Proc. Indian Acad. Sci. (Earth Planet. Sci.), Vol. 97, No. 1, July 1988, pp. 87–105.

Hydroclimatic fluctuations of the Upper Narmada catchment and its association with break-monsoon days over India

NITYANAND SINGH, M K SOMAN and K KRISHNA KUMAR
Indian Institute of Tropical Meteorology, Pune 411 005, India

MS received 14 March 1988; revised 22 July 1988

Abstract. In this paper, hydroclimatic fluctuations of the Upper Narmada catchment (upto Narmadasagar damsite) have been studied by examining the time series (1901–80) of (i) 1-to 10-day annual extreme rainfall; (ii) seasonal total rainfall between May and October; (iii) the precipitation concentration index (PCI); (iv) a modified version of PCI (MPCI); and (v) parameters of the periods contributing specified percentages of rainfall to annual total. Most of these parameters followed the normal distribution and did not show any significant long-term trend. However, some dominant long period oscillations have been noticed in extreme rainfall, seasonal rainfall, PCI and MPCI series. Influence of break-monsoon days over India during July and August on the rainfall activities of the Upper Narmada catchment has also been investigated and salient findings discussed.

Keywords. Seasonal rainfall; precipitation concentration index; hydrological floods and droughts; rainfall period; break-monsoon days.

1. Introduction

Information on the variability of rainfall processes over an area is vital for a variety of practical problems linked to rainfall. The present study provides such information on the interannual and long term features of the rainfall over Upper Narmada catchment (upto Narmadasagar damsite), where a gigantic multipurpose water resources project is to commence. Realizing the importance of the area, several studies have been undertaken to understand its long term rainfall characteristics.

Ramana Murthy *et al* (1987) examined the time series (1901–80) of monthly and total seasonal rainfall of June through September and annual rainfall exclusively of Upper Narmada catchment for long term trends. They found a rising trend in the seasonal and annual rainfall from the beginning of the century till 1945 and oscillatory changes later around the long term mean. Monthly rainfall values fluctuate around their long term means. Chaturvedi and Srivastava (1981) also reported an 80-year (1891–1970) long series of area-averaged annual rainfall for the entire Narmada catchment but did not discuss the characteristics of the rainfall series. Close similarity between the rainfall series reported in the above two studies is noteworthy.

Using 60 years' (1901–60) data of 230 stations, Parthasarathy and Dhar (1976) presented time series analysis of area-averaged annual rainfall over the eastern Madhya Pradesh (MP) and the western MP separately, and reported an increasing trend in the rainfall of east MP up to 1935 and that up to 1945 in west MP. In the case of annual rainfall, their study suggests a decreasing trend for the eastern MP after 1935 whereas for the western MP the series fluctuates around its mean after 1945.

In a separate study, using data of one raingauge station from each district, Parthasarathy (1984) calculated change in the mean summer monsoon rainfall (June to September) from the period 1871–1924 to the period 1925–1978 over east MP and west MP and found an increase of 5·9% (statistically significant at 10% level) in the rainfall of west MP and a decrease of 4·6% (statistically not significant) in east MP.

These studies, though useful for understanding the climate variability of the area, are of limited practical value. In the present study we propose to examine the finer details of the rainfall processes in addition to seasonal total so that useful information on rainfall characteristics can be provided to the water-based enterprises of the Upper Narmada catchment. The parameters of the rainfall processes over Upper Narmada catchment selected for the study are as follows:

(i) Area-averaged extreme rainfall of durations ranging from 1 to 10 days.
(ii) Area-averaged seasonal total rainfall during May to October, its time distribution characteristics and the combined characteristics of May-October rainfall and its time distribution.
(iii) The starting and the ending dates and the length of different periods contributing to each of 2, 5, 10, 20,... 90 and 95% rainfall to the annual total.

The association between break-monsoon days during the principal monsoon months of July and August (an important regional aspect of summer monsoon circulation) and the rainfall activities over Upper Narmada catchment is also investigated to understand the mechanism of rainfall fluctuations over the area.

2. Physiographic and climatic features

Narmada river originates from the Maikal ranges of the Vindhyas and after traversing a distance of about 1304 km nearly in the east-west direction at latitudes between 20° and 23°N, through the states of MP, Maharashtra and Gujarat—the maximum being in MP, it meets the Arabian Sea near Broach. It is a perennial river and the fifth largest in the country. However, in the present study we have considered the upper part of the catchment, upto Narmadasagar damsite in the downstream (figure 1). The total area of the Upper Narmada catchment is approximately 65,000 km^2 with an average elevation of 500 m above the sea level. Normally, this catchment receives larger rainfall compared to its surroundings. The annual isohyetal pattern displays decreasing magnitude from east to west, except for the two pockets of heavy rainfall (exceeding 1600 mm) in the Maikal ranges and around Pachmarhi (figure 1). The mean annual rainfall over the Upper Narmada catchment is 1252 mm of which 90% is contributed by the southwest monsoon system during June through September.

In general, the rainfall activities over this area are controlled by movement of the low pressure systems (the most common synoptic situation associated with monsoon activity) and depressions, and orography contributes to the enhancement of rainfall (Srinivasan *et al* 1971). According to a rough estimate, 80–90% of the annual rainfall over Narmada catchment occurs in association with disturbances (inclusive of lows, storms and depressions) of the monsoon season (Pant *et al* 1969). However, Raghavan (1973) showed that this anomalous rainfall is not because of orographic effect but primarily due to the presence of the monsoon trough over this area at 700 mb. In the tropics, the maximum contribution to total precipitation comes from the atmospheric

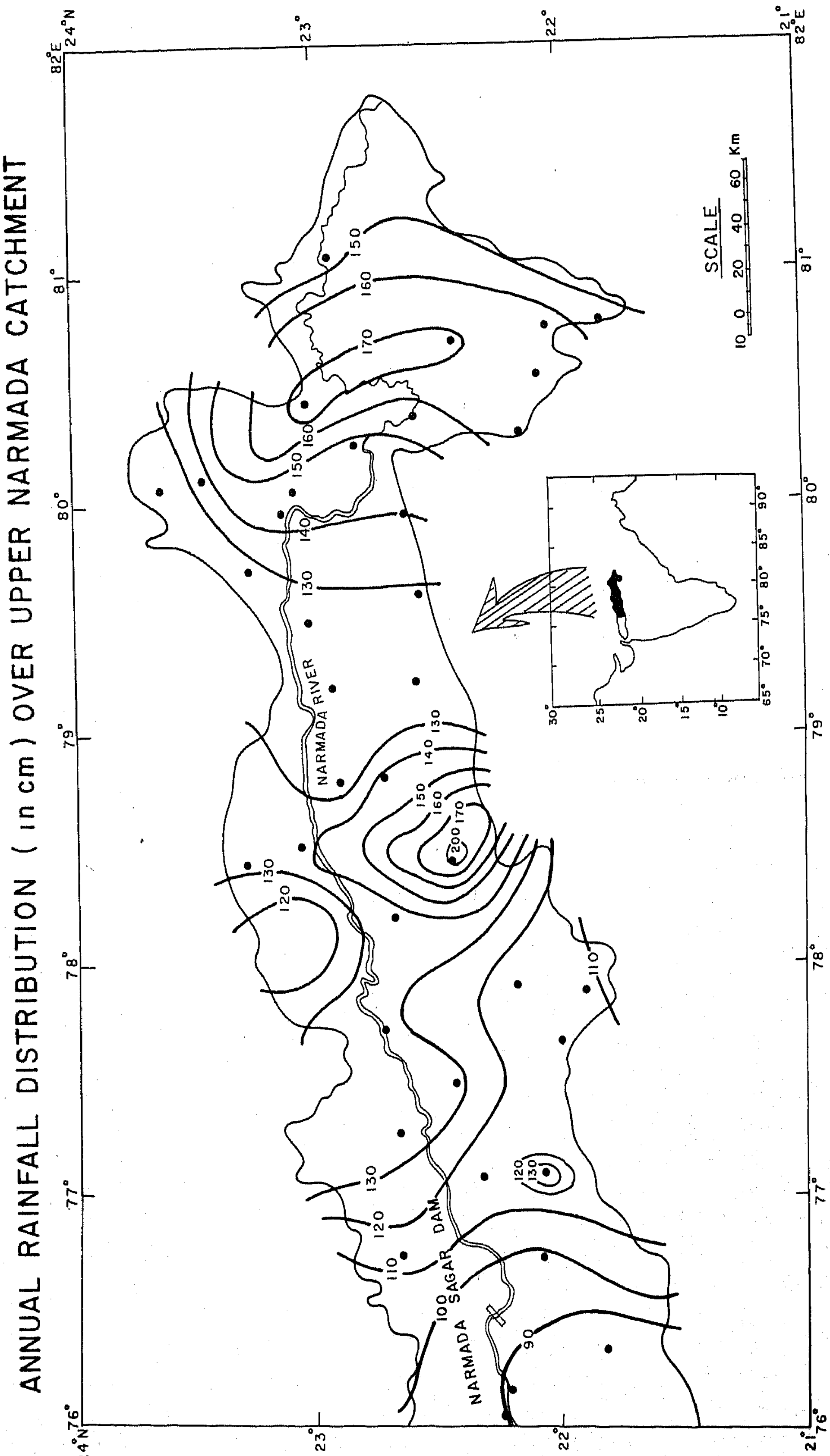

Figure 1. Location of the study area and the network of 38 raingauge stations. Continuous lines are the isopleths of the mean annual rainfall.

layer between 2·1 and 3·0 km (Banerji *et al* 1967). Raghavan (1973) explained that the 700 mb (3 km) level takes maximum advantage of the monsoon trough axis and its associated upward motion and produces greater rainfall around 23°N—the central part of the Upper Narmada catchment. According to Bedekar and Banerjee (1969) a trough zone forms over the central India right from the start of a depression in the Bay of Bengal which produces concentrated rainfall in the longitudinal belt of 80° to 81°E. It seems heavy rainfall results from the interactions between the monsoon trough, the low pressure systems and the orography. But this complicated process is not well understood.

On an average, one storm/depression, which forms over the Bay of Bengal during the monsoon season and moves in a west-northwest direction, passes over the eastern part of the catchment (see Ramage 1971). Narmada catchment lies slightly south of the mean depression path and receives heavy rainfall even from those disturbances whose surface centres are to the north of the catchment. Monsoon storms/depressions produce more rainfall in their southwest and southern sectors (Sikka 1977). Some of the storms/depressions maintain their west-northwesterly course through the catchment and cause severe floods (Pant *et al* 1969). Other physiographic details of the catchment (Mistry and Thatte 1969) and climatology of the area (Srinivasan *et al* 1971; IMD 1981) have been reported earlier.

3. Rainfall data

Location of 38 raingauge stations whose daily data for the period 1901–80 are used in the analysis is given in figure 1. For individual stations the period of record varies from 60 to 80 years. Based on available records, the mean rainfall for the catchment for each calendar date of the period 1901–80 is obtained through arithmetic averaging. From this area-averaged daily rainfall data the proposed parameters to be investigated were evaluated following the procedure given below. The basic statistical features of different parameters are also given.

4. Rainfall parameters and statistical properties

4.1 *1- to 10-day extreme rainfall*

For providing the desired information on rainfall characteristics for hydrologic design purposes as well as for flood severity assessment, characteristics of the extreme rainfall of wide ranging durations from 1 to 10 days have been studied for the Upper Narmada catchment. Extreme rainfall amount for each of 1, 2, 3 up to 10-day durations has been picked up year after year to form the extreme rainfall series of selected durations. The basic statistical properties, viz mean, standard deviation and coefficient of variation of different extreme rainfall series based on 80 years (1901–80) data are given in table 1. The mean of extreme rainfall for 1- to 10-day increases in nonlinear manner from 65 to 258 mm and they exhibit variability (C V) of 21 to 27%. The normality aspect of each extreme series has been tested by employing Fisher's g-statistic test to understand the nature of its frequency distribution. The coefficients of skewness (g_1) and kurtosis (g_2) and error statistics $g_1/\mathrm{SE}(g_1)$ and $g_2/\mathrm{SE}(g_2)$ (SE denotes standard error) for different

Table 1. Statistical parameters of the 1- to 10-day extreme rainfall, May–October total rainfall and PCI for Upper Narmada catchment.

Parameter	1-day	2-day	3-day	4-day	5-day	6-day	7-day	8-day	9-day	10-day	M–O	PCI
Mean (mm)	65·1	105·9	132·9	153·2	170·52	188·1	206·4	223·9	242·2	258·2	1174·4	4·93
SD (mm)	15·0	27·8	35·76	41·4	45·05	46·8	47·6	49·8	52·9	54·5	217·5	1·09
CV (%)	23·0	26·2	26·9	27·0	26·4	24·9	23·1	22·2	21·8	21·1	18·5	22·1
g_1	0·29	0·38	0·72	0·96	0·99	0·88	0·69	0·63	0·63	0·60	0·09	1·02
g_2	−0·37	−0·60	0·00	0·64	0·72	0·49	0·02	−0·2	−0·2	−0·3	−0·14	1·24
$g_1/SE(g_1)$	1·07	1·42	2·68*	3·56*	3·67*	3·27*	2·58*	2·33*	2·33*	2·22*	0·34	3·78*
$g_2/SE(g_2)$	−0·69	−1·12	0·01	1·20	1·35	0·92	0·04	−0·38	−0·39	−0·56	−0·27	2·33*

*Statistically significant at 5% level and above.

rainfall series are given in table 1. The test analysis shows that the rainfall series for 1- and 2-day durations follow approximately the normal distribution, whereas it is skewed for longer durations.

4.2 *May to October rainfall*

Over Upper Narmada catchment, the May–October (M–O) rainfall with a mean of 1174·4 mm contributes 93·8% to the annual total and is considered as the period of rainy season. The parameters of the basic statistical features and normality test for M–O rainfall series are given in table 1. This rainfall exhibits a variability of 18·5% and follows the normal distribution.

4.3 *Time distribution of May–October rainfall*

Apart from the total rainfall, features of the time distributions of seasonal rainfall are also equally important. The time distribution of May–October rainfall is quantified here by computing Oliver's precipitation concentration index (PCI) using 3-day (triad) rainfall totals. The index is defined as (Sato *et al* 1985),

$$\mathrm{PCI}_j = \frac{\sum_{i=1}^{N} X_{ji}^2}{(\sum X_{ji})^2} \times 100, \tag{1}$$

where X is the triad rainfall, N the number of triads (= 61) and j indicates the particular year, i.e. $j = 1, 2, \ldots, 80$.

After experimenting with daily, triad, pentad (5-day), weekly, decade (10-day) and monthly rainfall, 3-day total rainfall has been found optimum for computing PCI for hydrological purposes. Using short period (say daily) rainfall may underestimate the PCI values because of splitting of long and intense rain events into smaller rainfall amounts. On the other hand, longer period rainfall totals may overestimate the PCI because of pooling of smaller rainfall amounts. The characteristic property of PCI is that its high value (more than normal) indicates occurrence of rainfall in concentrated manner whereas a low value (less than normal) indicates well-distributed rainfall in time.

Mean, standard deviation, coefficient of variation and parameters of normality test for PCI series are given in table 1. The PCI series with a mean of 4·93% exhibits variability of 20% and is significantly different from normal distribution as indicated by Fisher's g-statistic test.

4.4 *The modified precipitation concentration index (MPCI)*

In order to assess rainfall of a year as hydrologically flood or drought, an index is evolved by a linear combination of May–October rainfall and its time distribution (PCI). For evaluating the index, firstly the mean of the standardized May–October rainfall and PCI is obtained year after year to form a third series,

$$\mathrm{XPCI}_i = \frac{1}{2}\left[\frac{\mathrm{PCI}_i - \overline{\mathrm{PCI}}}{\sigma_{\mathrm{PCI}}} + \frac{R_i - \bar{R}}{\sigma_{\mathrm{R}}}\right], \tag{2}$$

where XPCI is the element of the third series, $\overline{PCI}$ and σ_{PCI} are the mean and standard deviation of the PCI series and $\bar{R}$ and σ_R are the mean and standard deviation of the rainfall series respectively. The XPCl series is then normalized to form the series of a new index, designated as the modified precipitation concentration index (MPCI)

$$MPCI_i = (XPCI_i - \overline{XPCI})/\sigma_{XPCI}. \quad (3)$$

A high value (more than normal) of MPCI indicates the occurrence of high rainfall in few intense spells, whereas its low value (less than normal) indicates the occurrence of a low rainfall in a large number of spells. However, numerous combinations, probably infinite, are possible between different magnitudes of rainfall and PCI.

A large rainfall in a few spells may transform its major portion into run off and may result in floods. Run off component will be drastically reduced if the low rainfall is spread over a larger number of spells causing drought from a hydrological point of view. Depending on the magnitude of MPCl, the flood/drought year has been further categorized as normal, moderate flood/drought, severe flood/drought and disastrous flood/drought by giving arbitrary thresholds of $\pm \frac{1}{2}$, ± 1, ± 2 and $\gtrless \pm 2$ ($+$ denotes flood and-drought) to MPCI. However, there exists a highly significant (at 0·1% level) correlation ($r = 0{\cdot}50$) between May and October rainfall and MPCI, which shows that the seasonal total rainfall is a good indicator for a year to be hydrologically a flood or a drought but MPCI provides more exact information required for the purpose.

The MPCI series for Upper Narmada catchment is significantly different from the normal distribution as indicated by Fisher's g-statistic test.

4.5 *The period contributing specified percentages to annual total*

The different facets of the rainfall season viz its starting and ending dates, its length and its amount exhibit large variability. To demarcate the average period of the rainy season over a station or place numerous criteria can be traced in the literature; there does not appear to be a uniform criterion to demarcate the period of rainy season during a particular year over different rainfall regimes of India (Singh 1986). Rather than demarcate the period of rainy season yearwise over the Upper Narmada catchment, we picked up the period of shortest duration which contributed a fixed percentage of rainfall to the total rainfall of the year. In order to provide information on rainy season for a variety of practical problems we have picked up the rainfall period year after year which has contributed each of 2, 5, 10, 20,... 90 and 95% rainfall to the annual total and examined the statistical features of their parameters. The procedure for getting the rainfall period for a given percentage of annual total is given below.

The process started by picking 1-day highest rainfall amount of a year and comparing it with 2% value of the annual total. In case the 1-day extreme rainfall fell short of the 2% value of the annual rainfall, the extreme 2-day rainfall was picked up for comparison. As soon as the extreme amount of a certain duration equalled or exceeded the 2% value of the annual rainfall, the starting and ending dates of the period were noted, and the values compared with 5% value of the annual rainfall. The process of incrementing the duration by one day continued until the extreme amount equalled or exceeded the 5% value of the annual rainfall, and still further for higher percentages. It is expected that the features of the rainfall periods with wide ranging contributions from 2 to 95% may be of immense help for a variety of practical problems including hydrology, agriculture and forestry.

The basic statistical properties and parameters of the g-statistic test for starting and ending dates and length for different rainfall periods are given in tables 2, 3 and 4 respectively. The earliest and the latest observed starting and ending dates and the shortest and longest length of each rainfall period are also given in the tables along with the year.

4.5a *Starting date.* The mean starting date of the period contributing rainfall up to 10% to the annual total is in the first or second week of August, but it exhibits standard deviation of 3 weeks, which suggests that the period of occurrence of most intense rainfall activities of the year fluctuates abruptly from one year to another. In extreme cases the 10% rainfall period can start as early as 18th June (1921) and as late as 23rd September (1916). The mean starting date for higher percentages shifts monotonically to July, June and May months with increase of percentage values. The standard deviation of the starting date for the rainfall periods up to 90% is 10–25 days which is quite large. Interestingly, as indicated by g-statistic test the frequency distribution of starting date of the rainfall period up to 80% is, by and large, normal.

4.5b *Ending date.* For lower percentage rainfall periods (say up to 30%) the mean ending date is in the first or second week of August, and for higher percentages it shifts monotonically to the months of September and October. Like the starting date, the ending date of the lower rainfall periods also exhibits large (more than 3 weeks) standard deviation. The frequency distribution of the ending date for rainfall periods up to 80% is normal (table 3).

4.5c *Length of period.* The basic statistics and parameters of the normality test for the length series of different rainfall periods are given in table 4. It may be interesting to note that every year 1-day extreme rainfall contributes at least 2% to the annual total over the Upper Narmada catchment. On an average, 50% of the annual rainfall over the area occurs just in 41 days and up to 80% in 81 days. However, from 80% to 90% it requires an additional 37 days, and from 90% to 95% another 50 days. For 90% (30 days) and 95% (52 days) rainfall periods the standard deviation of the length series is also quite large. Except for 5, 10, 80 and 90% rainfall periods, the frequency distribution of the length series is normal. From the analysis it is inferred that the 80% rainfall period could be considered as the period of reliable rainfall.

In the mean, the 80% rainfall period starts on 24th June and ends on 12th September. In extreme cases, this period can start as early as 2nd June (1938) and end as late as 8th October (1903) and can have shortest length of 35 days (1930) and longest length of 111 days (1916).

5. Time series analysis

In this section, the time series of each of the above mentioned parameters are examined for long term trends. In the investigation student's t-test for difference in the mean between two equal subperiods, and Mann-Kendall (MK) Rank test (τ) for randomness against trend have been employed. These two tests can be applied for detecting linear as

Table 2. Statistical parameters of starting date of different rainfall periods in Upper Narmada catchment.

Parameter	Annual rainfall (%)											
	2	5	10	20	30	40	50	60	70	80	90	95
Mean (date/month)	10/8	8/8	4/8	29/7	26/7	26/7	16/7	8/7	2/7	24/6	11/6	5/5
SD (days)	24·3	24·7	24·0	22·2	20·9	17·2	15·0	12·8	9·9	9·9	22·4	51·0
g_1	0·13	0·09	0·12	0·21	0·05	0·21	0·10	0·05	0·63	0·20	2·80	0·86
g_2	−0·91	−0·81	−1·03	−0·76	−0·93	−0·91	−0·65	−0·17	0·23	−0·27	10·23	−0·81
g_1/SE(g_1)	0·47	0·33	0·46	0·79	0·17	0·77	0·36	0·18	2·33*	0·73	10·39*	3·18*
g_2/SE(g_2)	−1·72	−1·52	−1·93	−1·43	−1·74	−1·82	−1·22	−0·32	0·44	−0·52	19·23*	−1·53
Earliest	28/6	14/6	18/6	13/6	10/6	21/6	7/6	5/6	2/6	2/6	11/2	2/1
Year	17, 45	19	21	21	10	41	38	38	38	38	07	38
Latest	25/9	24/9	23/9	21/9	4/9	28/8	14/8	5/8	25/7	17/7	5/7	2/7
Year	16	16	16	16	54	54	05	55	34	03	23	23

*Statistically significant at 5% level and above.

Table 3. Statistical parameters of ending date of different rainfall periods in Upper Narmada catchment.

Parameter	Annual rainfall (%)											
	2	5	10	20	30	40	50	60	70	80	90	95
Mean (date/month)	10/8	9/8	7/8	8/8	13/8	18/8	25/8	30/8	4/9	12/9	5/10	18/10
SD (days)	24·3	24·6	24·0	22·8	21·5	18·0	18·0	15·4	12·4	11·7	24·3	27·0
g_1	0·13	0·11	0·16	0·36	0·35	0·38	0·21	0·24	0·01	0·05	1·19	0·87
g_2	−0·91	−0·81	−1·02	−0·60	−0·83	−0·67	−0·88	−0·40	−0·30	−0·15	0·89	0·09
g_1/SE(g_1)	0·47	0·39	0·58	1·33	1·30	1·42	0·77	0·88	0·02	0·18	4·44*	3·23*
g_2/SE(g_2)	−1·72	−1·52	−1·92	−1·13	−1·55	−1·25	−1·66	−0·74	−0·56	−0·28	−1·67	0·16
Earliest	28/6	15/6	21/6	23/6	6/7	15/7	24/7	1/8	6/8	12/8	27/8	2/9
Year	17,45	19	21	21	10	45	6	32	13	30	7	13
Latest	25/9	25/9	26/9	6/10	27/9	1/10	6/10	6/10	6/10	8/10	14/12	26/12
Year	16	16	16	16	49	54	16	16	16	03	67	9

*Statistically significant at 5% level and above.

Table 4. Statistical parameters of length of different rainfall periods in Upper Narmada catchment.

Parameter	Annual rainfall (%) 2	5	10	20	30	40	50	60	70	80	90	95
Mean (days)	1	1·5	3·6	10·6	19·3	29·8	41·2	51·6	65·8	80·7	116·8	166·8
SD (days)	—	0·6	1·3	3·1	5·4	7·2	8·9	10·1	10·1	12·2	29·7	51·9
g_1	—	0·68	0·75	0·28	0·24	0·12	0·20	0·06	0·05	0·72	1·12	0·53
g_2	—	−0·51	−0·72	0·15	−0·02	−0·21	0·01	−0·21	0·15	0·63	0·61	−0·68
$g_1/SE(g_1)$	—	2·52*	2·77*	1·06	0·88	0·44	0·73	0·21	0·20	2·66*	4·18*	1·96
$g_2/SE(g_2)$	—	−0·95	−0·33	0·28	−0·03	−0·39	0·01	−0·39	0·28	1·19	1·14	−1·28
Shortest	1	1	2	4	8	14	16	28	41	55	79	89
Year				72, 74	74, 79	72, 74	72	72	30	30	72	69
Longest	1	3	7	19	34	49	63	80	94	111	209	297
Year		34, 36, 38, 58	36, 58	17, 36	16	16	16	16	16	16	19	79

*Statistically significant at 5% level and above.

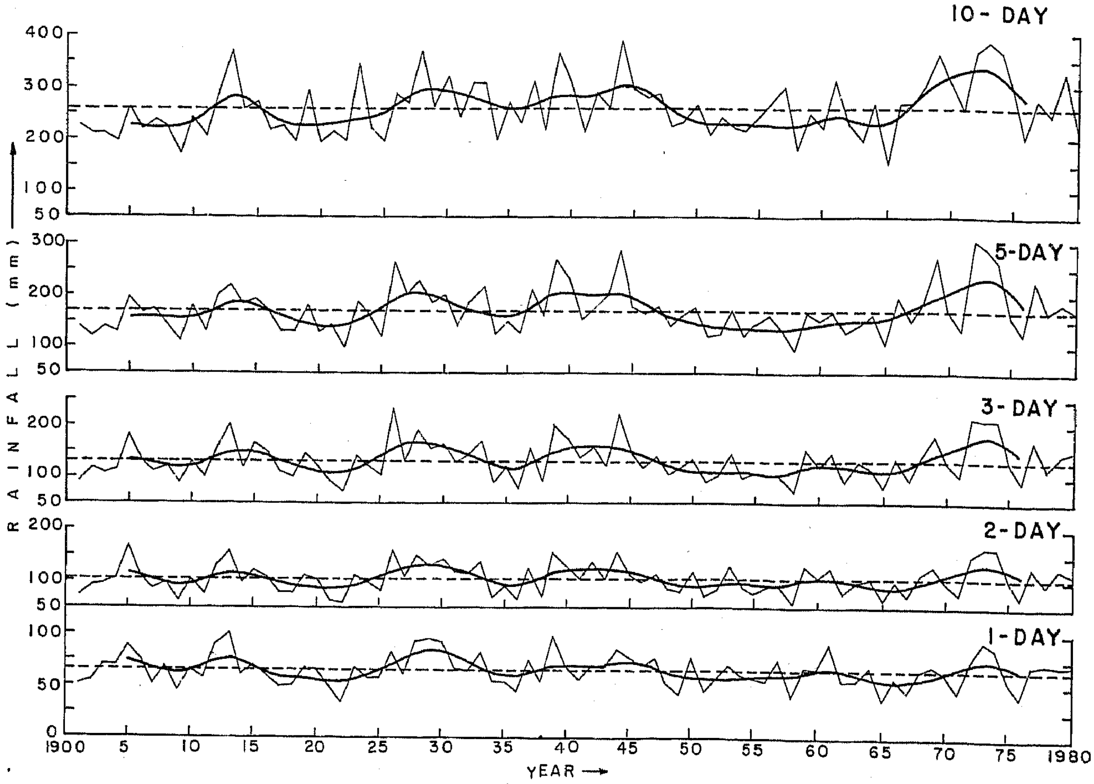

Figure 2. Time series plots of the area-averaged extreme rainfall over Upper Narmada catchment (thin line) for 1, 2, 3, 5 and 10-day durations. Thick line indicates the filtered (9-point gaussian low pass) values of the corresponding series.

well as nonlinear type of trends (WMO 1966). An abstract of the results of the analysis is given below.

5.1 *1- to 10-day extreme rainfall*

Though t and τ tests have been applied to each of the 1- to 10-day extreme rainfall and results discussed, the actual series is presented only for the five chosen, viz 1, 2, 3, 5 and 10-day durations (figure 2). The individual series smoothed by a 9-point gaussian low pass filter (WMO 1966) are also presented in figure 2 along with the actual series. The statistical tests do not show any significant long term trend in extreme rainfall series, and hence there is no indication that the storm rainfall intensity, and consequently severity of floods, over the Narmada catchment undergoes any significant change. However, from the filtered version of different extreme rainfall series four epochs of both the above and the below normal rainfall can be marked. In order to investigate whether there is any dominant periodicity in these extreme rainfall series, spectral analysis has been carried out which is discussed in a separate section.

5.2 *May–October rainfall, PCI and MPCI*

The time series of May–October rainfall, PCI and MPCI for Upper Narmada catchment are presented in figure 3. In MPCI series years with different categories of

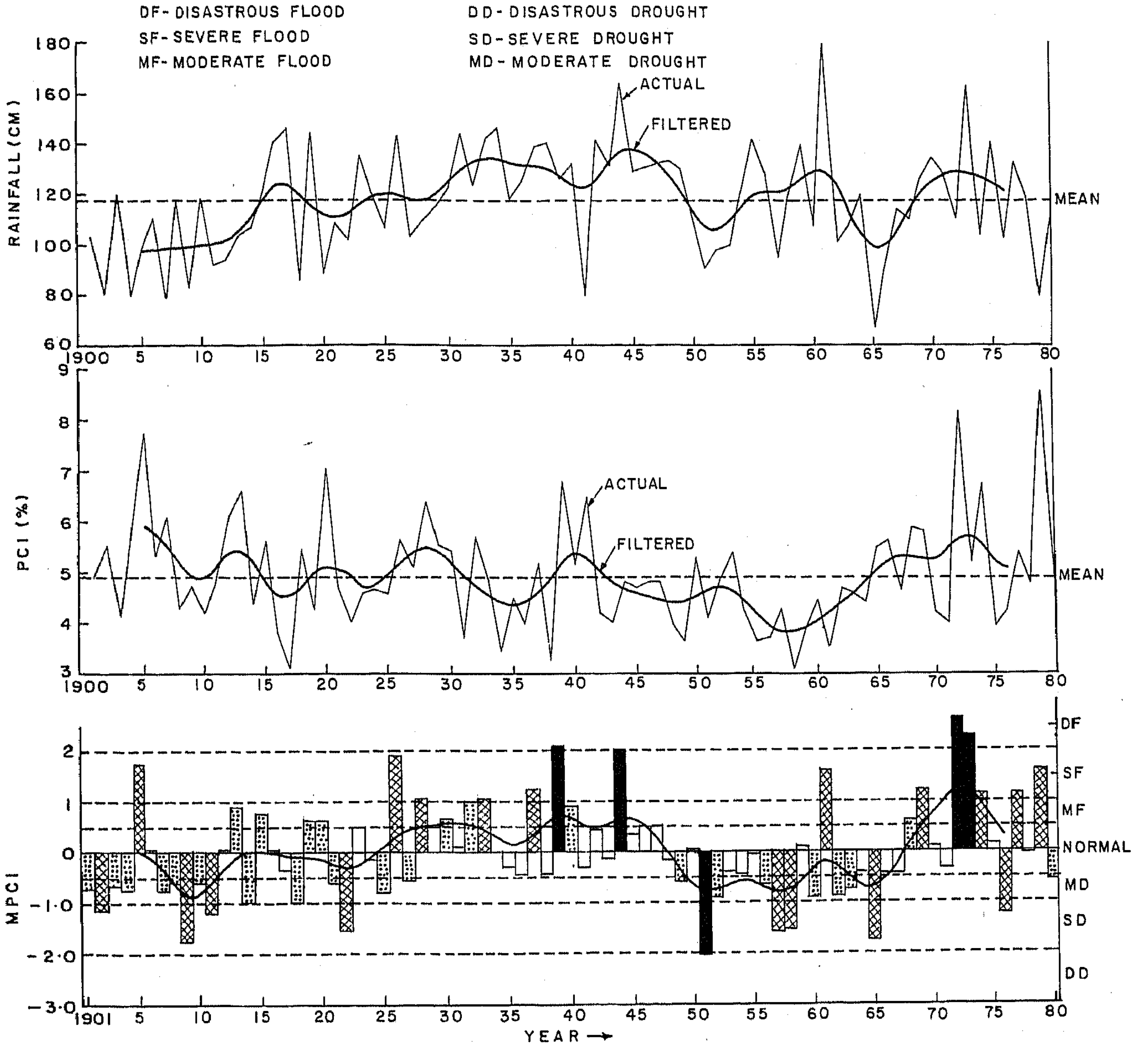

Figure 3. Time series plots of the May–October rainfall, PCI and MPCI. In MPCI series years with different categories of floods/ droughts are shaded differently. Thick line indicates filtered values.

floods/droughts are marked. Smoothing of high frequency waves in each series is done by applying the 9-point gaussian low pass filter and is presented in figure 3 along with the actual series.

Large year-to-year variability in the values of each series can be seen. Application of t and τ tests does not show any significant long term trend, and the three series can be assumed to be homogeneous.

A careful examination of rainfall and PCI series reveals that in general they fluctuate in the opposite manner. The negative correlation ($r = -0{\cdot}495$) between rainfall and PCI is significant at 0·1% level. The opposite association between seasonal rainfall and its time distribution (PCI) suggests that during good rainfall years, the rains will be distributed, by and large, throughout the period of rains. The fluctuation of MPCI, however, is fairly correlated with the seasonal total rainfall ($r = 0{\cdot}502$). Therefore, to a large extent total rainfall is sufficient to identify a year as a flood or drought year even for hydrological purposes.

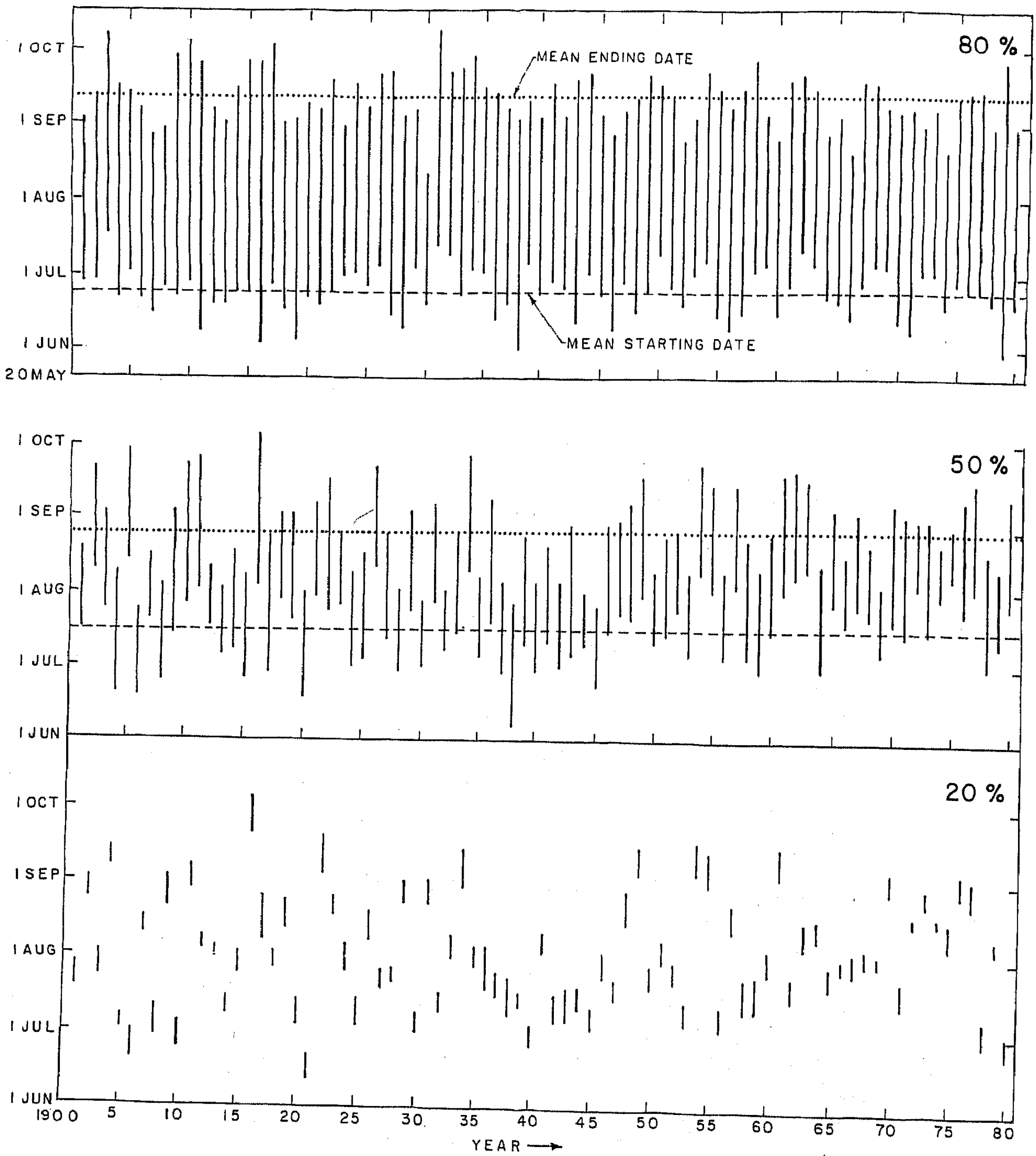

Figure 4. Time series plots of the starting and ending dates and the length of the shortest period contributing 20, 50 and 80% rainfall to the annual total over Upper Narmada catchment. For 50 and 80% rainfall periods the means of starting and ending dates are also presented.

5.3 *Starting and ending dates and length of the rainfall periods*

The time series of starting and ending dates and the length for chosen rainfall periods of 20, 50 and 80% values are presented in figure 4. For a given rainfall period, after marking the starting and ending dates of a particular year they are joined by a thick line to represent the length of period. Student's t and MK τ tests show that the starting and ending dates and the length series of different rainfall periods do not possess any trend.

The parameters of the period of major rainfall activities over the catchment area are stationary and hence no attempt is made to analyse them further.

6. Power spectrum analysis

A large number of techniques of spectral analysis currently in use were reviewed by Pestiaux and Berger (1984). Each method has its own merits and demerits in application. We have adopted here the method based on computing discrete Fourier transform (DFT). It is basically a harmonic analysis followed by some additional statistical manipulation. Details of estimating DFT power spectra and testing them for statistical significance are given by Schickedanz and Bowen (1975).

Normalized, smoothed spectral estimates of the selected extreme rainfall series as well as May–October rainfall, PCI and MPCI series are presented in figure 5. For convenience, the spectra are presented by taking the wave period on logarithmic scale along the abscissa. It is seen from the spectra that considerable power is contained in

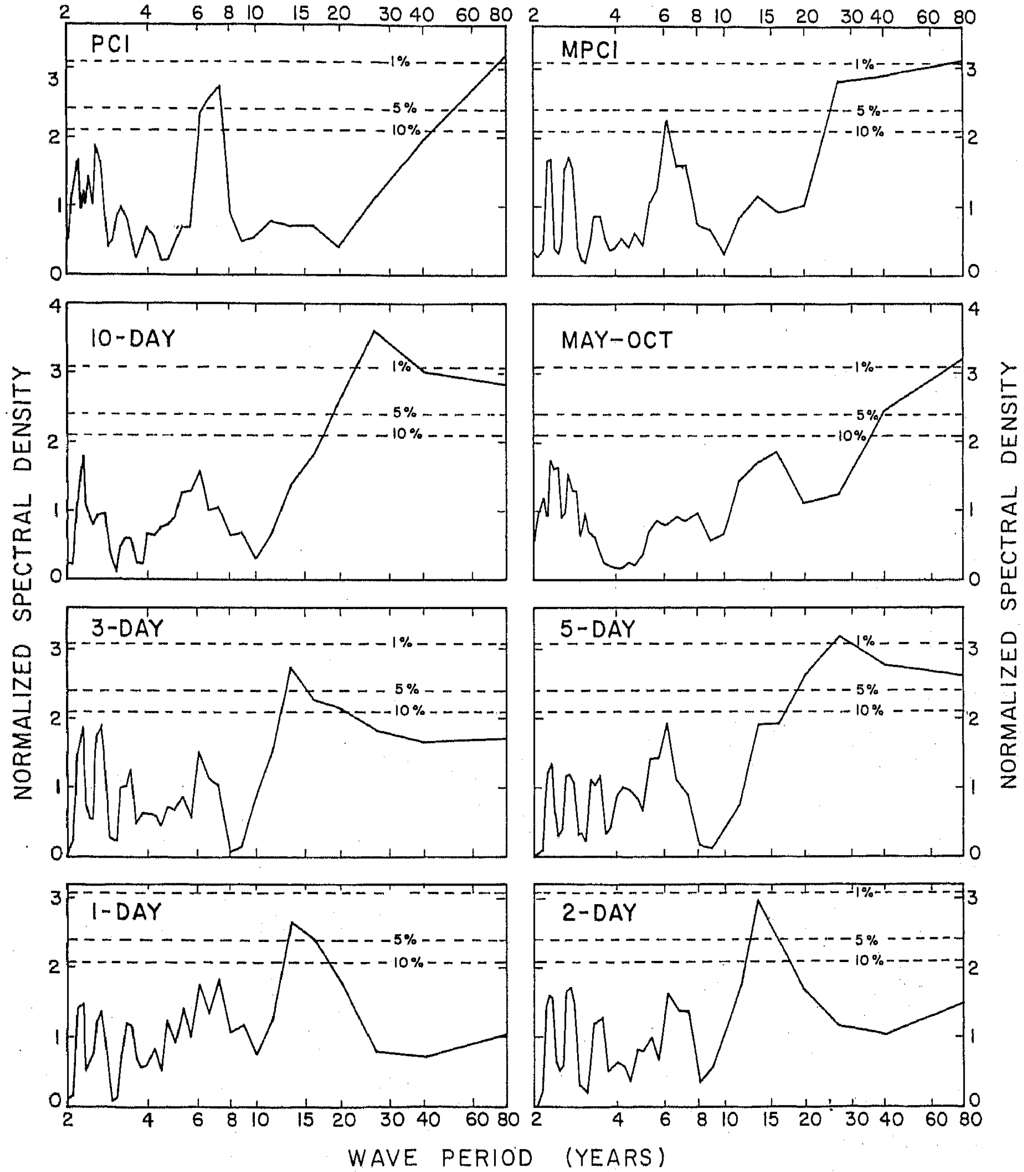

Figure 5. Power spectra of some representative parameters of the rainfall processes over Upper Narmada catchment.

the periods ranging from 13·3 to 16 years for extreme rainfall series of 1- to 3-day durations. However, for longer duration extreme series, the power contained in comparatively low frequency mode (wave period > 20 years) became greater and significant. In the May–October rainfall series, the amplitude of 40- and 80-year waves are significant. This also shows that extreme rainfall series and seasonal rainfall series of the same region can have different fluctuation characteristics.

The PCI spectra indicate concentration of power in high frequency waves with periods ranging from 6·7 to 7·3 years and in a low frequency wave of 80- year period. In the case of MPCI, however, the significant periodicities range from 26·7 to 80 years. The dominance of low frequency waves in extreme and seasonal rainfalls and MPCI are indicative of the occurrence of wet and dry epochs in the rainfall fluctuations of the Upper Narmada catchment. This may give sometimes a misleading impression of increasing/decreasing rainfall trend over the area. However, looking into the data limitation, the practical significance of 80-year wave in some hydroclimatic parameters should be interpreted with caution.

7. Rainfall over Upper Narmada catchment and break-monsoon days over India

The most conspicuous feature of the monsoon circulation over the Indian region is the monsoon trough. It is a quasi-permanent planetary scale low pressure area (or trough) in the lower and middle troposphere during the southwest monsoon period. The monsoon trough is fully developed by July and remains active up to the end of August (Raghavan 1973). In the mean, the sea level axis of the monsoon trough passes from Sri Ganganagar to Calcutta through Kanpur and Allahabad. It has a southward tilt in the vertical and at 700 mb, an atmospheric layer with maximum available precipitable water, lies over the eastern part (23°N) of the Narmada catchment. Because of favourable geographical location the Upper Narmada catchment receives larger rainfall than its surroundings. Occurrence and intensification of the monsoon trough at its normal and southerly position and formation of low pressure areas embedded in the trough is a favourable meteorological situation for good rainfall activity over the plains of north India (up to 20°N in the south). Northward shift of the trough axis brings about a dry weather condition over the north Indian plains. When the trough axis lies near the foot of the Himalaya, the northern plains are almost completely deprived of rainfall. This situation is commonly known as break-monsoon condition. During

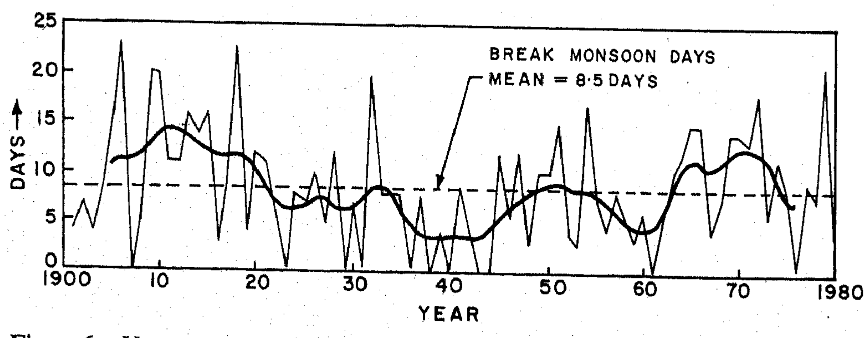

Figure 6. Year-to-year variation (thin line) of the break-monsoon days over India during July and August. Filtered values (9-point gaussian low pass) of the parameter is presented by the thick line (after Parthasarathy and Pant 1986).

break-monsoon condition the Narmada catchment is also an adversely affected area.

A long series of break-monsoon days during July and August is prepared by Parthasarathy and Pant (1986) (figure 5). The series displays opposite behaviour with respect to seasonal rainfall over Upper Narmada catchment. The negative correlation coefficient ($r = -0.375$) based on 80 data points is statistically significant at 1% level. But the correlation is not as strong as was expected. Sometimes, plains of the northern India (including Narmada catchment) receive ample rains and experience floods after a prolonged dry spell caused by a westward moving Bay depression or storm. This overcomes the rainfall deficiency caused by the break-monsoon condition. This assumption can be supported by the fact that there exists a highly significant positive correlation ($r = 0.395$) between break-monsoon days and the precipitation concentration index (PCI), that is during a year with large number of break-monsoon days the total seasonal rainfall will be concentrated in comparatively less number of rainfalls. Therefore, the effectiveness of rainfall activities over the Upper Narmada catchment for hydrological purposes is independent of the number of break-monsoon days over India. The correlation coefficient between the break-monsoon days and the MPCI of the Upper Narmada catchment is 0·018 which indicates the independent nature of the two series.

The break-monsoon condition is known for low or no rainfall activities over the northern plains, but some times deficiency in July and August rainfall due to break-monsoon condition is compensated by the good rainfall activities during June and September caused by the storms/depressions. Of the 22 heavy rainstorms, which occurred over the Narmada catchment during 1930 to 1968, as reported by Pant *et al* (1969), 10 had occurred during June and September. Hence, even if some year happens to be a below-normal rainfall year, it can be a hydrologically flood year because of the concentration of total seasonal rainfall into a few intense rainspells.

8. Summary and conclusions

The important features of hydroclimatic fluctuations of the Upper Narmada catchment and its association with break-monsoon days over India noticed in this investigation are as follows:

(i) The area-averaged extreme rainfall series of Upper Narmada catchment for 1 and 2 days is normally distributed, whereas it is skew distributed for longer durations. The dominant periodicities noticed in different extreme rainfall series vary from 13·3 to 16 years and 26·7 years.

(ii) The frequency distribution of May–October rainfall over the Upper Narmada catchment is normal. But the PCI and MPCI series are significantly different from normal. Some dominant periodicities have been noticed in May–October rainfall (40 and 80 yrs), PCI (6·7 to 7·3 and 80 yrs) and MPCI (26·7 to 80 yrs) series.

(iii) The time series of the starting and ending dates and the length of each of the period contributing 2, 5, 10, 20, ... 90 and 95% rainfall to the annual total is homogeneous and random. The frequency distribution of these parameters in most cases is normal. The 80% rainfall period can be considered as the period of reliable rainfall over the Upper Narmada catchment. In the mean, this period starts on 24th June and ends on 12th September.

(iv) The number of break-monsoon days over India during the peak monsoon months of July and August significantly affects the rainfall activities over the Upper Narmada catchment.

It is expected that the behaviour of the characteristic parameters, viz extreme rainfall, seasonal rainfall, PCI and MPCI, representing features of the rainfall processes over Upper Narmada catchment which are found to observe epochs of high and low values can provide forecasters and water managers a valuable aid for issuing flood forecast and planning long term management of water resources in the basin respectively. Due to data limitation it is suggested that the significance of the dominant 80-year wave in some hydroclimatic parameters should be used with caution.

Acknowledgements

Authors are grateful to Shri D R Sikka for encouragement, to Dr G B Pant and Dr B Parthasarathy for stimulating discussion and critically reviewing the paper.

References

Banerji S, Rao D V L N, Julka M L and Anand C M 1967 Some further results of investigations on quantitative precipitation forecasting over selected areas in North India; *Indian J. Meteorol. Geophys.* **18** 465

Bedekar V C and Banerjee A K 1969 A study of climatological and other rainfall patterns over central India; *Indian J. Meteorol. Geophys.* **20** 23

Chaturvedi M C and Srivastava D K 1981 Study of a complex water resources system with screening and simultaneous models; *Water Resources Res.* **17** 783

India Met. Deptt. 1981 *Climate of Madhya Pradesh.* Office of the Additional Director General of Meteorology (Res.), I M D, Pune, p. 265

Mistry J F and Thatte C D 1969 Floods in river Narmada—August 1968. *Flood control and the use of river water resources,* Symp. held at South Gujarat University, Surat (Surat: South Gujarat University) p. 87

Pant P S, Abbi S D S and Gupta D K 1969 A hydrometeorological study of the heavy floods in Narmada and Tapti. *Flood control and the use of river water resources* Symp. held at South Gujarat University, Surat (Surat: South Gujarat University) p. 151

Parthasarathy B 1984 *Some aspects of large-scale fluctuations in the summer monsoon rainfall over India during 1871–1978,* Ph.D. thesis, University of Poona, Pune, p. 370

Parthasarathy B and Dhar O N 1976 Studies on trends and periodicities of rainfall over Madhya Pradesh; *Proc. Indian Natl. Sci. Acad.* **A42** 73

Parthasarathy B and Pant G B 1986 Summer monsoon rainfall over different regions of India and circulation features during 1981–84. *The diagnosis and prediction of monthly and seasonal atmospheric variations over the globe,* Symp. held at Maryland, USA, during July 1985 WMO No. TD-87, p. 235

Pestiaux P and Berger A 1984 An optimal approach to the spectral characteristics of deep-sea climatic records. *Milankovitch and climate, Part 1* (Dordrecht: D Reidel) p. 417

Raghavan K 1973 Break-monsoon over India; *Mon. Weather Rev.* **101** 33

Ramage C S 1971 *Monsoon meteorology* (New York: Academic Press) p. 61

Ramana Murthy K V, Soman M K and Mulye S S 1987 Long term variations in the rainfall over Upper Narmada catchment; *Mausam* **37** 313

Sato N, Yamada M and Murakami C 1985 Distribution of the precipitation concentration index over east Asia and regional division by its use; 1984 *Jpn. Progr. Climatol.* p. 56

Schickendanz P T and Bowen E G 1975 Computation of climatological power spectra using variable record lengths. *Fourth conference on probability and statistics in atmospheric sciences* held at Tallahassee, Florida, USA, (Boston, USA: American Meteorological Society) p. 102

Sikka D R 1977 Some aspects of the life history, structure and movement of monsoon depressions; *Pure Appl. Geophys.* **115** 1501
Singh N 1986 On the duration of the rainy season over different parts of India; *Theor. Appl. Climatol.* **37** 51
Srinivasan V, Raman S and Mukherji S 1971 Southwest monsoon—Typical situations over Madhya Pradesh and Vidarbha. *FMU* Rep. No. III-3.4, India Meteorol. Deptt., Pune p. 68
WMO 1966 Climatic change WMO Tech. No. 79, WMO-195, TP 100