

Flood hydrometeorological situations associated with monsoon floods on the Par River in Western India

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सार – प्रस्तुत शोध पत्र का उद्देश्य पार नदी में मॉनसून की बाढ़ से संबद्ध बाढ़ जल मौसम स्थितियों को समझना है। अतः अधिक बाढ़ से जुड़ी सामयिक स्थितियों का विश्लेषण किया गया। इसमें दो वर्षों के बीच वर्षा की परिवर्तनशीलता और संबद्ध बाढ़ों का विश्लेषण, तूफान मार्ग का विश्लेषण, माध्य से सामान्यीकृत संचित विचलन (NADM) का पता लगाना और एल नीनो और मॉनसून की वर्षा में संबंध का मूल्यांकन करना शामिल है। उपर्युक्त विश्लेषण करने के लिए भारत मौसम विज्ञान विभाग, पुणे और चेन्नै से पार बेसिन के 118 वर्षों की वर्षा के वार्षिक आँकड़े प्राप्त किए गए। प्रभापी क्षेत्र ननिवाहियाल के 45 वर्षों के वार्षिक अधिकतम श्रृंखला (AMS) चरणों के आँकड़े गुजरात राज्य के अहमदाबाद के सिंचाई विभाग से प्राप्त किए गए। परिणाम दर्शाते हैं कि पार नदी पर मुख्य रूप से 1930 के बाद दो वर्षों के बीच परिवर्तनशीलता की आवृत्ति और बाढ़ के परिमाण में वृद्धि देखी गई। बेसिन में अधिकांश बड़ी बाढ़ की स्थितियाँ निम्न दाब प्रणाली से जुड़ी थी। यह देखा गया कि बेसिन में अधिकांश बाढ़ औसत वर्षा से धनात्मक विचलन से संबद्ध थी NADM ग्राफ बेसिन में उच्च और निम्न वर्षा और बाढ़ का कालावधिक व्यवहार दर्शाता है। अल नीनो और दक्षिण दोलन के विश्लेषण दिखाते हैं कि पार बेसिन में बाढ़ की घटना की संभावना औसत एस एस टी सूचकांक के दौरान होती है और बेसिन में अधिकांश बाढ़ सामान्य से अधिक वर्षा की स्थितियों से आई। अतः वर्तमान अध्ययन भारत सरकार से संबद्ध गुजरात सरकार की पार-तापी नर्मदा परियोजनाओं और महाराष्ट्र सरकार की जल अपसारी परियोजना के लिए महत्वपूर्ण योगदान साबित हो सकता है।

ABSTRACT. The objective of present work is to understand flood hydrometeorological situations associated with monsoon floods on the Par River, therefore, the analyses of synoptic conditions connected with large floods was carried out. This encompasses analysis of interannual rainfall variability and associated floods, analysis of storm tracts, investigation of normalized accumulated departure from mean (NADM) and evaluation of the relation between El Niño and monsoon rainfall. In order to accomplish above analyses, the annual rainfall data of the Par Basin have been obtained for 118 years from India Meteorological Department (IMD), Pune and Chennai. The annual maximum series (AMS)/stage data were procured for a gauging site namely Nanivahial for 45 years from Irrigation Department of Gujarat State, Ahmedabad. The results indicate that the interannual variability was characterized by increased frequency and magnitude of floods on the Par River primarily after 1930s. Majority of the large floods in the basin were connected with low pressure systems. It is observed that most of the floods were associated with positive departure from mean rainfall in the basin. The NADM graph shows epochal behaviour of high and low rainfall of the basin and floods. The analysis of El Niño and Southern Oscillation indicates that the probability of the occurrence of the floods in the Par Basin is high during the average SST index and majority of the floods in the basin have occurred during above normal conditions of rainfall. The present study can, therefore, prove to be a significant contribution towards the Par-Tapi-Narmada link project of the Government of Gujarat and water divergent projects of the Government of Maharashtra in association with Government of India.

Key words – Flood hydrometeorology, Monsoon, Floods, Par River.

1. Introduction

In flood hydrometeorology, the occurrence of very heavy to excessive rainfall that governs the distribution and occurrence of large floods has been one of the focal areas of investigation. In general, the causes behind occurrence of floods are extraordinary synoptic situations

responsible for more precipitation to a drainage basin in comparison with the capacity of basin to absorb and store within it (Hirschboeck, 1988). Most of the river floods are climatological in nature and produced by precipitation resulting directly by rainfall or indirectly by snow and ice melt (Ward, 1978). Consequently, rainfall-producing processes on different scales have received attention from

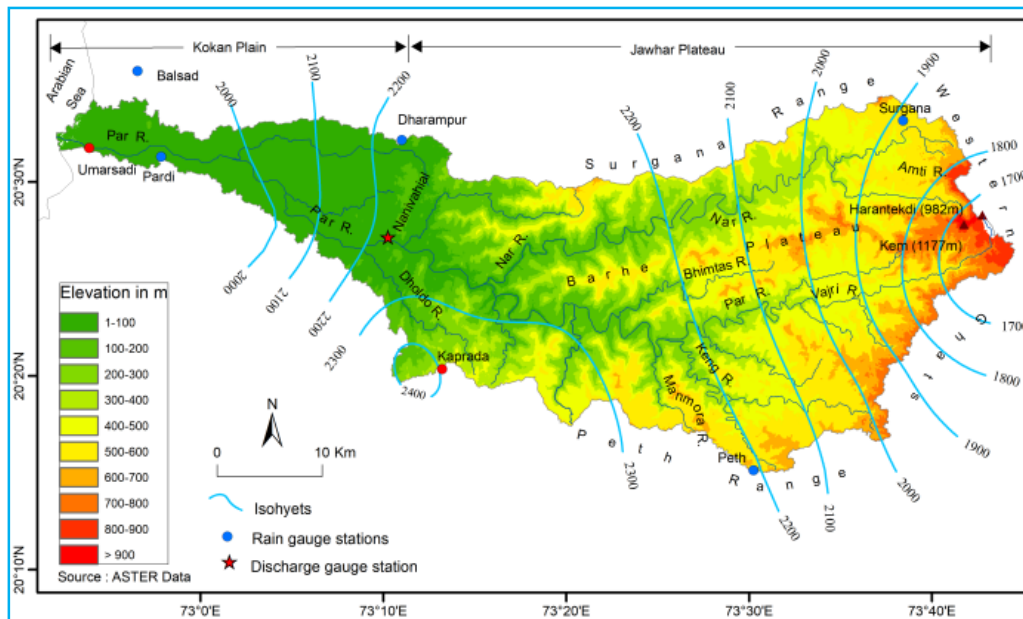


Fig. 1. Geomorphological setting of the Par River, Western India with Isohyets

TABLE 1

Annual rainfall characteristics of selected stations in the Par Basin (between 1901 and 2018)

Site	Record length in years	Rmax mm (year)	Rmin mm (year)	AARmm	σ	Cv	C _s
Balsad	118	3955 (1954)	744 (1905)	1939	599	0.31	0.48
Dharampur	118	5470 (1977)	693 (1974)	2363	760	0.32	0.92
Pardi	118	4376 (1963)	916 (1911)	1982	558	0.28	0.96
Peth	118	4673(1931)	451 (1982)	2208	619	0.28	0.69
Surgana	063	3440 (1981)	652(2015)	1927	585	0.30	0.61

Data Source : IMD; Based on 63-118 years of record; Rmax = Maximum annual rainfall; Rmin = Minimum annual rainfall; AAR = Average Annual Rainfall; σ = Standard deviation; Cv = Coefficient of variation; C_s = Coefficient of skewness; See Fig. 1 for location of sites

meteorologists, climatologists and hydrologists. Usually, hydrometeorology has been applied to study the floods, nevertheless, in the broader view, information emerging from hydrometeorological studies has been used to understand flood variability for longer period of time (Hirschboeck, 1988).

The objective of present work is to understand flood hydrometeorological situations associated with monsoon floods on the Par River, therefore, the analyses of synoptic conditions connected with large floods was carried out. This encompasses analysis of (i) interannual rainfall variability and associated floods (ii) analysis of flood generating low pressure systems (iii) investigation of normalized accumulated departure from mean (NADM) and floods (iv) evaluation of the relation between El Niño and monsoon rainfall in the basin and resultant floods.

2. Par River: geomorphic and climatic setting

With a catchment area of 1664 km² and 142 km length, the Par River is one of the west flowing monsoonal rivers of the Western India. The river originates at an elevation of 982 m ASL at Harantekadi (Fig. 1). The average gradient of the river is 0.0069. The Par Basin is bordered by, roughly east-west trending Surgana and Peth Ranges to north and south respectively and by Western Ghats to the East (Fig. 1). The Par River flows to the west through Maharashtra (46.45% area) and Gujarat (53.55% area) states and drains into the Arabian Sea near Umarsadi in the Gujarat State. The geology of the basin mainly comprises Cretaceous-Eocene Deccan Trap basalts. However, Quaternary alluvium has been observed at a small reach of the Par River particularly at Nanivahial. The basin is situated in an environment classic of

monsoonal tropics, with periodic high-magnitude rainfall. Analyses of long-duration rainfall records for the Par Basin states that the average annual rainfall of the basin is 2099 mm and 98% of the annual rainfall occurs during southwest summer monsoon season. July is the rainiest month throughout the basin followed by August and both the months account for 39% and 27% of the total annual rainfall of the basin respectively. Mean annual rainfall of the basin ranges from 1927 mm at Surgana to 2363 mm at Dharampur. Interannual variability is not particularly high, which is proved by the less coefficient of variation (C_v) (28-32%) of annual rainfall in most parts of the Par Basin. All the sites show very high range of annual rainfall (Table 1). For instance, the minimum annual rainfall recorded at the Peth Station was 451 mm for the year 1982, and the maximum annual rainfall was 5470 mm for the year 1977 at the Dharampur station. The values of the coefficient of skewness (C_s) are positive for all the stations, ranging between 0.48 and 0.96. The Pardi site reveals relatively high positive C_s value. The positive C_s values suggest the occurrence of one or two or a few very wet years during the gauged period. Since skewness values for the study area have been determined on the basis of more than 100 years of data, they are all statistically significant (Viessman and Lewis, 2003).

Spatially, the annual rainfall displays a marked variation within the basin (Fig. 1). Geographical location, orographic effect of the Barhe Plateau (interfluvium of Par and its major tributary Nar) and the east-west trending ranges in the Par Basin (Fig. 1) play significant role in rainfall distribution. For instance, Peth Range, Surgana Range and other interfluves act as barrier for the rain bearing south-west monsoon clouds. It attributes to maximum amount of rainfall in the middle of the Par Basin (2200 mm to 2300 mm). Being distant from the coast, and gradual increase in height of Western Ghat, the amount of rainfall reduces towards the source of the river. It ranges between 1700 mm and 1800 mm. However, due to proximity of the coast, the amount of rainfall is more in the western part of the basin ranging from 2000 mm to 2200 mm. Most part of the basin receives about 1800 mm to 2200 mm rainfall. The basin occasionally receives heavy rains due to cyclonic storms and depressions originating over the Bay of Bengal or adjoining land and traverse toward the basin.

3. Data source

The annual rainfall data for five stations located within and close to the Par Basin, have been obtained for the period of about 118 years (1901-2018) from India Meteorological Department (IMD), Pune and from cited references. The data of LPS tracks from 1891 to 2007 were derived from software eAtlas obtained from IMD,

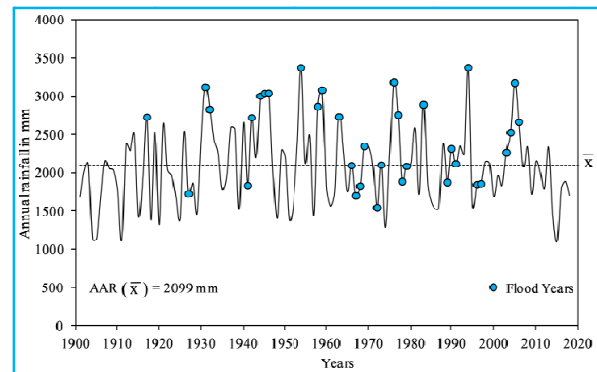


Fig. 2. Interannual rainfall variability and associated floods in the Par Basin (1901 to 2018)

Chennai. The annual maximum series (AMS)/stage data were procured from Irrigation Department of Gujarat State for a gauging site namely Nanivahial on the Par River for 45 years specifically from 1960 to 2005. The El Niño and Southern Oscillation (ENSO) index published by Wright (1989) for the period 1891-1983 has been employed in the study and for 1984 onwards, the ENSO index were obtained from Climate Prediction Centre (CPC) of National Oceanic and Atmospheric Administration (NOAA).

4. Interannual rainfall variability and associated floods

An attempt has been made to understand interannual rainfall variability and its association with floods in the Par Basin. Similar to other monsoon-dominated rivers of India, the Par Basin also shows significant interannual variation in the rainfall and flood events, mainly intensity and frequency of rain producing weather systems (western disturbances, cyclonic storms, monsoon depressions, monsoon troughs, etc.). The time series plot of interannual variability of rainfall (Fig. 2) shows that prior to 1930, the rainfall was frequently below-average, however the interannual variability was low. On the other hand, from 1930 to 2008, many years recorded above-average annual rainfall, nevertheless the interannual variability was high. After 2008, the rainfall was frequently below-average, however the interannual variability was moderate. Interannual variability was characterized by increased frequency and magnitude of floods on the Par River primarily after 1930s. Furthermore, Fig. 2 shows that majority of the floods *i.e.*, 25 out of 34 (74%) large flood events in the Par Basin have occurred when rainfall was above average.

Hire (2000) has prepared the time series plot of the annual rainfall for three sites of the Tapi Basin which reveals similar results and remarkable interannual

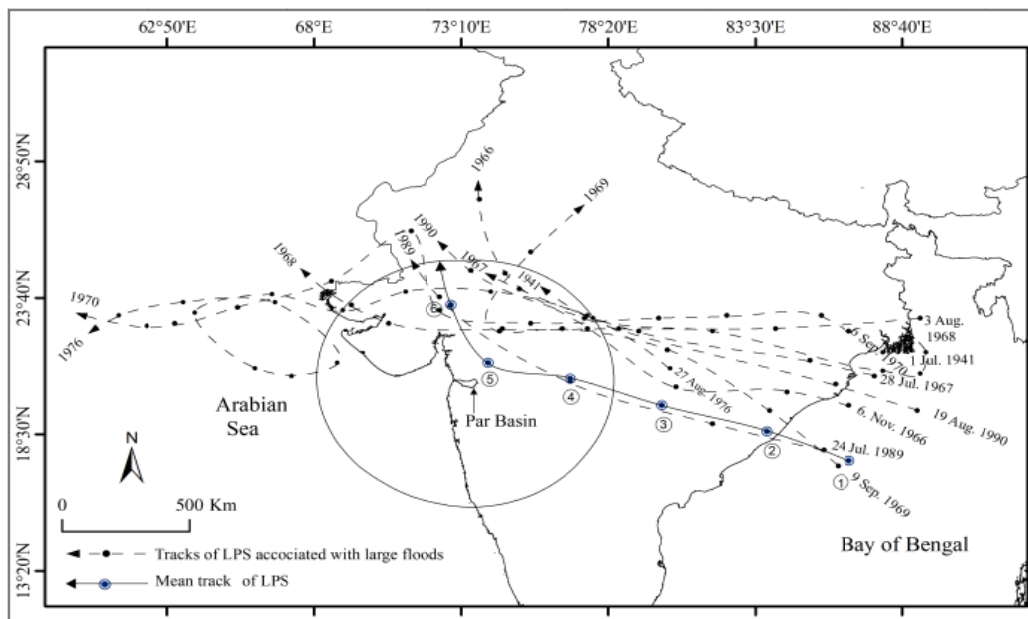


Fig. 3. Mean track of Low Pressure System (LPS) and tracks of LPS associated with large floods in the Par Basin (1891 to 2007)

variability in the rainfall totals. According to him, the rainfall was frequently below-average before 1930, nevertheless the interannual variability was low. Moreover, many years recorded above-average annual rainfall, however the interannual variability was high from 1930s to 1990s. As reported by Kale (1999), noteworthy, high interannual variability was characterized by increased frequency and magnitude of floods on the Tapi River during this period. According to Pawar and Hire (2018), inter-monsoon variability for the Mahi River, was characterized by increased frequency and magnitude of floods mainly after 1930s.

5. Characteristics of the flood-generating low pressure systems (LPS)

The Indian subcontinent has experienced cyclonic disturbances (*viz.* depressions and cyclonic storms) in all months of the year except February (Dhar *et al.*, 1984). According to Rao (1976), monsoon depressions are the low pressure areas with two or three closed isobars. It covers an area of about five degrees square, which form in the Bay of Bengal (18° N), which move westnorthwest at least up to the central parts of the country, and give widespread and heavy to very heavy rainfall in the southwest quadrant before weakening. The heavy rainfall is confined to a belt some 400 km wide and 500 km long to the left of the track of these disturbances (Rao, 1976). Due to the heavy rainfalls associated with these disturbances, floods occur in those rivers whose catchments lie in the rainstorm area (Dhar *et al.*, 1984a).

These floods represent the largest recorded peaks in a flood time series (Kale *et al.*, 1994). As per earlier and recent studies of the synoptic situations associated with the rainstorms, flood-generating rainstorms are connected with (i) Bay of Bengal depressions moving westwards, (ii) General active monsoon conditions over Madhya Pradesh and Gujarat and (iii) Land depressions moving westwards (Abbi and Jain, 1971; Ramaswamy, 1985). Mooley and Shukla (1987) examined the characteristics of the summer monsoon season low pressure systems (LPS) for the period of 1888-1983 over the Indian region. The analysis shows that on an average, 13 LPS arrive from the Bay of Bengal and travel towards central India. Studies by Nandargi (1996) show that the major flood-producing rainstorms are confined to two major zones in the country. The first zone is located over the Ganga Basin and Punjab Plains, and the second zone includes the central India and northern half of peninsular India. Similar studies have also been carried out in other regions of the world where cyclones, hurricanes and typhoons produce large floods (Gupta, 1988).

In order to understand correlativity between LPS and floods in the Par Basin, an attempt has been made to identify and analyse the tracks of the low pressure system that had produced largest discharges in the basin. The tracks have been identified by using software eAtlas, procured from IMD, Chennai and analysed with the help of software ArcGIS 9.3. A buffer zone of five-hundred km from the basin periphery was computed (Fig. 3) and those LPS tracks which range within buffer zone have been

TABLE 2
Synoptic conditions associated with major floods on the Par River

Month, date and year of flood	Annual rainfall of the basin mm	Monsoon rainfall of the basin mm	Associated LPS	El Niño or La Niña year	Remark
September 6, 1966	2106.8 (+0.60%)	2098.6 (+2.14%)	Bay Depression	-	LPS transit in north-east with respect to basin
July 28, 1967	1709.5 (-18.37%)	1677.2 (-18.37%)	Bay Depression	Weak La Niña	Transit in north-east with respect to basin
August 6, 1968	1839 (-12.19%)	1823.5 (-11.25%)	Bay Depression	Weak El Niño	Transit roughly parallel to the basin axis
September 9, 1969	2355.9 (+12.49)	2337.2 (+13.75%)	Bay Depression	Weak El Niño	Transit in north-east with respect to basin
September 6, 1970	2341.6 (+11.81%)	2329.6 (+13.38%)	Bay Depression	Moderate La Niña	Transit roughly parallel to the basin axis
August 20, 1972	1557.2 (-25.65%)	1552.3 (-24.45%)	Bay Depression	Strong El Niño	Transit in north-east with respect to basin
July 31, 1976	3192.5 (+52.44%)	3139.4 (+52.80%)	Land Depression	Weak El Niño	Transit roughly parallel to the basin axis
August 29, 1978	1898.5 (-9.35%)	1791.5 (-12.81%)	Bay Depression	-	Transit in north-east with respect to basin
August 10, 1979	2097.5 (+0.15%)	2112.3 (+2.80%)	Bay Depression	Weak El Niño	Transit in north-east with respect to basin
July 24, 1989	1888.3 (-9.84%)	1878.7 (-8.56%)	Land Depression	-	Transit in north-east with respect to basin
August 19, 1990	2323.1 (+10.93%)	2247.8 (+9.40%)	Bay Depression	-	Transit in north-east with respect to basin
July 28, 1991	2129.2 (+1.67%)	2114.7 (+2.92%)	Bay Depression	Moderate El Niño	Transit in north-east with respect to basin
July 23, 1996	1858.2 (-11.27%)	1857.4 (-9.60%)	Bay Depression	-	Transit in north-east with respect to basin
July 27, 2003	2273.8 (+8.57%)	2247.6 (+9.39%)	Bay Depression	-	Transit in north-east with respect to basin

LPS = Low Pressure Systems; Values in bracket represent percentage departure from mean

selected for investigation to understand the characteristics of the flood-generating low pressure systems in the Par Basin. An overwhelming number of the depressions form in the Bay of Bengal north of 20° and move in a westerly direction (Rao, 1976) that produces high discharge in the rivers. Therefore, in order to prepare mean track of the LPS that affect the Par Basin, the land depressions and the LPS tracks, that originate at the Bay of Bengal and transit towards west, have been chosen for the analysis. Moreover, with the help of the AMS/stage data, the association of LPS and consequent floods was established.

Examination of the synoptic conditions associated with the flood-generating LPS in the Par Basin reveals that, not all, but several of them are the result of Bay depressions and active monsoon conditions over central India. The analysis of depression tracks further reveals

that 217 tracks of LPS transit through the buffer for 117 years (1891-2007). These tracks have been classified according to their source of origin into three categories *i.e.*, Bay of Bengal, Arabian Sea and Land Depressions. The classification states that 96 LPS tracks originated from the Bay of Bengal, 82 tracks have their source in the Arabian Sea and 14 were the land depressions. As reported by Mooley (1973), the rainfall field is flat in the quadrants to the right of the depression track. Nevertheless, large gradients of rainfall subsist in the left quadrants, especially along and west of 80° E. In addition, maximum rainfall is located in the left front quadrant, more or less 150 km from the centre and 50-150 km from the depression track. Besides, the Par Basin is located in the left front quadrant of the mean track of LPS that travel in a WNW or NW direction (Fig. 3) to produce intense floods in the Par Basin.

The track and duration of the LPS over the basin, antecedent precipitation and the pressure deficiency determine the rainfall depths and consequently the intensity of floods (Kale *et al.*, 1994). In the Par Basin, majority of the large floods were associated with Bay depressions, nevertheless, two largest floods of the 20th Century (1968 and 1976) resulted from the land depression (Fig. 3; Table 2). Table 2 indicates that all the LPS associated with floods on the Par River generally occur either in the month of July or August. By this time, on an average about 67% of the annual rainfall is received and soils are fully saturated, which in addition boosts the magnitude of floods.

5.1. LPS that moved roughly parallel to the basin axis

The floods are of greater magnitude when the LPS travel more or less parallel to the basin axis (Kale *et al.*, 1994), the August 1968, September 1970, September 1976 LPS are excellent examples of this kind (Fig. 3; Table 2). These tracks were responsible for high flood levels and discharges on the Par River, for instance due to passage of the LPS in 1968 (Fig. 3), highest gauged discharge *i.e.*, 23820 m³s⁻¹ had occurred at Nanivahial (Fig. 1). Sometime, antecedent precipitation causes large floods in the basin. Well-known example of above situation is that of 4-6 August, 1968 flood. It is interesting to note that the LPS that produced the largest flood of the 20th Century was preceded by another depression between 29th and 31st July, 1968, that is about a week before the mega event. Thus, in spite of the fact that the year 1968 was a normal rainfall year, two rainstorms deposited large amounts of precipitation within a short period, and thus produced the largest ever recorded flood of the 20th Century. The second large flood of the last century *i.e.*, 31st July, 1976 also had occurred because of LPS that moved roughly parallel to the basin axis, with gauged discharge of 22600 m³s⁻¹.

As reported by Hire (2000), the August 1968 (Q = 42450 m³s⁻¹) and September 1970 (Q = 42200 m³s⁻¹) LPS were responsible for heavy rainfall, thereafter large magnitude floods, in the Tapi Basin, of western India since the LPS travelled more or less parallel to the basin axis and basin had remained in the southwest sector of these LPS.

5.1.1. LPS that passed from north-east direction of the basin

The position of the Par Basin had remained in the left front quadrant during the transit of the bulk of the LPS (Fig. 3 and Table 2), therefore, produced high-magnitude floods in the basin. The flood magnitude due to such cyclones may vary over the different reaches of the Par

River. The best example of this is provided by the 1966 and 1969 depressions (Fig. 3), which are responsible for high flood levels on the Par River with 8000 and 6060 m³s⁻¹ (> mean discharge at Nanivahial Site which is 5030 m³s⁻¹) discharges respectively at the Nanivahial gauging site.

5.2. Depth-area-duration (DAD) analysis of the LPS

A number of hydrometeorological investigations on analysis of rainfall were carried out since late fourties. Satakopan (1949) applied the modern techniques of depth-area-duration (DAD) and storm transposition procedures to get estimation of maximum basin rainfall for study of the Damodar Basin and is still considered to be a model hydromet study of a river basin. A DAD curve is a graphical characterisation of the gradual decrease of precipitation depth with the progressive growth of the area of the storm or drainage area away from the storm centre for a given duration (Parzybok *et al.*, 2009). A depth-area curve delineates the maximum average depth of precipitation over various area sizes within a specified time interval (World Meteorological Organization Manual, 1969). In this method, the maximum rainstorm depths are stated in terms of three factors, *viz.*, depth, area, and duration, and an appropriate relationship between these three parameters is established. The technique, consequently, is known as the DAD method for rainstorm analysis. According to Parzybok *et al.* (2009), the intent of a DAD analysis was to ascertain the maximum precipitation amounts over various area sizes during the passage of storms of say 6, 12, or 24-hour continuance to assist in the figuring of probable maximum precipitation (PMP) estimates.

In the DAD analysis of LPS, the greatest depth of precipitation experienced over respective areas and durations were determined (PMP Atlas, 2015). The severe LPS of the Par Basin, *viz.*, the 1941 and 1968 have been selected for the analyses due to their significance and modified from PMP Atlas, 2015. The 1941 LPS has been selected because it has produced the largest ever recorded highest 24 hour (987 mm on 2nd July) rainfall at Dharampur (Fig. 4) which is considered to be the highest rainfall of one-day duration for a plain-area station in India (Dhar and Mandal, 1981). The 1968 LPS has been chosen as it has produced highest ever recorded flood (Q = 23820 m³s⁻¹) in the Par Basin (Patil *et al.*, 2017). Preparation of isohyetal maps for chosen LPS(s) is the first step in the DAD analysis. The isohyetal patterns of 1941 and 1968 LPS of Dharampur, available from isopluvial maps of India, Indian Institute of Tropical Meteorology (IITM), Pune and Probable Maximum Precipitation (PMP) atlas prepared by Water and Power Consultancy Services, India (WAPCOS, 1998), were

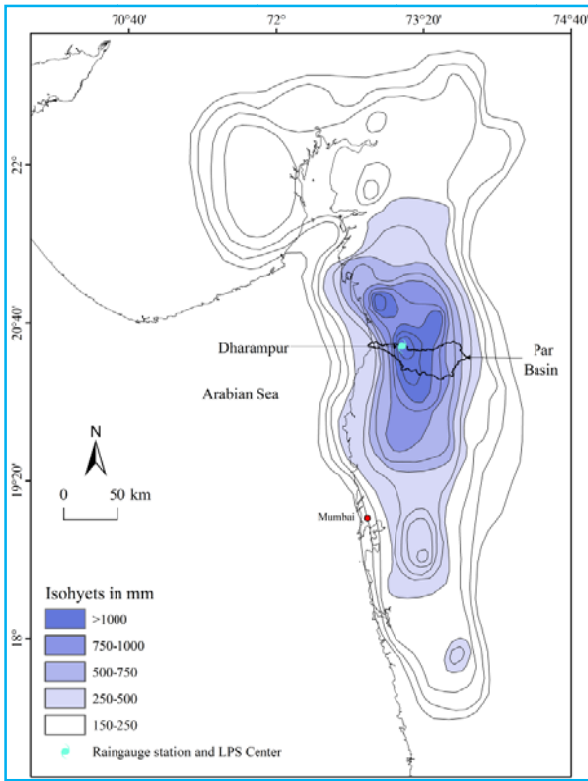


Fig. 4. The 3-day isohyetal (mm) pattern of 1-3 July, 1941 LPS over the Par Basin; Source : PMP Atlas, 2015

digitized and georeferenced in GIS software for further use. Moreover, the average rain depths, for year 1941 and 1968, derived from report of PMP Atlas (2015), were plotted against the accumulated area and smooth DAD curves for each LPS and duration have been prepared. Such curves were drawn for considered LPS(s) for 1-day, 2-day and 3-day durations.

In view of Dhar *et al.* (1984a), the July 1941 LPS may be considered as the most severe rainstorm in India for durations of one to three days (Fig. 4). Incidentally, the centre of the LPS was located at Dharampur (20.55° N, 73.18° E) in the Par Basin (Fig. 4). Depth-area-duration (DAD) analysis of the July 1941 LPS (Fig. 5) indicates that the DAD curve of 1-3 July, 1941 event has contributed the highest average depth of rainfall over the Par Basin for 1-, 2- and 3-day (1434, 1259 and 971 mm respectively) duration. This event, perhaps, would have produced highest flood in the Par Basin. However, due to paucity of flood records before 1961, the 1968 flood is recognised as the largest flood event in the basin. The centre of the highest rainfall of 1968 LPS for 1-day duration was located at Ukai Dam (21.32° N, 73.72° E) in Gujarat, 2-day duration at Jawhar (19.92° N, 73.23° E) in Maharashtra and 3-day duration at Golkund (20.62° N,

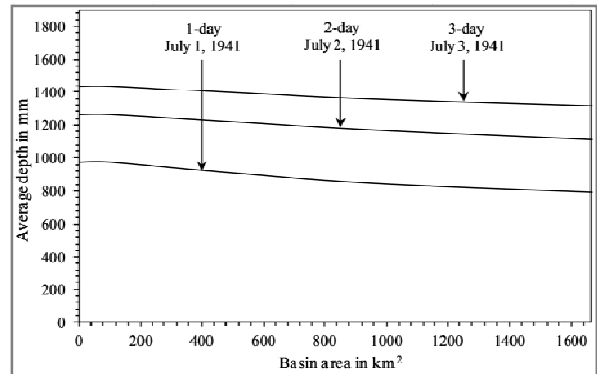


Fig. 5. DAD curves of severe LPS of the Par Basin for 1-3 July, 1941 event; Modified from PMP Atlas, 2015

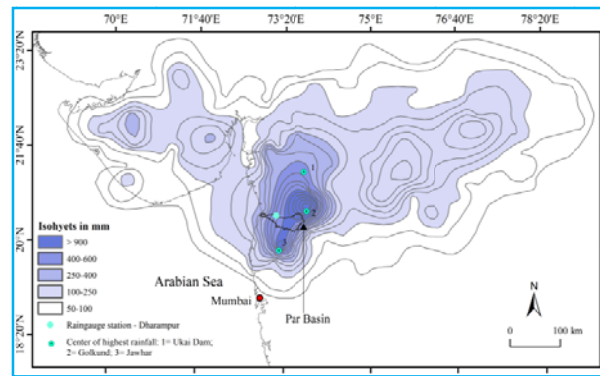


Fig. 6. The 3-day isohyetal (mm) pattern of 4-6 August, 1968 LPS over the Par Basin; Source : PMP Atlas, 2015

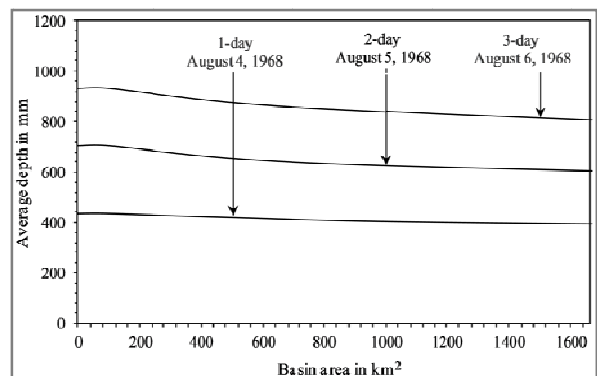


Fig. 7. DAD curves of severe LPS of the Par Basin for 4-6 August, 1968 event; Modified from: PMP Atlas, 2015

73.78° E) in Gujarat (PMP Atlas, 2015) (Fig. 6). The DAD curve of 4-6 August 1968 event has imparted the second highest average depth of rainfall over the basin for 1-, 2- and 3-day (932, 705 and 437 mm respectively) (Fig. 7) duration. Therefore, this event provided highest ever recorded flood levels ($Q = 23820 \text{ m}^3\text{s}^{-1}$) on the Par River at Nanivahial (Fig. 1) (Hire and Patil, 2018).

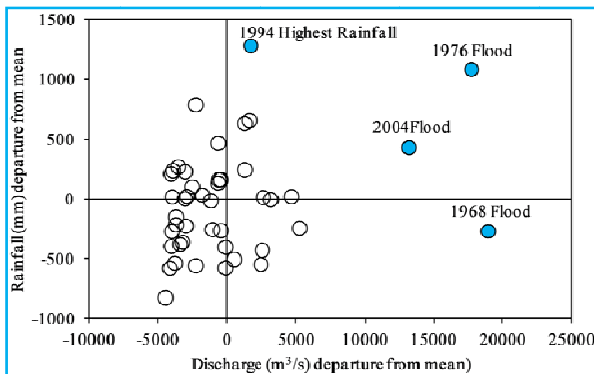


Fig. 8. Discharge (Nanivahial) and Rainfall (Average annual rainfall of the basin) departure from mean

5.3. Relationship between annual rainfall totals and flood occurrences

Fig. 8 gives a plot of average annual rainfall (Par Basin) and discharge (Nanivahial site) departure from their respective averages. The graph clearly reveals that two major floods (1976 and 2004) recorded at Nanivahial, had occurred during the years of above-average annual rainfall. However, it is of interest to note that the 1968 flood, which was the largest flood of the 20th Century, occurred during a below-average rainfall year. The year 1994 has produced the highest average annual rainfall in the basin (3389 mm). However, the year 1994 did not record the largest flood ($Q = 6560 \text{ m}^3\text{s}^{-1}$) in the basin (Fig. 8). It may be attributed to the well distributed rainfall throughout the monsoon season but not the intense flood producing rainfall for instance rainfall produced by LPS.

6. Normalized accumulated departure from mean (NADM) and floods

It is widely known that the monsoon rainfall of the same region goes through variations from one year to another. Nevertheless, departures of rainfall from its long-term mean in any two years are not same (Gadgil, 2002). Successive attributes within long-term data can be simply solved by applying normalized accumulated departure from mean method (NADM) (Riehl *et al.*, 1979; Mooley and Parthasarathy, 1984; Probst and Tardy, 1987; Kale, 1999). Therefore, NADM is one of the statistical methods often used in the study of rainfall variability (Kale, 1999; Hire, 2000; Gunjal, 2016; Patil, 2017; Pawar and Hire, 2018).

The NADM method has been used to filter short-term fluctuations and to highlight the long term variability in the stream flow and monsoonal rainfall. NADM is the accumulated departure from mean (ADM), divided by

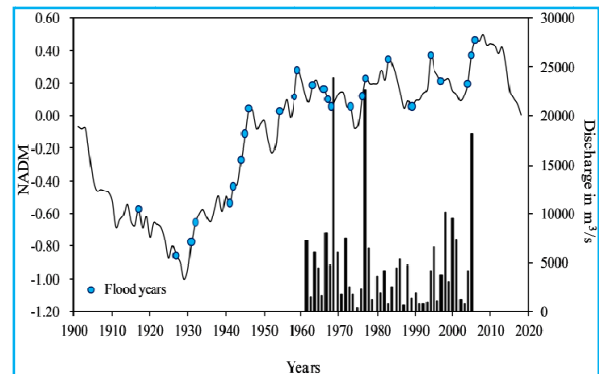


Fig. 9. Normalized Accumulated Departure from Mean (NADM) and Discharge (Nanivahial)

the largest number (absolute) in order to plot between -1 and +1 (Thomas, 1993). Thus, permits, apparent as well as statistical association of dissimilar data (Thomas, 1993). Periods featured by above-average state are generally shown by positive slopes of the graph and *vice-versa* (Gregory, 1989b; Thomas, 1993). In contrast with other methods used for similar purpose, such as running means, the ADM clearly shows the difference between periods of high and low rainfalls (Probst and Tardy, 1987). In order to compute NADM for the Par Basin, annual average rainfall data (1901-2018) and AMS data (1960 to 2005) were used to represents floods.

The NADM graph given in Fig. 9 shows the long-term trends of rainfall pattern for the Par Basin. The rising slope of NADM graph indicates above-average conditions, while, falling slope of the graph reveals below-average conditions of rainfall. The NADM graph proposes that the rainfall amounts were below-average in the beginning of the 20th century *i.e.*, up to 1930 (Fig. 9). The later part of the century *i.e.*, from 1930 to 1960 is characterised by sharp rise in the graph, which specifies the period of above-average rainfall conditions. The graph shows short term rising and falling trends after 1960, nevertheless, above average condition in general. This period has yielded the largest ever recorded floods on the river, for instance, 1968 and 1976 floods (Fig. 9). It is, therefore, reasonable to state that the large magnitude floods on the Par River have occurred in the above average condition.

It is not easy to draw general conclusion regarding the rainfall pattern of the Par Basin from the above illustrations, nonetheless, they point towards some general characteristics of the rainfall over the basin.

(i) 1901 to 1930 is associated with the below-average (low) rainfall period.

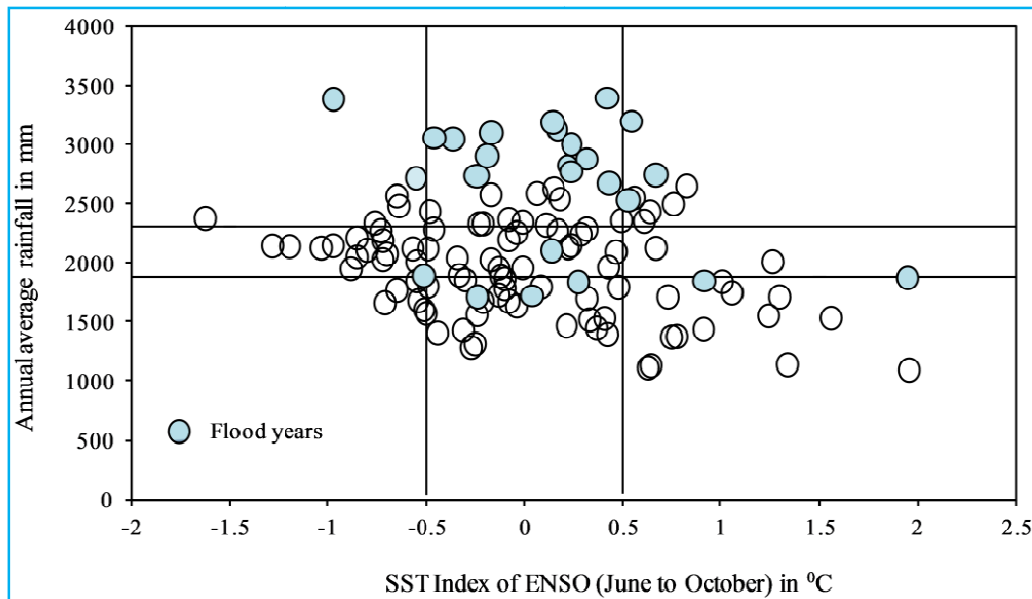


Fig. 10. Categories of annual rainfall and ENSO index of the Par Basin; Data source : India Meteorological Department (IMD)

(ii) Above-average (high) rainfall period is observed between 1930 and 1960.

(iii) Short term fluctuations are seen in the later half of the 20th century particularly after 1960. Consequently, the analysis of the annual rainfall data of the basin relating to the deviations in the amount clearly indicates that the major changes in the rainfall occurred around 1930 and 1960. Similar noteworthy changes have been identified by Mooley and Parthasarathy (1984); Fu and Fletcher (1988); Parthasarathy *et al.* (1991); Kripalani and Kulkarni (1997) and Pawar and Hire (2018) in the monsoon conditions about the same years in India. The association of all-India monsoon rainfall (Parthasarathy *et al.*, 1991) with the rainfall of the Par Basin shows remarkable similarity in their long-term fluctuations.

7. El Niño Southern Oscillation (ENSO) and floods

The El Niño Southern Oscillation (ENSO) phenomenon is the large-scale oceans atmospheric circulation processes in the equatorial Pacific (Chiew and McMahan, 2002). It is believed to be a major cause of rainfall variability as well as floods and droughts in many parts of the world, including India (Ropelewski and Halpert, 1987; Kane, 1989; Simpson *et al.*, 1993; Lutgens and Tarbuck, 1995). The fluctuations in the monsoon rainfall (and therefore floods) have been found to be significantly related with ENSO (Bhalme and Jadhav, 1984; Burn and Arnell, 1993). According

to Kripalani *et al.* (2003), Panda and Kumar (2014), Panda *et al.* (2014) and Dwivedi *et al.* (2015) the warm phase (El Niño) is linked with decreasing Indian monsoon rainfall and the length of rainy season, while the cold phase (La Niña) is associated with increasing of the Indian monsoon rainfall and number of rainy days. Kale *et al.* (1996) have concluded that many of the modern and historical flood events coincided with ENSO events.

The rainfall (therefore floods) over the basin is highly susceptible to the changes in the Indian southwest monsoon which is teleconnected with the ENSO events. Therefore, an attempt has been made to recognize natural variability in annual rainfall (and therefore floods) in the Par Basin and its correlation with ENSO events. The ENSO is a monthly series of the mean sea surface temperature (SST) anomaly averaged over the central and eastern Pacific Ocean. The index finally applied here is averaged over the monsoon season (June-October). The method implemented by Eltahir (1996) for the Nile River was used for the analysis. As recommended by Eltahir (1996), the data of SST were categorized into cold, warm and normal conditions on the basis of temperature (-0.5 °C and $+0.5$ °C). The conditional probabilities of the rainfall have been calculated to examine the relationship of the magnitude of the rainfall and the condition of the ENSO in different years and presented in Table 3.

The analysis specifies that the probability of excess monsoon rainfall and associated floods in the Par Basin is 8% during La Niña/cold ENSO conditions and

TABLE 3

Conditional probabilities of the monsoon rainfall over the Par Basin given the SST index of ENSO (N = 118 years)

Region	AAR	SST		
		Cold	Average	Warm
Par Basin	High	0.08	0.21	0.12
	Normal	0.92	0.64	0.52
	Low	0.00	0.15	0.36

Data Source : IMD and Wright (1989); Low < AAR - 1 σ and High > AAR + 1 σ ; AAR = Average Annual Rainfall; σ = Standard deviation

TABLE 4

Occurrence of floods and its relation with the annual rainfall and SST index of ENSO

Basin	Rainfall	Cold	Average	Warm
Par Basin	Above Normal	1942, 1954	1917, 1931, 1932, 1944, 1945, 1946, 1958, 1976, 1977, 1983, 1994, 2005, 2006	1959, 1963
	Normal	1973, 2016	1927, 1966, 1967, 1968	1941, 1997, 2004
	Below Normal	-	-	-

Below normal < AAR - 1 σ and above normal >AAR + 1 σ

the probability of low rainfall is 36% during warm phase of ENSO condition (Table 3 and Fig. 10). Kripalani *et al.* (2003) also stated that during the warm phase (El Niño) the Indian monsoon rainfall decrease and the cold phase (La Niña) is associated with increasing Indian monsoon rainfall.

In general, flood events occur in effect with abundant rainfall over a short period of time, especially when antecedent moisture conditions prevailed in the basin. Therefore, an attempt has been made to show that the frequency of occurrence of floods and teleconnections between climatic patterns and hydrological variability. Table 4 shows that the frequency of occurrence of floods is generally high during the average rainfall years. The result of the conditional probability and occurrence of floods clearly indicates that 17 floods in the Par Basin have occurred during above normal conditions and 13 floods during the average conditions of SST index of ENSO.

8. Conclusions

The time series of annual average rainfall displays remarkable interannual variability in rainfall and associated floods in the Par Basin. Accordingly, long period temporal variations in the annual average rainfall of the Par Basin highlights some notable years when

monsoon rainfall was above (high) and below (low) average rainfall of the basin and consequently intensity of the floods. The Par Basin is located at the southern margin of the zone commonly visited by low pressure systems originating over the Bay of Bengal and land. Therefore, the principal cause of large floods on the Par River is severe rainstorms or LPS(s). It is been observed that the majority of the large floods were associated with Bay depressions, nevertheless, two largest floods of the 20th Century that are 1968 and 1970 floods resulted from the land depression. The analysis of average annual rainfall (Par Basin) and discharge (Nanivahial site on the Par River) departure from their respective averages shows that two major floods that are 1976 and 2004 floods have occurred during the years of above-average annual rainfall. However, the largest flood of the 20th Century *i.e.*, 1968 flood had occurred during a below-average rainfall year in the basin. The year of highest average annual rainfall (1994) did not record the largest flood in the basin. It may be attributed to the well distributed rainfall throughout the monsoon season but not the intense flood producing rainfall. The major epochs of monsoon rainfall fluctuation are: 1901 to 1930 low rainfall period, 1930 and 1960 high rainfall period and short term fluctuations are seen in the later half of the 20th century particularly after 1960. The four largest (1968, 1976, 1994 and 2004) recorded floods in the Par Basin have occurred during wet epoch *i.e.*, after 1960. The NADM graph

clearly illustrates that most of the floods have occurred when rainfall was above average (rising limb) and very few floods were experienced during below average (falling limb) rainfall. In addition to this, result of the conditional probability and occurrence of floods clearly indicates that the frequency of floods is generally high during the average SST index of ENSO and majority of the floods in the Par Basin have occurred during above normal conditions of rainfall. The present study can, therefore, prove to be a significant contribution towards the Par-Tapi-Narmada link project of the Government of Gujarat and water divergent projects of the Government of Maharashtra in association with Government of India.

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