



Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Extreme rainfall indices and its impact on rice productivity—A case study over sub-humid climatic environment

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ARTICLE INFO

Article history:

Received 21 October 2010

Accepted 15 April 2011

Available online 10 May 2011

Keywords:

Extreme rainfall indices

Mann–Kendall nonparametric test

Trend analysis

Agro-climatological zone

Productivity anomaly index

Correlation

ABSTRACT

Frequent occurrences of extreme rainfall events create severe threat to agricultural production. This is one of the most significant consequences of global warming due to increase in greenhouse gases. A precise understanding of frequency and magnitude of these events and its influence on agricultural productivity can extensively help in policy decisions and planning agricultural as well as water management operations. This study has analyzed observed trends in extreme rainfall indices during monsoon months as well as seasonally at four stations located over different agro-ecological zones of Bihar, namely Samastipur (zone-I), Madhepura (zone-II), Sabour (zone-IIIa) and Patna (zone-IIIb). Mann–Kendall nonparametric test was employed for detection of trends and the slopes of the trend lines were determined using the method of least square linear fitting. Since rice is the important crop in this part of the region, the vulnerability of extreme rainfall indices on productivity also analysed using simple correlations. All the sites show an increasing trend of number of days with rainfall 10.0 cm or more (very heavy precipitation event) during monsoon season. Sabour shows a significant increasing trend of 0.4 and 0.6 day/decade, respectively during monsoon and annually. During September, occurrence of heavy precipitation events over Madhepura recorded a significant positive trend of 0.4 day/decade. Highly significant magnitudes of increasing trends were noticed for Madhepura (46.6 mm/decade) and Sabour (27.5 mm/decade) for occurrence of highest five-day total precipitation during monsoon season. The results show statistically significant positive trends of number of days with rainfall > R2.5 cm for all the study sites during August. All the sites, the magnitude of highest 1-day and 5-days maximum rainfall is showing increasing trend. Increasing trends of fraction of rainfall due to extremely wet days is also showing increasing trend in all the sites. The rice productivity showed 10th degree polynomial technological trend in all the sites and steady increase in all the sites except Samastipur. The correlation between extreme rainfall indices during monsoon season and productivity anomaly index indicate that almost all the extreme rainfall indices contribute positively to rice productivity except P95pTOT and R99pTOT over Sabour and R7.5 cm over Patna. If we assume the observed increasing trends in different extreme rainfall indices will continue, as estimated by the global circulation models, the chances of occurrence of intense rainfall events in near future will also increase proportionally and efforts should be made to prepare detailed site specific—at least at district level—disastrous management plan especially to reduce impact of extreme rainfall event on agricultural production system under changing climatic scenarios.

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1. Introduction

Intergovernmental Panel on Climate Change (IPCC, 2007) in its fourth assessment report (AR4) indicated with very high confidence (90% probability of being correct) that human activities, since industrialization have caused the planet to warm by about 1 °C

and future climate change is likely to affect agriculture, increase risk of hunger and water scarcity. Several works has been done for analyzing trends in monthly, seasonal or annual rainfall for many areas of the globe using different sources of observed or gridded long-term data set (Peterson and Vose, 1997; Hansen et al., 2001; New et al., 2001; Jones and Moberg, 2003; Subash and Ram Mohan, 2010a,b). However, these trends can only address a subset of climate change issues. Therefore, changes/trends in extremes can be strong indicators of climate change as it has been hypothesized that in a warming world where the atmosphere can hold more water vapour and the hydrological cycle could become more active (Foland et al., 2001). Moreover, extremes have more influ-

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Table 1
Characteristics of agro-climatic zone, study area and data period.

Agro-climatic zone	Soil and topography	Normal initiation/cessation of rainfall	Study site	Data period	Location		
					Latitude	Longitude	Altitude (m)
Zone I (North west alluvial plain)	Heavy textured sandy loam to clay, medium acidic, flood prone, pH 6.5–8.4	12th June/30th September to 10th October	Samastipur	1960–2006	25.65°N	85.50°E	52
Zone II (North west alluvial plain)	Light to medium textured slightly acidic, sandy loam to clay loam with saline/alkaline patches, pH 6.5–7.8)	7th June/30th September to 10th October	Madhepura	1974–2000	25.50°N	86.40°E	42
Zone IIIA (South alluvial plain)	Old alluvium sandy loam to clay, slightly alkaline patches, pH 6.8–8.0	15th June/30th September to 10th October	Sabour	1972–2003	25.14°N	87.40°E	37
Zone IIIB (South alluvial plain)	Old alluvium sandy loam to clay, slightly alkaline patches, pH 6.8–8.0	10th June/30th September to 10th October	Patna	1960–2007	25.30°N	85.15°E	52

ence on agricultural productivity as far as almost all the crops are concerned. Widespread increases in heavy precipitation events have been observed even in places where total amounts have decreased (Bates et al., 2008). Future projections of climate change using Global and Regional Circulation Climate Models with different IPCC emission scenarios indicate an increase of about 5–10% in summer monsoon rainfall over India (NATCOM, 2004). It is also projected that number of rainy days may decrease by 20–30%, which would mean that the intensity of rainfall is expected to increase. Extremes in rainfall also show increase in their frequency and intensity by the end of the year 2100. Based on observational and theoretical modeling studies lead to an overall conclusion that an increase in the frequency of heavy precipitation events is like to have occurred over most land areas over the late 20th century (Bates et al., 2008).

The joint World Meteorological Organization Commission for Climatology (CCI)/World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection, Monitoring and Indices (ETC-CDMI) coordinated several efforts to enable global analysis of extremes (Manton et al., 2001; Peterson et al., 2001, 2002; Frich et al., 2002; Easterling et al., 2003; Griffiths et al., 2003; Mokssit, 2003; Aguilar et al., 2005; Peterson, 2005; Vincent et al., 2005; Zhang et al., 2005; Haylock et al., 2006; Klein Tank et al., 2006; Sensoy et al., 2006). Statistically significant increase in the occurrence of heavy precipitation has been observed across different continents/regions/places by several workers (Klein Tank and Können, 2003; Kunkel et al., 2003; Groisman et al., 2004; Haylock and Goodness, 2004; Sen Roy and Balling, 2004; Alexander et al., 2006; Goswami et al., 2006; Guhathakurta and Rajeevan, 2007;



Fig. 1. Agro-ecological zones of Bihar and location of study sites.

Table 2
Extreme rainfall indices considered for the study.

Sl.No.	Description/definition	Acronyms	Unit
1.	Good precipitation days (precipitation ≥ 2.5 cm)	R2.5cm	Number of days
2.	Moderate precipitation days (≥ 5.0 cm)	R5.0cm	Number of days
3.	Heavy precipitation days (≥ 7.5 cm)	R7.5 cm	Number of days
4.	Very heavy precipitation days (≥ 10.0 cm)	R10.0 cm	Number of days
5.	Very very heavy precipitation days (≥ 12.5 cm)	R12.5cm	Number of days
6.	Highest 1 day precipitation amount	RX1day	mm
7.	Highest 5 day precipitation amount	RX5day	mm
8.	Moderate wet days (days with RR > 75th percentile of daily precipitation amount)	R75p	Number of days
9.	Precipitation fraction due to moderate wet days	R75pTOT	%
10.	Very wet days (days with RR > 95th percentile)	R95p	Number of days
11.	Precipitation fraction due to very wet days	R95pTOT	%
12.	Extremely wet days (days with RR > 99th percentile)	R99p	Number of days
13.	Precipitation fraction due to extremely wet days	R99pTOT	%

Rajeevan et al., 2008). Rajeevan et al. (2008) used high resolution daily gridded rainfall data for India for 104 years and found that frequency of extreme rainfall events show significant inter-annual and inter-decadal variation in addition to a statistically significant long term trend of 6% per decade. The increasing trend of extreme rainfall events in the last five decades could be associated with the increasing trend of sea surface temperatures and surface latent heat flux over the tropical Indian Ocean. Another study using daily rainfall data for over 50 years show significant increasing trend in extreme rainfall events over central India (Goswami et al., 2006). A recent study found that the intra-region variability for extreme monsoon seasonal precipitation is large over India and mostly exhibited a negative tendency leading to increasing frequency and magnitude of monsoon rainfall deficit and decreasing frequency and magnitude of monsoon rainfall excess (Pal and Al-Tabbaa, 2010). All the above studies, the authors used rainfall indices independently and not dealt with its impact on agriculture.

To get the actual picture of variability and trends in extreme precipitation events on agriculture, it is better to restrict the study into micro level such as administrative district, basically to link it with the availability of crop data. Moreover, as far as occurrence of rainfall extremes with respect to agriculture is concerned, it is purely localized phenomena with its cause may be local/regional/global, but its impact will be localized. Hence, we have considered an administrative district as the boundary of the study area. Similarly, long data pertaining to rice productivity is available as administrative district only.

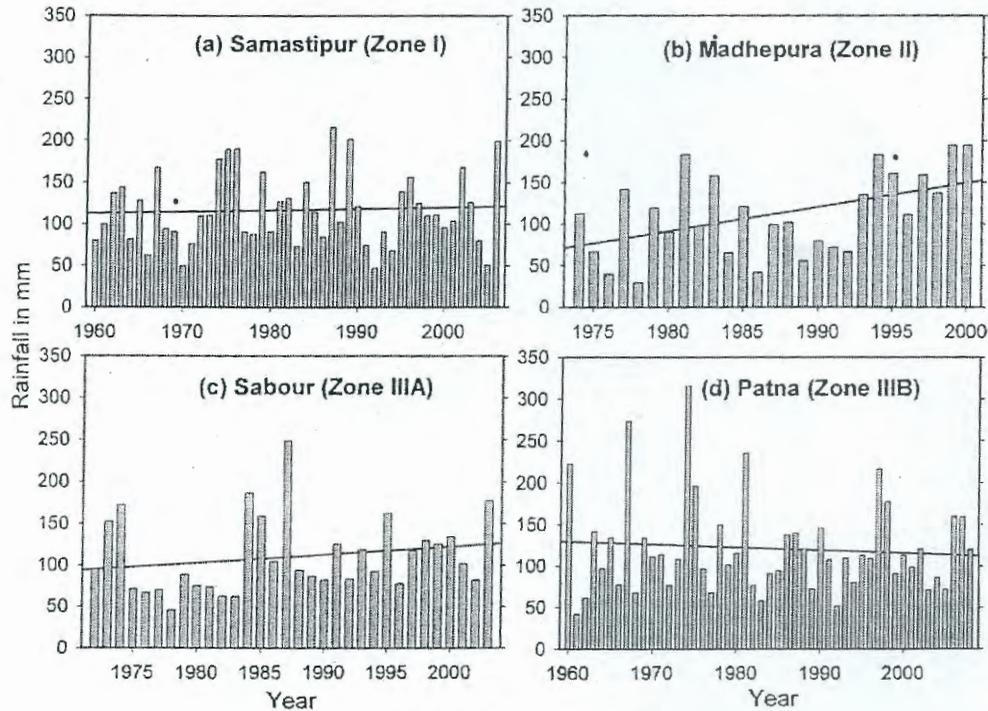
Agriculture is the vital source of wealth in Bihar. 76% of its population is engaged in agricultural pursuits directly or indirectly and 90 percent are marginal and small farmers. Principal food crops are rice, wheat, maize and pulses. Rice (*Oryza sativa* L.) is a major food grain and it is cultivated during rainy season. South-west monsoon rainfall (June to September) is the major source of water for rainfed agriculture. But its erratic distribution pattern—temporal as well

Table 3
Trends of rainfall indices over different agro-climatological zones of Bihar.

Month/season and sites	R2.5 cm	R5.0 cm	R7.5 cm	R10.0 cm	R12.5 cm	RX1day	R75p	R75pTOT	R95p	R95pTOT	R99p	R99pTOT
June												
Samastipur	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
Madhepura	-ve	-ve	-ve	-ve	+ve	-ve	-ve	+ve	-ve	+ve	-ve	+ve
Sabour	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
Patna	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
July												
Samastipur	+ve	+ve	+ve	-ve	-ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
Madhepura	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
Sabour	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
Patna	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
August												
Samastipur	-ve	-ve	-ve	+ve	+ve	-ve	-ve	-ve	-ve	+ve	-ve	-ve
Madhepura	+ve	+ve	+ve	+ve	-ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
Sabour	-ve	+ve	+ve	+ve	-ve	+ve	+ve	+ve	+ve	-ve	+ve	+ve
Patna	+ve	+ve	+ve	+ve	-ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
September												
Samastipur	-ve	+ve	-ve	-ve	-ve	-ve	-ve	-ve	-ve	-ve	-ve	-ve
Madhepura	+ve	+ve	+ve	+ve	+ve	+ve	-ve	+ve	+ve	+ve	+ve	+ve
Sabour	-ve	+ve	+ve	+ve	+ve	+ve	-ve	-ve	-ve	-ve	-ve	+ve
Patna	+ve	-ve	-ve	-ve	-ve	-ve	+ve	-ve	+ve	-ve	+ve	-ve
Monsoon season												
Samastipur	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	-ve	+ve
Madhepura	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
Sabour	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
Patna	+ve	+ve	+ve	+ve	-ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
Annual												
Samastipur	+ve	+ve	+ve	-ve	-ve	-ve	+ve	+ve	+ve	-ve	-ve	-ve
Madhepura	+ve	+ve	+ve	+ve	+ve	+ve	-ve	+ve	-ve	+ve	+ve	+ve
Sabour	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
Patna	+ve	+ve	+ve	-ve	-ve	-ve	+ve	+ve	+ve	+ve	+ve	+ve

Shaded cells indicate significant at 95% level.

1. Rainfall Index RX1 day



2. Rainfall Index RX5 day

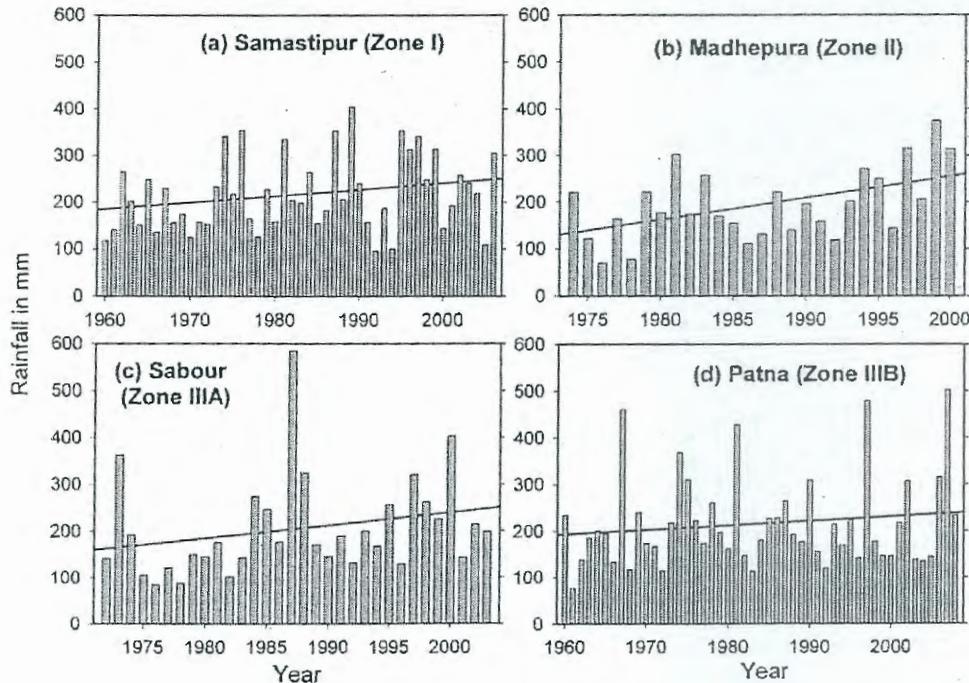


Fig. 2. Time series of the extreme rainfall indices during monsoon season over different agro-climatological zones of Bihar (1. rainfall index RX1 day; 2. rainfall index RX5 days).

as spatial—affect the rice growth and thereby influence production in one or other part of the region every year. Any aberrations of rainfall pattern such as delay of monsoon, breaks in the monsoon activity, prolonged dry periods during the crop season and even continuous flooding also affect the production. Tillering to flower-

ing is the most critical stage when rice crop should not be subjected to any moisture stress. According to Jearakongman et al. (1995), grain yields were severely reduced when standing water disappeared more than 20 days before anthesis, while the presence of standing water 20 days after anthesis resulted in the highest yields.

Table 5
Trends and magnitude of rainfall index (RX5day) during monsoon season.

Site	Trends	Magnitude
Samastipur (Zone I)	+ve	N
Madhepura (Zone II)	+ve	46.6
Sabour (Zone IIIA)	+ve	27.5
Patna (Zone IIIB)	+ve	N

Shaded cells indicate significant at 95% level; N, not significant.

Depending on climate, soils, cultivars and management practices, the total irrigation water requirement of the rice crop ranges from 450 mm in upland conditions to 1300 mm in lowland conditions (Yoshida, 1975, 1978; Doorenbos and Kassam, 1979). Even though monsoon enters over the main lands of India through Kerala Coast during the last week of May or first week of June, so that it can be transplanted in puddled field after good initial monsoon showers. Similarly, the monsoon starts its withdrawal from the northwestern part of the country from first September and it completely withdraws from the country by 15th October. Hence, as far as rice crop is concerned, June–September rainfall is considered as the core period. Even though Bihar falls under high rainfall region, recurrent floods and droughts during the monsoon season is a serious concern. Surprisingly, the occurrence of severe drought/floods in recent years 2003, 2004, 2005, 2008 and 2009 in one or other agro-climatological zones, supports the IPCC (2007) fourth assessment report. The recent extreme rainfall deficit occurred over Bihar during June and July months incurred a loss of 18.39 billion INR to state exchequer (Khan et al., 2009).

In the present study, the variability of extreme rainfall indices during monsoon months, season and annual for four stations viz., Patna, Sabour, Samastipur and Madhepura districts, representing different agro-climatological zones of Bihar and its impact on rice productivity have been examined. We have also investigated the trends of extreme rainfall indices and estimated the slopes of the trend lines to know the magnitude of trends.

2. Materials and methods

2.1. Study site

Bihar is lying approximately between 21°58'10" and 27°31'15"N latitudes and 82°19'50" and 88°17'40"E longitudes in the middle Indo-Gangetic Plains extending 483 km from west to east. Temperature varies from a maximum of 43°C in summer to a minimum of around 5°C in the winters. It receives medium to heavy rainfall during the monsoon season. This state embraces some of the most

Table 6
F-Statistic and the Spearman rank correlation coefficient (r_s) between extreme rainfall indices and rice productivity index over different agro-climatological zones of Bihar.

Sl. No.	Rainfall indices	Samastipur		Madhepura		Sabour		Patna	
		F-Stat	r_s	F-Stat	r_s	F-Stat	r_s	F-Stat	r_s
1	R2.5	1.963	0.32*	2.888	0.46**	0.014	0.02	3.210	0.25
2	R5.0	2.376	0.35*	1.753	0.37*	0.067	0.05	2.290	0.21
3	R7.5	0.673	0.20	3.383	0.48**	0.120	0.06	0.214	-0.07
4	R10.0	0.065	0.20	1.654	0.36*	0.042	0.04	0.000	0.00
5	R12.5	0.389	0.15	0.647	0.24	0.132	0.07	0.545	0.11
6	RX1	2.737	0.37*	0.615	0.23	0.039	0.04	1.097	0.15
7	RX5	1.282	0.26	0.629	0.23	0.038	0.04	0.176	0.06
8	R75p	1.766	0.31*	3.433	0.49**	1.967	0.25	7.417**	0.37*
9	R95p	0.643	0.19	3.586	0.50**	0.194	0.08	9.320**	0.41*
10	R99p	0.960	0.23	2.248	0.41*	0.003	0.01	7.714**	0.38*
11	R75pTOT	0.931	0.23	0.171	0.12	0.000	0.00	10.66**	0.43**
12	R95pTOT	0.297	0.13	0.530	0.21	0.782	-0.16	11.92**	0.45**
13	R99pTOT	1.179	0.25	0.538	0.22	0.994	-0.18	7.611**	0.37*

* Significant at 95% level.

** Significant at 99% level.

Table 7
Critical/cut-off extreme rainfall indices during monsoon season over different agro-climatological zones of Bihar.

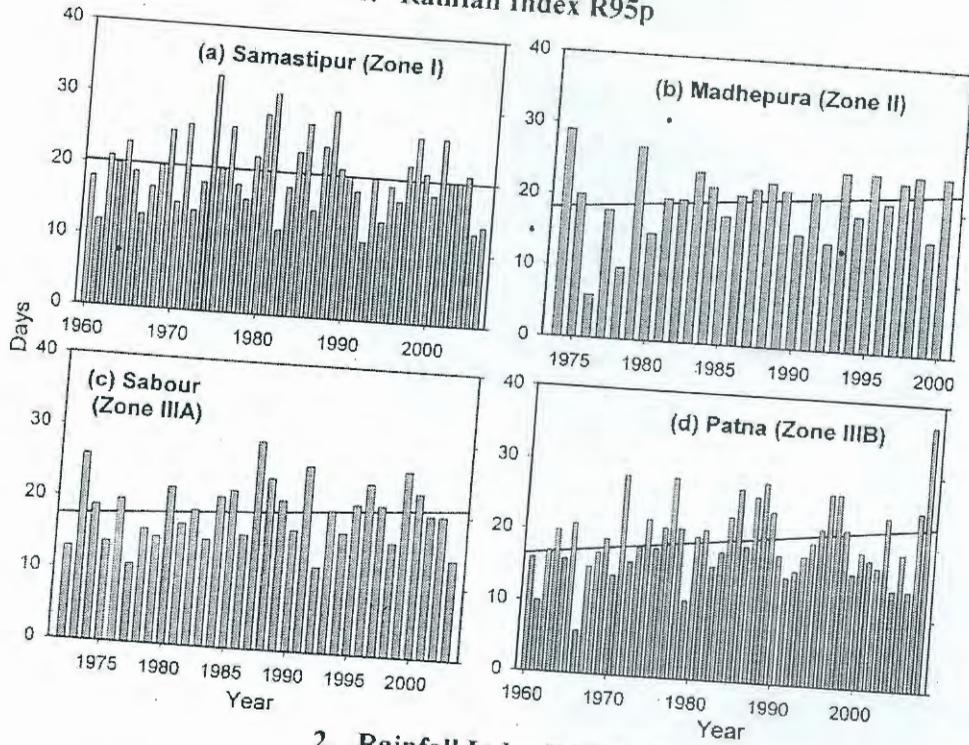
Sl. No.	Rainfall indices	Samastipur	Madhepura	Sabour	Patna
1	R2.5 cm (days)	13	13	6	12
2	R5.0 cm (days)	5	4	2	4.5
3	R7.5 cm (days)	2	2	<1	3.5
4	R10.0 cm (days)	1	1	<1	<1
5	R12.5 cm (days)	<1	<1	<1	<1
6	RX1day (mm)	120	125	80	125
7	RX5day (mm)	250	250	175	300
8	R75p (days)	25	27	25	24
9	R95p (days)	20	21	17	20
10	R99p (days)	16	19	12	15
11	R75pTOT (%)	88	90	-	87
12	R95pTOT (%)	83	83	80	82
13	R99pTOT (%)	78	78	75	74

fertile lands of India, squeezed in between West Bengal, Jharkhand and Uttar Pradesh, reaches up to the Himalayas in the north and is completely land locked. Bihar is bounded on the north by Nepal, on the south by Jharkhand, on the east by West Bengal and on the west by Uttar Pradesh. The topography of Bihar can be easily described as a fertile alluvial plain occupying the Gangetic Valley. The plain extends from the foothills of the Himalayas in the north to a few miles south of the river Ganges as it flows through the State from the west to the east. The river Ganga flows right across it from west to east. North Bihar is extremely fertile, the land being watered by the rivers Sarayu, Gandak and Ganga. The other rivers are the Sone, Poonpoo, Falgu, Karmanasa, Durgawati, Kosi, Ghaghara etc. Bihar is traditionally divided into (1) The North Ganga plain and (2) The South Ganga plain. Rice (May/June–October/November) followed by wheat (November/December–March/April) is the dominant cropping sequence in this part of the study area. Based on soil characterization, rainfall, temperature and terrain, the state is divided into four agro-climatological zones with zone-I and zone-II corresponding to north Bihar whereas zone-IIIA and zone-IIIB comprising districts of south Bihar. The soil type and topography, normal climatic conditions of the agro-climatic zones are reported in Table 1. Four representative districts, viz., Samastipur (zone-I), Madhepura (zone-II), Sabour (zone-IIIA) and Patna (zone-IIIB)—having more or less agro-climatological as well as agro-ecological conditions were selected based on data availability (Fig. 1).

2.2. Data

The daily meteorological parameters recorded at IARI regional station, Pusa, Samastipur; Agricultural College, Sabour; Agricultural

1. Rainfall Index R95p



2. Rainfall Index R95pTOT

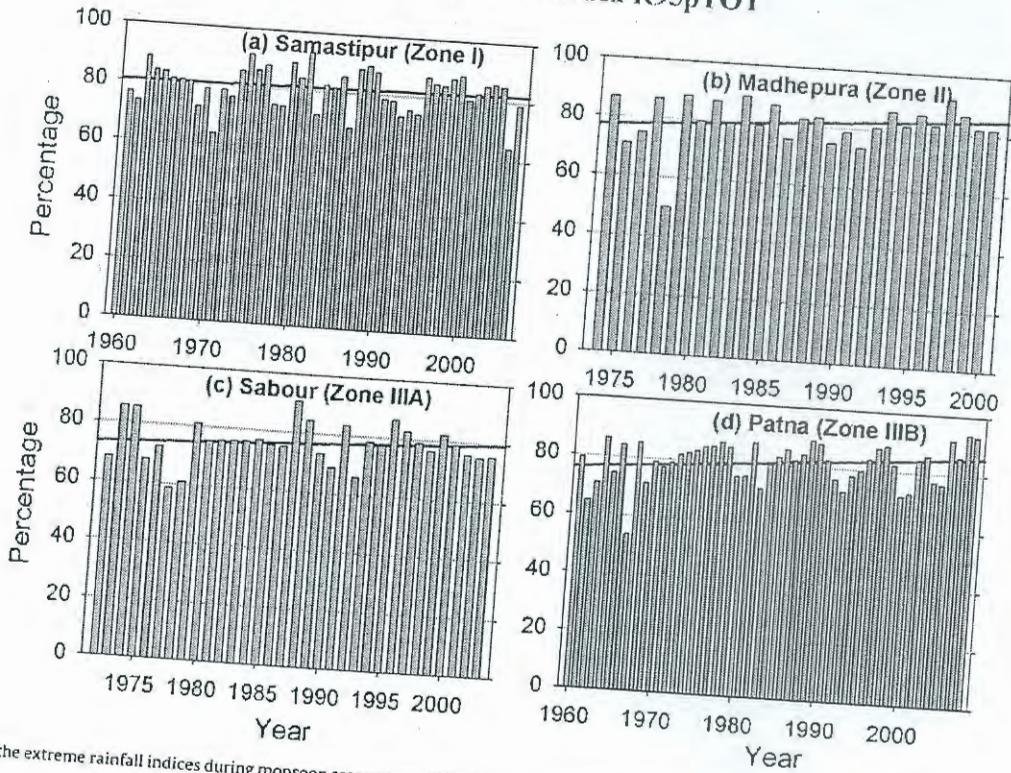


Fig. 3. Time series of the extreme rainfall indices during monsoon season over different agro-climatological zones of Bihar (1. rainfall index R95p; 2. rainfall index R95pTOT).

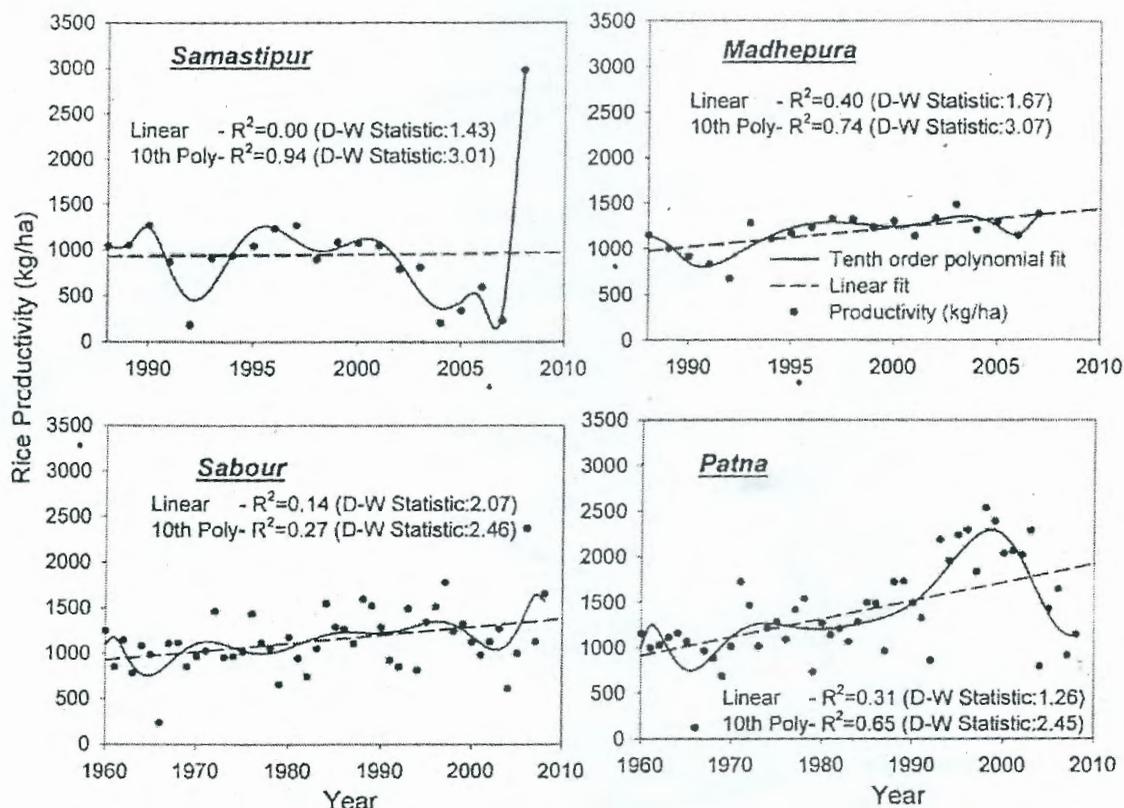


Fig. 4. Rice productivity trends (linear and tenth order polynomial fit) and its Durbin-Watson (DW) test statistic for different agro-climatological zones of Bihar.

Research Institute, Patna and RARS, Rajendra Agricultural University, Madhepura were collected. These observatories have been installed long back under the guidance of technically qualified officers and calibrated the instruments according to the IMD/WMO standard. The productivity of rainy season (kharif) rice over the selected sires from 1960 to 2008 was taken from the Directorate of Rice, Ministry of Agriculture, Govt. of India and is available on-line at <http://www.dacnet.nic.in>.

2.3. Rainfall indices

A list of over 50 internationally agreed climate change indices for temperature and rainfall (WMO-CCI/CLIVAR) are available on web site (<http://www.wmo.int>) with their explanation and equations for calculating them. For the present study, we have considered a set of 13 rainfall indices (Table 2). From the list prescribed by WMO, we have not considered indices of R10 mm and R20 mm, because rainfall events of 10 or 20 mm are quite common in the Indian sub-continent during the southwest monsoon season (Joshi and Rajeevan, 2006). Hence, we have considered R2.5 cm, R5.0 cm, R7.5 cm, R10.0 cm and R12.5 cm to study the trends in different precipitation frequencies of rainfall greater than or equal to 2 cm, 5 cm, 7 cm, 10 cm and 12.5 cm. The definitions of indices allow seasonal and monthly partitions and we have considered month-wise analysis during the southwest monsoon season (June–September), the main rainy season in this part. Most of the indices are defined in terms of counts of days crossing the thresholds either absolute (fixed) thresholds or percentile (variable) thresholds. Annual/seasonal/monthly day-count indices based on percentile thresholds are expressions of anomalies relative to the local climate. Extreme rainfall indices considered for the

analysis are calculated for each year for each station. Since most of the indices are counts of days, a non-parametric model will be the best suited to test the significance rather than using Students' *t* test (Joshi and Rajeevan, 2006). Hence, we have used the Mann-Kendall test to examine the significance of the trend.

2.4. Mann-Kendall test

For all above indices, the Mann-Kendall nonparametric test, as described by Sneyers (1990), was applied in order to detect trends. The Mann-Kendall test has been used by several researchers to detect trends in hydro-meteorological time series data (Serrano et al., 1999; Brunetti et al., 2000a,b; Subash and Ram Mohan, 2010a,b). The slopes of the trends were calculated by fitting the data series into method of least-square linear fitting. Mann-Kendall test basically involves the ranks obtained by each data in the data series. The n time series values ($X_1, X_2, X_3, \dots, X_n$) are replaced by their relative ranks ($R_1, R_2, R_3, \dots, R_n$) (starting at 1 for the lowest up to n) (Kundzewicz and Robson, 2000; Chiew and Sirivardena, 2005).

The test statistic S is:

$$S = \sum_{i=1}^{n-1} \left[\sum_{j=i+1}^n \text{sgn}(R_j - R_i) \right]$$

where

$$\text{sgn}(x) = 1 \quad \text{for } x > 0$$

$$\text{sgn}(x) = 0 \quad \text{for } x = 0$$

$$\text{sgn}(x) = -1 \quad \text{for } x < 0$$

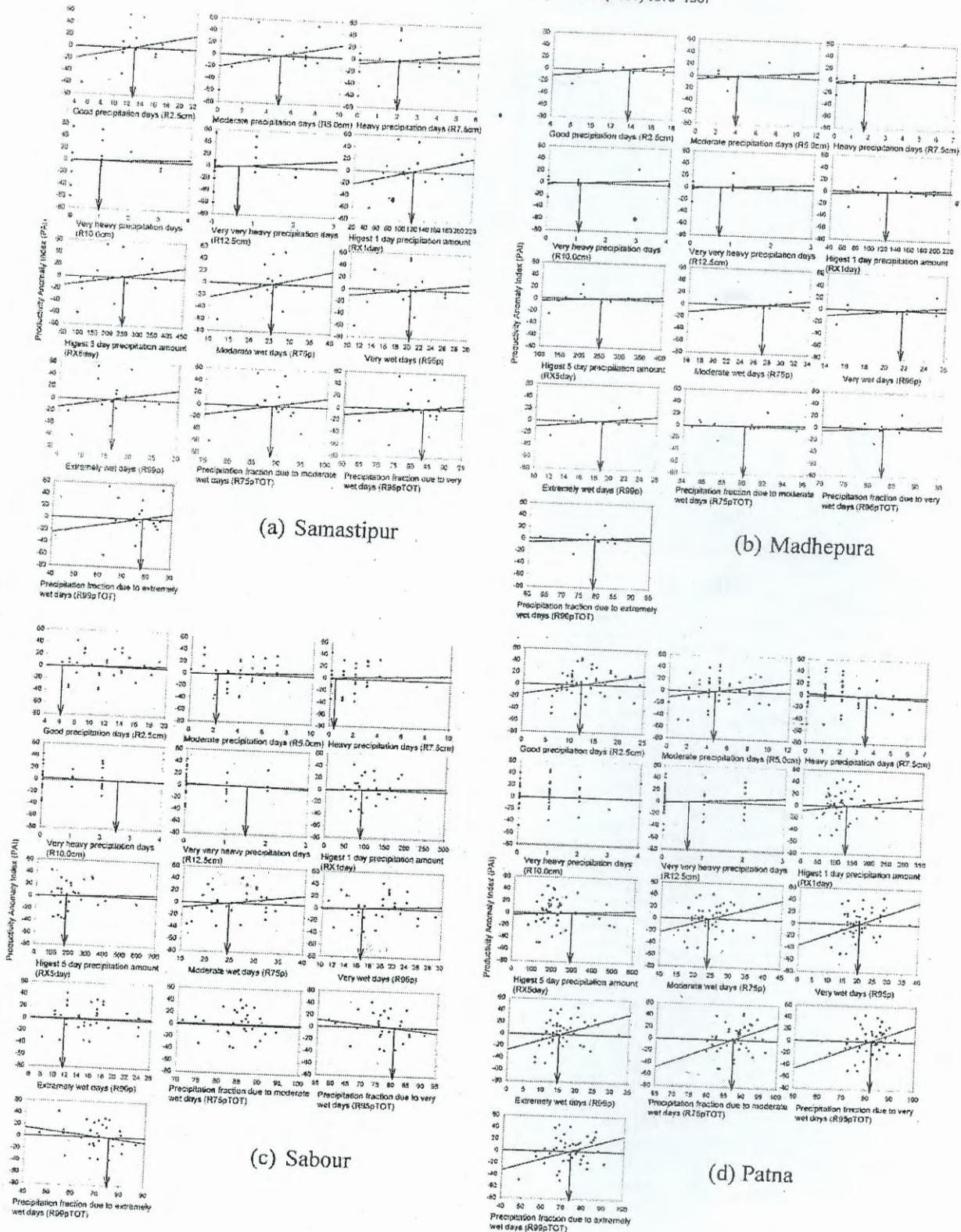


Fig. 5. Relation between productivity anomaly index and different rainfall indices over different study districts (a–d).

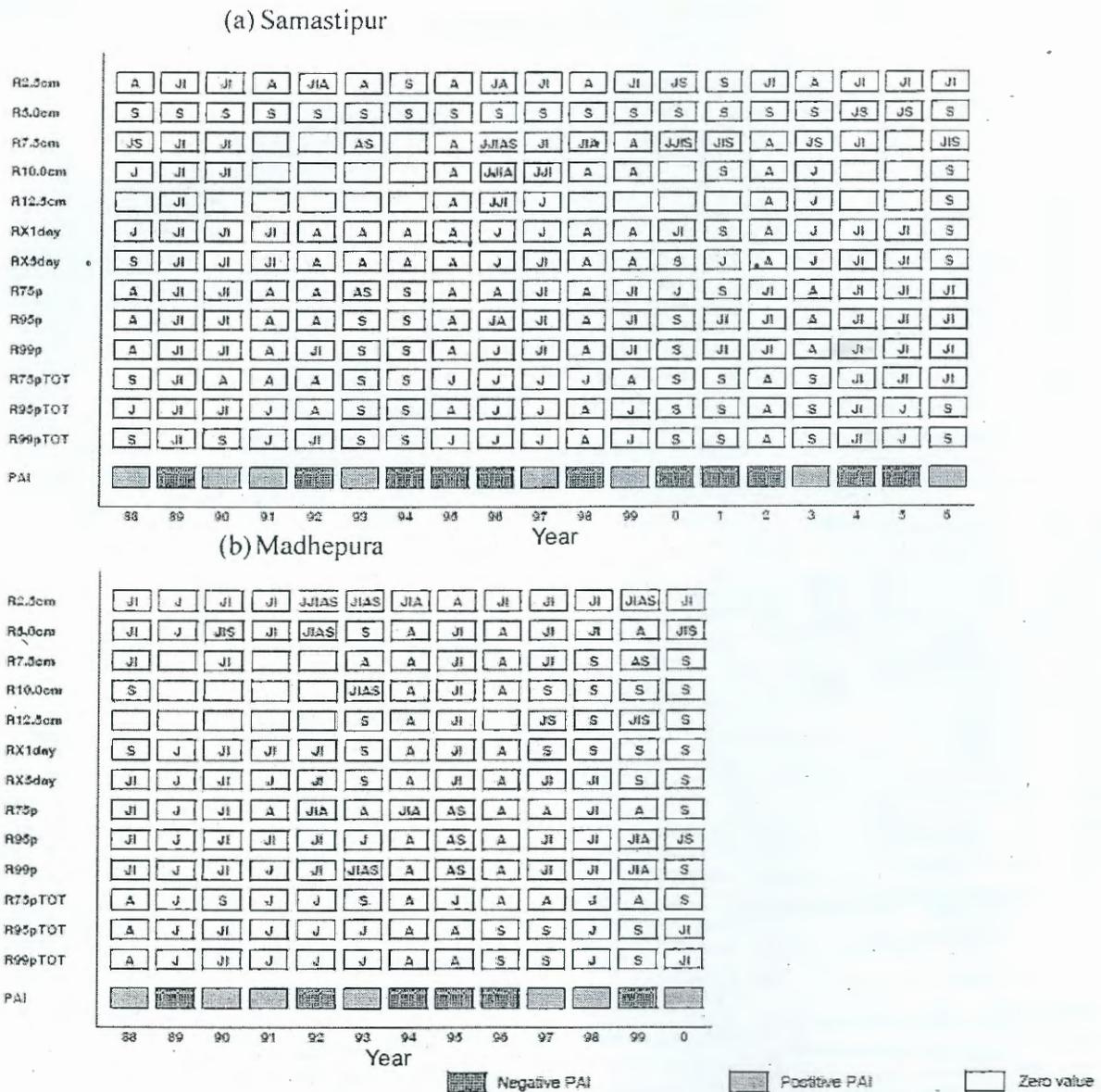


Fig. 6. Variability of rainfall extreme indices over (a) Samastipur, (b) Madhepura.

If the null hypothesis H_0 (i.e., there is no trend in the data set) is true, then S is approximately normally distributed with:

$$\mu = 0$$

$$\sigma = \frac{n(n-1)(2n+5)}{18}$$

The z-statistic is therefore (critical test statistic values for various significance levels can be obtained from normal probability tables):

$$z = \frac{|S|}{\sigma^{0.5}}$$

A positive value of S indicates that there is an increasing trend and vice versa.

The magnitude of the significant trends per year (slope) was computed by fitting the time series into linear fitting and converted the same into decadal magnitude by multiplying by 10 to compare the trend difference between agro-climatological zones.

2.5. Rice productivity

The production of rice depends on type of soil, seeds used, crop area, availability of irrigation facilities, fertilizers, pesticides and also on the government incentives to the farming sector during a year as well as on the meteorological parameters such as rainfall, temperature, relative humidity and solar energy. The non-meteorological parameters, i.e., the total technological inputs to the farming sector have been growing steadily and are difficult to quantify. Therefore, to know the pattern of trends and to quantify the growth rate of total technological inputs to the agricultural sector the actual productivity was fitted best fit model using "Curvefit"

3.1.7. R75p and R75pTOT

All the sites have shown positive trends during monsoon (Fig. 3). Patna has recorded a significant increasing trend of 1.1 day/decade. As far as individual months are concerned, no definite pattern have been observed. However, Madhepura shows a significant increasing trend of 2.2 days/decade during August. A significant increasing trend of 3.2 days/decade has been observed for Sabour annually. The index R75pTOT determines the contribution of moderate wet days (rainfall with more than 75 percentile) on the total rainfall of time scale considered. All the stations, the contribution from the rainfall amount higher than 75 percentile has increased during monsoon as well as annually. However, a significant increasing trend of 1.3 percent/decade has been observed for Patna during monsoon season. Similarly, significant positive trend were observed during June (4.7 percent/decade), July (1.8 percent/decade) and August (2.8 percent/decade) for Patna. Similarly, two more indices for 95 percentile and 99 percentile are also calculated. The R95p index also shows similar pattern during monsoon and annual. However, significant positive trends have been noticed during August (0.4 day/decade) and September (0.3 day/decade) for Patna.

3.2. Rice productivity trends

The rice productivity values were fitted into different models in curve fit program and found that R^2 value is higher for 10th degree polynomial fit for all the districts (Fig. 4). The rice crop continuous to show steady increase in all the Districts except Samastipur for which the growth is almost nil. Even though, there is a best fit for 10th degree polynomial curve, the scattering of points from the trend line indicate that the year-to-year variability is more in all the districts. In Patna, the productivity decreased tremendously from 2004 onwards and not recovered. The higher productivity during 2008 at Samastipur may be due to even distribution of rainfall pattern, particularly during August–September months. Samastipur falls under the category of very low productivity (<1000 kg/ha) group during the triennium ending 2007 while all the other districts fall under the category of low productivity group (<1500 kg/ha).

3.3. Relation between rice productivity and rainfall indices

The influence of extreme rainfall indices on rice productivity over different districts is shown in Fig. 5. There is a positive correlation exists between all the extreme rainfall indices and productivity anomaly indices over Zones I and II. The Spearman rank correlation coefficient (r_s) between R2.5 cm, R5.0 cm, RX1day and R75p with productivity anomaly index show significant correlations in zone I (Table 6). However in zone II, between R2.5 cm, R5.0 cm, R7.5 cm, R10.0 cm, R75p, R95p and R99p and productivity anomaly indices show significant correlations. The critical value/cut-off of extreme rainfall indices, which is the value of intersection point of the trend line plot between extreme rainfall indices and productivity anomaly indices on the extreme rainfall indices axis (Table 7), indicated that the number of good precipitation days (R2.5 cm) > 13 days during the monsoon season (June–September) increases the rice productivity in zones I and II. Interestingly in zone I, the positive correlations between highest 1-day precipitation amount to rice productivity shows a rainfall amount of 120 mm or more may be advantage for the rice crop. Out of 8 years received more than 120 mm rainfall in 1 day during monsoon season, 4 years produced higher rice productivity. The occurrence of 1 day maximum during water sensitive phenological phases is important rather than the entire season; however, rice crop requires water in almost all the growth stages. The temporal variability of occurrence of 1 day maximum rainfall for these 8 years indicate that three years (1996,

1997 and 2003) RX1day occurred in June, 2 years (1989 and 1990) in July, 2 years (1995 and 2002) in August and one year (2006) in September (Fig. 6). Thus, there is no clear indication with the distribution of occurrence of maximum 1 day rainfall with PAI. But maximum number of 1 day maximum rainfall occurred in August followed by July, which coincides with the vegetative/maximum tillering phase. As far as occurrence of RX5days rainfall greater than 250 mm rainfall occurred in 7 years (1989, 1995, 1996, 1997, 1999, 2002 and 2006). Even though there is a positive correlation between RX5day and productivity anomaly index, out of these 7 years (for which RX5days > 250 mm), 4 years got negative productivity anomaly index. Thus, as far as Samastipur district is concerned, occurrence of more than 250 mm in 5 days may be detrimental to rice productivity, particularly during August. However, in zone II, out of 7 years received 13 days or more R2.5 cm, 5 years got positive productivity anomaly index. Interestingly, the positive correlations between highest 1 day precipitation amount to rice productivity shows a rainfall amount of 125 mm or more may be advantage for the rice crop is concerned. Out of 7 years of more than 125 mm rainfall in 1 day during monsoon season, 4 years produced higher rice productivity. Even though there is positive correlation between RX5days with productivity anomaly indices, out of 5 years (1994, 1995, 1997, 1999 and 2000) received more than 250 mm cumulative rainfall in 5 days during monsoon season, 3 years (1997, 1999 and 2000) produced positive productivity anomaly index explains the extreme rainfall may have provided beneficial for rice crop. However, in 1999 and 1995, even with higher RX5days responded negatively to productivity advocated that the occurrence of time of extreme event with the phenological stage of the rice is important rather than during the season (Fig. 6).

As far as zone IIIA is concerned, out of 13 negative PAI years, maximum highest RX1day occurred during August (6 years—1974, 1975, 1979, 1982, 1987 and 1994) and minimum during September (3 years—1983, 1991 and 2001). Interestingly, highest RX1day maximum rainfall occurred during June in 3 years (1984, 1993 and 2003) and these years the productivity falls in the positive side (Fig. 7). Out of 17 years received more than 175 mm rainfall in RX5day, 10 years got positive productivity anomaly. Interestingly, 4 out of 7 negative productivity anomaly index years received a rainfall greater than 175 mm in July. This indicated that extreme rainfall during July may have delayed the transplanting operations or damaged the just transplanted crop and thereby decrease the productivity considerably. The negative correlation of R95pTOT and R99pTOT with rice productivity anomaly pointed towards the vulnerability of rice crop to irregular distribution pattern as this represents the fraction of rainfall received during the very wet days and extremely wet days. As far as zone IIIB is concerned, out of 21 negative PAI years, 9 years (1962, 1969, 1973, 1982, 1983, 1987, 1991, 1992 and 2007) received maximum RX5days rainfall in August (Fig. 8). Out of 4 years having more than 4 days of R7.5 cm (1987, 1995, 1997 and 1999), only one year (1987) got negative rice productivity anomaly. In 1987, 8 days received R7.5 cm and even 6 days and 4 days, respectively received R10.0 cm and R12.5 cm rainfall. This may be the reason for negative productivity anomaly. Out of 7 years (1967, 1981, 1990, 1997, 2002, 2006 and 2007), 3 years (1981, 1997 and 2007) occurred negative productivity anomaly, interestingly all these negative productivity years the value of RX5days reached more than 425 mm. However, these extreme rainfalls occurred in different months in these years. Since the critical duration of most of the water sensitive phenological phases of rice crop will be between 10 and 15 days and therefore to get more clear understanding of vulnerability of extreme rainfall indices on rice productivity, it is better to analyse the rainfall data at biweekly time interval rather than monthly or seasonal.

(d) Patna

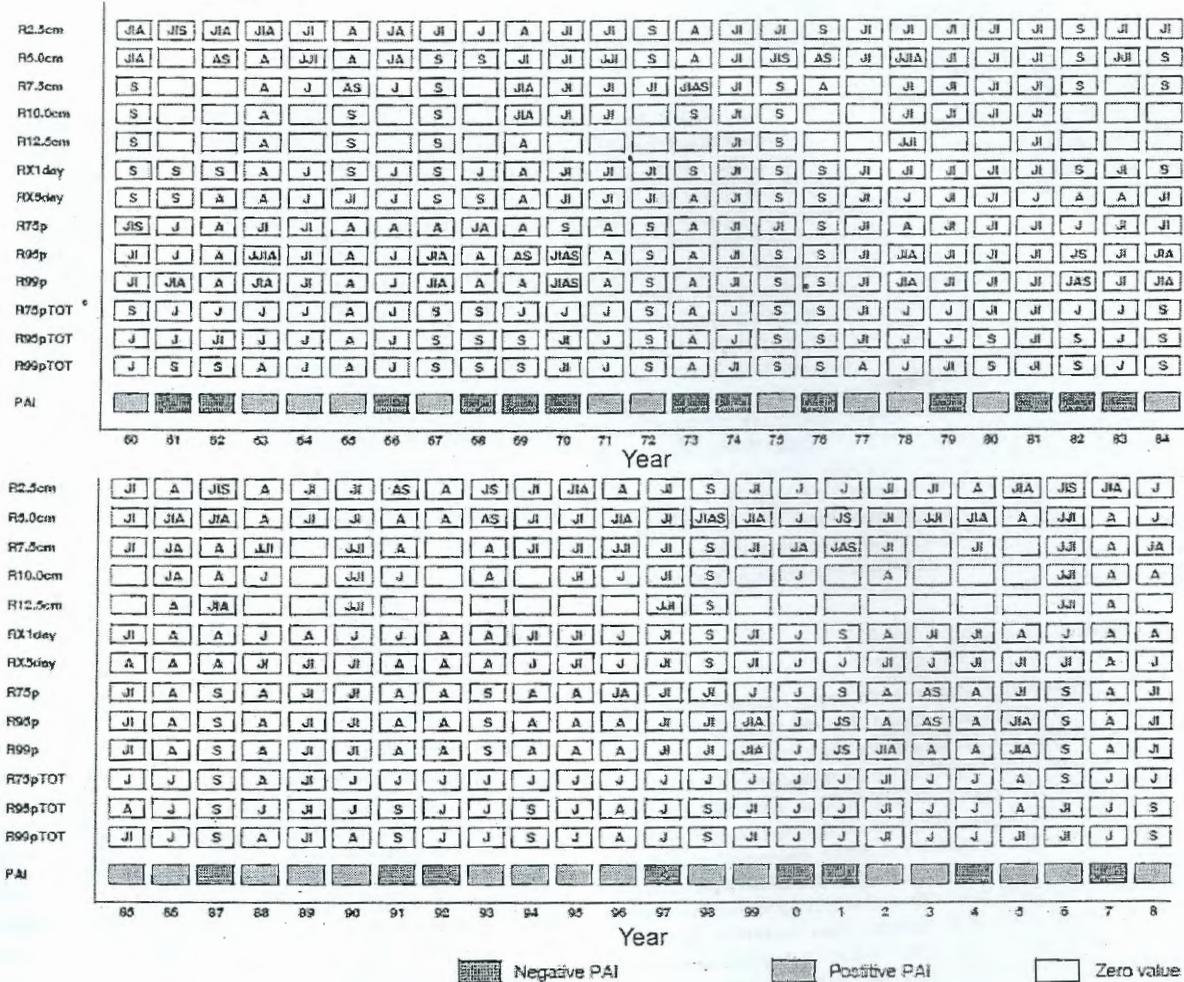


Fig. 8. Variability of rainfall extreme indices over (d) Patna.

and 1.0 day/decade during monsoon and annual, respectively. As far as monthly distribution is concerned, Sabour shows a significant increasing trend of 0.4 day/decade during September. The increasing trend of heavy precipitation days with precipitation 7.5 cm or more during monsoon season as well as annual draw attention to the importance of disaster preparedness to minimise the vulnerability.

3.1.4. R10.0 cm—number of days with rainfall 10.0 cm or more

All the sites show increasing trend during monsoon season. Sabour shows a significant increasing trend of 0.4 and 0.6 day/decade, respectively during monsoon and annual season. During September occurrence of heavy precipitation events over Madhepura recorded a significant positive trend of 0.4 day/decade.

3.1.5. R12.5 cm—number of days with rainfall 12.5 cm or more

Monthly distribution during monsoon season shows that all the sites show an increasing trend during June. But no definite pattern has been observed during other months. However, as far as monsoon season is concerned, all the sites except Patna show positive trend. When we considered annual rainfall, Madhepura and Sabour

showed positive trends and Samastipur and Patna showed negative trends. Even though, Madhepura showed a significant increasing of 0.4 day/decade during monsoon and annual season.

3.1.6. RX1day and RX5day

All the sites show increasing trend of highest 1-day maximum rainfall during monsoon season (Fig. 2). However, a decreasing trend of RX1day has been observed for Patna annually. Madhepura and Sabour show an increasing trend of 28.9 and 9.6 mm/decade, respectively during monsoon season. But individual months, Madhepura shows significant increasing trends during July (19.7 mm/decade), August (12.8 mm/decade) and September (33.7 mm/decade). Highly significant magnitudes of trends were noticed for Madhepura (46.6 mm/decade) and Sabour (27.5 mm/decade) for occurrence of highest five-day total precipitation (Table 5). The higher magnitudes of trends in highest 1-day maximum and highest 5-day total point towards the significance of taking up of flood tolerant and tall rice varieties in this part of the region. It also suggests the importance of construction of drainage structures/facilities to drain out excess water immediately from the agricultural fields.

4. Conclusions

Analysis of variability and trends of extreme rainfall indices provide an opportunity to evaluate the capability of present disaster management/contingency plan and mechanism to cope up with the situations under possible/projected climate change scenarios/conditions. We have examined the trends in 13 extreme rainfall indices over 4 stations representing different agro-climatological zones of Bihar, India, which is part of the middle Indo-Gangetic plains, contribute largely to food security of the region. The study also tried to find out the vulnerability of rice productivity, which is the main staple food grain of the region, to extreme rainfall indices, by the way of simple correlations. The results show statistically significant positive trends of number of days with rainfall > R2.5 cm for all the study sites during August and this may be beneficial to rice crop, as this period may coincides with the grain filling/maximum vegetative pheno phase of the crop. All the sites, the magnitude of highest 1-day and 5-days maximum rainfall is showing increasing trend and there is urgent need to take up flood tolerant and tall rice varieties in this part of the region and measures should also be taken to drain out excess water from the agricultural plots immediately. Increasing trends of fraction of rainfall due to extremely wet days suggest the need for creation of water storage structures and increase of bund height/or creation of bunds in rice fields, so that rain water can be stored/harvested and utilized as and when required for the plants and also to increase the ground water table.

The rice productivity showed 10th degree polynomial technological trend in all the sites and steady increase in all the sites except Samastipur. The correlation between extreme rainfall indices during monsoon season and productivity anomaly index indicate that almost all the extreme rainfall indices contribute positively to rice productivity except P95pTOT and R99pTOT over Sabour and R7.5 cm over Patna. However, based on *F*-statistic, no significant correlation existed between extreme rainfall indices and rice productivity anomaly over Samastipur, Madhepura and Sabour. Highly significant correlations were noticed between R75p, R95p, R99p, R75pTOT, R95pTOT and R99pTOT over Patna. The lower value of Spearman rank correlation coefficient and scattering of points over the trend line of plot between rice productivity anomaly index and extreme rainfall indices indicates the higher year-to-year variability and limitation of use of these regression equations for prediction/forecasting of rice productivity. The critical/cut-off value of extreme rainfall indices and its relation to rice productivity anomaly indices for study sites provide a base for vulnerability assessment and also help to prepare contingency/management plan under different scenarios under possible climate change conditions. Since the duration of different water sensitive pheno phases of rice crop vary between 10 and 15 days, biweekly analysis of extreme rainfall indices may provide more accurate understanding. If we assume the observed increasing trends in different extreme rainfall indices will continue, as estimated by the global circulation models, the chances of occurrence of intense rainfall events in near future will also increase proportionally and efforts should be made to prepare detailed site specific—at least at district level—disastrous management plan especially to reduce impact of extreme rainfall event on agricultural production system under changing climatic scenarios.

Acknowledgements

Authors are thankful to National Agricultural Innovation Project (NAIP) for providing necessary funds to taken up this study. The authors are also thankful to Joint Director, Agricultural Research Institute, Rajendra Agricultural University; Project Coordinator, AICRPAM, CRIDA, Hyderabad; Head, IARI Regional Station, Pusa and

RARS, Madhepura, Rajendra Agricultural University for providing the meteorological data. We are thankful to the two anonymous reviewers who have made critical comments and suggestions to improve the manuscript.

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