil evaporation and conserving moisture in top layers of the soil during the dry weeks of the cropping season. These management strategies will help to lead our country to form improved water policies to combat future challenges.

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