Hydrometeorological Studies for the Development of Water Resources in India

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***Abstract*-Hydrometeorology, like many other branches of meteorology, developed in response to pressing demands for information related to rainfall statistics for use in the safe and economical design of water resource projects.From analyses of rainfall data available at approximately 3000 stations in India, this paper provides:the availability of rain water resources in different states of India, information regarding the greatest rainfalls at different stations, the use of severe rainstorms to estimate design storms including the PMP rainfalls forcertainwater projects, and guidelines for the homogeneous meteorological zones for storm transposition.It has been established that developed countries require approximately1,000 m^3 of fresh water per capita per year; the water availability per person in India stands at approximately1,902 m^3/year, which is nearly twice the water needed by the people of developed countries. In this sense,water resources in India are of relatively high order.**

Keywords-Hydrometeorology; Monsoon; Rainstorm; Moisture Maximization; Climate Change

I. INTRODUCTION

India is the 7th largest country in the world and 2nd largest in Asia in terms of area (3,287,263 km^2). Its population has tripled over the past 70 years and water use has grown sixfold as the result of industrial development and increased irrigation.Due to the large population, the most pressing need in India is the management of its fresh water resources for various applicationssuch as agriculture,drinking water, industrial water, and hydropower while preserving the ecosystem. Rainfall is the major source of all fresh water in India; because most of the annual rainfalls during the four months of the southwest monsoon season (from June until September), dams and reservoirs rebuiltacross rivers to store fresh water runoff,to meet the water needs of the people throughout the year. There are some 3,650 dams in India withatotalwater storage of 252km^3, withnew dams under construction to further improve water supply in the country.

The planning and design of dams and other critical engineering works require reliable long period hydrological data of actual measurements of river discharges at a number of points along a river. This data for most of the Indian rivers isinadequate due to the limited number of surface gauging sites, and thusisof limited hydrologic value. As for water resources in India, the primary source is rainfall; fortunately records of daily rainfall beginning in1891 are available for over 3,000 rain gauges in the country. Meteorologists and hydrologists have recognized that in the absence of hydrological data, the meteorological data of rainfall and evaporation can best be used to assess and develop water resources by using the science of hydrometeorology, anintegral component in solving the problems of hydrology worldwide.This paper has been prepared with the following objectives:

1).To introduce the utilization of hydrometeorological data to estimate the water resources of the various states in India;

2). To discuss the application of effective hydrometeorological methods to evaluate design storm rainfalls and the PMP values,in order to design a range of water projects based on the relative climatology and areal rainfall from severe rainstorms;

3). To provide the results of important hydrometeorological studies carried out by various researchers in India for the benefit of the field engineers without easy access to scientific and technical journals.

II. CLIMATE OF INDIA

From north to south, the Indian climate shiftsfrom subtropical to tropical. Meteorologically, the year is divided into the four seasons for the country as a whole: cold weather period(January to February), hot weather period (March to May), southwest monsoon or rainy period (June to September) and northeast monsoon period(October to December).The cold season is characterized by low temperatures averaging approximately 10-15^{0}C in the north to approximately20-25^{0}C in the south. The month of March marks the beginning of hot weather and the temperature starts rising progressively from April through June, averageinapproximately30-40^{0}C. The southwest monsoon months constitute the major rainy season which brings water to the Indian landscape; most parts of the country receive 75-80% of their annual rainfall during this season. Hence, the distribution of monsoon rainfall in space and time is ofgreat importance, and any large abnormalities in the rainfall have significant adverse effects on the availability of water.Occasionally, monsoonal depression and tropical storms from the Bay of Bengal and the Arabian Sea travel across the country,bringing heavy and widespread rainfall and flooding the Indian rivers.The northeast monsoon period is comparatively dry,but serves as a major source of rainfall forthe states of Andhra Pradesh, Telangana and Tamil Nadu.

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A. MeteorologicalInstruments for Rainfall Measurement

The development of water resources requiresprecipitation measurements. Rainfall is the predominant form of precipitation in India and is responsible for causing stream flow in the majority of Indian rivers. It is therefore necessary to measure the amount of rainfall at a particular site, and determine its distribution at various sites in the river basin. A rain guage is the standard instrument used tomeasurerainfall as the vertical depth of water that would accumulate on a level surface. Two types of rain gauges are commonly used:the non-recording rain gauge and the recording rain gauge.

Although rain guagemeasurements provide an accurate depiction of the distribution of rainfall, especially when long term averages are necessary, they are spot measurements; rainfall amounts, particularly from a single storm, can have great spatial variation. Unless there is a dense network of rain gauges,such variations will not be identified. The lack of spatial coverage by rain gauges can be overcome by obtaining informationfrom the meteorological radar. Radar emits a pulse of energy which is reflected off any obstacle in the emission path, and then returned to the source. By measuring the time between emission and receipt, the distance between the obstacle and the source can be determined. By choosing an appropriate emission wavelength, raindrops can act asthe obstacles; in a sophisticated system, the direction and speed of motion of the raindrops can also be identified. The results can be translated into rainfall rates by calibration with conventional rain gauges. By using a full radar sweep, it is possible to determine rainfall over a wide area. Meteorological radars operate with wavelengths ranging from 3 to 10 cm, the most common valuesbeing 5 and 10 cm. 10 cm radar is used to observe details of heavy flood producing storms, while 5 cm radar is used for light rain and snow. Thus radar can be considered a remote sensing super gauge, covering an areal extent of up to 100,000 km^2. Radar measurement is continuous in time and space. Present-day developments in the field include: (i) online processing of radar data by computer and (ii) Doppler-type radars for measuring the velocity and distribution of raindrops.The India Meteorological Department (IMD)has a network of 18 Doppler weather radar stations.

The use of satellites for the transmission of hydrometeorological data has become important in water resource planning, particularlyfor remote and inaccessible areas. The advanced meteorological satellite INSAT-3D,with a6-channel imager and a 19-channel sounder,was recently launched, and its meteorological data is being received and processed by the IMD.

III. RIVER BASINS OF INDIA

India has 14 major river basins with catchment areas of 20,000 km^2 and larger(Fig. 2). There are 46 medium-sized river basins with catchment areas between 2,000 and 20,000 km^2.All major rivers and many medium-sized rivers cross state borders, and their water resources are shared among more than 1,210 million people.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 flow continuously throughout the year. 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 Cauveri, and the Pennar; these rivers are entirely rain fed, with the result that many of them shrink into rivulets during the hot season.There are numerous coastal rivers; these rivers, especially on the west coast, are short in length and have limited catchment areas.

IV. POPULATION AND WATER RESOURCES OF DIFFERENTSTATES OF INDIA

Adequate and dependable water availability is essential for human health, food production and economic development. India is a union of 29 states and 7 union territories. The source of all fresh water in the different states of India is rainfall brought by the southwest monsoon season between June and September. As such, it is important to know how much water from rainfall is received by each state of the country, and determine estimates of surface water and groundwater for utilization. Of practical necessity, rainfall is measured at about 5,480 stations in different Indian states[1].Table 1 demonstrates area average annual rainfallswith the coefficient of variability of annual rainfall for each of the 29 states, as well as for the country as a whole.Estimated from point rainfall values, Table 1demonstrates that the rainfall is unequally distributed among the 29 states of the country: eight states have mean annual rainfall values between 50 and 100 cm, ninestates fall between 100 and 150 cm, twostates receive between 150 and 200 cm, and ten states receiveover 200 cm of average annual rainfall. These proportions play an important part in the relative water availability statuses of the 29 states.The average annual rainfall over the country as a whole is approximately 117 cm; the coefficient variability (CV) is 10% and the 75% dependable rainfall is 105 cm. The total volume of water calculated from the product of the rainfall and the land area of India (3,287,263 km^2) is approximately 4,000 km^3. Of this, about 1,400 km^3 of water is lost through evaporation and transpiration and approximately730 km^3 of water is absorbed into the soil. After deduction for evapo-transpiration and infiltration, the average surface runoff in the river systems of the country is only 1,869 km^3[2]. The average annual amount of groundwater resource from rainfall has been assessed at approximately432 km^3[3].

Thus,the total water resources of the India are 2,301 km^3.Itis generally agreedthat developed countries require approximately 1,000m^3 of fresh water resources per capita per year, while the water availability in India stands atapproximately 1,902m^3/year. In this sense, water resources in India are relatively of higher order.

On the basis of rainfall and estimated runoff as given above, the rainfall-runoff ratio has been determinedto be approximately47% for the country as a whole. Average annual rainfall values are available for each state of India in Table 1. By assuming a rainfall-runoff ratio of 47%, estimates of annual runoff water available in each state of the country can be

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made.A summary of the population, the average annual rainfall, the average annual runoff, the average annual amount of groundwater and per capita annual water availability in each state of India are given in Table 1. Areas with water resources in the range of 1,000 to 1,500 m^3/year per capitabegin to experience water stress. Figures suggest that water is scarce in the four contiguous northern states of Haryana, Uttar Pradesh (UP), Bihar, and West Bengal because their per capita water availability is less than 1,000 m^3/year.Recently, researchers[4] have written a comprehensive book which coversthe water resources of India in sufficient detail for the benefit of hydrologists.

It is important to acknowledge that India's finite water resources, however, are under pressure from declining per capita water availability due to rapid population growth, urbanization, and industrialization. At the time of India's independence in 1947, the country's population was less than 400 million and water available per capita was over 5,500 m^3/year. Now, after 68 years of independence, India's population has increased to approximately1.2 billion[5] and per capita water availability has fallen to approximately 1,902 m^3/year. This per capita water availability will further fall to approximately1,500 m^3/year by the year 2025 due to increasing population, which will exert further pressure on water availability.This necessitates great changes to be made with a national perspective in this regard.

V. VARIABILITY OF RAINFALL

The coefficient of variability (CV) of the annual rainwater for each of the 29 states is given in Table 1. The CV values range from 11 to 34%. ACV value of 25% demonstrates that in approximately68 out of every 100 years, the rainfall in the region will range from an excess of 25% over the mean annual rainfall to a deficiency of 25%. The deviation will be greater than25% in the remaining32 years: a deficit greater than 25 % in approximately16 of those years, and an excess greater than 25% in the other 16 years. For instance, in Uttar Pradesh where annual average rainfall is approximately99 cm and CV is 20%, it will be observed that in approximately68 out of 100 years, the annual rainfall will be between 79 cm and 119 cm. In 16 years, the annual rainfall may be reduced to less than 79 cm while in another 16 years it may exceed 119 cm. The rainfall reliability will drop significantly as variability increases. There are many contributing factors that increase variability in rainfall. The methods by whichwatersheds are cleared and managed, as well asclimate change, already contribute to the variability of rainfall. This characteristic of variability must be considered when water resources engineers harness water.

TABLE 1LAND,POPULATION AND WATER RESOURCES OFDIFFERENTSTATES IN INDIA[1, 5]

Sr no.	State	Area (km^2)	People (million) (2011 census)	Annual rainfall (cm)	CV (%)	Vol. of water (km^3/yr)	Runoff (km^3/yr)	Ground water (km^3/yr)	Water resource(km^3/yr)	Per capita water (m^3/yr)
1	Andhra Pradesh	160229	49.4	88	20	141.0	66.3	5.3	71.6	1449
2	Arunachal Pradesh	83743	1.4	228	11	190.9	89.7	1.4	91.1	65071
3	Assam	78438	31.2	252	11	197.7	92.9	22.5	115.4	3699
4	Bihar	94161	103.8	134	13	126.2	59.3	27.0	86.3	831
5	Chattisgarh	136034	25.6	135	16	183.4	86.3	16.1	102.4	4000
6	Goa	3702	1.5	254	20	9.4	4.4	0.2	4.6	3066
7	Gujarat	196024	60.4	83	30	162.7	76.5	20.4	96.9	1604
8	Haryana	44212	25.4	55	28	24.3	11.4	11.2	22.6	890
9	Himachal Pradesh	55673	6.9	175	21	97.4	45.8	0.3	46.1	6681
10	Jammu & Kashmir	222236	12.6	100	22	222.2	104.4	4.4	108.8	8635
11	Jharkhand	79714	33.0	119	16	94.9	44.6	6.6	51.2	1551
12	Karnataka	191791	61.2	136	18	260.8	122.6	16.2	138.8	2268
13	Kerala	38863	33.4	300	14	116.6	54.8	7.9	62.7	1877
14	Madhya Pradesh	308144	72.6	122	20	375.9	176.7	34.8	211.5	2913
15	Maharashtra	307713	112.4	132	21	406.2	190.9	37.4	228.3	2031
16	Manipur	22327	2.7	252	11	56.3	26.5	3.2	29.7	11000
17	Meghalaya	22429	3.0	283	11	63.5	29.8	0.5	30.3	10100
18	Mizoram	21081	1.1	283	11	59.0	28.1	-	28.1	25545
19	Nagaland	16579	2.0	283	11	46.9	22.1	0.7	22.8	11400
20	Orissa	155707	42.0	149	14	232.0	109.1	20.1	129.2	3076
21	Punjab	50362	27.7	63	34	31.7	14.9	18.2	33.1	1195
22	Rajasthan	342239	68.6	59	31	201.9	94.9	12.6	107.5	1567
23	Sikkam	7096	0.6	274	12	19.5	9.2	-	9.2	15333
24	Tamil Nadu	130058	72.2	101	14	131.4	61.8	26.4	88.2	1222
25	Telangana	114840	35.3	93	20	106.8	50.2	3.8	54.0	1530
26	Tripura	10491	3.7	252	11	26.4	12.4	0.7	13.1	3540
27	Uttaranchal	53483	10.2	103	19	55.1	25.9	28.4	54.3	5324
28	Uttar Pradesh	238566	199.3	99	20	236.2	110.0	82.6	192.6	966
29	West Bengal	88752	91.4	165	15	146.5	68.9	23.1	92.0	1007

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	India	3287263	1210	117	10	4000	1869	432	2301	1902

VI. WATER CONSERVATION IN INDIA

Because most of the annual rainfall over different parts of India occurs during the southwest monsoon season from June until September, dams are built to store water for use throughout the year. Before India's independence in 1947, there were only 250 storage dams in the country with a total storage capacity of approximately 12 km^3 [6]. Conscious of the fact that development of water resources in the country has direct bearing on India's emergence as a modern and prosperous nation, governmental efforts placedgreat emphasis on the development of water resources.As a result, after gaining independence, a great number of dams for water storage have been built to meet the water needs of the growing population. Consequently, there has been a rise in the number of dams and by 1990, the number reached 3,650 [6] with a totalstorage capacity of 252 km^3. It is estimated that out of 1,869 $km^3$of surface water, only 690 km^3 or 37 % of the surface water can be stored because of limitations of the most technically attractive sites, climate and soil conditions [2]. If the present available storage of existing dams is taken into account, it appears that only 36% of the storage space is being utilized. Thus, there is great potential for increasing reservoir capacity for monsoon waters by constructing new dams. India proposes to continue with the program of dam construction to create another 200 km^3 of storage overthe next 25 years.

VII. GREATEST OBSERVED POINT RAINFALLS

The occurrence of noteworthy rainfallsofvarious durations at a site has long been of value for the engineering designs of a wide range of structures, from urban water drainage systems to dams and spillways. Several investigators have studied the historical records of rainfall to identifythe magnitudes of highest rainfall occurrences at different stations in India. For the first time beginning in 1891[7] using the daily rainfall data of approximately300 stations around the country provided generalized maps of the greatest point rainfalls for durations of 1 to 3days. This data for storm periods of 1 to 3 days for some high and low level stations are given in Table2.The spatial distribution for 3-day greatest rainfall is shown in Fig. 1,in the form of a generalized map. Greatest daily rainfall at most stations in India has ranged between 50 and 104 cm.

TABLE 2GREATEST RECORDED POINTRAINFALLS (CM) FOR 1, 2 AND 3-DAY DURATIONS (1875 TO 2005)[7]

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	MP	549	54	58	61	June1882
Khandala	Maharashtra	539	52	67	73	July 1958
Bassi	Rajasthan	351	56	84	85	July 1981
Rewa	MP	286	77	77	82	June 1882
Dhampur	UP	258	77	99	99	Sept. 1880
Bamanwas	Rajasthan	252	51	76	103	July 1981
Nagina	UP	250	82	104	104	Sept. 1880
Najibabad	UP	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	Maharashtr	11	94	-	-	July 2005
Vengurla	Maharashtra	9	53	82	88	June 1958
Kakinada	AP	8	50	53	57	June 1941
Quilandi	Kerala	8	91	109	113	May 1961

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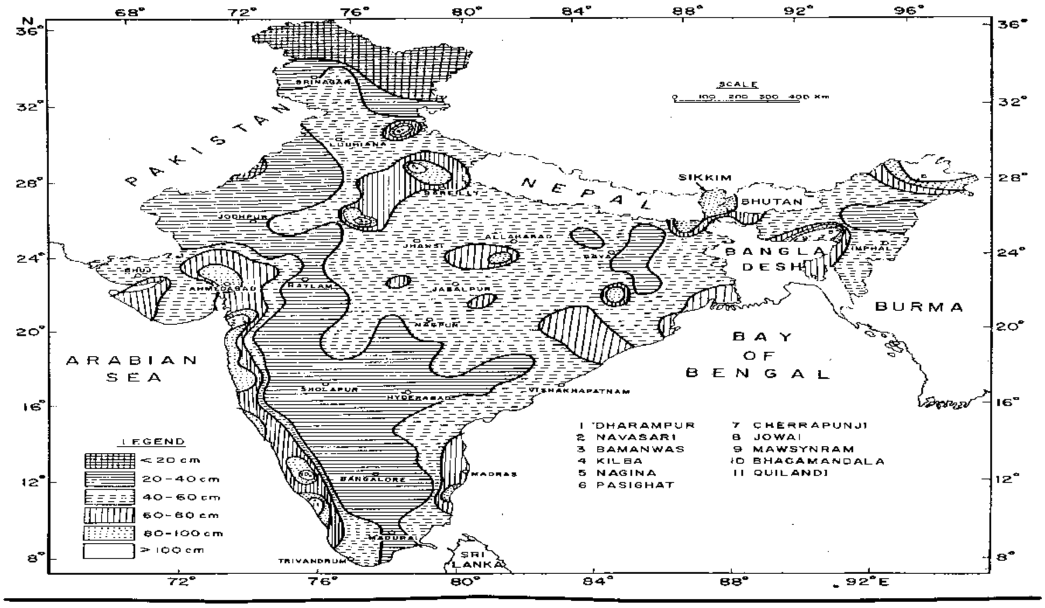

Fig. 1Greatest rainfall (cm) for 3 -day duration[7]

VIII. MAJOR RAINSTORMS FROM CYCLONIC DISTURBANCES IN INDIA

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, which produce heavy, widespread rainfall for a few days' duration and resulting in severe rainstorms as discussed in section II. 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 destructive floods, landslides, levee breaches, dam overtopping, and other such occurrences. Unfortunately, these storms are frequently more discussed for the economic losses and human suffering causedby the floods.However, the hydrometeorological analysis of severe rainstorms is highly importantfor estimating floods in the region of their occurrence. In the daily rainfall records of stations in India,12rainstorms predominate which produced the greatest rain depths over different parts of the Indian region [8-10]. The date these storms occurred are given in Table 3,and the main centers of these storms are shown in Fig.2. These 12 rainstorms occurred in two seasonal periods: the southwest monsoon period (June-September) and the northeast monsoon period (October).

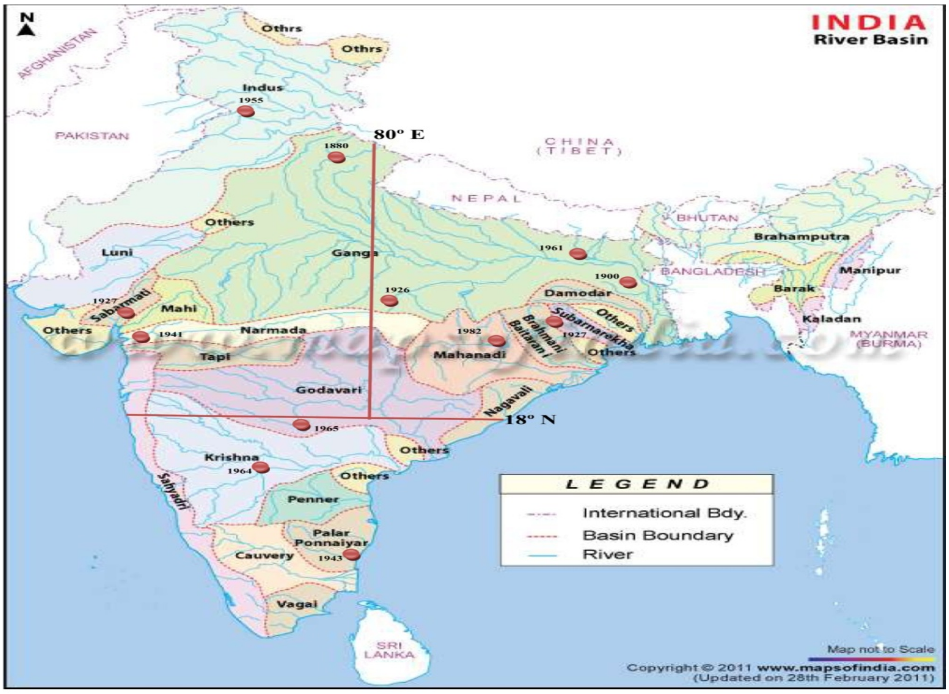

Fig.2River basins, locations of the 12 rainstorms and the three meteorological homogeneous zones [17,18]

To determine the flood potentiality of a rainstorm, it must be analysed in such a way that the results can be applied toflood estimation. The required information is the depth of rain which falls over different durations of time and over specified

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areas,expressed in terms of depth-area-duration (DAD). Thus a rainstorm has three hydrologic dimensions,withtheir relationships of vital importance to the assessment of the flood potentialities of a region as well as for the planning and design of flood defence structures. Based on the DAD method, the greatest average depth of rainfall that fell over various sizes of areas during 1, 2 and 3-day rainfalls from each of the 12 rainstorms are given in Table 3.

The rainstorm of 1-3 July, 1941 produced the largest areal rain depths in Gujarat, and stands out above all rainfall durations of 1, 2 and 3 days. The rainstorm was caused by adepression from the Bay of Bengal during which Dharampur station in the 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 duration of 24 hours, and has not yet been exceeded. It is also interesting to note that the highest areal rainfalls of the July 1941 storm in India are greater than the corresponding highest areal rainfalls in the world [11]. The data given in Table 3is quite useful to design engineers for obtaining the design storm estimates of river basins in which water projects are being planned.

TABLE 3DEPTH-AREA-DURATIONVALUES (CM) OF SEVERERAINSTORMS IN INDIA[8-10]

No.	Rainstorm date	Area affec	Day	Area in 100 km^2					
				0.1	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	MP	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

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IX. DERIVATION OF DESIGN STORMS IN INDIA

A design storm of a river catchment is defined as the estimate of the highest average depth of rainfall over the catchment in the design of dam spillways. The determination of a design storm therefore requires the availability of an adequate sample of rainstorms that have occurred within or near the catchment. The estimate of the highest average depth of rainfall is then obtained by the depth duration (DD) or by DAD analysis. Design storms in common use are the standard project storm (SPS) and the probable maximum storm (PMS) or probable maximum precipitation (PMP)[12]. The SPS represents the most severe rainstorm thathas actually occurred over the catchment during the period of available record. It is used in the design of all water projects where little risk is involved and economic considerations are taken into account.

The PMP represents the greatest depth of precipitation that is meteorologically possible for a given duration over a given area [12]. The PMP is used for the design of high risk structures.Two estimation methods are used to estimate PMP rainfall. The first is the hydrometeorological method, in which the PMP for different durations over an area is derived by moisture maximizing the highest areal rainfall depths of major rainstorms that have occurred over the area under study. The maximization consists of simply multiplying the highest rainfall values by the moisture maximization factor (MMF). The MMF is a ratio of the maximum moisture for the month and location of each storm to the moisture actually available in the storm. These ratios typically fall in arrange of 1.2 to 1.6. When the sample of severe rainstorms over the catchment is not adequate, the storm record is augmented by transposition of major storms from the meteorologically homogeneous area surrounding the catchment. Details of the PMP estimation by the hydrometeorologicalmethod can be found in previous research [12]. The second method to estimate PMP rainfall is the statistical method, in which the estimates of PMP are derived from the frequency analysis of the annual maximum areal rainfall series of the catchment. The IndiaMeteorological Department (IMD) began its design storm studies in 1950 to meet the needs of building a large number of water projects.The design storms have been estimated forseveral water projects in India [13-16] as shown in Table 4.

TABLE 4PMP RAINFALLS (CM) FOR DIFFERENT RIVER CATCHMENTS IN INDIA[13; 14; 15, 16]

No.	River catchment	Area (km^2)	Annual rainfall	1-day	2-day	3-day	MMF	Storm date
1	R. Koyana- Koyana dam	892	500	48	87	117	1.26	1912
2	R. Karanja- Halhali dam	2,025	90	35	41	43	1.10	1965
3	R. Malprabha- Malprabha dam	2,176	120	34	61	67	1.23	1914
4	R. Subarnarekha- Chandil dam	5,664	145	51	73	75	1.30	1982
5	R. Ponnaiyar- Sathanur dam	10,820	81	24	41	57	1.23	1943
6	R. Krishna- Narayanpur dam	12,000	81	17	29	30	1.25	1914
7	R. Subarnarekha- Ghatsila dam	14,162	145	38	57	60	1.30	1927
8	R. Mahi – Kadana dam	25,500	85	36	59	85	1.37	1927
9	R. Tungabhadra- Tungabhadra dam	27,853	137	15	23	30	1.25	1923
10	R. Krishna- Almatti dam	35,925	111	18	27	31	1.23	1914
11	R. Tapi- Ukai dam	62,224	79	15	28	32	1.37	1968

X. METEOROLOGICAL HOMOGENEOUS ZONES

There is a need to delineate meteorological homogeneous zones for storm transposition. Zones of meteorological homogeneity are defined as areas in which the occurrence probability of a storm of a given intensity is the same throughout; the heavy rainfall is therefore the same at all points in such an area.Apparently, the spatial distribution of the 12 severe rainstorms given in section VIII offer much promise in the determination ofbroad meteorologically homogeneous zones for storm transposition[17]. All of the 12 rainstorms were caused by Bay of Bengal depressions. It is known that the depressions which travel long distances over India are usually weakened due to the depletion of their moisture supply and merge with the seasonal low over northwest India. However, sometimes under typical conditions, the disturbances from the Bay of Bengal intensify after arriving in central India (about 80^0 E)due to the influx of fresh moisture from the Arabian Sea, and produce heavy rainfall over the region west of 80^0 E. For example,the rainstorms of September 1880, July 1941, July 1927 and October 1955,despite being generated from the Bay of Bengal, produced heavy rainfall and destructive floods far inside the country. This was mainly due to the influx of fresh moisture from the Arabian Sea monsoon currents. Such storms which produced extreme rainfalls after significant modification from the Arabian Sea currents must form a separate group, distinct from those storms which occurred without any modification. Considering the meteorological features of heavy rainfall as described above, three meteorological homogeneous zones are delineated[17,18]: (1) the zone east of 80^0 E and north of 18^0 N; (2) the zone west of 80^0 E and north of 18^0 N; and (3) the zone south of 18^0 N, as shown in Fig. 2. The maximum areal rain depths in the three zones vary widely. The rainstorms south of 18^0 N generally produce lower areal raindepths than thosein the north. Additionally,the maximum areal rainfall values from storms west of 80^0 E and north of 18^0 N are much higher in magnitude compared to the areal rainfall values from the storms east of 80^0 E and north of 18^0 N.

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XI. EVAPORATION

Many meteorological elements are important in hydrometeorology in addition to rainfall. Of particular importance are evaporation and transpiration, as approximately 35% of the annual rainfall over the Indian region is returned to the atmosphere by such processes. Evaporation data is therefore useful in water conservation studies and in estimating potentialevapo-transpiration for irrigation and plant growth studies. In India, where surface water storage is vital over large areas, evaporation is a highly significant element. Evaporation is determined by measuring the amount of water evaporated from a free water surface exposed in a pan. The evaporation at all the stations in India isdeterminedby the use ofaU.S. Weather Bureau Class A Pan Evaporimetercovered with mesh. The IMD [19]has published monthly and annual mean evaporation values for 30 stations in India. Evaporation from a free water surface depends on a number of meteorological elements,primarily temperature, humidity and wind. Evaporation formulas for the estimation of pan evaporation from meteorological data have been developed in India [20]. The rate of evaporation obtained from the Pan Evaporimeter is multiplied by a suitable pan coefficient so as to obtain the evaporation rate of the large water surface. Research[21] found an average pan coefficient (reservoir to pan ratio) of 0.67 for estimating reservoir evaporation in the region of Rajasthan.

XII. RAINFALL CONCERNS FROM CLIMATE CHANGE

There is a growing realization from a set of massive reports by the Intergovernmental Panel on Climate Change [22] that the world’s climate may be changing in response to human activities combined with land clearings and global warming arising from the increase in carbon dioxide and other greenhouse gases. Emissions of carbon dioxide grew twelvefold between 1900 and 2000, from 534 million metric tons per year in 1900 to 6.59 billion metric tons in 1997. In the same period, the human population has nearly quadrupled from 1.6 billion to 6.1 billion, progressively consuming greater quantities of fossil fuels. Expanded agriculture, the destruction of forests and increased production of certain chemicals also increase greenhouse gases in the atmosphere. The IPCC predicted that the greenhouse gases are likely to warm the atmosphere by 2^0C and cause a sea level rise of approximatelyone-halfmeter by 2100. This may result in an increased tropical sea surface temperature. Because tropical storms derive their heat input from warm tropical oceans, it is quite possible that an increase in the surface ocean temperature would lead to more frequent and intense tropical cyclones, typhoons and hurricanes. Global warming is also suspected to have contributed to more frequent extreme weather events like floods, heat waves, droughts, etc. Many aspects of climate change in India have been discussed in the proceedings of nationaland internationalconferences [23, 24].

The issue before the Meteorologists and Hydrologists was whether or not a warming climate poses a significant threat to rainfall; several studies relating to rainfall analysis over India showed no obvious trend of increase or decrease in rainfall over the country [25-27]. Also,analysis of the annual extreme rainfall series of 1 to 3days’ duration at 316 stations well distributed over the Indian region did not show any obvious trends in extreme rainfalls for a majority of the stations [28].

XIII. CONCLUSIONS

It is demonstrated the hydro-meteorological studies of Indian rainfall that there is enough fresh water from rainfall in India as a whole to support its growing population;remaining challenges are its availability, distribution and the distribution of India’s growing population. However, water scarcity is present in the states of Haryana, Uttar Pradesh, Bihar and West Bengal. Approximately 80-90% of freshwater in the form of rainover different parts of India occurs during the southwest monsoon months from June to September, and as such, water is stored in dams for supplying water throughout the year. India’s population is increasing, placing increasing demands on water for drinking, food production, sanitation and other basic social and economic needs, but India’s water resources are finite. Human population is incurring an ever-growing,disastrous impact on water resources through water depletion and pollution. For example, at the time of India’s independence in 1947, the country’s population was less than 400 million and available per capita water was over 5,500 m^3/year. Now, after nearly 70 years of independence, India’s population has increased to approximately 1.2billion and per capita water availability has fallen to approximately 1,902 m^3/year (see Table 1). While the amount of available freshwater resources remain constant, water demands continue to grow. In order to adequately manage India’s water resources in the coming years,more efforts to achieve proper management of water resources are needed so that water can be available to meet the requirements of stakeholders. The solution lies in the continued development of water resources by conservation through dams,including developing means fortransfer of water between states to meet the water demands of the growing population in states where water is scarce. The hydrometeorological informationwhich has been given in this paper will be beneficial to all those engaged in the planning and development of water resources of India.

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