International Conference "Water, Environment, Energy and Society" (WEES–2009)
New Delhi, 12–16 January 2009

A Review of Indian Rainfall

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ABSTRACT: This paper summarizes a number of studies on Indian rainfall from an applied perspective. The aim is to provide rainfall statistics which can be of use in design and construction of a wide range of water resources development projects in the country.

INTRODUCTION

India, with a land area of 3.29 million km^2, is the 7th largest country in the world. The population, which in 1951 was around 361 million, has increased to 1028 million at the dawn of the 21st century. With this rapid growth of population, the need for the development and management of water resources has taken on added importance. The availability of water in India depends largely on rainfall brought by the southwest and northeast monsoons. The study of water resources of India is closely linked with the distribution of rainfall. Comprehensive research studies on rainfall climatology have been carried out by numerous investigators. The aim of some of these studies has been to produce rainfall statistics for use in design and construction of a wide range of water resources projects in the country. The studies encompass the assessment of rainwater resources over different regions of India, the frequency analysis of point rainfall, the climatology of severe rainstorms, design storm rainfall including Probable Maximum Precipitation (PMP) estimates, analysis of floods and droughts, and rainfall trends. A brief summary of the results of some of the important studies in these areas is provided here.

HISTORY OF RAINFALL MEASUREMENT IN INDIA

A study of water resources rightly commences with rainfall measurement. Rainfall measurement in India began towards the 18th century, when the first rainfall station was set up in 1784 at Calcutta by the East India Company. From 1785 to 1840 rainfall stations were established at Madras in 1792, at Bombay (Mumbai) in 1823 and at Shimla in 1840. Thereafter more rainfall gauges were installed at about 50 stations in different provinces of the country. With the establishment of the India Meteorological Department (IMD) in 1875 by the then government of India, the rainfall station network grew rapidly. At the time of independence in 1947, there were around 2750 rainfall stations (Ahuja, 1960). The need for increasing the rainfall station network in support of agriculture and water resources development work was felt after 1947 and as a result more rainfall stations were set up throughout the country. Presently, there are some 5000 rainfall stations whose data are processed and archived by IMD. In addition to these there are about 4050 rainfall stations that are being maintained by the railways, forest, agriculture and irrigation departments. There are also about 600 self-recording rainfall stations which provide records of rainfall intensity variations. The rainfall data are available with the National Data Centre, IMD, Pune. Apparently, the rainfall records in India are excellent by world standards.

ASSESSMENT OF RAINWATER RESOURCES OF INDIA

Rainfall (also called precipitation) is the quantity of water available naturally. Therefore, a proper assessment of rainfall for various regions and river basins gives their rainwater potential. India is divided into 28 states and 6 union territories (Figure 1). The distribution of rainfall over these regions is dependent on the southwest (June–September) and northeast (October–December) monsoons, on cyclonic disturbances, and on thunderstorms. Mean seasonal and annual rainfall, together with the coefficient of variability of annual rainfall for these 28 states as well as for the country as a whole, are given in Table 1 (IMD, 1962). The rainfall in India varies widely from one state to another. Among the 28 states of the country, the highest average annual rainfall is 300 cm in Kerala and the lowest annual rainfall is 55 cm in Haryana. According to Table 1, 7 states have the mean annual rainfall values between 50 and 100 cm, 9 between 100 and 150 cm, 2 between 150 and 200 cm and 10 have over 200 cm. About 10% of India has an annual rainfall greater than 200 cm while about 40% has less than 100 cm. These proportions play an important part in the relative water availability status of the 28 states. Table 1 shows that about 75–85% of the total annual rain over moşt parts of India falls during the south-west monsoon period between June and September.

In the winter season (October–December), a high atmospheric pressure zone hovers over Mangolia and Siberia. Under its influence, the general flow of winds is from the northeast. These winds being of continental origin are therefore dry. During their passage over the Bay of Bengal, these winds pick up moisture and cause rains over Tamil Nadu, Andhra Pradesh, Karnataka and Kerala.

Table 1: Average Annual Rainfall Over Different States of India

Sr No	*States of India*	*Area (km^2)*	*Av. Annual Rainfall (cm)*	*CV (%)*	*Rainfall during SW Monsoon (cm)*	*Monsoon Rainfall as % of Annual*
1.	Andhra Pradesh	275069	88	20	55	63
2.	Arunachal Pradesh	83743	228	11	150	67
3.	Assam	78438	252	11	165	65
4.	Bihar	94163	134	13	113	82
5.	Chattisgarh	136034	135	16	119	88
6.	Goa	3702	254	20	239	94
7.	Gujarat	196024	83	30	79	95
8.	Haryana	44212	55	28	46	84
9.	Himachal Pradesh	55673	175	21	135	77
10.	Jammu&Kashmir	222236	100	22	47	47
11.	Jharkand	79714	119	16	102	86
12.	Karnataka	191791	136	18	99	73
13.	Kerala	38863	300	14	200	68
14.	Madhya Pradesh	308144	122	20	108	89
15.	Maharashtra	307713	132	21	116	88
16.	Manipur	22327	252	11	165	65
17.	Meghalaya	22429	283	11	181	64
18.	Mizoram	21081	283	11	181	64
19.	Nagaland	16579	283	11	181	64
20.	Orissa	155707	149	14	113	76
21.	Punjab	50362	63	34	50	80
22.	Rajasthan	342239	59	31	54	92
23.	Sikkim	7096	274	12	192	70
24.	Tamil Nadu	130058	101	14	33	33
25.	Tripura	10491	252	11	165	65
26.	Uttaranchal	53483	103	19	88	86
27.	Uttar Pradesh	238566	99	20	86	87
28.	West Bengal	88752	165	15	125	76
–	India	3290000	117	10	89	76

Fig. 1: Different States of India

RELIABILITY OF INDIAN RAINFALL

The Coefficient of Variability (CV) of the annual rainwater for each of the 28 states is given in Table 1. It is a statistical measure of the reliability of rainfall. CV is a ratio of the standard deviation of yearly rainfall to average annual rainfall. A CV value of 25% tells us that in about 68 years out of every 100, the rainfall in the region will range from an excess of 25% over the mean annual rainfall to a deficiency of 25% (or plus or minus 25% of the region's mean annual rainfall). The deviation will be over 25% in the rest of the 32 years—a deficit of over 25% in about 16 years and an excess of over 25% in another 16 years. For instance, in Uttar Pradesh where annual average rainfall is around 99 cm and CV is 20%, it will be observed that in about 68 years out of 100 years, the annual rainfall will be between 79 cm and 119 cm. In the 16 years, the annual rainfall may be reduced to less than 79 cm while in another 16 years it may exceed 119 cm.

WATER RESOURCES OF INDIA

Rainfall is the major contributing factor to India's water resources. The average annual rainfall over the country is about 117 cm (Table 1) which yields about 4000 km^3 of water. This is almost one and half times larger than the world average of 80 cm/year. Of this about 1400 km^3 of water is lost through evaporation and 720 km^3 of water goes into the soil. After deduction for evaporation and infiltration, the average surface runoff in the river systems of the country is estimated at 1880 km^3 (Rao, 1975). The ground water recharge from rainfall in India made by the Central Ground Water Board, New Delhi, is about 432 km^3.The surface water of about 1880 km^3 flows in different river basins of the country. These river basins are the principal sources of water for about 1028 million people in India. The water availability per person stands at 1818 m^3/year which is about 1/12 of the world average of 21800 m^3/year per person. The per capita water availability has been steadily diminishing in proportion to the growth of the population. It is estimated that the population of India would be around 1.5 to 1.8 billion in 2050. The per capita availability of water will then be around 1200 m^3/year. Therefore, India's water resources cannot be considered abundant, consequently effective water management in India is of greater urgency than in most of the other countries.

MAJOR RIVER BASINS OF INDIA

India has 14 major river basins (Figure 6). The Indus River, the Ganga River and the Brahmaputra River are the important Himalayan Rivers in the northern part of India. These rivers are both snow fed and rain fed and therefore have continuous flow throughout the year. The Ganga River and its tributaries spread out like a fan on the plain of India, forming the largest river basin with an area equal to one quarter of the total area of India. The highest water levels and strongest flows in these rivers occur in the summer monsoon season. The Ganga River basin is a very fertile and densely populated region of India.

The main rivers in central and southern India are the Mahanadi, the Subarnarekha, the Tapi, the Narmada, the Godavari, the Krishna, the Mahi, the Sabarmati, the Cauvery and the Pennar. These rivers are entirely rain fed with the result that many of them shrink into rivulets during the hot season.

Floods are caused by extraordinary meteorological situations that produce heavy to very heavy rainfall on a drainage area. The meteorological causes of heavy rainfall in India are briefly discussed.

METEOROLOGICAL CAUSES OF HEAVY RAINFALL

The principle causes of heavy to very heavy rainfall in India are:

- formation and movement of cyclonic disturbances across the country
- orographic lift of monsoonal winds as they rise along the slope of a mountain barrier
- brakes in the monsoon and
- thunderstorms.

The cyclonic disturbances are intense low pressure systems in which the associated wind blows counter-clockwise in the northern hemisphere. Maximum sustained wind speeds are used to classify cyclonic storms in terms of their intensities in the following way: low pressure, winds less than 17 knots (9 m/s); tropical depression, winds 17–33 knots (9–17 m/s); tropical storm, winds 34–47 knots (18–24 m/station); severe tropical storm, winds 48–63 knots (25–32 m/s); cyclone (hurricane, typhoon) winds 64 knots (33 m/s) and above. The average annual frequency of cyclonic disturbances in the monsoon season (June–September) and post monsoon season (October–December) is 7 and 3, respectively. These cyclonic disturbances are known to generate widespread and heavy rainfall.

Normally, during the monsoon season the cyclonic disturbances (mainly depressions from the Bay of Bengal and the Arabian Sea) move across the country and produce heavy rainfall. The rainfall area may be 400 km wide and 1000 km long and 1 day point rainfall at a station may range from 40–80 cm. When disturbances from the Arabian Sea cross the Gujarat coast and move in a northerly or northeasterly direction, north Gujarat and southern Rajasthan receive heavy rains. When a depression from the Bay of Bengal moves, a belt of heavy rainfall spreads over the eastern part of the Uttar Pradesh. With further movement of the depression, the area receiving rain extends to Orissa and its adjoining areas. By the time the depression moves over central India it is weakened due to the depletion of moisture supply. Sometimes the depression after reaching central India intensifies due to the fresh feed of moisture from the Arabian Sea. This causes another spell of heavy rains over central and southern parts of India. Towards the end of monsoon, some depressions after reaching central India curve northwards causing heavy rains both in the plains and hills of northern India.

Rainfall during the monsoon season is not continuous but it alternates with active and break monsoon conditions. During the break, the monsoon trough shifts northward from its normal position and heavy rainfall occurs over the foothills of the Himalayas resulting in severe floods in the Himalayan Rivers.

During the post monsoon months of October–November more severe cyclonic storms form in the south Bay of Bengal in the latitude belt of 10°–15° N. These storms move inland and produce heavy rainfall in the southern states of India.

HIGHEST OBSERVED 1, 2, 3 DAY POINT RAINFALLS

We have discussed the various meteorological systems responsible for heavy rains. We now provide the values of the highest rainfalls that have occurred at different rainfall stations. The magnitudes of the highest rainfall values of various durations at a site have been of value to professionals concerned with the engineering designs of a wide range of structures from urban water drainage systems to dams and spillways. This information is also useful to people curious about the magnitudes of unusual or rare natural phenomena. In view of the importance of the highest rainfall values in many types of engineering design, several investigators have studied the historical records of rainfall to see the magnitudes of highest rainfall that had occurred at different stations in India. Reference should be made to the studies of Iyer and Zafar (1938), Parthasarthy (1959), Rao (1959), Saseendran *et al.* (1983) and Rakhecha *et al.* (1990a). For the first time Rakhecha and Pisharoty (1996), using the daily rainfall data of about 300 stations from 1875–1982, provided generalized maps of the highest point rainfalls for durations of 1 to 3 days. These maps are useful for obtaining information of highest rainfalls of 1 to 3 days durations in any part of the country. The study improved on previous studies by using a longer period of rainfall records. These data for storm periods of 1 to 3 days for some coastal as also for some high and low level stations are given in Table 2 and for 1 day plotted in Figure 2.

Table 2: Highest Recorded Point Rainfalls (cm) for 1, 2 and 3 Day Durations (1875 to 1982)

Stations	*State*	*Height (m)*	*1 Day*	*2 Day*	*3 Day*	*Date*
Mawsynram	Meghalaya	1401	99	143	201	July, 1952
Cherrapunji	Meghalaya	1313	104	165	224	June, 1876
Bhagamandala	Karnataka	876	84	136	136	July, 1924
Ponnampet	Karnataka	857	52	61	67	July, 1965
Agumbe	Karnataka	659	62	93	95	July, 1963
Satna	Madhya Pradesh	549	54	58	61	June, 1882
Khandala	Maharashtra	539	52	67	73	July, 1958
Bassi	Rajasthan	351	56	84	85	July, 1981
Rewa	Madhya Pradesh	286	77	77	82	June, 1882
Dhampur	Uttar Pradesh	258	77	99	99	Sept., 1880
Bamanwas	Rajasthan	252	51	76	103	July, 1981
Nagina	Uttar Pradesh	250	82	104	104	Sept., 1880
Najibabad	Uttar Pradesh	240	72	98	98	Sept., 1880
Karjat	Maharashtra	107	61	67	73	July, 1958
Dharampur	Gujarat	38	99	126	145	July, 1941
Gopalpur	Orissa	17	51	65	70	Oct., 1954
Porbandar	Gujarat	12	51	62	66	Sept., 1977
Cuddalore	Tamil Nadu	12	57	82	95	May, 1943
Mumbai	Maharashtra	11	57	80	88	July, 1974
Vengurla	Maharashtra	9	53	82	88	June, 1958
Kakinada	Andhra Pradesh	8	50	53	57	June, 1941
Quilandi	Kerala	8	91	109	113	May, 1961

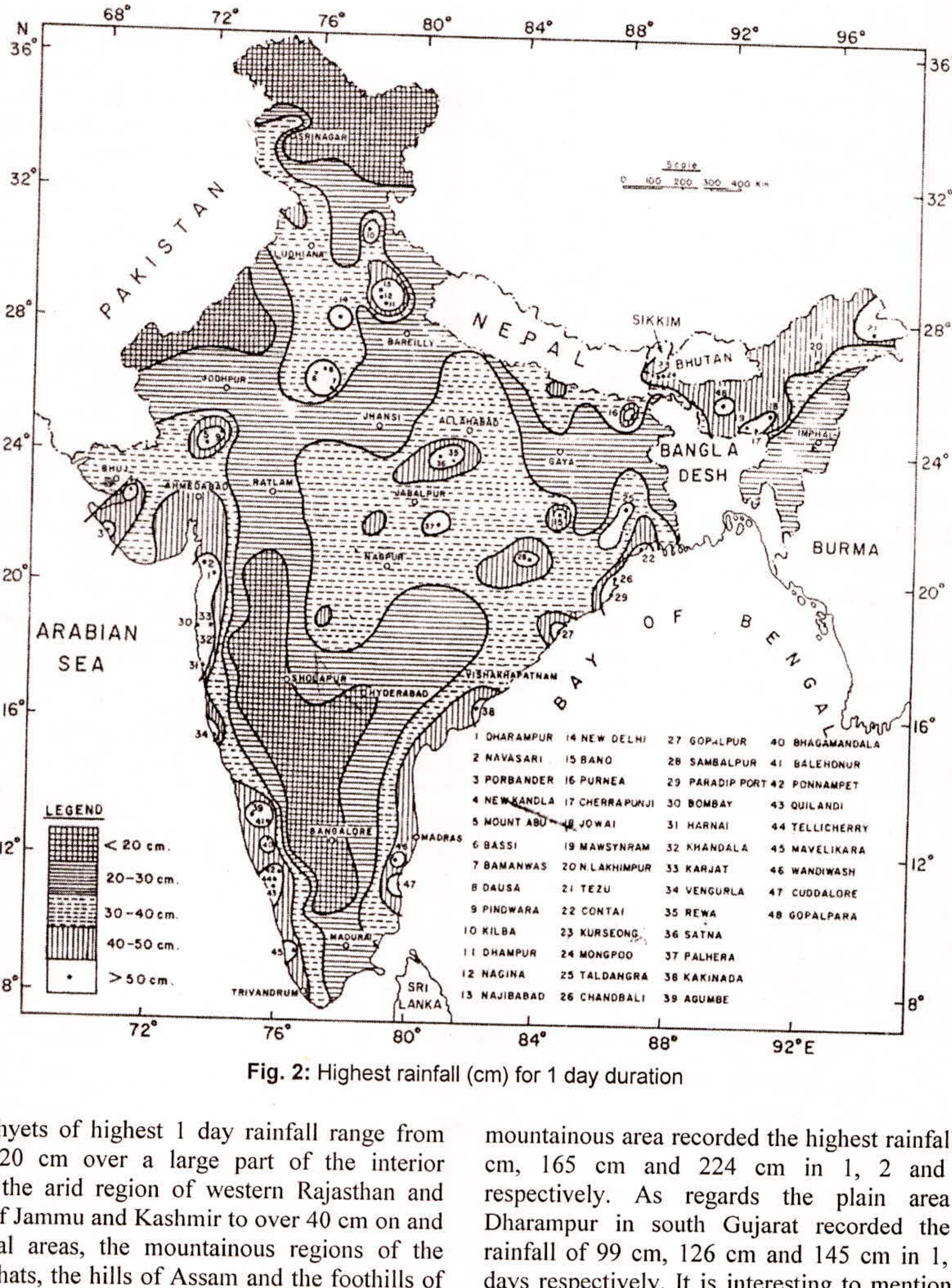

Fig. 2: Highest rainfall (cm) for 1 day duration

The isohyets of highest 1 day rainfall range from less than 20 cm over a large part of the interior peninsula, the arid region of western Rajasthan and northeast of Jammu and Kashmir to over 40 cm on and near coastal areas, the mountainous regions of the Western Ghats, the hills of Assam and the foothills of the Himalayas. Heavy rainfall exceeding 30 cm in a 1 day has also occurred over central parts of India lying between 19°–25° N and 70°–84° E. Some places on or near the coast, for example, Mumbai, Cuddalore, Kakinada and Gopalpur and some places in hills such as Agumbe, Khandala, Cherrapunji, and Mawsynram, have recorded 60 to 100 cm in 1day. Cherrapunji in the mountainous area recorded the highest rainfalls of 104 cm, 165 cm and 224 cm in 1, 2 and 3 days respectively. As regards the plain area station Dharampur in south Gujarat recorded the highest rainfall of 99 cm, 126 cm and 145 cm in 1, 2 and 3 days respectively. It is interesting to mention that the magnitude of the largest measured rainfall at Mumbai increased from 57 cm in July 1974 to 94 cm in 26 July 2005. Predominant factors in the locations of highest measured rainfalls in India appeared to be tropical storms impacted regions and windward facing upland areas that form the orographic barriers to the moist air masses.

FREQUENCY ANALYSIS OF MAXIMUM RAINFALLS

Instead of knowing what the highest rainfall for a particular duration is, engineers prefer to have the maximum amount of rainfall for different durations that may be expected to occur once in about 5 to 100 years return periods. An annual maximum rainfall has a return period of T years if its magnitude is equaled or exceeded once, on average, every T years. The theory of extreme values has been successfully used to determine the values of maximum rainfalls for different return periods from analyzing the series of maximum annual rainfalls. The return period analysis of the series of maximum 1 day rainfall of many stations in different parts of India having long period rainfall data has been made by several workers. References should be made to the work of Krishnan *et al.* (1959), and Rakhecha (1993). An analysis of the annual maximum 1 day rainfall has led to the development of generalized estimates of 1 day maximum rainfalls for return periods of 2 to 100 years. Figures 3 (a–c) show 10 years, 50 years and 100 years 1 day maximum rainfalls. These maps can serve to obtain the practical maximum rainfall values of 1 day which are expected to occur once in 10, 50 and 100 years.

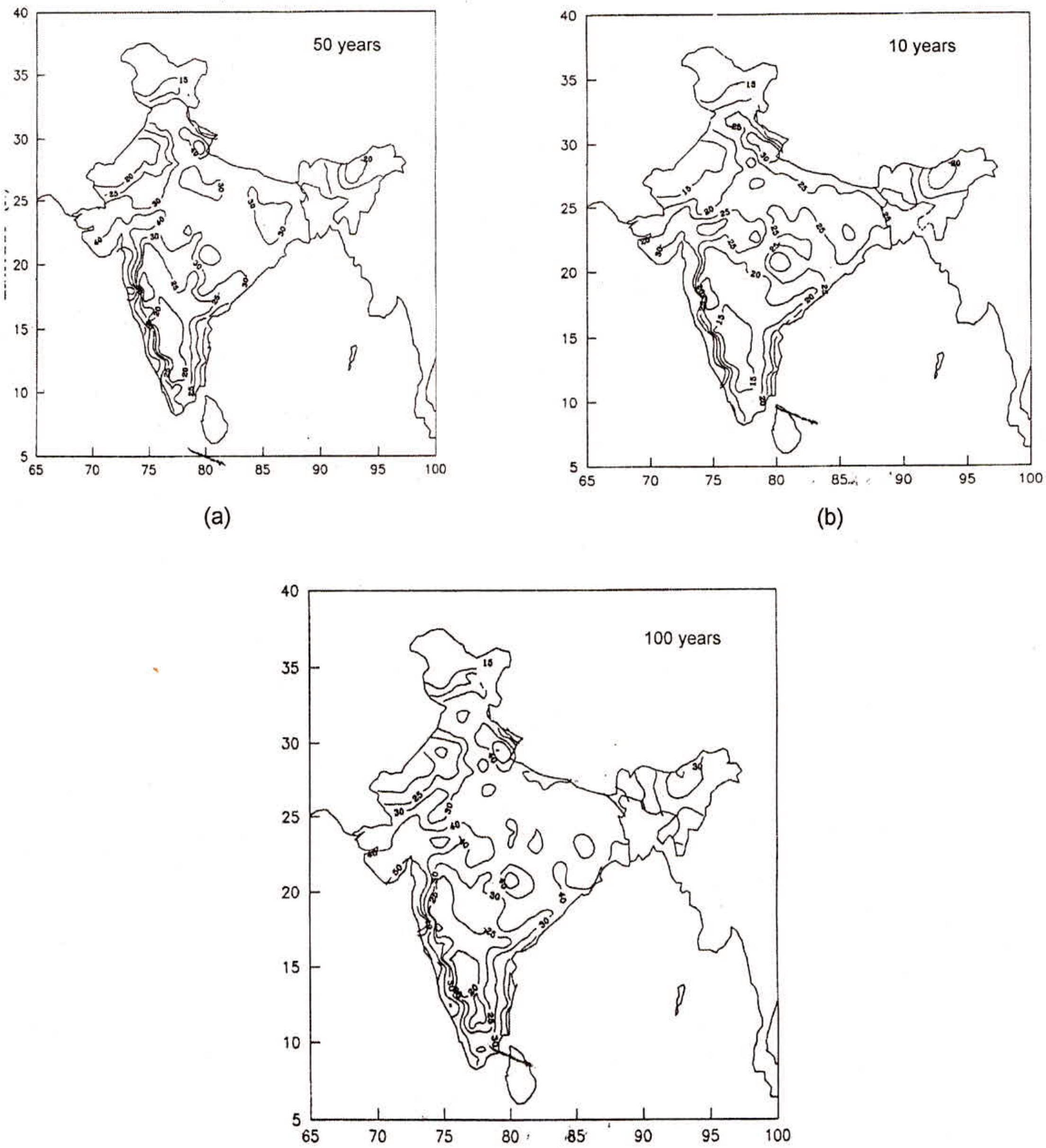

Fig. 3: Generalized maps of 10 years, 50 years and 100 years 1 day rainfall (cm)

SEVERE RAINSTORM

India is frequently and severely hit by cyclonic disturbances which include monsoon depressions and tropical storms from the Bay of Bengal and the Arabian Sea and produce heavy and widespread rainfall for a number of days resulting in severe rainstorms. The rainstorm area can be as large as 400,000 km^2 and point rainfalls range between 40 cm and 80 cm per day. These rainstorms are responsible for causing destructive floods, landslides, levee breaches, dam overtopping, and other such occurrences. Some of the most severe rainstorms have even destroyed dams causing enormous loss of life and property damage. For example, the most well known recent dam failure in India is the Machhu-2 dam in the state of Gujarat which failed owing to an extreme flood resulting from the severe rainstorm of August, 1979 over the Machhu river catchment (Rakhecha and Mandal, 1983).

It is evident from the above that severe rainstorms cause floods. As such information about the largest areal rainfalls for various durations from severe rainstorms is needed for assessing the flood potentialities of a region. Also such high magnitude areal rainfall values are useful for determining design storms and the PMP for the spillways of the large water supply dams. The form of information required is the depth of rain which falls during different durations of time and over specified areas. That is, rainfall should be expressed in terms of Depth-Area-Duration (DAD).

Recognizing the great practical utility of DAD values in hydraulic designs, several investigators notably from the India Meteorological Department (IMD), the Indian Institute of Tropical Meteorology (IITM), the Central Water Commission (CWC), and the National Institute of Hydrology (NIH) have carried out DAD analysis of numerous rainstorms that have occurred over different parts of the country. The results of several research studies concerned with DAD analysis of severe rainstorms in India have been published in the proceedings of workshops on "unusual storm events and their relevance to dam safety by CBIP (1993). More recently, investigations of the most severe rainstorms with maximum point rainfall near or over 40 cm a day, Rakhecha *et al.* (1992, 1993) and IITM (1994) have found that in the daily rainfall records of stations in India 12 rainstorms predominate which produced the extreme point and areal rainfalls.

The DAD values of these highest rainstorms for periods of 1 to 3 days and areas of 10 to 20,000 km^2 as calculated by the IITM (1994) are shown in Table 3

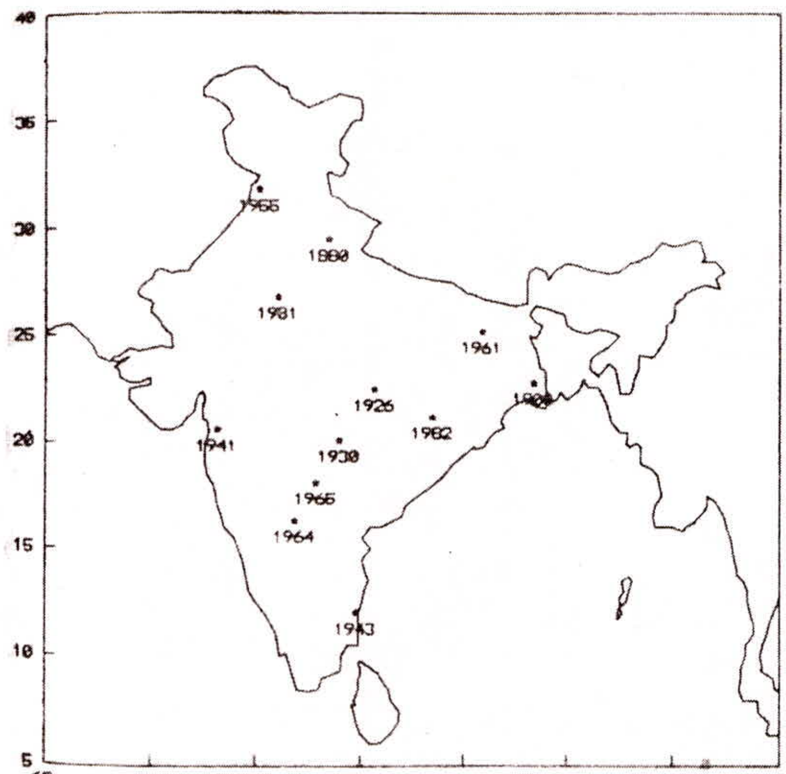

Fig. 4: Centers of Storms

Table 3: Depth-Area-Duration Values (cm) of Severe Rainstorms in India

No.	Rainstorm Date	Area Affected	Day	Area in 100 km²					
				0	1	10	50	100	200
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	West 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.	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
5.	1–3 July, 1941	Gujarat	1	99	97	85	65	54	43
			2	127	126	118	97	83	66
			3	145	143	134	117	105	86
6.	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
7.	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
8.	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
9.	28–30 Sept., 1964	Karnataka	1	24	23	23	22	21	19
			2	44	43	32	21	25	22
			3	62	61	51	38	34	30
10.	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
11.	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
12.	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

and their locations in Figure 4. For a 5000 km^2 area, the maximum rainfall from these storms varied from 22 to 65 cm for 1 day, from 21 to 97 cm for 2 days and from 38 to 117 cm for 3 days duration. Also as Table 3 shows that the 1–3 July, 1941 rainstorm produced the largest areal rain depths in Gujarat and stands out above all others for durations of 1, 2 and 3 days. The spatial pattern for this rainstorm for 1 day duration is shown in Figure 5. The rainstorm was caused by the depression from the Bay of Bengal during which a rainguage Dharampur station in Surat district recorded 99 cm of rainfall in 1 day ending at 0830 hours on

2 July. This is a record non-orographic rainfall caused by monsoon depression in India for 24 hours duration and has not yet been exceeded. It is also interesting to mention that the highest areal rainfalls of July, 1941 storm in India are greater than the corresponding highest areal rainfalls in the world (Rakhecha, 2003).

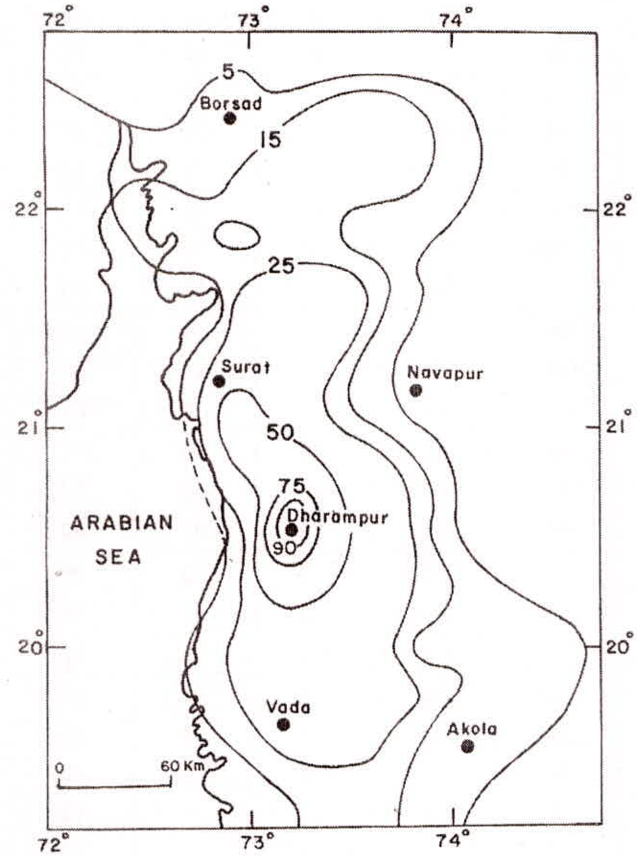

Fig. 5: Isohyets (cm) of 1 day (2 July, 1941) rainstorm

RELATIONSHIP OF POINT TO AREAL MEAN RAINFALL IN SEVERE RAINSTORMS

The maximum intensity of rainfall in severe storms occurs at a point at the center of the storm and outside this intensity gradually decreases. Horton (1924) observed that in many storms there was an exponential relationship of point rainfall to areal mean rainfall in the form of,

$$\bar{p} = p_m \, e^{-k.A^n} \qquad \ldots (1)$$

where $\bar{p}$ is the mean rainfall over an area A, p_m is the maximum point rainfall at the center of the storm, and k and n are coefficients determined from storm depth-area values. Raman and Chhabra (1966) studied the relationship of point to areal rainfall from depth–area data compiled for rainstorms of Bihar and Madhya Pradesh states and suggested the values of k and n as 0.0006 and 0.72, respectively. For Indian rainstorms, Dhar and Bhattacharya (1977) using severe rainstorm data of north Indian plains suggested the values of k as 0.0016, 0.0018 and 0.0030 and the values of n as 0.66, 0.63 and 0.57 for 1, 2 and 3 day storms, respectively. Rakhecha *et al.* (1998), using severe rainstorm data of Koyna catchment, found the values of k and n as 0.0054 and 0.5, respectively, for 1 day duration. The above relationship can be used to convert storm center rainfall into areal average rainfall, particularly over small size basins for drainage design works.

DESIGN STORM STUDIES

Design floods for water conservancy and hydroelectric power projects are calculated from the storm rainfall data in the catchment because rainfall data are available for larger areas and longer durations as compared to gauge and discharge data. The word storm rainfall in meteorology means the period of heavy rainfall. The basic assumption therefore used is the identity of the design storm or heavy rainfall information. A design storm of a river catchment is an estimate of the highest rainfall over the catchment which may serve in determining the design flood. Design storms in common use are the Probable Maximum Storm (PMS) or Probable Maximum Precipitation (PMP) and the Standard Project Storm (SPS). The PMP is the greatest depth of precipitation that is meteorologically possible for a given duration over a given area (WMO, 1986). The SPS is the most severe rainstorm which has actually occurred over the catchment during the period of available record. The PMP is used for design of high risk structures and where no such risk is involved and economic considerations are taken into account the SPS is used. Computation of PMP is a specialized science requiring considerable knowledge of hydrometeorology and will be dealt in a separate section.

As regards SPS, the two methods are mainly used for the estimation of SPS design storm rainfall. First is the Depth-Duration (DD) method in which the highest areal rainfalls for the whole catchment for various durations are determined from the heavy rainstorms that have occurred within the catchment. When in the catchment, there is a lack of records of heavy rainstorms which did happen in the adjacent area and is liable to occur in the catchment under study according to meteorological contributing factors, the storm records are transposed to the area under study. The second method is the frequency analysis of annual maximum areal rainfall series of the catchment.

Table 4: Design Storm Rainfalls by the DD Method

S. No.	Catchment up to Dam Site	Area (km^2)	Mean Annual Rainfall (cm)	Design Storm Rainfall (cm) 1 day	2 day	3 day	3 day Rainfall as % of Annual
1.	Koyna – Koyna dam	892	500	36	66	92	19
2.	Karanja – Halhali dam	2025	90	20	26	32	36
3.	Malaprabha – Malaprabha dam	2176	120	22	41	44	37
4.	Subarnarekha – Chandil dam	5664	145	17	26	32	22
5.	Krishna – Sangli dam	9842	136	15	22	27	20
6.	Ponnaiyar – Sathanur dam	10820	81	11	15	19	24
7.	Yamuna – Tajewala dam	11137	146	8	15	19	13
8.	Krishna – Narayanpur dam	12000	81	13	23	24	30
9.	Subarnarekha – Ghatsila dam	14162	145	16	21	25	17
10.	Beas – Pong dam	14504	147	11	20	25	17
11.	Bhima – Ujjani dam	14867	94	11	17	21	22
12.	Godavari – Gangapur dam	15540	75	11	17	21	28
13.	Betwa – Rajghat dam	16317	116	14	24	31	27
14.	Mahi – Kadana dam	25500	85	18	30	36	42
15.	Tungabhadra-Tungabhadra dam	27853	137	12	19	24	18
16.	Krishna – Almatti dam	35925	111	14	22	25	23
17.	Mahanadi – Tikkarpur dam	42476	145	15	27	35	24
18.	Tapi – Ukai dam	62224	79	12	23	26	33

Since 1950, the design storms have been estimated for several water projects in India to ensure the safety of projects (CBIP, 1993; Rakhecha *et al.*, 1990b, 1995, 1998). This section provides a summary of available information on design storm values for 18 dam sites for 1 to 3 day durations obtained by the DD method (Table 4). The work involved the collection and processing of large volumes of daily rainfalls for several stations in catchment areas.

Table 4 shows that the design storm rainfalls for the 18 river catchments in India range from 11 to 36 cm for 1 day, 17 to 66 cm for 2 day and 20 to 92 cm for 3 days. Further, it has been observed that 3 day design storm values are 13 to 42% of mean annual catchment rainfall. This shows that as large as 42% of the annual rainfall over a catchment can occur in the course of 3 days.

DROUGHTS IN INDIA

The rainfall in India is not only unevenly distributed spatially, but it also varies considerably from year to year. The uneven spatial and temporal distribution of rainfall has caused droughts and floods in India. Dhar *et al.* (1979) and Parthasarthy *et al.* (1987) have studied the large scale drought years experienced in India during the period 1871 to 1984 based on monsoon rainfall deficiency. Table 5 gives details of the large scale drought years. This table shows that there were 14 major droughts recorded in the period form 1871 to 1984 in which a large number of contiguous areas of the country experienced troublesome conditions. In India where the average monsoon rainfall is around 89 cm (Table 1), it has been observed that in major drought years the monsoon rainfall may be reduced to only 60 to 75 cm. The drought of 1918 was the most severe from the consideration of areal extent while from the rainfall deficiency point of view the drought of 1877 was the worst. It was found that there was no systematic time interval between any two successive drought years but on average one large scale drought year can occur about every 8 years. Also, it is seen from Table 5 that the average area of India which suffers from drought conditions during these 14 years of large scale drought is around 49%.

Table 5: Large Scale Droughts of India (Average monsoon rainfall 89 cm)

No	*Year*	*Mean Monsoon Rainfall in the Drought Year (cm)*	*% of Indian Area Under Drought (%)*	*Mean Monsoon Rainfall as % of Average Monsoon Rainfall*	*Time Interval Between Two Successive Droughts (yrs)*
1.	1877	60	49	67	–
2.	1899	63	70	71	22
3.	1901	72	38	80	2
4.	1905	72	47	80	4
5.	1911	74	40	83	6
6.	1918	65	73	73	7
7.	1920	72	55	80	2
8.	1941	73	42	82	21
9.	1951	74	56	83	10
10.	1965	71	54	79	14
11.	1966	74	48	83	1
12.	1972	65	41	73	6
13.	1974	75	36	84	2
14.	1979	71	36	79	5
	Mean	–	49	–	8

FLOODS IN INDIA

There are 14 major river systems in India (Figure 6). These rivers are subject to flooding in the rainy season when heavy and widespread rainfall occurs in their catchments areas. According to the available records about 210 severe floods with serious consequences have occurred in India during the period of 30 years from 1966 to 1985—almost 7 floods every year. Of these, some large floods overflowed the banks of the rivers and inundated a lot of land and human habitat. Some extreme floods have damaged levee systems and destroyed dams as mentioned earlier. The primary purpose of this section is to provide information on high magnitude floods that may serve as a guide in hydrologic design of projects in India.

The magnitude of a flood is measured by its either stage or its discharge rate. The stage is important in designing the extent of the area inundated and the minimum elevation of any structure built on the flood plain, as is the peak discharge in the design of spillways of dams. Systematic stages and discharges on several rivers at different sites in India are available since about 1950 as most of the gauging stations were established after Indian independence in 1947. Rakhecha (2002) provided information on the highest recorded floods at some sites in India's major river basins (See Table 6). The locations of these floods are shown in Figure 5. Table 6 shows that the highest floods recorded on rivers in India had peak discharges ranging from about 1170 m^3/s for a 133 km^2 area to about 72900 m^3/s for a 935000 km^2 area. The highest ever flood of 72900 m^3/s was recorded in the mighty Ganga River in 1954. The flood comparison studies showed that the recorded floods in India are comparable with the highest floods reported from other parts of the world for drainage areas larger than 1000 km^2. (See Figure 7).

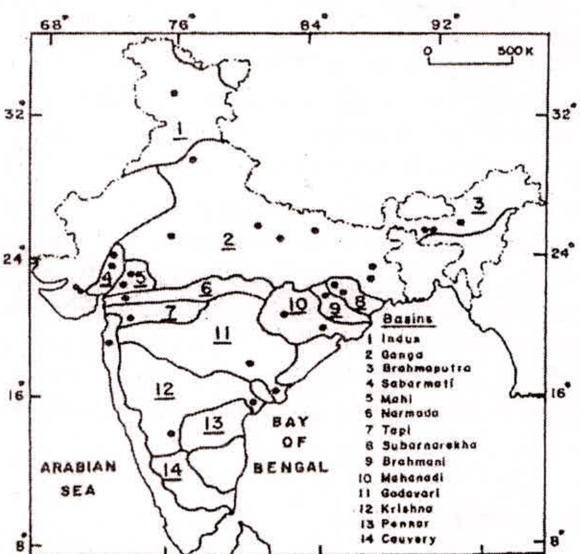

Fig. 6: Major river basins of India and locations of the highest floods in India

Table 6: Highest Floods in the Major River Basins of India

No.	*River Basin*	*Stream*	*Site*	*Area (km^2)*	*Flood m^3/s*	*Year*
1.	Bramhaputra	Gish	–	133	1170	July, 1968
2.	Mahi	Kharm	Patadungri	212	1177	–
3.	Subarnarekha	Ramiala	Ramiala	328	3108	Sept, 1983
4.	Kutch	Moj	Moj	440	3981	–
5.	Kutch	Brahmani	Brahmani	699	5450	–
6.	Kutch	Machhu	Machhu-1	735	9340	August, 1979
7.	Kutch	Damanganga	Damanganga	1813	12900	–
8.	Kutch	Machhu	Machhu-2	1930	16307	August, 1979
9.	Godavari	Kadam	Kadam	2590	13450	August, 1958
10.	Sabarmati	Banas	Dantiwada	2862	11950	August, 1973
11.	Mahi	Mahi	Chandargarh	4320	8160	June, 1977
12.	Sabarmati	Sabarmati	Dharoi	5540	14150	August, 1973
13.	Indus	Ravi	Madhopur	6087	26052	Sept, 1988
14.	Ganga	Yamuna	Tajewala	11059	15947	Sept, 1947
15.	Ganga	Tons	Meja Rd	17400	10800	July, 1971
16.	Brahmani	Brahmani	Bolani	18070	13570	August, 1974
17.	Mahanadi	Mahanadi	Kantamel	19600	15400	Sept, 1977
18.	Ganga	Damodar	Rhondia	19900	18100	August, 1935
19.	Ganga	Ganga	Rishikesh	21800	16000	August, 1924
20.	Ganga	Chambal	Jhalawar	22584	37000	August, 1968
21.	Mahi	Mahi	Kadana	25491	33000	–
22.	Godavari	Indravati	Barthagudem	40000	24860	August, 1976
23.	Ganga	Betwa	Sahijna	43870	43800	July, 1971
24.	Ganga	Kosi	Barakshetra	59052	23085	August, 1924
25.	Tapi	Tapi	Ukai	62225	42475	August, 1968
26.	Ganga	Sone	Kolewar	67878	36800	July, 1971
27.	Narmada	Narmada	Garudeshwar	88000	69400	Sept, 1970
28.	Mahanadi	Mahanadi	Naraj	127000	44827	August, 1982
29.	Krishna	Krishna	Vijayawada	257000	39000	July, 1903
30.	Godavari	Godavari	Dowlaishwaram	309000	78800	Sept, 1959
31.	Brahmaputra	Brahmaputra	Pandu	404000	72700	August, 1962
32.	Ganga	Ganga	Farrakka	935000	72900	August, 1954

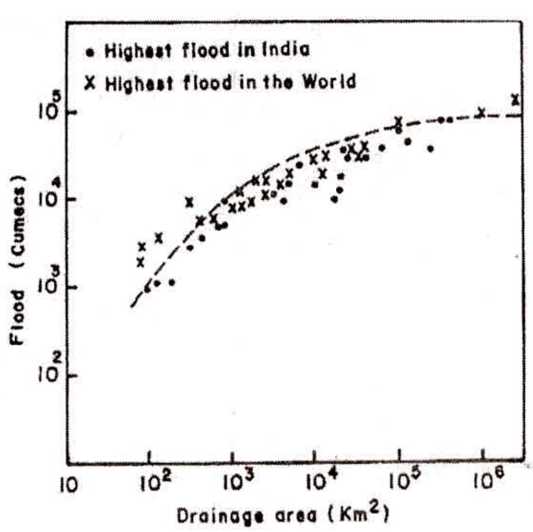

Fig. 7: Highest floods in India and in the world

ESTIMATION OF PMP OVER INDIA

A major problem of hydrometeorology is the estimation of Probable Maximum Precipitation (PMP) for different durations that are likely to occur over a point or an area. These estimates are required for calculating the Probable Maximum Flood (PMF) for spillways of large earth and rock-fill dams. The main objective of designing spillways using PMF is to provide maximum protection against their failure. PMP is defined as the greatest depth of precipitation for a given duration that is meteorologically possible over a given station or a specified area (WMO, 1986). There are two main methods for the estimation of PMP. The physical method and the statistical method. Many countries favor the physical method and therefore are discussed in detail.

The physical method involves storm data selection, storm transposition (i.e., the transfer of storms from where they have occurred to where they could occur), Depth-Area-Duration (DAD) analysis which yields a set of curves relating depth of rainfall to area for a given duration, and rainfall enhancement through Moisture Maximization Factor (MMF). MMF (R_m) is calculated as the ratio of the climatologically maximum precipitable water (W_m) to the precipitable water estimated for the storm concerned (W_s). These ratios typically fall in the range of 1.2 to 1.6. The product of R_m and the observed rainfall gives PMP. Details of the PMP estimation by the physical method can be found in WMO (1986). The PMP studies for many river catchments throughout India where dams are built have been carried by several workers (See for example Rakhecha *et al.*, 1990b, 1995, 1998; CBIP, 1993). The estimates of the PMP rainfalls for different durations using the physical method are given in Table 7.

Table 7: PMP (cm) for Different River Catchments in India

No.	*Catchment upto Respective Dam Sites*	*Area (km²)*	*1 Day*	*2 Day*	*3 Day*	*MMF*
1.	Koyna – Koyna dam	892	48	87	117	1.26
2.	Karanja – Halhalli dam	2025	35	41	43	1.10
3.	Malaprabha – Malprabha dam	2176	34	61	67	1.23
4.	Subarnarekha – Chandil	5664	51	73	75	1.30
5.	Ponnaiyar – Sathanur	10820	24	41	57	1.23
6.	Krishna – Narayanpur dam	12000	17	29	30	1.25
7.	Subarnarekha – Ghatsila dam	14162	38	57	60	1.30
8.	Tungabhadra – Tungabhadra dam	27853	15	23	30	1.25
9.	Krishna – Almatti dam	35925	18	27	31	1.23
10.	Tapi – Ukai dam	62224	15	28	32	1.37

Recently Rakhecha and Clark (1999) estimated PMP values for 1 day duration for different locations in India by maximization and transposition of the highest point rainfalls. Before doing this, the highest point rainfall values were scaled up using the depth-area relations. This was done for the reason that more of these rainstorms occurred when the density of rain gauges was low over the storm area and as such in reality the point rainfall could be higher. For this purpose, the line of best fit between the depth-area values of a storm was extended to an area of 10 km² excluding the highest point value. The depth of rainfall at an area of 10 km² was taken as being representative of the point value. The storm rainfall depth was then maximized by the factor of moisture. When a storm is transposed relevant factors are considered and adjustments made. Based on these PMP values a generalized map of 1 day PMP as shown in Figure 8 was produced. It was found that 1 day PMP over the Indian region varied from 70 cm to 170 cm. Recent extreme point rainfall events occurring in India brings out a confidence on 1 day estimates of PMP shown in this figure. For instance, the 1 day record breaking rainfall of 94 cm that occurred at Mumbai on 26 July 2005 was the second largest total in India. The highest was 99 cm on 22 July, 1941 at Dharampur. The 1 day PMP at Mumbai is 70 cm (IITM, 1989) which has clearly been broken by July 2005 storm. According to Figure 8 the PMP for Mumbai is 120 cm.

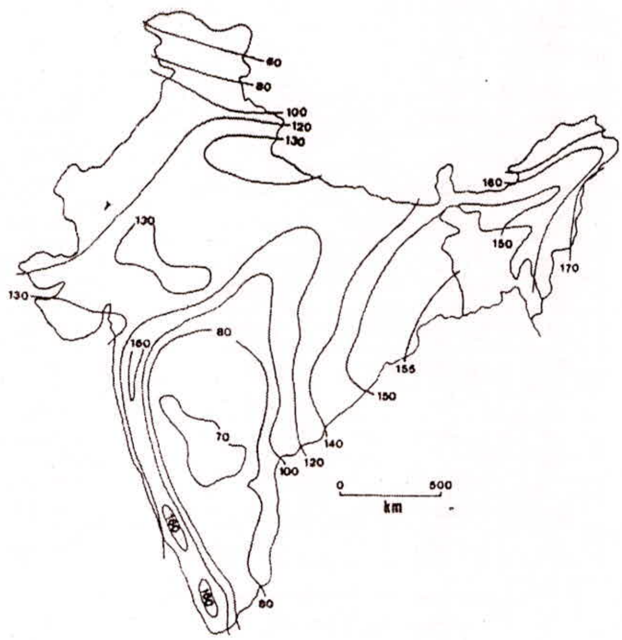

Fig. 8: 1 day PMP (cm.) for India

RAINFALL TRENDS IN INDIA

One of the important aspects of rainfall climatology in which the hydrologists are interested is rainfall trends and periodicities and their influence on future water resources. Several research studies relating to trends and periodicity in either the annual or seasonal rainfall for individual stations (Koteshwaram and Alvi, 1969; Jagannathan and Parthasarthy, 1973; Alvi and Koteshwaram, 1985) for different sub-divisions (Parthasarthy, 1984) as well for India as a whole (Moolay and Parthasarthy, 1984) have been made. These studies have not indicated any significant trends in the monsoon rainfall. But the fact is that the number of dry years remarkably increased in the decade 1965 to 1974 (see Table 5). Rakhecha and Soman (1994) have examined the changes in the occurrence of extreme rainfall. They used annual maximum rainfall series of 1 to 3 day duration from 316 widely spread stations in India over a 80 year period from 1901 to 1980. They found that annual extreme records of most stations are free from trends. However at locations on the west coast south of 12° N and some locations to the east of the Western Ghats over the central parts of the peninsula showed an upward trend in extreme rainfalls. However for southern India and the lower Ganga valley region, a decreasing trend of extreme rainfall was noted. The resulting map for 3 day duration is shown in Figure 9. The region of lower Ganga valley that falls under the direct part of the cyclonic disturbances from the Bay of Bengal is expected to receive heavy rainfall more or less in a consistent manner every year. The decrease in the incidence of heavy rainfall over the lower Ganga valley suggests a possible latitudinal shift in the frequency of cyclonic disturbances or changes in the intensity of rainfall producing systems. The increasing or decreasing trend in the extreme rainfalls at few places will have implications in the hydrologic studies and dam design projects.

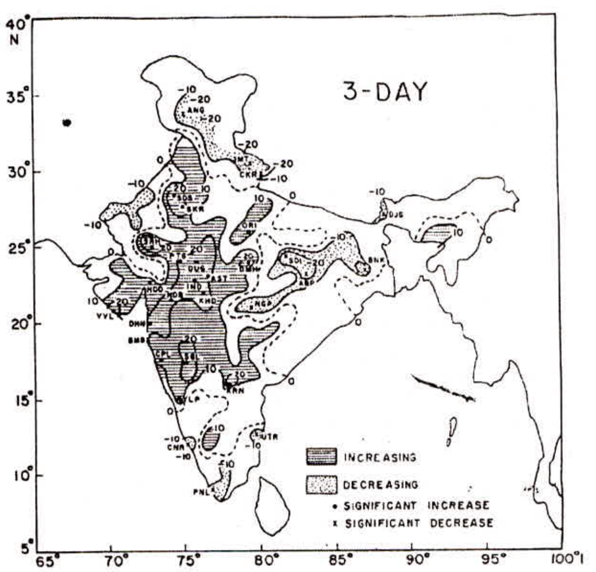

Fig. 9: Trends in the 3 Day Extreme rainfall

CONCLUDING REMARKS

The following conclusions are drawn from this review: (1) Water resources in India are not abundant but would meet the needs of her population, if managed effectively and efficiently. Stress on water resources would grow with increasing population and attendant consequences. (2) India has a long history of rainfall measurement and the measurements are extremely helpful to water managers and planners. These measurements should be archived and be easily accessible to public. (3) The rainfall over the country is highly variable from one part to another and its variability is going to grow with looming climate change/global warming. India's rainfall is monsoonal. (4) India experiences some of the world's highest 1, 2 and 3 day rainfalls which lead to extreme floods occurring only too frequently. (5) Droughts are a recurrent feature in India, with an average inter-arrival time of 7 to 8 years. (6) What is interesting is that floods and droughts follow each other in the same area, reflecting less than adequate water resources management.

ACKNOWLEDGMENTS

Authors gratefully acknowledge the help of Miss Pooja Rakhecha during data preparation and for typing the manuscript.

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