# HYDROMETEOROLOGICAL STUDIES

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## Introduction

Water is a precious resource and plays a vital role in the development of agriculture, industry and power generation. The extent to which this resource is tapped for its manifold uses can well be a clu- to the advancement of an economy.

In India, because of rapid increase in population and large scale expansion in industry and agriculture, the need for all round development of water resources has been given very high priority since independence. As a result, large amounts of money are being invested every year in the construction of medium and large scale hydraulic strcutres such as dams, storage reservoirs, irrigation tanks, etc. for optimum utilisation of available water resources of the cour ry. For a better understanding of the water resources of a river basin and for designing costly hydraulic structure, it is necessary to have long period hydrological data like gauge and discharge observations at a number of places along a river. Barring a few rivers, the discharge observations over a long periods are not available for most of the rivers. It is only during the last 2 to 3 decades efforts are being made in an integrated manner to collect hydrological data. On the other hand, the recording of meteorological data like rainfall, temperature, wind, humidity and atmospheric pressure were initiated long back. Consequently, rainfall and other climatic records going back to 80-90 years are available for a good network of stations. Specially, rainfall data are available for a close network of stations. Meteorologists, hydrologists and engineers have recognised that in the absence of actual hydrological data, the long term rainfall and other meteorological data can be used for the development of water resources of a region by the technique of hydrometeorology.

The application of meteorological data and their proper analysis to the solution of hydrologic problems has in recent times come to known as the science of Hydrometeorology.

Daily rainfall records for about 3000 stations spread over the country are available for a period of over 90 years. This valuable data source have been used by several investigators notably from the India Meteorological Department (IMD), the Indian Institute of Tropical Meteorology (IITM), the National Institute of Hydrology (NIH) and the Central Water Commission (CWC) for carrying out hydrometeorological studies of different river basins of this country. Dhar and Rakhecha (1975), 1979) have written comprehensive review articles on hydrometeorological studies on Indian rainfall. These articles contained the results of studies undertaken at the IITM. In this article important aspects of hydrometeorological studies on rainfall of different river basins in India that have been carried out by different organisations and workers since independence are presented in the following sections.

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## Rainfall network

India has a long history of rainfall measurement. Calcutta observatory possesses the longest rainfall records in India going back to 1784. Mani (1975) described in detail the history of rainfall measurement in India. However, systematic observations for more number of stations in India was started from the middle of 19 century. At the time of independence there were about 2750 rainfall stations (Ahuja, 1960).

The need for increasing the network of raingauges for hydrologic purposes was, however, felt and as a result IMD in collaboration with Central Water and Power Commission reviewed in 1956-57 the network of ordinary raingauges for all the river basins in the country and recommended one raingauge for every 500 sq.km area. Since then a systematic approach was made on network planning, selection and installation of raingauge stations in various river basins and as a result the network of raingauge stations in India has increased rapidly during the last 4 decades. Important aspects covering network of rainfall for hydrologic purposes have been discussed in the issue of Jalvigyan Sameeksha (1987), a publication of high level technical committee on hydrology. The raingauge network at present comprises of about 4900 stations whose data are processed and archieved by IMD. This network gives one raingauge in about every 600 sq. km and the average distance between adjacent raingauge stations is between 20 to 30 km. About 4650 additional raingauges are being maintained by the Railways, Forest, Agricultural and Irrigation Departments. There are about 522 self-recording raingauge are being maintained by the Railways, Forest, Agriculture and Irrigation Departments. There are about 522 self-recording raingauges which provide records not only of the total daily rainfall but also of the intensity variations throughout the day. The hourly, daily and monthly rainfall data of these stations are available in the National Data Centre, IMD, Pune on magnetic tapes.

## Rain water assessment studies over different river basins/regions

Rainfall is the major contributing factor to our water resources and as such information on mean values of rain water, its variability in space and time in respect of various river basins and regions are valuable to the development of water resources. Using long period rainfall data, several workers have estimated mean depth of rain water in respect of various regions and river basins. Pramanik and Rao (1950) and IMD (1970a, 1971, 1977) used the available rainfall data of stations in different river basins ans worked out the mean monthly and annual values of rain water for each basin. The seasonal and annual rain water values for the major river basins of the country are given in Table 1. The table indicate the amount of rain water one could expect on the average in different river basins. Using the rainfall data of stations for the period 1901-1950 IMD (1981) has published a comprehensive Rainfall Atlas of India which contains 98 maps on different aspects of rainfall distribution.

On the basis of rainfall distribution and other meteorological parameters, the contiguous Indian area has been divided by IMD into different meteorologically homogeneous subdivisions roughly corresponding to political subdivisions of the country. Dhar and Rakhecha (1979) using rainfall data for the 80 years (1891-1970) of the stations in different meteorogical subdivisions estimated the montly and annual depth of rain water on different subdivisions for each of the years 1891 to 1970. Table 2 gives the mean seasonal and annual average depth of rain water obtained on the basis of 80 years of data for the different subdivisions. The amount of summer and winter monsoon rain water expressed as percentage of annual rain water and the coefficient of variability (CV) of annual rain water have also been included in the Table. The basic data given in Tables 1&2 provide a valuable aid in the study of problems related to surface and ground water resources. Among the different subdivisions of the country the mean annual rain water is highest in the coastal Karnataka and lowest in west Rajasthan. Low CV values are obtained over high rainfall regions and high CV over low rainfall regions. The amount of seasonal rain water during the four months of June to September is more than 75 per cent of the annual rain water in almost all the subdivisions excepting Assam, Jammu and Kashmir and some subdivisions of peninsular India, lowest being for Tamil Nadu. Dhar and Rakhecha (1979) have also estimated the mean monthly and annual rain water for each of the years 1891 to 1970 for India as a whole. The average annual rain water for the India as a whole on the basis of 80-year data has been estimated as 117 cm. The CV was worked out to be 9.5 per cent thereby indicating the stable nature of Indian rain water.

**Table 1 Seasonal and annual normals of rain water (cm) for major river basins on India. (a is rainfall in cm; b is no. of rainy days)**

| River Basin | | Jan-Feb | Mar-May | Jun-Sep | Oct-Dec | Annual |
|---|---|---|---|---|---|---|
| Indus | a | 12.6 | 13.8 | 56.4 | 5.9 | 88.7 |
| | b | 8 | 9 | 25 | 4 | 46 |
| Brahma- | a | 5.4 | 56.6 | 188.7 | 18.0 | 268.7 |
| putra | b | 5 | 31 | 67 | 9 | 112 |
| Ganga | a | 4.0 | 7.8 | 97.3 | 6.7 | 115.8 |
| | b | 3 | 5 | 41 | 3 | 52 |
| Narmada | a | 2.9 | 2.7 | 110.8 | 6.7 | 123.1 |
| | b | 1 | 5 | 36 | 8 | 50 |
| Godavari | a | 3.6 | 5.3 | 95.9 | 12.3 | 116.1 |
| | b | 2 | 5 | 47 | 6 | 59 |
| Mahanadi | a | 4.0 | 7.3 | 120.5 | 10.4 | 142.2 |
| | b | 3 | 6 | 54 | 6 | 69 |
| Tapi | a | 1.6 | 2.0 | 68.9 | 7.2 | 79.7 |
| | b | 1 | 2 | 39 | 4 | 46 |
| Cavery | a | 3.0 | 18.3 | 64.0 | 34.5 | 119.8 |
| | b | 2 | 11 | 33 | 19 | 65 |
| Mahi and | a | 0.5 | 1.1 | 80.3 | 2.1 | 84.0 |
| Sabarmati | b | 0 | 1 | 35 | 1 | 37 |
| Luni | a | 0.9 | 1.4 | 37.3 | 0.9 | 40.6 |
| | b | 1 | 1 | 17 | 1 | 20 |

**Table 2 Mean seasonal and annual rainfall (cm) for different sub-divisions of India as on 1971 (period 1891-1970).**

| Subdivisions | Jan Feb | Mar May | Jun Sept | Oct Dec | Annual | % of annual Jun-Sept | % of annual Oct-Dec. | CV |
|---|---|---|---|---|---|---|---|---|
| North Assam | 5.3 | 57.7 | 149.7 | 15.4 | 228.1 | 66 | 7 | 11 |
| South Assam | 5.5 | 73.4 | 180.8 | 23.6 | 283.3 | 64 | 8 | 11 |
| Sub-Himalayan West Bengal | 2.8 | 42.5 | 219.1 | 15.5 | 279.9 | 78 | 5 | 15 |
| Gangetic West Bengal | 3.6 | 17.4 | 107.8 | 13.1 | 141.9 | 76 | 9 | 15 |
| Orissa | 3.8 | 12.7 | 112.5 | 19.6 | 148.6 | 76 | 13 | 14 |
| Bihar Plateau | 4.6 | 8.9 | 110.4 | 9.7 | 133.6 | 83 | 7 | 13 |
| Bihar Plains | 3.2 | 7.2 | 101.6 | 7.2 | 119.2 | 85 | 6 | 16 |
| East U.P. | 3.3 | 3.0 | 89.4 | 5.9 | 101.6 | 88 | 6 | 20 |
| West U.P. | 5.3 | 4.3 | 88.3 | 5.1 | 103.0 | 86 | 5 | 19 |
| Hariyana, Chandigarh & Delhi | 3.6 | 2.9 | 45.7 | 2.5 | 54.7 | 83 | 5 | 28 |
| Panjab | 5.9 | 4.8 | 47.9 | 3.4 | 62.0 | 77 | 5 | 34 |
| Himachal Pradesh | 16.5 | 15.2 | 134.5 | 8.3 | 174.5 | 77 | 5 | 21 |
| Jammu & Kashmir | 17.2 | 22.6 | 50.6 | 9.3 | 99.7 | 51 | 9 | 22 |
| West Rajasthan | 0.9 | 1.5 | 27.0 | 0.9 | 30.3 | 89 | 3 | 40 |
| East Rajasthan | 1.4 | 1.8 | 61.5 | 2.4 | 67.1 | 92 | 3 | 23 |
| West M.P. | 2.2 | 2.1 | 94.0 | 5.0 | 103.3 | 91 | 5 | 20 |
| East M.P. | 3.8 | 4.8 | 119.3 | 7.3 | 135.2 | 88 | 5 | 15 |
| Gujarat | 0.4 | 0.9 | 92.2 | 3.1 | 96.6 | 95 | 0.3 | 29 |
| Saurastra & Kutch | 0.3 | 0.9 | 48.9 | 2.1 | 52.2 | 94 | 4 | 37 |
| Konkan | 0.3 | 3.4 | 276.5 | 13.4 | 293.6 | 94 | 5 | 18 |
| Madhya Maharashtra | 0.5 | 4.2 | 85.3 | 10.4 | 100.4 | 85 | 10 | 23 |
| Marathwada | 1.2 | 3.5 | 70.1 | 7.9 | 82.7 | 85 | 9 | 25 |
| Vidharba | 2.5 | 3.6 | 93.8 | 7.2 | 107.1 | 87 | 7 | 19 |
| Coastal A.P. | 1.9 | 8.4 | 57.7 | 31.5 | 99.5 | 58 | 32 | 18 |
| Telanagana | 1.5 | 5.6 | 74.5 | 9.5 | 91.1 | 82 | 10 | 21 |
| Rayalseema | 1.2 | 7.5 | 38.2 | 20.8 | 67.7 | 56 | 31 | 20 |
| Tamil Nadu | 4.6 | 14.3 | 34.6 | 47.1 | 100.6 | 34 | 47 | 14 |
| Coastal Karnataka | 0.3 | 16.7 | 289.7 | 26.1 | 332.8 | 87 | 8 | 15 |
| North Interior Karnataka | 0.5 | 9.5 | 46.7 | 14.6 | 71.3 | 65 | 20 | 19 |
| South Interior Karnataka | 0.8 | 16.8 | 74.4 | 22.5 | 114.5 | 65 | 20 | 20 |
| Kerala | 0.3 | 40.8 | 200.5 | 50.3 | 294.9 | 68 | 17 | 14 |
| Indian area as whole | 3.9 | 12.4 | 89.0 | 11.9 | 117.2 | 76 | 10 | 10 |

The frequency distribution of annual and monsoon rain water series for all the subdivisions (excepting for Punjab., West Rajasthan and Jammu & Kashmir) was found to be Gaussian. This knowledge of frequency distribution could be used to estimate probabilities of recieving more/less rain water than certain specified amounts. Sreenivasaiah and Yegnanarayanan (1959) prepared maps showing the probability of occurrence of rain water of less or more than 25cm, 50cm, 75cm, 100cm and 125cm during the monsoon season over India based on the data for the years 1901-1950 of 330 stations.

It may be mentioned that although India is endowed with abundant renewable water resources, its availability in time is, however, restricted to a period of 4 months of SW monsoon season. As such most of the flow in the rivers to an extent of 80-90 percent is confined to the SW monsoon season. For rest of the year excepting snowfed rivers there is inadequate flow in the rivers. Further, the distribution of rain water varies widely from one part of the country to another. These factors limit the scope for easy management of water resources. The only way to make the most efficeint use of the available water resources is by the conservation of the monsoon flow through dams and storage reservoirs (Patel, 1979).

**Water resources studies of India**

The mean annual rain water of 117 cm over the country is equivalent to a volume of water of about 3840 x $10^9 m^3$. According to Murthy (1977), average annual flow of surface water in different rivers of India including ground water recharge from rain water is 1881x$10^9$ $m^3$. This works out that roughly 49 percent of annual rainwater is converted into surface run-off and ground water and the remaining 51 percent is lost to the atmosphere by evaporation and transpiration. Because of limitations imposed by topography, climate and soil conditions, about 700 x $10^9 m^3$ representing 39 percent of the average annual flow can only be utilized.

Before Indian independence in 1947 there were only a few storage reservoirs in the country and the total storage capacity was about 12.3 x $10^9 m^3$. This has increased to 252 x $10^9 m^3$ by the year 1984 under various five year plan schemes of the Central and State Govrnments and more are being planned. If the present available storage impounded by existing dams is considered, it appears that barely 36% of the usable flow is being stored. This shows that there is ample scope for creating more storage reservoirs to conserve the remaining 64 percent of the usable flow for the all round development of the country.

**Maximum observed point rainfall studies**

Large parts of India receive heavy falls of rain associated with certain meteorological situations. Rainfall caused by a depression can be as high as 30 to 40 cm a day. Information regarding the greatest rainfall for a particular duration that has occured or is likely to occur at a place are of great practical utility to the design engineers who have to design flood control works, waterway openings in bridges, highway and railway culverts, urban storm sewers, air field drainage and many other hydraulic structres. It enables the designer in evaluating the largest quantity of water that will be caught over an area from which he can derive the amount of water that will run-off depending upon the land characteristics.

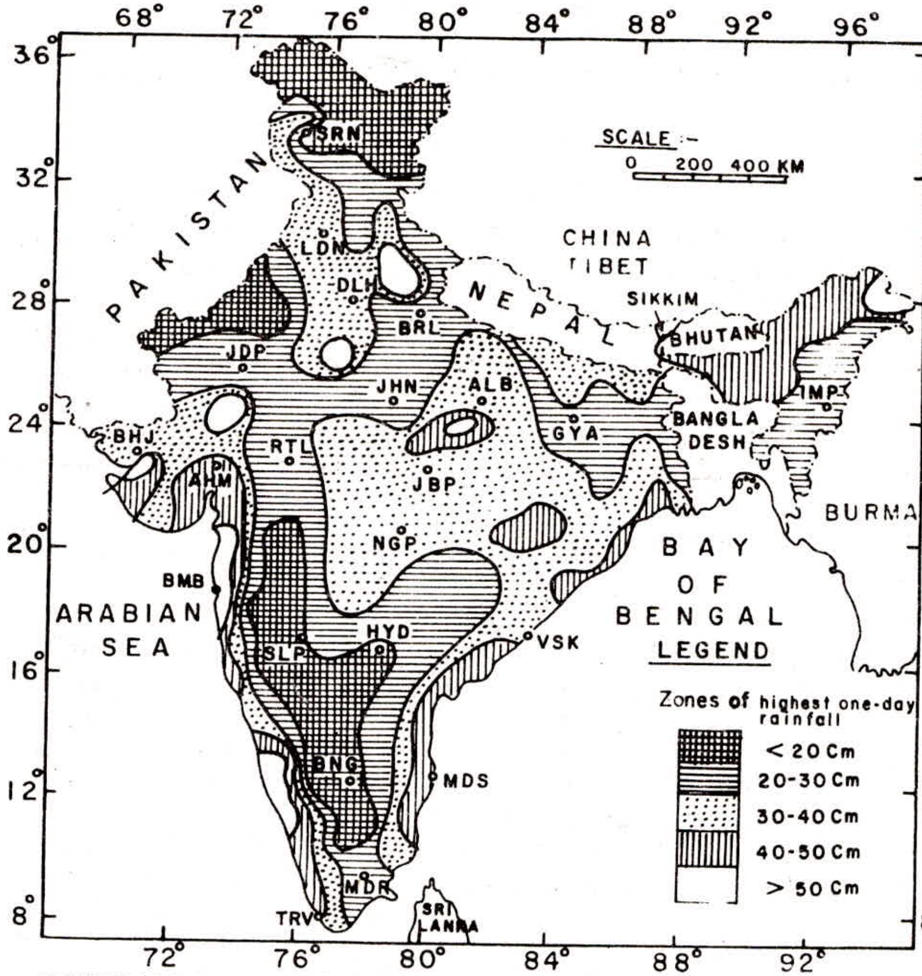
In view of the importance of the distribution of maximum rainfall in many types of hydrological analysis, several workers have studied the past records of rainfall to see the manitudes of largest rainfall that had occurred over different stations. One of the early studies on the distribution of 24- hour point maximum rainfall in India was by Iyer and Zafar (1938) based on data from 1891 to 1920. Parthasarthy (1959a) utilising the daily rainfall data of about 3000 raingauge stations updated this information up to 1955 and also studied the frequency of Occurrence of 1-day rainfall of 25 cm and more in different parts of the country. Rao (1959) worked out monthly frequency of days of very heavy falls exceeding 25 cm in one day. Saseendran et al (1983) using daily rainfall data of about 75 stations in Kerala state prepared a family generalised maps of highest rainfall of 1 to 10-day durations. Rakhecha et al (1990) using the daily rainfall data of about 300 stations from 1875 to 1982 prepared a generalised map of the highest point rainfall for 24 hours duration in India. Fig. 1 is a map showing the distribution of 24-hour highest rainfall over different parts of the Indian region. This map can be used for obtaining information about the maximum rainfall in 24 hours which can be expected over small areas in any part of the country. The information on the spatial distribution of highest 24 hours rainfall was also applied to demarcate the homogeneous zones of heavy rainfall.

## Studies on frequency of maximum rainfall of different durations

An important problem in hydrometeorology is to determine maximum values of rainfall of different durations that may be expected to occur with any given frequency. The Frequency or return period is the average interval of time within which rainfall of a specified amount will be equaled or exceeded once. For example, 1-day rainfall with a 10 year return period is that magnitude of daily rainfall which can be expected to be equaled or exceeded ten times in 100 years. It should not be considered that such rains will be separated by 10-year intervals. Several statistical or probability methods have been proposed to determine the rainfall magnitudes that may be expected to occur at any station with a given return period. Details of different statistical procedures can b!e seen in any text book on Hydrology.

Return period analysis of maximum one-day rainfall for several stations in different parts of the country having long period rainfall data has been made by several investigators. Krishnan et al (1959) using the 1-day annual maximum rainfall data for the period 1901-1950 of 150 observatory stations throughout the country determined the estimates of 1-day maximum rainfall likely to be exceeded once in 25,50,100 and 250 years by Jenkinson probability method. Dhar and Kulkarni (1970a,1970b) prepared frequency interpolation nomograms for estimating maximum one-day point rainfall for different return periods for Uttar Pradesh on the basis of long period rainfall stations.

In an another study Dhar and Kulkarni (1971a) prepared nomograms for different sub-divisions of north India for estimating maximum 1-day point rainfall for 2 to 25 years return periods from the corresponding mean annual rainfall of a station. Harihara Aiyyar and Tripathi (1971b) examined the heaviest 1-day reocrded point rainfall of about 50 stations in the country and determined the probability occurrence of such heaviest rainfall. The return periods of these heaviest 1-day rainfalls ranged from 20 years to 3000 years Harihara Ayyar and Prasad (1971) studied maximum 1-hour rainfall of about 100 self recording raingauge stations having rainfall data of 20 years and prepared generalised maps of 1-hour rainfall of different return periods from 2 to 50 years. Another similar study of maximum 1-hour rainfall for 9 stations in southern half of the Indian Peninsula was made by Dhar and Kulkarni (1971). Dhar et al (1979a) gave generalised charts of maximum 1-day rainfall for different return periods of 2, 5, 10, 25, 50 and 100 years for the Karnataka state Care should be taken in determining the magnitude of maximum rainfall of specified return periods from generalised charts because local conditions may




GENERALIZED CHART OF INDIA SHOWING HIGHEST RAINFALL ZONES FOR ONE-DAY DURATION : PERIOD (1875-1982)

FIG. 1

cause differences in rainfall characteristics. If records are available, it is always better to make return period analysis with data obtained at the location where they are to be used. An extensive study of maximum one-day point rainfall estimates for return periods of 2,5,10,25,50 and 100 years ws made by Dhar et al (1980a) for about 1000 stations in north Indian plains. In this paper they have developed a simple procedure for evaluating maximum point rainfall for different return periods for any location in the plains of north India. In flood computation problems depths of specified rainfall are required not only for durations of 1-day but also for higher durations such as 2 days, 3 days etc. Recently a study in this direction has been made by Rakhecha et al (1992) in which the estimation of maximum rainfall for different return periods for 2-day and 3-day durations was made for stations in Gujarat.

**Studies on severe rainstorms**

The hydrometeorological analysis of severe rainstorms is most important for planning and designing of water resources projects. In the absence of actual records of stream flow data, they are useful for assessing the flood potentialities as well as the design flood of a river basin. In order to derive the design flood of a river, rainstorms should be analysed in such a way that the results can be applied to any hydraulic project. The form of information required is depth of rain which falls during different durations of time and over specified area. That is rainfall should be expressed in terms of Depth-Area-Duratión (DAD). Thus a rainstorm has three hydrologic dimensions and their relationships are of vital importance for assessing flood potentiality of a region as well as for planning and designing water resources projects. Recognising the great practical utility of rainstorm in design aspects many investigators have carried out DAD analysis of severe rainstorms that have occurred over different parts of the Indian region.

Satakopan (1950) described the method of deriving the DAD curves of rainfall for designing flood control reservoirs and gave such cruves of maximum rainfall for Damador river catchment from the rainstorm of 16-18 June 1898. A more detailed description and step by step procedures for the DAD analysis is described in the Manual of Hydrology (IMD), 1972). Parthasarthy (1959b) presented DAD curves of five biggest rainstorms viz., October, 1955 over Punjab, September, 1924 over west Uttar Pradesh, June 1898 over Damodar river basin, August, 1953 over Godavari basin and September, 1958 over the lower Mahanadi basin. He found from this analysis that storms of very high rainfall can occur in low rainfall areas far removed from the sea. Raman and Dhar (1966) carried out DAD analysis of major rainstorms that occured during the period 1891 to 1966 over Bihar and Madhya Pradesh. Abbi et al (1970a) made a detailed study of 85 heavy rainstorms over north Bengal and showed that 11-13 June 1950 rainstorm has contributed the highest average depth of rainfall for 1-3 day durations. a study of the rainstorms during the period from 1901 to 1960 over plains of Assam was made by Pant et al (1970). Dhar et al (1974, 1982) analysed all the severemost recorded rainstorms of 1-day, 2-day and 3-day durations over different regions of north Indian plains and over the central parts of the Indian peninsula. Dhar et al (1975a, 1980b) analysed the most severe rainstorm of September, 1880 over northwest Uttar Pradesh and found it was one of the catastrophic rainstorms of north India.

Rainstorms have been studied by Banerji and Anand (1966) for the Gomti river basin for the period 1901-1960, by Dhar et al (1968a) for the Godavari river basin for the period

1891-1963, by Dhar and Kamte (1968) for the Baitarni river basin for the period 1901-1961 and by Abbi et al (1970b, 1971) for the Narmada and Tapi river basins for the period 1891-1968. Recently, the results of DAD analysis of severe rainstorms of different river basins/regions were published in the proceedings of Workshops on "Unusual storm events and their relevance to dam safety" by CBIP (1989, 1990). The DAD values for 1,2 and 3-day durations for the most predominant rainstorms obtained by various workers are given in Table 3 for the flood and design storm studies for any river valley project in the country. The maximum point rainfall for these 13 rainstroms varied from 24 to 99 cm for 1-day, from 44 to 127 cm for 2-day and from 60 to 145 cm for 3-day durations. The main centres of these storms are shown in Fig. 2.

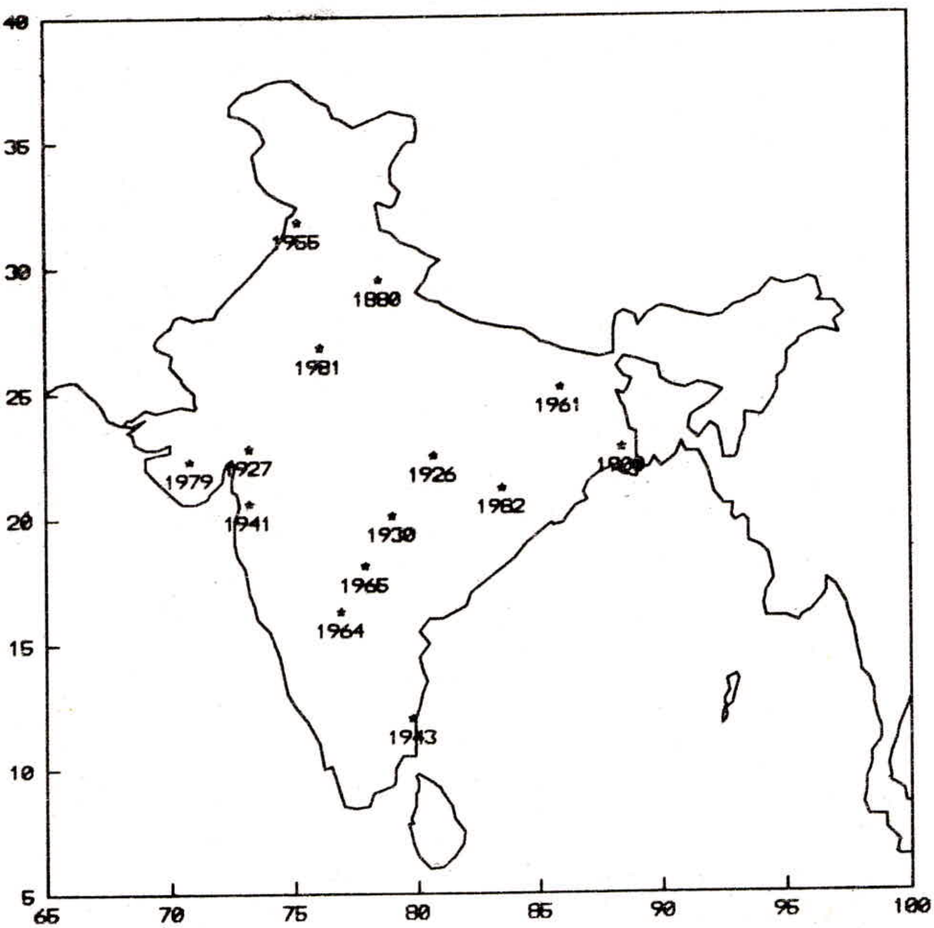



Fig. 2 Centres of storms

**Table 3 DAD values (cm) of severe rainstorms over India**

| Sr. no. | Severe rainstorm date | Affected region | Duration (days) | Area in sq.km | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 10 | 100 | 1000 | 5000 | 10000 | 20000 |
| 1. | 17-18 Sept,1880 | Uttar Pradesh | 1 | 82 | 82 | 78 | 63 | 52 | 40 |
| | | | 2 | 104 | 103 | 99 | 87 | 77 | 62 |
| 2. | 20-22 Sept,1900 | Bengal | 1 | 44 | 43 | 41 | 36 | 33 | 28 |
| | | | 2 | 73 | 72 | 67 | 58 | 52 | 44 |
| | | | 3 | 83 | 82 | 78 | 69 | 62 | 52 |
| 3. | 19-21 Sept,1926 | Madhya Pradesh | 1 | 36 | 36 | 35 | 33 | 30 | 26 |
| | | | 2 | 65 | 65 | 63 | 57 | 53 | 47 |
| | | | 3 | 83 | 82 | 81 | 76 | 71 | 62 |
| 4. | 26-28 July,1927 | Gujarat | 1 | 54 | 53 | 48 | 39 | 33 | 29 |
| | | | 2 | 100 | 94 | 79 | 63 | 56 | 49 |
| | | | 3 | 129 | 126 | 114 | 94 | 83 | 71 |
| 5. | 1-3 July,1930 | Maharashtra | 1 | 36 | 36 | 31 | 24 | 22 | 19 |
| | | | 2 | 71 | 70 | 58 | 40 | 33 | 28 |
| | | | 3 | 77 | 76 | 66 | 47 | 39 | 35 |
| 6. | 1-3 July, 1941 | South Gujarat | 1 | 99 | 97 | 85 | 65 | 54 | 43 |
| | | | 2 | 127 | 126 | 118 | 97 | 83 | 66 |
| | | | 3 | 145 | 143 | 134 | 117 | 105 | 86 |
| 7. | 17-19 May,1943 | Tamil Nadu | 1 | 42 | 41 | 37 | 29 | 25 | 21 |
| | | | 2 | 72 | 72 | 69 | 55 | 46 | 37 |
| | | | 3 | 95 | 95 | 91 | 73 | 61 | 49 |
| 8. | 3-5 Oct, 1955 | Punjab | 1 | 50 | 47 | 45 | 40 | 35 | 29 |
| | | | 2 | 72 | 70 | 64 | 56 | 51 | 44 |
| | | | 3 | 72 | 71 | 67 | 59 | 53 | 47 |
| 9. | 1-3 Oct, 1961 | Bihar | 1 | 37 | 37 | 36 | 32 | 28 | 23 |
| | | | 2. | 55 | 54 | 53 | 49 | 44 | 35 |
| | | | 3 | 58 | 57 | 57 | 54 | 50 | 42 |
| 10. | 28-30 Sept.1964 | Karnataka | 1 | 24 | 23 | 23 | 22 | 21 | 19 |
| | | | 2 | 44 | 43 | 32 | 27 | 25 | 22 |
| | | | 3 | 62 | 61 | 51 | 38 | 34 | 30 |
| 11. | 13-15 July, 1965 | Andhra Pradesh | 1 | 51 | 49 | 39 | 25 | 20 | 16 |
| | | | 2 | 54 | 52 | 41 | 27 | 23 | 20 |
| | | | 3 | 60 | 57 | 45 | 30 | 27 | 23 |
| 12. | 18-20 July,1981 | Rajasthan | 1 | 56 | 56 | 54 | 45 | 37 | 27 |
| | | | 2 | 84 | 83 | 76 | 62 | 52 | 40 |
| | | | 3 | 97 | 95 | 85 | 71 | 61 | 48 |
| 13. | 28-30 Aug, 1982 | Orissa | 1 | 52 | 52 | 51 | 45 | 38 | 30 |
| | | | 2 | 70 | 70 | 69 | 65 | 59 | 50 |
| | | | 3 | 88 | 88 | 84 | 74 | 66 | 55 |

## Relationship of point to areal rainfall studies

The maximum intensity of rainfall in a rainstorm occurs at a point at the centre of the storm and outside this the intensity gradaully decreases. A large number of formulae have been developed which relate storm point rainfall to storm areal rainfall. From the analyses of rainstorms in different parts of India Parthasarathy et al (1960) gave a simple relationship of point to areal rainfall in the form

$$R = 100 - C.A^{0.5} \quad (1)$$

where R is the ratio expressed in percent of rainfall over area A surrounding the storm centre to the storm centre maximum rainfall and C is a constant varies with geographical location. Raman and Chabra (1966) studied the relationship for rainstorms of Bihar and Madhya Pradesh and suggested a generalised formula of

$$P = Pm \quad \exp(-0.0006 \ A^{0.72}) \quad (2)$$

where P is the average rainfall (in inches) over area A (sq.miles) and $P_m$ is the maximum point rainfall at storm centre.

Dhar and Bhattacharya (1977) using severe rainstorm data of north Indian plains derived the following equation

$$P = P_m \exp(-kA^n) \quad (3)$$

where P and $P_m$ are same as explained above and k and n are constants varying with duration of the storm. Dhar and Bhattacharya gave values of k and n for various durations as shown below.

**Values of k, n for rainstorms of north Indian plains**

| Duration | k | n |
|---|---|---|
| 1-day | 0.0016 | 0.6614 |
| 2-day | 0.0018 | 0.6306 |
| 3-day | 0.0030 | 0.5691 |

The relationship can be used to convert storm centre rainfall to areal average particularly over small size basins for drainage design purposes.

## Probable maximum precipitation studies

The probable maximum precipitation (PMP) is defined as the theoretically greatest depth of precipitation for a given duration that is physically possible over a given station or a specified area (WMO, 1986). Estimates of PMP for different durations that are likely to occur over a station or an area are required for calculating the probable maximum flood (PMF) hydrograph. The PMF hydrograph is used in the desing of spillways on large dams for which no risks can ever be taken. According to Central Water Commission (1972). the major hydraulic structure having a reservoir capacity of 60 million $m^3$ and more should be designed for PMF derived from PMP.

There are two main approaches for estimating the magnitude of the PMP. The first is the physical approach in which PMP is derived by the analysis of a large number of major rainstorms in and near the basin and then transposing the outstanding storm pattern over the basin so as to obtain the maximum raindepths for different durations. The transposed raindepths are then adjusted for moisture maximisation. For moisture maximisation, the areal rainfall values are adjusted to the highest amount of moisture index corresponding to a maximum persisting dew point temperature. Rakhecha et al (1990) have given generalised maps of highest 24-hour persisting dew point temperatures for the individual months of June to September for the Indian region useful for maximisation studies. The details of PMP estimation by physical method are given in the Manual on Hydrometerology (IMD, 1972). The documentation of historic rainstorms that have been analysed by various investigators have already been given in Section 7. The second approach involves statistical procedures whereby the estimates of PMP rainfall at a particular location or area are determined from the frequency analysis of the annual maximum rainfall data such as Gumbel and the log-normal methods. A different type of statistical method which is used for estimating PMP for small areas has been developed by Hershfield (1961,1965). The use of Hershfield technique has shown that the PMP estimates obtained by this method are closely comparable to those obtained by the eleborate physical methods (Bruce and Clark, 1966; Myers, 1967). Estimates of PMP by physical and statistical methods have been made for many catchments throughout India, in most cases for specific development projects. Details of PMP studies for specific projects are described in a separate section on design storm studies.

## 9.1 PMP studies by Hershfield method

Several workers notably Majumdar and Ranga Rajan (1966), Dhar and Kamte (1971), Sarma et al (1975), and Dhar et al (1981a) have carried out extensive investigations into the estimation of point PMP for 1-day duration for stations throught India using the Hershfield (1961, 1965) technique. The Hershfield technique is briefly discussed below :

For estimating PMP Hershfield (1961, 1965) used Chow"s general frequency equation in a modified form as:

$$X_e = \bar{X} + k_m \sigma \qquad .......(4)$$

$$k_m = (X_1 - \bar{X}_{n-1}) / \sigma_{n-1} \qquad ........(5)$$

where $X_e$ is the PMP rainfall for a given station for specific duration, $k_m$ is frequency factor and $X_1$, $\bar{X}_n$ and $\sigma$ are respectively the highest, mean and standard deviation for a series of n annual maximum rainfall values of a given duration and $\bar{X}_{n-1}$, $\sigma_{n-1}$ are respectively the mean and standard deviation for this series excluding the highest value from the series.

Dhar and Kulkarni (1974) applied the Hershfield method to about 1000 stations having long period rainfall data in the plain areas of north India and prepared a generalised map of PMP estimates for 1-day duration. Dhar et al (1981a) extended the study to the stations in the Indian peninsula and a separate PMP chart for the region was prepared. The PMP rainfall distribution for the Indian region as a whole is shown in Fig. 3.

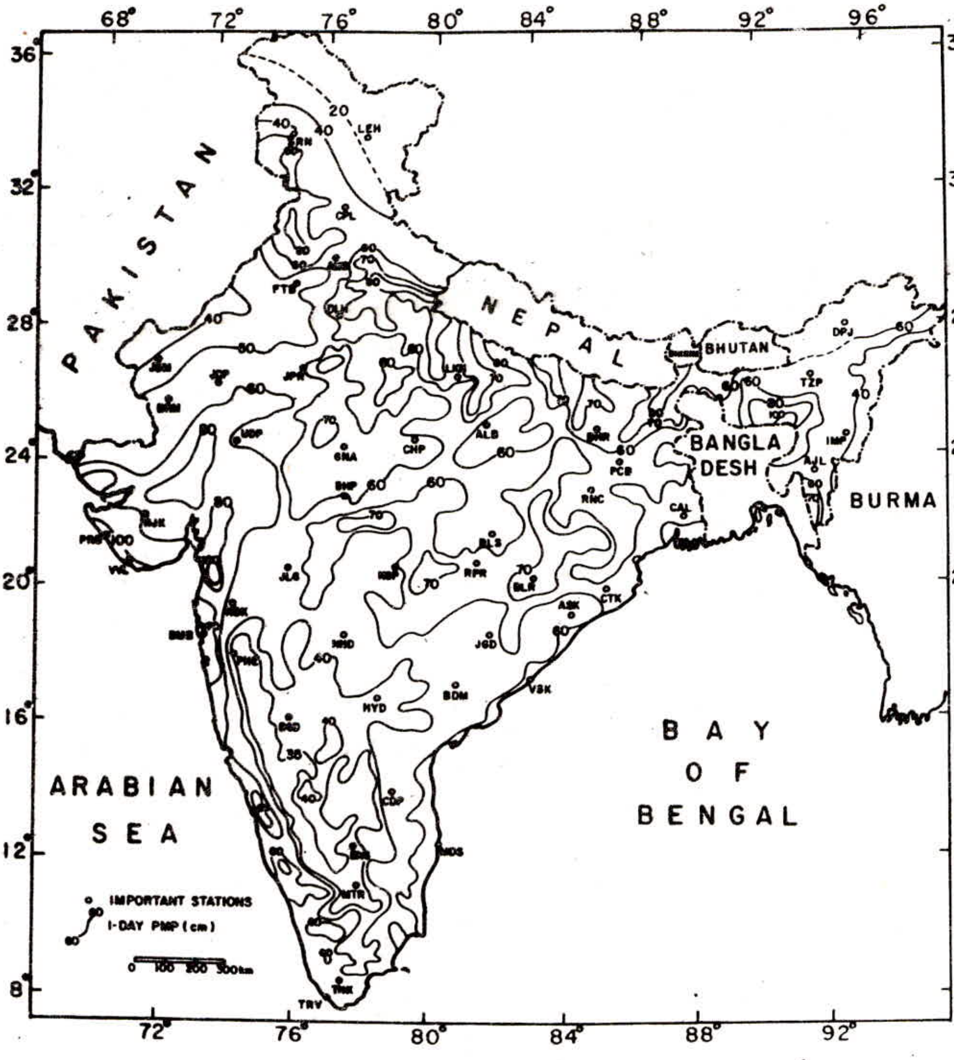



Fig. 3 : Generalised one-day probable maximum precipitation map.

Recently, the Indian Institute of Tropical Meteorology (IITM,) 1989) HAS published an atlas containing generalised charts of PM P estimates based on Hershfield method for 1-day duration for different states of the Indian Union. It was found that the 1-day PMP for stations in the different states of the Indian Union varied between 30 and 110 cm. This publication is being extensively used by the hydrologists for estimating PMP for 1-day duration at any location.

Estimates of PMP for 1-day duration have been made for several stations in India, but no systematic studies have been made for longer durations. For the design purpose. Hydrologists need PMP values for the entire rainstorm of two to three days as synoptic scale disturbances which cause heavy rainfall over India during monsoons last for 2 to

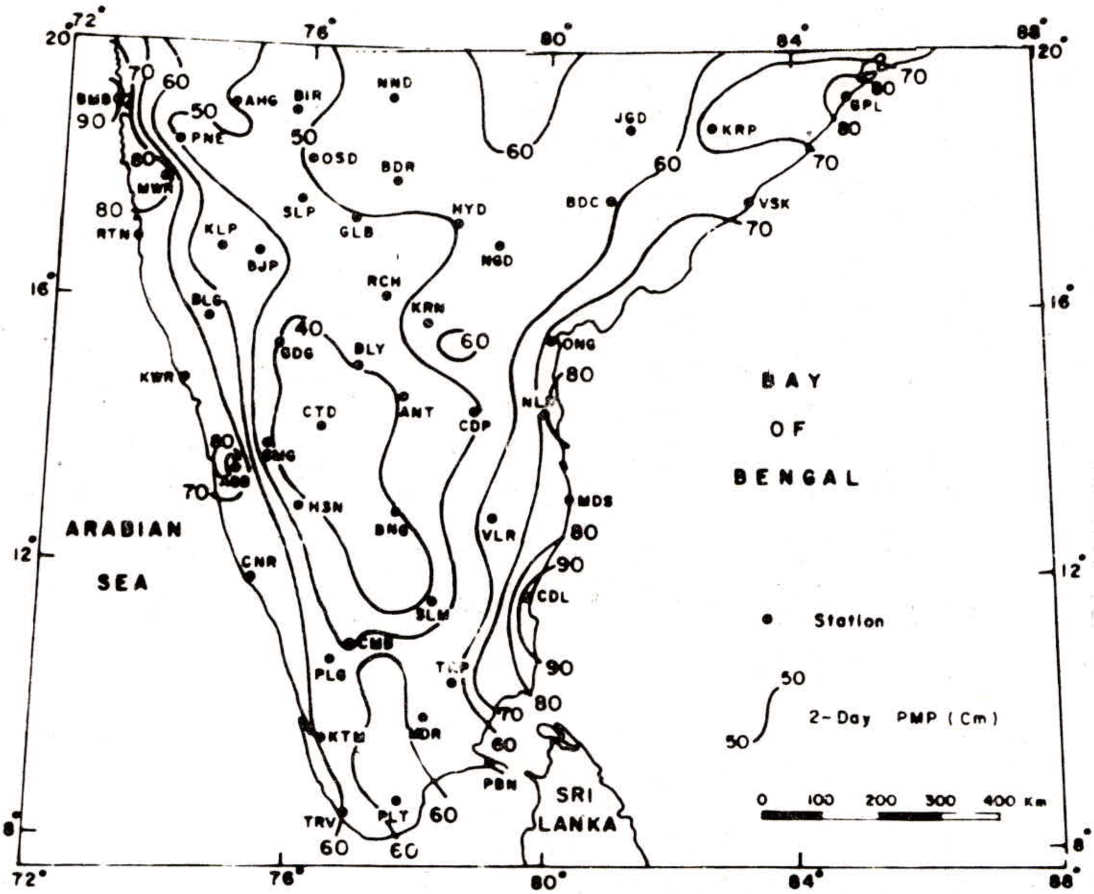



FIG.4- GENERALISED MAP OF TWO-DAY EXTREME RAINFALL (Cm) OVER INDIAN PENINSULA.

3 days. Recently, Rakhecha et al (1992) carried out a study on the estimation of PMP for a 2-day duration for stations in Indian peninsula lying between 8° to 20°N. A generalised map showing the spatial distribution of 2-day PMP is shown in Fig. 4. Authors found that the 2-day PMP estimates over the Indian peninsula varied from 40 to 95 cm and the average ratio of 2-day PMP to the highest observed 2-day rainfall was found to be 1.76.

## Design storm studies of different river catchments

A design storm of a river catchment is an estimate of maximum average depth of rainfall over the catchment which is accepted for working out the spillway design flood of a Hydraulic structure. Design storms in common use are the probable maximum storm (PMS) and the standard project storm (SPS) and their use depend upon the degree of safety required for the structure. The PMS is an estimate of greatest depth of rainfall for a given duration that is physically possible over a drainage basin. The PMS is used in design of spillway on large dams for which no risks can ever be taken. The SPS is the largest rainstorm so far on record that has actually occurred over the basin under consideration. Manual of Hydrometheorology (IMD, 1972) has described the methods for estimating PMS and SPS.

A number of Hydrometeorological studies on the estimation of design storms were carried out for different sections of various river basins where water and power projects were being planned. Pioneering work in this connection was done by Satakopan (1949) for the Damodar river, Pramanik and Rao (1950, 1952, 1953, 1954) for the Mahanadi, the Koyana, the Damodar and the Mayurakshi rivers and Satakopan and Parthasarthy (1955) for the Kosi river.

Satakopan was one of the earliest Hydrometerologists of this country who employed the technique of DAD and storm transposition to obtain estimates of design storm. His classic study of Damodar basin is still considered to be a model rainfall study for any Hydrometeorological study of a river basin. The design storm studies of important river basins that are available in the published literature are listed below:-

| | | |
|---|---|---|
| (1) | Damodar river | Satakopan, 1949, 1950; Pramanik and Rao, 1953; Ghose, 1960, 1966 |
| (2) | Mahanadi river | Pramanik and Rao, 1950; Dhar et al. 1966 a; Rao et al, 1972 |
| (3) | Koyana river | Pramanik and Rao, 1952 |
| (4) | Mayurakshi river | Pramanik and Rao, 1954 |
| (5) | Kosi river | Satakopan and Parthasarthy, 1955 |
| (6) | Jhelum river | Bhan, 1958 |
| (7) | Yamuna river | Dhar, 1962; Apte and Datta Roy, 1982 |
| (8) | Beas river | Dhar and Narayanan, 1965; Sharma et al. 1982 |
| (9) | Gomti river | Benerji and Anand, 1966 |
| (10) | Cauvery river | Banerji and Narayanan, 1966 |
| (11) | Baitarni river | Dhar et al, 1968b |
| (12) | Teesta river | Dhar et al, 1966 b |
| (13) | Godavari river | Dhar et al, 1968a |
| (14) | Bhima river | Dhar and Mhaiskar, 1970 |
| (15) | Brahmaputra river | Pant et al, 1970 |
| (16) | Narmada river | Abbi et al. 1970b |
| (17) | Barak river | Changraney et al. 1970 |
| (18) | Tapi river | Abbi and Jain, 1971 |
| (19) | Mahi river | Dhar et al, 1974b |

| | | |
|---|---|---|
| (20) | Brahmani, Burhabalong and Rushikulya rivers | Changaraney et al, 1975 |
| (21) | Subarnarekha river | Dhar et al, 1977; Saxena et al, 1989 |
| (22) | Betwa river | Dhar et al, 1978 |
| (23) | Krishna river | Dhar et al, 1979b |
| (24) | Ravi river | Mehra and Jain, 1982 |
| (25) | Karanja river | Ramanamurthy et al 1987 |
| (26) | Chenab river | Rao and Madan, 1989 |
| (27) | Chambal river | Madan and Nanda, 1989 |
| (28) | Ponniayar river | Rakhecha et al, 1990 |
| (29) | Lodhari river | Rao and madan 1991 |

The estimates of design storm depths for different durations were obtained by Depth-duration (DD) or DAD analysis of severe ,rainstorms in and around a river basin on the basis of 70-80 years of rainfall data. The DAD data of severe rainstorms which have been used for design storm studies are given in section 7. Estimates of PMP rainfall likely to be experienced by the catchments were obtained by storm transposition and moisture maximisation techniques. Frequency of maximum rainfall of different durations were also worked out by extreme value analysis techniques. The magnitudes of maximum rain depths for high return periods ranging from 200 to 1000 years were also estimated for some of the basins for the use of design engineers. The design storm studies have revealed that in the most severe 3-day rainstorm about 50 per cent of basin rainfall is obtained on the heaviest of the 3 days, 30 per cent on second heaviest day and only 20 per cent on the third day. Further, it was found that 3-day maximum basin rain depths vary from 13 to 42 per cent of the respective mean annual basin rainfall. In the majority of basins, however, this ratio varies from 20 to 30 per cent, thereby showing that more than one fifth of the annual rainfall over a basin can occur in the course of threed days. It was also shown that a spillway design storm of a river basin did not depend upon the mean annual rainfall, as a low annual rainfall basin could have high design storm and vice versa.

### Areal PMP studied by Generalised method

The approach used in India to extimate PMP has been the physical method based on transposition and maximisation of major recorded rainstorms. This method proved to be adequate but lacks credibility if a storm of maximum efficiency have not been recorded over a catchment under study. For this reason, generalised methods have been developed which use the maximum recorded rain depths for all combinations of area and duration and allow for free transposition in space. The generalised method for the estimation of PMP gives consistent and more reliable results than those obtained by the method of storm maximisation and limited transposition. Rakhecha and Kennedy (1985) first time for the Indian region have developed a generalised method of estimating areal PMP of 1 to 3-day durations by pooling together all the rainfall data from a very large area. The rainfall depths are normalised for factors as storm dew point temperature, distance of the storm from the coast, topography effects and any intervening mountain barrier between the rainfall and the moisture source. These normalised values can be applied to any individual catchment for estimating areal PMP with the appropriate adjustment factors. The technique has been applied to estimate PMP for durations of 1,2 and 3 days for four major dam sites namely, the Mahi river up to Kadana, the Betwa river up to Rajghat, the Subarnarekha river up to Ghatsila and the Subarnarekha up to Chandil. In a separate study, Rakhecha and Sangam (1985) applied the generalised technique to estimate areal PMP for 1000 and 5000 $Mi^2$ for 1-day duration over different locations in the north-western Indian region.

## Rainfall Intensity-Frequency-Duration (IFD)studies

The intensity of rainfall of various frequencies and for specific durations are of great importance for hydrological purposes. The relationship between intensity (I), frequency (F) and duration (D) at any location can be determined from an analysis of the rainfall records

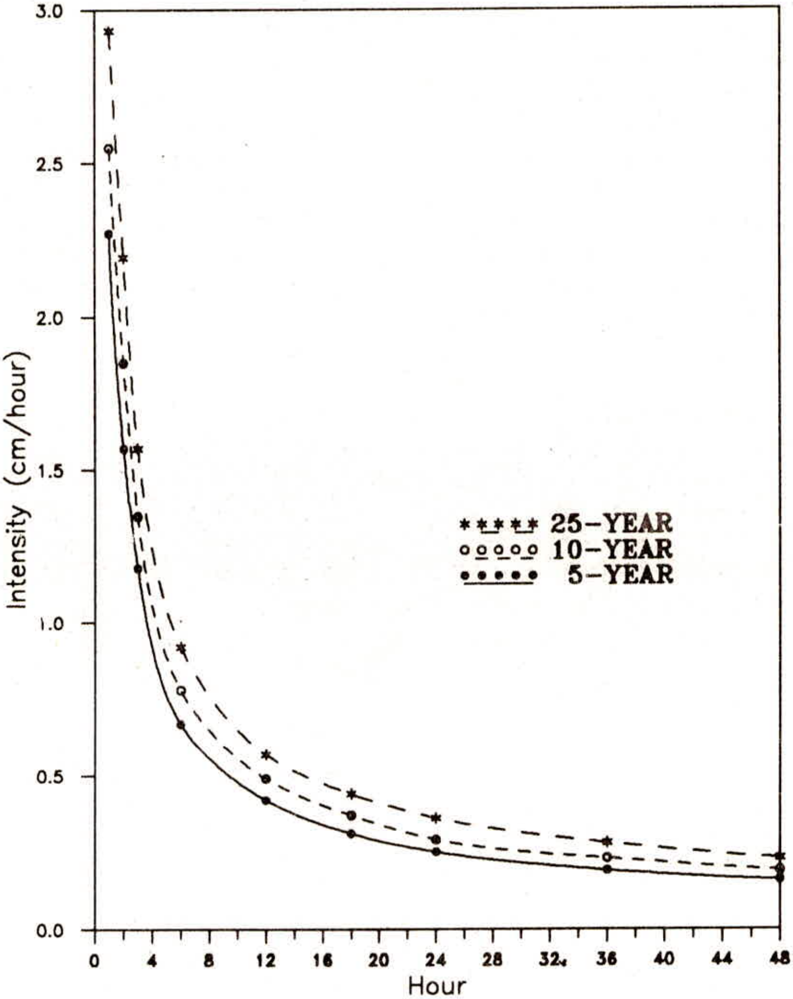



**Fig 5 IFD curves for Calcutta**

obtained from self recording rainfall charts at that location. The magnitudes of rains of various durations such as 5 min, 15 min, 30 min, 60 min and so on are determined and these data for selected durations can then be used to determine the magnitudes of rains of various frequencies. For example, the 10-year frequency of 30 min rainfall can be determined from a record of annual maximum 30 minutes values. The average rainfall intensity when plotted against duration for a particular frequency provides intensity-duration curve and is an important tool for the prediction of run-off. Different empirical formulae connecting rainfall intensity, frequency and duration have been given by various workers.

Raman and Krishnan (1959) analysed the self recording raingauge records of New Delhi, Calcutta and Madras for a period of 10 years (1946-55) and estimated the intensity of maximum rainfall which will be equalled or exceeded for various durations on the average once in 1,2,5 and 10 years. Parthasarthy and Singh (1961) analysed the available self recording raingauge of 40 stations data and prepared generalised charts of 2-year frequency of 1,2,3,6, and 24-hour durations and have also derived ratios for otabining intensities for longer return periods. These charts are useful in the design of local drainage works, road culverts and railway bridges. Dhar and Ramchandran (1970) analysed the self recording rainfall data of Calcutta for a period of 20 years and estimated the intensity of maximum rainfall of various frequencies (2 to 25 years) and for specific durations ranging from 1 to 48 hours. Based on 15 min tabulations Harihara Ayyar and Tripathi (1974) prepared generalized charts of 2,5,10,25 and 50 years return periods of 15 min, 30 min, 45 min, 3 hr, 6 hr, 9 hr, 12 hr and 15 hr rainfall. An example of the results of frequency analysis is shown in Fig. 5 for Calcutta station. This Fig. shows that average intensity decreases as the duration increases. Similarly, high intensities will occur less frequently than lower.

The Central Soil and Water Conservation Research and Training Centre, Dehra Dun (Ram Babu et al, 1979) have developed rainfall intensity-frequency-duration equations and nomographs for 42 stations as well as for different zones of the country namely north, central, eastern, western and southern from analysis of self recording pluviograph records. These equations and nomograms enable quick determination of rainfall intensity for any desired duration and frequency. The IFD relationships for N.Delhi, Nagpur, Bhuj, Calcutta and Banglore obtained by them are given below:

New Delhi: $$I = \frac{5.2F^{0.157}}{(D + 0.5)^{1.107}}$$

Nagpur $$I = \frac{11.5\ F^{0.156}}{(D + 0.25)^{0.990}}$$

Bhuj : $$I = \frac{3.8F^{0.199}}{(D + 0.25)^{0.990}}$$

Calcutta: $$I = \frac{5.9F^{0.115}}{(D + 0.15)^{0.924}}$$

Bangalore: $$I = \frac{6.3\ F^{0.126}}{(D + 0.50)^{1.128}}$$

where I, F and D are intensity (cm/hr.), Frequency (years) cna duration(hours)respectively.

**Time distribution studies**

The variation of rainfall intensity with time throughout a storm period is known as the time distribution of rainfall. The time distribution of the rainfall during the design storm can have a significant effect on the magnitude of the flood peak. For example, if the rainfall is distributed uniformly over a periods of say 24 hours, the peak rate will be less than if the same rain occurs during 2 to 4 hours of 24-hour period. It is therefore, necessary to know what proportion of 24 hours or 48 hours rain usually fell in 1,3,6 hours and so forth. This is done by splitting 24-hour and 48-hour storm rain depths into smaller intevals of 1,3,6, hours based on autographic records.

Studies on time distribution of Indian rainfall have been carried out by many workers. Shenoy and Chopra (1966) have prepared average time distribution for seven storm in different parts of the country. Dhar et al (1981b) determined the time distribution of 10-12 August 1979 rainstorm which caused the Morvi dam disaster. Analysis of hourly rainfall distribution of 6 most intense 1-day rains recorded over Karanja catchment was studied by Rakhecha et al (1985). Recently, time distribution studies have been presented for some of the major storms by Saxena et al (1989), Kathuria and Kulkarni (1989), Madan and Nanda(1989) and Mukherjee et al (1989). These distributions can be utilised as a basis for finding out time distribution of design storm rainfall in their respective regions.

**Evaporation studies**

Many meteorological factors in addition to rainfall are used in hydrometeorology. Of particular importance are evaporation and transpiration as about 51 per cent of the annual rainfall over the Indian region is returned to the atmosphere by evaporation and transpiration. For augmenting water storage and ensuring efficient management of water resources, it is most essential to obtain an estimate of evaporation from large water surface such as rivers, ponds, reservoirs, lakes etc. The rate of evaporation can be determined by pan measurement method, energy budget method, storage equation method and empirical formulae. In pan meausrement, evaporation is determined by measuring the amount of water evaporated from a free water surface exposed in a pan. The observation at all the stations in India are taken with the standard U.S. Evaporation pan (Class A) covered with mesh. India Meteorological Department (IMD, 1970, 1980) have published monthly and annual mean evaporation values in respect of 30 stations in India. Rao et al (1971) have presented monthly and annual evaporation maps for the Indian region based on evaporation observations recorded with wire mesh covered class A pans at about 80 stations in India. Empirical formulae for the estimation of pan evaporation from meteorological parameters have been developed by Venkatraman and Krishnamurthy (1965), Reddy and Rao (1973), Venkatraman and Krishnamurthy (1973) used the energy budget method for computing evaporation losses.

The rate of evaporation obtained from the class A pan evaporation is multiplied by a suitable pan coefficient so as to obtain the evaporation rate from the large water surface. This is necessary because it is found that the evaporation from a large surface source is not the same as from a small pan. Based on studies of reservoir evaporation and pan evaporation data from the Sardar Samand reservoir in west Rajasthan, Khan and Bohra (1990) found the average pan coefficient (reservoir to pan ratio) value of 0.67 for estimating reservoir evaporation in the region of west Rajasthan.

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