JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.53, Jan. 1999, pp.5-15

# Long-period Fluctuations in Monsoon Floods in the Deccan Peninsula, India

VISHWAS S. KALE
Department of Geography, University of Pune, Pune 411 007
(E-mail: vskale@unipune.ernet.in)

**Abstract:** In the present study, the temporal patterns of monsoon floods on five large rivers of the Deccan Peninsula have been investigated. Analyses of the long-term annual maximum discharge/ stage data, available for the last 100 years or so, show non-random behaviour in terms of distinct periods of high and low floods. The normalized accumulated departure from mean (NADM) plotting method has been used to identify great periods of below-average (low) and above-average (high) floods. Examination of the data reveals lower frequency and magnitude of large floods during the late-1800 and early-1900 period, and a period of increased frequency of large floods between 1940s and 1960s. The results of the investigation also indicate that the high (low) flood response is consistent with increased (decreased) precipitation in the basins. There is a clear evidence of an enhancement in the magnitude and frequency of large floods in the post-1940 period.

**Keywords:** Flood studies, Monsoon rainfall, High/low flood periods, Climatic changes, Deccan Peninsula.

## INTRODUCTION

A question of fundamental importance to flood hazards research in India is whether the pattern of flooding has changed over the last few decades and whether a change is likely to occur in future. Though, it is difficult to know the likely future pattern of flooding, it is possible to detect the nature and magnitude of changes that have occurred in the past. Ascertaining the trends or changes in the streamflow records is also exceedingly important because changes in the hydro-meteorological conditions are reflected in the streamflow records (Burn and Arnell, 1993; Chiew and McMahon, 1993), and as such, it may be possible to detect climatic changes. However, detecting changes or trends is always challenging given the shortness of the hydrological records in comparison to the time scale of the climatic changes. River discharges have been measured on several Indian rivers since about 1950s/1960s, but streamflow records for the earlier period are either non-existent, non-continuous or not readily available. As a result, it has been difficult to identify the long-term trends and evaluate the influence of climatic conditions and variability on trends in flood magnitudes and frequency. Although previous studies have examined the secular variations in the Indian monsoon rainfall and the regional rainfall, and have identified epochs of high and low rainfall (Mooley and Parthasarathy, 1984; Gregory, 1989; Parthasarathy et al. 1991; Kripalani and Kulkarni, 1997), studies of streamflow records to determine the long range natural patterns in floods at the all-India or regional level have not been done. In this paper, an attempt has been made to analyze all the available data and to identify the temporal patterns in large floods on five large rivers of the Deccan Peninsula. The objectives of this paper are: 1) to analyze the long-range records of peak floods on five large rivers of the Deccan Peninsula, and to identify great periods of above-average (high) and below-average (low) floods, and 2) to examine the relationship between annual maximum floods on the one hand, and the all-India or macro-regional monsoon rainfall on the other.

**Table 1.** Major rivers of the Deccan Peninsula

| River | Drainage area in $km^2$ | Length in km | Peak discharge record in $m^3s^{-1}$ | Average slope in % | Sediment load in $10^6$ t/yr |
|---|---|---|---|---|---|
| Mahanadi | 141589 | 851 | 44827 | 0.05 | 15.7 |
| Narmada | 98796 | 1312 | 69000 | 0.08 | 70.0 |
| Tapi | 65145 | 724 | 41700 | 0.10 | 25.0 |
| Godavari | 312812 | 1465 | 78800 | 0.04 | 170.0 |
| Krishna | 258948 | 1401 | 33600 | 0.09 | 4.0 |
| Kaveri | 81155 | 800 | 14716 | 0.17 | 1.5 |

Source: Rao (1975), Subramanian (1993), CWC (1996), UNESCO and other sources.

## DATA AND METHOD OF ANALYSIS

The Deccan Peninsula forms a distinct hydro-geomorphic and morpho-tectonic unit of the Indian subcontinent. The main rivers of this unit are the Mahanadi, Narmada, Tapi, Godavari, Krishna and Kaveri (Table 1). In the present study five large rivers of the Deccan Peninsula namely Mahanadi, Narmada, Tapi, Godavari and Krishna have been included. It would have been desirable to include the Kaveri River also. However, the readily available flood series is too short, and hence unsuitable for long-range studies.

### Data set

The data analyzed in this paper consist of long-term annual peak discharge/stage series available for five large rivers of the Deccan Peninsula. The annual peak discharge/stage is used as an indicator of the flood response for a river (Burn and Arnell, 1993). The gauging sites (Fig. 1) were selected because they are located in the lower reaches and thus represent the flood characteristics of the entire basin. The gauging sites have long records and hence are suitable for recognizing long-term trends that might have resulted from long-term changes in the climate (chiefly rainfall). The data were mostly obtained from numerous research articles, published reports and a few unpublished reports. The time-span and sources of data are given in Table 2.

The data for Mahanadi and Narmada consist of time series of annual peak stages. These data were used because long and continuous records of peak discharges are not available for the Naraj site on Mahanadi and Baroch site on Narmada (Fig.1). However, correlation analyses using short-term discharge series indicate that the use of either annual peak stage or discharge data would give about the same direction and magnitude of trends.

Continuous flood magnitude or flood stage data are not available for the Tapi River, but there is information about flood magnitude/stage for all the large floods that exceeded the gauge level 95 feet (about 29 m) at Surat, between 1876 and 1994. In the absence of continuos records, the annual rainfall data of Betul (Fig. 1) and the Narmada flood level series have been used to interpret the long-term behaviour of the Tapi River. The annual peak discharge records for the River Godavari at Dowleshwaram from 1905 to 1967 were published by Gole et al. (1978) and UNESCO. Since post-1967 data were not available for the same site, the discharge data available for Polavaram gauging site were used. Student t-test applied to the data sets shows that the differences are statistically insignificant.

Table 2 also shows that data for some sites are missing for short durations. Logarithmic regression equation (r =0.91) was used to estimate the flood stage for the missing period (1951-1957) for the Naraj site by using the Baramul discharge data. The peak discharges for the missing period for Vijayawada (Krishna) and Dowleshwaram (Godavari) were filled by the long-term period mean. For the 1964 peak flood on Krishna, the maximum discharge at Vijayapure was adopted. Since the 1986 flood

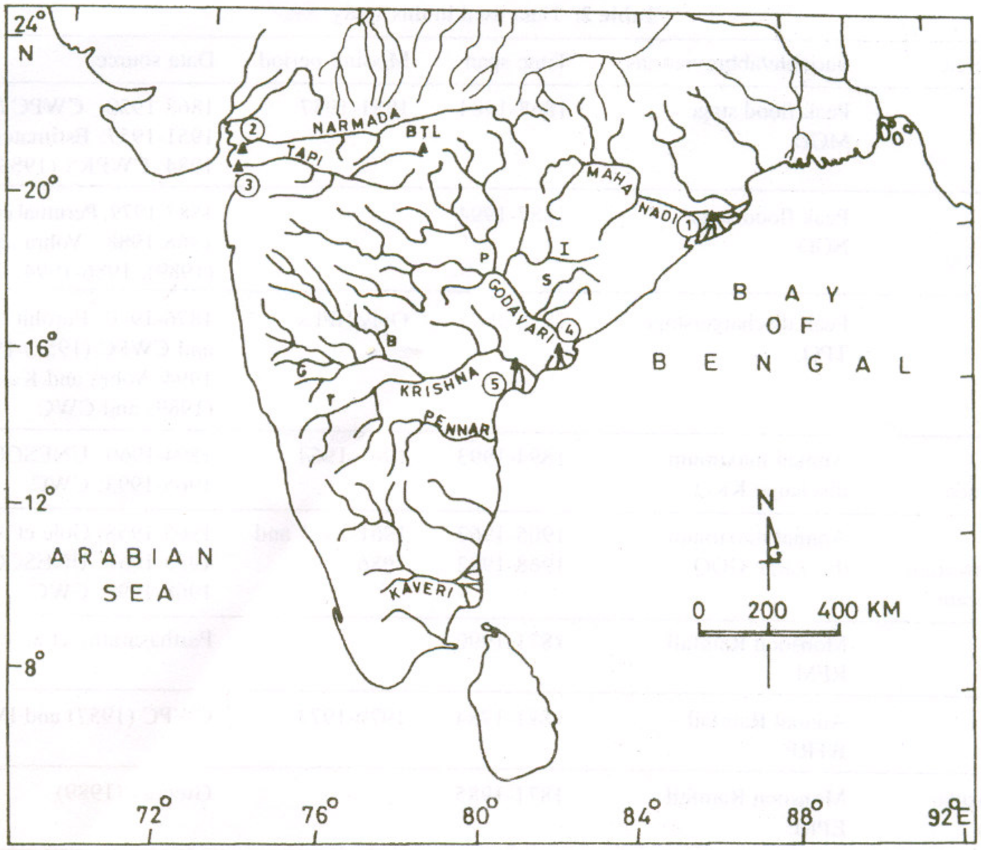



**Fig.1.** Map showing the major rivers of the Deccan Peninsula. 1 = Naraj site on Mahanadi; 2 = Baroch site on Narmada; 3 = Surat site on Tapi; 4 = Dowleshwaram site on Godavari; and 5 = Vijayawada site on Krishna. BTL= Betul; I = Indravati; S = Sabari; P = Pranhita; B = Bhima; G = Ghataprabha; T = Tungabhadra.

stage on Godavari was higher than the highest flood level recorded in 1953, the maximum discharge recorded for the 1953 flood was considered as the representative of the 1986 flood.

In the present study the data regarding all-India monsoon rainfall (1871-1990) were taken from Parthasarathy et al. (1991), and monsoon rainfall data for the subregions (macro-regions) of the Deccan Peninsula were obtained from Gregory (1989).

**Normalized Accumulated Departure from Mean (NADM)**

The successive characteristics of long series data sets can be easily determined by using accumulated departure from mean (ADM) (Riehl et al. 1979; Mooley and Parthasarathy, 1984; Probst and Tardy, 1987). In order to filter short-term fluctuations and to highlight the long-range variability in streamflow and monsoon rainfall, the normalized accumulated departure from mean (NADM) plotting method has been used in this study. The normalized accumulated departure from mean (NADM) is the accumulated departure from mean (ADM), divided by the largest number (absolute) in order to plot between -1 and +1 (Thomas, 1993). The normalized ADM, therefore, permits visual as well as statistical comparison of unlike data (Thomas, 1993). Periods characterized by above-average (below-average) conditions are commonly indicated by positive (negative) slopes of the graph (Gregory, 1989; Thomas, 1993). Unlike other filtering methods, such as moving-averages, the ADM permits the distinction between periods of high and low floods by clearly defining the limits (Probst and Tardy, 1987). Studies by Riehl et al. (1979) and Thomas (1993) have shown that it is necessary

**Table 2.** Data used in this study

| River/site/area | Variable/abbreviations | Time span | Missing period | Data source |
|---|---|---|---|---|
| Mahanadi - at Naraj | Peak flood stage - MGD | 1868-1984 | 1951-1957 | 1868-1950: CWPC (1952) 1951-1957: Estimated 1958-1984: CWPRS (1988) |
| Narmada - at Broach | Peak flood stage - NGD | 1887-1994 | - | 1887-1979: Perumal et al. (1985), 1968-1988: Vohra and Kumar (1989), 1986-1994: CWC |
| Tapi - at Surat | Peak discharge/stage - TPQ | 1876-1994 | Only HFLs | 1876-1970: Purohit (1972) and CWPC (1957) 1971-1994: Vohra and Kumar (1989) and CWC |
| Krishna - at Vijayawada | Annual maximum - discharge KRQ | 1894-1993 | 1961-1964 | 1894-1960: UNESCO 1965-1993: CWC |
| Godavari - at Dowleshwaram and Polavaram | Annual maximum - discharge GOQ | 1905-1967 1968-1992 | 1961-1964 and 1986 | 1905-1958: Gole et al. (1978) 1959-1967: UNESCO 1968-1992: CWC |
| All-India | Monsoon Rainfall - RFM | 1871-1990 | - | Parthasarathy et al. (1991) |
| Betul | Annual Rainfall - BTRF | 1891-1984 | 1970-1971 | CWPC (1957) and IMD |
| East Peninsular Region (4) | Monsoon Rainfall - EPRF | 1871-1985 | - | Gregory (1989) |
| Southern Peninsular Region (9) | Monsoon Rainfall - SPRF | 1871-1985 | - | Gregory (1989) |

CWC = Water Year Books/Flood forecasting and warning network performance appraisal (1986-1994) - Central Water Commission. IMD = India Meteorological Department. HFL = High Flood Levels/discharge.

to compare only records covering equal periods. Therefore, while comparing different records the length of the plot period has been kept equal. The correlation coefficient (r) has been used in this study as an index measure of the degree of correspondence or association between NADM graphs.

## LONG-RANGE TEMPORAL PATTERNS

The NADM graphs given in Fig. 2 show the long-term trends. The graphs for Narmada and Godavari are 'V' shaped with one major episode of low floods in the earlier part and one major period of high floods in the later part of the record. The Mahanadi graph reveals two low-flood phases in the early and late period, and a marked phase of high floods in between. The graph for Krishna is 'M' shaped with high-flood phases in the early and the middle period followed by low-flood phases. Since falling (rising) nature of NADM graph implies below-average (above-average) conditions, the NADM graphs suggest that for Mahanadi, Narmada and Godavari, flood magnitudes were lower than average during the late-1800 and early-1900. In contrast, the Krishna NADM discharge graph steadily rises at about the same time, and indicates a period of above-average floods during the early part of this century. For the most recent decades the NADM graphs exhibit positive slope (period of high floods) for the Narmada and Godavari Rivers, and a negative slope (period of low floods) for the Krishna and Mahanadi Rivers. The graphs (Fig. 2) also show a lag of about fourteen years in the

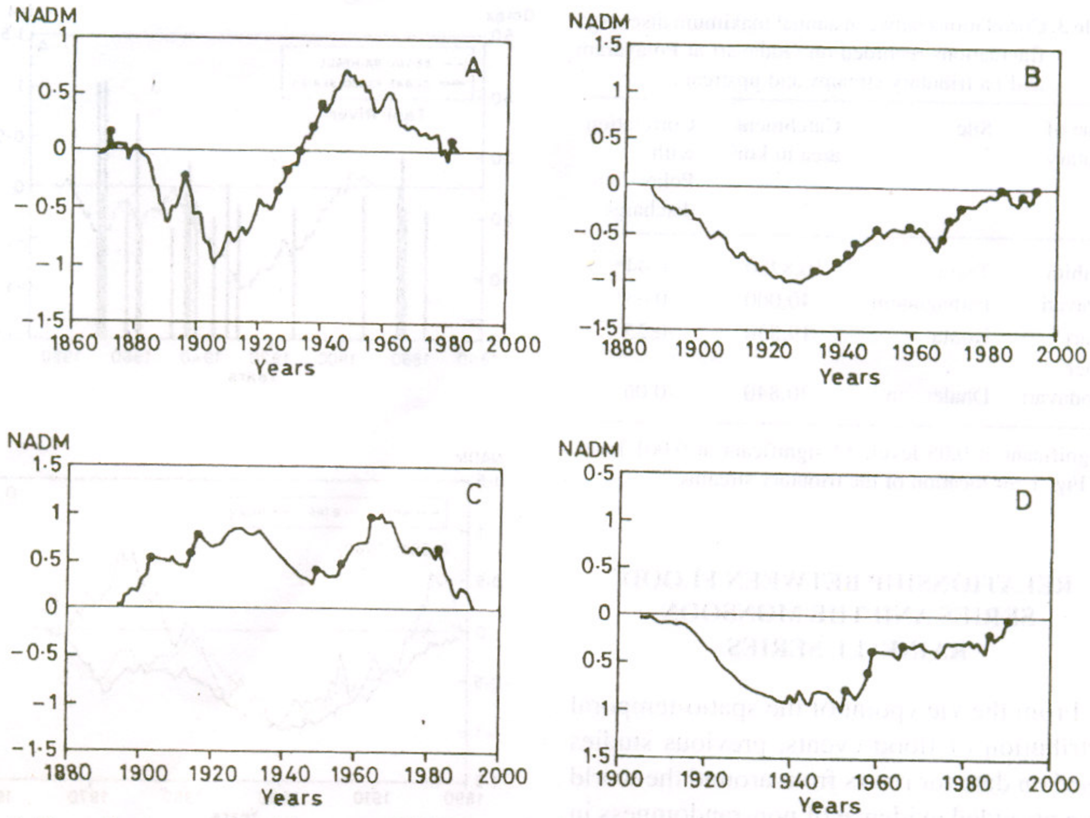



**Fig.2.** Normalized accumulated departure (NADM) graphs for annual peak discharge/stage. **A** = Mahanadi at Naraj, **B** = Narmada at Baroch, **C** = Krishna at Vijayawada, and **D** = Godavari at Dowleshwaram/ Polavaram. The flattening of the graphs in early 1960s for Godavari and Krishna Rivers is due to long-term mean used to fill the missing values. Major flood years shown by solid circles on the NADM graph.

correspondence between the Narmada and Godavari NADM curves, and a lag of about two decades between the Mahanadi and Narmada NADM curves.

Although the NADM graph could not be constructed for the Tapi River, because only high flood level and discharge data are available, a plot of the high flood data shows an identical trend. Figure 3A clearly reveals lower frequency and magnitude of large floods during the late-1800 and early-1900 period, and a period of increased frequency of large floods between 1930s and 1960s. Even though the timing and duration of high and low flood conditions differed between the rivers, there is some evidence of a common high-flood phase between 1940s and 1960s.

The source areas of the Mahanadi, Narmada and Tapi Rivers, and a large part of the Godavari Basin fall in the zone of severe rainstorms. Therefore a, more or less, similar pattern for the central Indian rivers is not unexpected. Correlation analysis for the Godavari River shows that the interannual variability in peak discharges at Polavaram is significantly correlated with the peak flows on the tributaries rising in central India rather than with the upper Godavari (Table 3). In comparison, Krishna and all its major tributaries originate in the Western Ghats and do not directly fall in the mean monsoon track of the Summer Bay depressions. It appears, therefore, that there is a close correspondence between the rainfall that falls over the basins and the flood response. Studies carried by Gregory (1989) show that there are clear regional differences in the temporal patterns of monsoon rainfall over the period 1871-1985.

**Table 3.** Correlations between annual maximum discharge fluctuations recorded on Godavari at Polavaram and on tributary streams and upstream

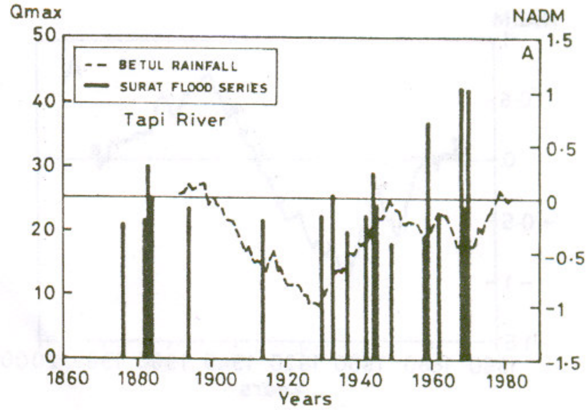
| Name of tributary | Site | Catchment area in km$^2$ | Correlation with Polavaram discharge |
|---|---|---|---|
| Pranhita | Tekra | 10,8780 | 0.44* |
| Indravati | Pathagudem | 40,000 | 0.65** |
| Sabari | Konta | 19,550 | 0.25 |
| Upper Godavari | Dhalegaon | 30,840 | -0.06 |

* significant at 0.05 level; ** significant at 0.001 level. *See* Fig. 1 for location of the tributary streams.

## RELATIONSHIP BETWEEN FLOOD SERIES AND THE MONSOON RAINFALL SERIES

From the viewpoint of the spatio-temporal distribution of flood events, previous studies based on data for rivers from around the world have provided evidence of non-randomness in the occurrence of large floods and the Hurst's persistence phenomenon (Riehl et al. 1979; Probst and Tardy, 1987; Burn and Arnell, 1993; Eltahir, 1996). That is, there is a tendency for wet and dry years to occur in groups (i.e. persistence), and periods of large floods (low floods) are associated with wet or humid periods (dry periods). In order to determine whether there is a similar tendency for periods of high and low floods to coincide with periods of high and low monsoon rainfall, the relationships between the all-India monsoon rainfall and the flood series were evaluated. Analyses were carried out separately for all the rivers because the time-span for which flood data are available is different.

Fig.3B shows the NADM graphs for the all-India monsoon rainfall (RFM), Betul rainfall (BTRF) and the Narmada flood stage data at Baroch (NGD). The graphs show remarkable similarity in their long-term behaviour. Comparison of the Narmada NADM flood levels and the all-India NADM monsoon rainfall produces a correlation of 0.77 (Table 4). The



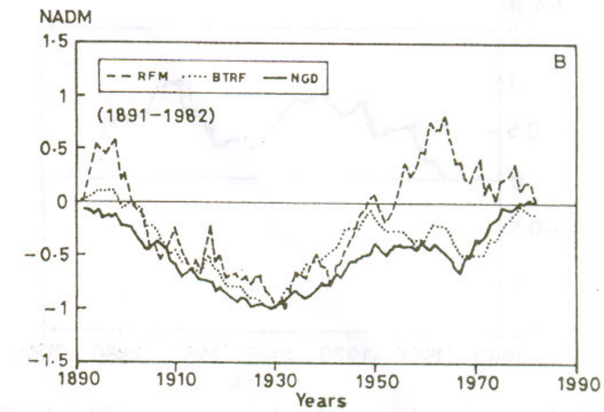




**Fig.3. A.** Plot of the peak flood discharges of the Tapi River at Surat, for floods exceeding gauge level 29 m (1876 to 1990). The dash line is the NADM graph for Betul rainfall. The flattening of the graph around 1970 is due to long-term mean used to fill the missing values. Qmax = annual peak discharge in $10^3$ x $m^3$ $s^{-1}$. **B.** Normalized ADM graphs. RFM = all-India monsoon rainfall, BTRF = Betul rainfall, and NGD = Narmada annual peak flood stage.

r-value between Betul rainfall (representative of the Tapi flood series) and the all-India monsoon NADM is equally high (r = 0.74). These relations imply that long periods of positive departure (negative departure) in the

**Table 4.** Correlation coefficients for 1891-1982.

| | RFM | BTRF | NGD |
|---|---|---|---|
| RFM | - | 0.51 | 0.32 |
| BTRF | 0.74 | - | 0.54 |
| NGD | 0.77 | 0.89 | - |

The upper right numbers are correlations for raw data sets and the lower left are for the NADM of the same data set. All NADM correlations significant at 0.001 level.

flood magnitude are associated with periods of positive departure (negative departure) in the all-India monsoon rainfall (RFM). Similar, but a relatively weaker relationship was observed between the Godavari flood series (GOQ) and RFM (r = 0.26). The weaker relation for the Godavari River can be attributed to the shift or lag in the correspondence between the above-average GOQ and RFM conditions. Since there is a lag of about fourteen years, lagging the GOQ series by 14 years produces a correlation coefficient of 0.85 between RFM and GOQ. Fig.3A reveals that the periods of high (low) floods in Tapi are associated with above-average (below-average) periods of rainfall in the source region. Hence, it is reasonable to infer that the long-term flood responses exhibit evidence of non-randomness and suggest that the above-average (high) and below-average (low) monsoon rainfall and discharge conditions are grouped together.

Mahanadi and Krishna Rivers, however, display a flood response that is out of synchronicity with the all-India monsoon rainfall. To ascertain the causes for this deviant behaviour, the flood series were compared with the regional monsoon rainfall. The data for east Peninsular Region (drained by Mahanadi River) and the southern Peninsular region (occupied by Tungabhadra River, the southern tributary of Krishna; Fig. 1) were obtained from Gregory (1989). Visual comparison of the NADM graphs given in Fig.4 demonstrates a noteworthy similarity. The long-term fluctuations in the average rainfall of the east Peninsular Region (EPRF) and the southern Peninsular region (SPRF) respectively show a good correlation between the flood stage at Naraj on Mahanadi, and the discharge at Vijayawada on the Krishna River (KRQ).

Given the large catchment size and the differences in the rainfall regimes of the parent and tributary streams, the low correlation (r = 0.42) between KRQ and SPRF is scarcely surprising. The Krishna Basin occupies more than one rainfall macro-region, and implies that the flood experienced on the river is a complex

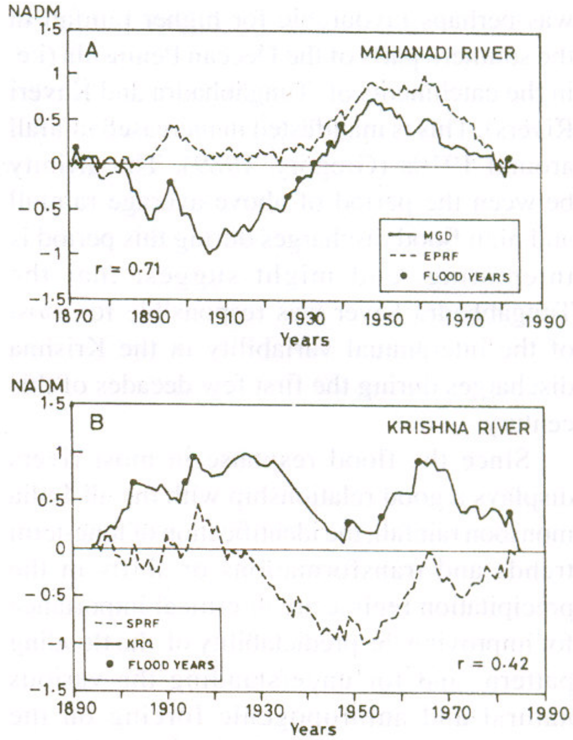



**Fig.4.** NADM graphs. **A.** Mahanadi annual peak flood stage (MGD) and east Peninsular region rainfall (EPRF). **B.** Krishna annual peak discharge (KRQ) and south Peninsular region rainfall (SPRF).

phenomenon. Correlation analysis using recent discharge data indicates that the interannual variability in peak flood discharges at Vijaywada is largely related to the influx of water from Bhima and Ghataprabha Rivers (Table 5). The situation was perhaps different during the early part of this century. This period

**Table 5.** Correlations between annual maximum discharge fluctuations recorded on Krishna at Vijayawada and on tributary streams and upstream

| Name of tributary | Site | Catchment area in km$^2$ | Correlation with Polavaram discharge |
|---|---|---|---|
| Bhima | Yadgir | 69863 | 0.64** |
| Tungabhadra | Bawapuram | 67180 | 0.34 |
| Ghatprabha | Bagalkot | 8829 | 0.65** |
| Upper Krishna | Karad | 5462 | 0.42* |

* significant at 0.05 level; ** significant at 0.001 level. *See* Fig. 1 for location of the tributary streams.

was perhaps favourable for higher rainfall in the southern parts of the Deccan Peninsula (i.e. in the catchments of Tungabhadra and Kaveri Rivers). This is manifested in increased rainfall around 1910s (Gregory, 1989). The affinity between the period of above-average rainfall and high flood discharges during this period is interesting, and might suggest that the Tungabhadra River was responsible for most of the interannual variability in the Krishna discharges during the first few decades of this century.

Since the flood response in most rivers displays a good relationship with the all-India monsoon rainfall, the identification of long-term trends and transformations or shifts in the precipitation regime are of critical importance for improving the predictability of the flooding pattern, and for understanding the various natural and anthropogenic forcing on the hydrological system. The NADM graph for the all-India monsoon rainfall given in Fig.5 clearly shows major changes in the rainfall conditions around 1877, 1898, 1932, 1964 and 1987. Mooley and Parthasarathy (1984), Fu and Fletcher (1988) and Kripalani and Kulkarni (1997) identified significant changes in the monsoon conditions about the same years. Fu and Fletcher (1988) have attributed these changes to large-scale shifts in flow patterns of monsoon currents (wind). In the course of present study, a similar shift in the monsoon rainfall conditions was also identified close to 1836, using the rainfall series reconstructed by Sontakke (1996). Interestingly, these years correspond with known El Niño years. While 1877-1878, 1899-1900 and 1932 were strong El Niños, 1837, 1965 and 1987 were moderate El Niños in intensity (Quinn et al. 1987). This coincidence perhaps implies that the shift in the precipitation regime, and consequently in the flood response, is in some way connected to

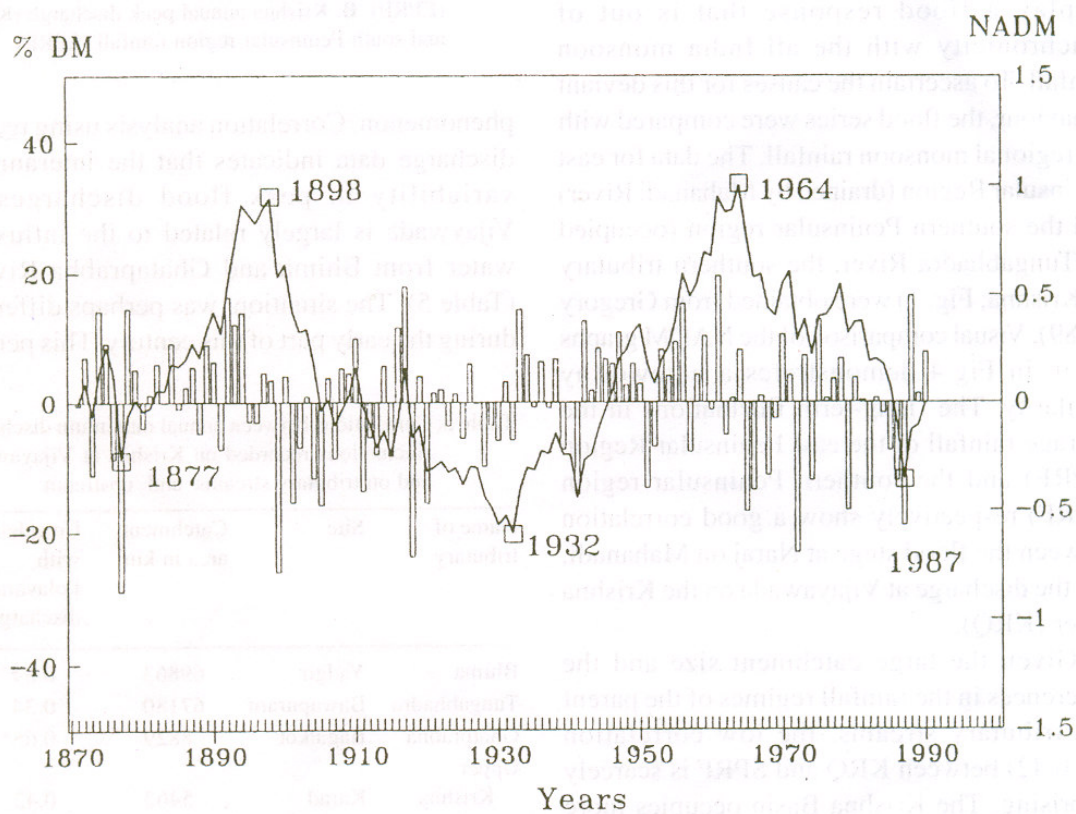



**Fig.5.** All-India monsoon rainfall in percentage departure from the mean (% DM), for the period 1871-1990 (Parthasarathy et al. 1991). The heavy line is the normalized accumulated departure from mean (NADM) curve. The years defining the limits of the above-average (high rainfall) and below-average (low rainfall) conditions are also given.

'*certain*' El Niño events. Comparable signals are also provided by palaeofloods records. Sedimentological records of palaeofloods from central Narmada Basin indicate a distinct change in the magnitude and frequency of large floods around ca 1600, 1000 and 700 years BP (Kale et al. 1997b). Notably, Meggers (1994) has indicated the occurrence of mega-Niño events at about the same time (ca 1500, 1000, 700 and 400 years BP). This, however, is an initial observation that will need to be confirmed as various forms of proxy records from the region become more complete.

## DISCUSSION AND CONCLUSIONS

The foregoing discussion has brought out several interesting aspects of the long-term flood responses of the Deccan Peninsula rivers that have significant implications for flood hydrology and flood hazard assessment. All the flood series display temporal patterns characterized by long period fluctuations and non-random behaviour in terms of discrete periods of low and high floods. The overall picture for the Deccan Peninsular region is presented in Fig.6. In spite of the differences in the timing and the length of these conditions between the rivers, two general patterns emerge. More or less, synchronous fluctuations in flood magnitudes/stages over a long period of time are reflected by most rivers. The late-1800 and early-1900 below-average flood condition is followed by a period of high floods centered around 1950. This is the case of rivers originating in central India such as Narmada, Tapi and Mahanadi. Godavari also reveals a similar, but shifted, trend because a significant part of its catchment also lies in central India. For Krishna the observed trend is different, with high-flood conditions in the early and middle phase and a marked low-flood phase in between, as well as towards the end of the gauge record. All the rivers show periods of high and low flow, which are compatible with the high and low periods of all-India monsoon or macro-regional

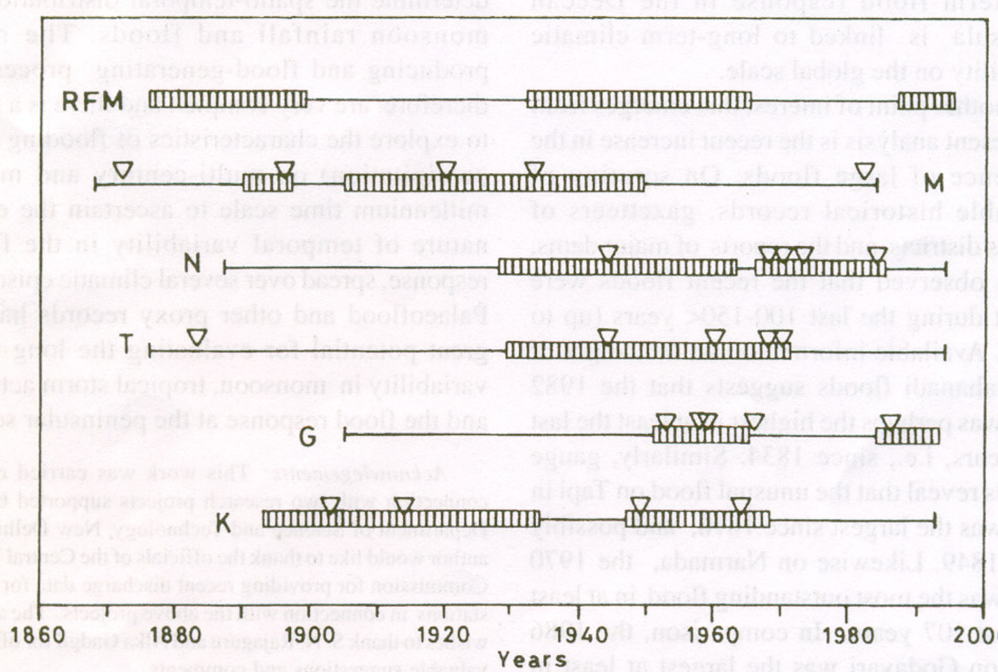



**Fig.6.** Major periods of above-average (stippled bars) and below-average (thin line) conditions for all the five rivers of the Deccan Peninsula. RFM - all-India monsoon rainfall, M - Mahanadi, N -Narmada, T - Tapi, G - Godavari, and K - Krishna. Inverted triangles represent large flood years. The phases of low and high floods for Tapi are based on the Tapi flood data, the Betul rainfall series and the Narmada flood series (*see* text for explanation).

rainfall. The present analysis thus, indicates that the variations in flood peaks are related to variations in monsoon rainfall.

The coincidence between periods of above-average floods (below-average floods) with the meridional monsoon (zonal monsoonal) periods suggests that the long-term changes in the climatic conditions at the continental scale have a strong influence on the temporal flood response of the Deccan rivers. Further, the late-1800 and early-1900 phase of below-average flood and precipitation conditions (except in Krishna), and the common phase of high floods around 1950, identified for the Deccan rivers, have also been noted for other regions of the world, indicating that the connections are widespread. A distinct decrease in the Nile flood height and a sudden decrease in rainfall in many tropical and subtropical regions around 1900 are well documented (Wheaton and Rutherfurd, 1994). Similarly, increased flooding in the 1950s was also observed in many rivers of the world (Probst and Tardy, 1987; Burn and Arnell, 1993). Therefore, it may be reasoned that the long-term flood response in the Deccan Peninsula is linked to long-term climatic variability on the global scale.

Another point of interest that emerges from the present analysis is the recent increase in the incidence of large floods. On scrutiny of available historical records, gazetteers of various districts, and the reports of major dams, it was observed that the recent floods were largest during the last 100-150< years (up to 1994). Available information on the height of the Mahanadi floods suggests that the 1982 flood was perhaps the highest in at least the last 160 years, i.e., since 1834. Similarly, gauge records reveal that the unusual flood on Tapi in 1968 was the largest since 1876, and possibly since 1849. Likewise on Narmada, the 1970 flood was the most outstanding flood in at least the past 107 years. In comparison, the 1986 flood on Godavari was the largest at least in this century. Interestingly, palaeoflood records from central India also support these inferences drawn on the basis of gauge and historical records, and suggest that no floods comparable in magnitude to the post-1950 floods have occurred in the last several hundred years (Ely et al. 1996; Kale et al. 1997a,b).

In spite of the fact that there is a good correspondence between rainfall (all-India or macro-regional) and the flood response, there are some noteworthy exceptions. Large floods have also occurred during periods of rainfall deficiency (for example the most outstanding flood on Mahanadi River in 1982). Another point worth noting is that despite the physical proximity of the basins, there are clear differences in the timing and length of the high and low flood conditions between the rivers. These aberrations, hence, imply that there are many other factors, such as time interval between two successive rainstorms, monsoon breaks, drainage and basin morphology, vegetation cover, antecedent precipitation, anthropogenic effects etc., that ultimately determine the spatio-temporal distribution of monsoon rainfall and floods. The rain-producing and flood-generating processes, therefore, are very complex and there is a need to explore the characteristics of flooding (and precipitation) on multi-century and multi-millennium time scale to ascertain the exact nature of temporal variability in the flood response, spread over several climatic episodes. Palaeoflood and other proxy records have a great potential for evaluating the long-term variability in monsoon, tropical storm activity and the flood response at the peninsular scale.

*Acknowlegements:* This work was carried out in connection with two research projects supported by the Department of Science and Technology, New Delhi. The author would like to thank the officials of the Central Water Commission for providing recent discharge data for some stations in connection with the above projects. The author wishes to thank S. N. Rajaguru and Alka Gadgil for offering valuable suggestions and comments.

## References


Burn, D. H. and Arnell, N. W. (1993). Synchronicity in global flood responses. Jour. of Hydrology, v.44, pp.381-404.

Chiew, F. and McMahon, T. (1993). Detection of trend or change in annual flow of Australian rivers. Int. Jour. Climatol., v.13, pp.643-653.

CWC (1996). Water and related statistics. Central Water Commission Publication, New Delhi, India, pp.232-236.

CWPC (1952). Hydrological Data of River Basins of India: The Mahanadi Basin (up to 1950). Central Water and Power Commission Publication, New Delhi, India.

CWPC (1957). Hydrological Data of River Basins of India: The Tapi Basin (up to 1950). Central Water and Power Commission Publication, New Delhi, India.

CWPRS (1988). Design discharge at Mahanadi and Birupa Barrages, Orissa. Technical report, Central Water and Power Research Station , Pune, India.

Eltahir, E. A. B. (1996). El Niño and the natural variability in the flow of the Nile River. Water Resource Research, v.32, pp.131-137.

Ely, L. L., Enzel, Y., Baker, V. R., Kale, V. S. and Mishra, S. (1996). Changes in the magnitude and frequency of late Holocene monsoon floods on the Narmada River, central India. Geol. Soc. Amer. Bull., v.108, pp.1134-1148.

Fu, C. and Fletcher, J. (1988). Large signals of climatic variations over the ocean in the Asian monsoon region. Adv. Atmos. Sci., v.5, pp.389-404.

Gole, C. V., Krishnamurthy, K. K. and Bathia, T. S. (1978). Extrapolation of peak floods by frequency analysis. Proc. 47th Research Session, Central Board of Irrigation and Power, Hubli-Dharwad, v.2, pp.1-12.

Gregory, S. (1989). Macro-regional definition and characteristics of Indian summer monsoon rainfall, 1871-1985. Int. Jour. Climatol., v.9, pp.465-483.

Kale, V. S., Hire, P. and Baker, V. R. (1997a). Flood hydrology and geomorphology of monsoon-dominated rivers: The Indian Peninsula. Water International, v.22, pp.259-265.

Kale, V. S., Mishra, S. and Baker, V. R. (1997b). A 2000-year palaeoflood record from Sakarghat on Narmada, central India. Jour. Geol. Soc. India, v.50, pp.283-288.

Kriplani, R. H. and Kulkarni, A. (1997). Climatic impact of El Niño/ La Niña on the Indian monsoon: A new perspective. Weather, v.52, pp.39-46.

Meggers, B. J. (1994). Archaeological evidence for the impact of mega-Niño events on Amazonia during the past two millennia. Climate Change, v.28, pp.321-338.

Mooley, D. A. and Parthasarathy, B. (1984). Fluctuations in all-India summer monsoon rainfall during 1871-1978. Climate Change, v.6, pp.287-301.

Parthasarathy, B., Rupa Kumar, K. and Munot, A. A. (1991). Evidence of secular variations in Indian monsoon rainfall-circulation relationship. Jour. Climate., v.4, pp.927-938.

Perumal, M., Seth, S. M. and Datta. B. (1985). Tentative Spillway Design flood estimation for Sardar Sarovar Project - A case study. Proc. Sem. on Flood frequency Analysis, National Institute of Hydrology, Roorkee, pp.55-77.

Probst, J. I., and Tardy, Y. (1987). Long range stream flow and world continental runoff fluctuations since the beginning of this century. Jour. of Hydrology, v. 94, pp. 289-311.

Purohit, M. U. (1972). Role of Ukai Project in controlling floods in the lower Tapi region. Ukai Project Souvenir, Government of Gujarat, Ahmedabad, pp.32-42.

Quinn, W. H., Neal, V. T. and Antunez De Mayolo, S. E. (1987). El Niño occurrences over the past four and half centuries. Jour. Geophy. Res., v.92, pp.14449-14461.

Rao, K. L. (1975). India's water wealth: Its assessment, uses and projects. Orient Longman, New Delhi.

Riehl, H., El-Bakry, M. and Meitin, J. (1979). Nile river discharge. Mon. Weather Rev., v.107, pp.1546-1553.

Sontakke, N. A. (1996). Study of climatic variations and climatic monitoring over India and neighbourhood. Ph.D. Thesis submitted to the University of Pune, Pune.

Subramanian, V. (1993). Sediment load of Indian rivers. Current Science., v.64, pp.928-930.

Thomas, R. G. (1993). Rome rainfall and sunspot numbers. Jour. Atmospheric and Terrestrial Physics, v.55, pp.155-164.

UNESCO (1971, 1974, 1979, 1985). Discharge of selected rivers of the world, Volume I to III, Unesco, Paris.

UNESCO (1976). World catalogue of very large floods. Unesco, Paris.

Vohra, D. R. and Kumar, A. (1989). Flood forecasting by CWC in Narmada, Tapi and Damanganga Rivers. *In:* Proc. Symp. on Preparedness, mitigation and management of natural disasters, Central Water and Power Commission, New Delhi, pp.249-254.

Wheaton, P. and Rutherfurd, I. (1994). Historical ENSO teleconnections in the eastern hemisphere. Climate Change, v.28, pp.221-253.


*(Received: 5 April 1998; Revised form accepted: 22 July 1998)*