

Research Article

Hydrometeorological Study of the Himalayan Region

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Abstract

The Himalayan mountain ranges uniquely placed to modulate the regional monsoon climate in the Indian subcontinent. Many studies over the last 30 years focused on investigating the large-scale modes of variability of the Indian monsoon climate with respect to the role of the Himalayan ranges and the Tibetan Plateau. On seasonal and inter-annual time-scales, the monsoon season in the Himalayas provides a stage where rapid environmental change and extreme events (viz. rainstorms, floods, landslides, etc.) occur on schedule. In view of this, the present study deals with the hydrometeorological studies of the three major sections of the Himalayas i.e. a) Northwest b) Central and c) Northeast Himalayas with special reference to 24-hr highest rainfall, rainstorms and floods occurred during the last 135 years or so besides mentioning meteorological situations responsible for causing such extreme events during monsoon as well as non-monsoon season.

Keywords: Himalayas; Variation of rainfall; Extreme one-day rainfall; Climate change

Introduction

While writing about the Himalayas one is reminded of the famous lines from Frank S. Symphie that legendary mountaineer and writer, who wrote in his book “Kamet Conquered” as follows :-

“The Himalayas must be approached humbly. Respect their beauty, their majesty and their power and they will treat you as you deserve. Approach them ignorantly or in a spirit of bravado and they will destroy you. Other mountains forgive mistakes but not the Himalayas!!”

The Himalayan mountain ranges exercise a very dominant influence on the climate of the Indian subcontinent and the Tibetan plateau extending from Nanga Parbat (8126m) in the northwest to Namche Barwa (7756m) in the east, in the form of a convex arc with its convexity to the south (Figure 1). As a result of its southerly dip, it is nearer to the equator by about 700kms in its eastern end. The total length of this mountain range is about 2400kms and its width varies from about 250 to 400kms. This loftiest mountain complex contains eleven of the fourteen world's peaks exceeding 8000m (Figure 1) and 31 peaks exceeding 7600m in elevation. There are series of narrow chains of high mountains with their crest-lines (falling between 5000m to 5500m) are transverse by a number of trans-Himalayan rivers and their tributaries which play an active role in eroding and shaping the high mountains, producing deep valleys and gorges. Physically the entire range is divided into three almost parallel sub-ranges.

Outer Himalayan ranges (or the Shivalik hills or foot-hills of the Himalayas): separate the Himalayas from the Indo-Gangetic plains to the south. Average height: ~900m to 1200m, width- between 1000m to 5000m.

Middle Himalayan ranges (also called as the Pir Panjal in NW India and Mahabharat range in Nepal): These are a series of broken mountain ranges. Mean elevation ranges between 3700m to 4500m a.s.l. and width of about 5000m.

The great Himalayan range: is the innermost line of the highest ranges of perpetual snow and ice. Average height varies from 6000m to 8800m a.s.l., which separates the Tibetan Plateau from the Indian sub-continent. The highest peaks are located in this range.

Himalayan Meteorology and its dominant role in controlling the weather and climate of the Indian sub-continent has been described by several workers in recent years [1-5]. The Himalayas are responsible for the formation of a heat low over Sind (Pakistan) and its neighbourhood and the seasonal monsoon trough over the Indo-Gangetic plains during the summer monsoon months from June to September [1,5]. The rugged topography enhances heavy to very heavy rainfall in the rivers originating in the Himalayas causing serious floods and destruction to human lives in the plains.

The role of the Himalayas and the Tibetan Plateau to its north for the generation and maintenance of the Asian summer monsoon was demonstrated by the numerical model studies [6] mentioning that if the ‘Himalayas’ is removed from its present position, Asian countries will have no weather like ‘southwest monsoon’. The Third Assessment Report of the Intergovernmental Panel on Climate Change [7] also pointed out the critical role of the Himalayas in the provision of water to continental monsoon Asia and clearly revealed its vulnerability to climate change in terms of hydrology and water resources.

In view of the above, an attempt has been made to study the hydro-climatic features of the Himalayan region in the Indian sub-continent dividing the entire Himalayan region into three suitable regions – a) Northwest (NW) (India), b) Central (Nepal) and c) Northeast (NE) (India, Bhutan).

Data Used

In the present study, daily rainfall data of 267 stations (Figure 2) homogeneously distributed in the NE Himalayan region of India and Bhutan are considered. It may be noted that in the extreme northern part of Bhutan, Kameng river basin in Arunachal Pradesh and

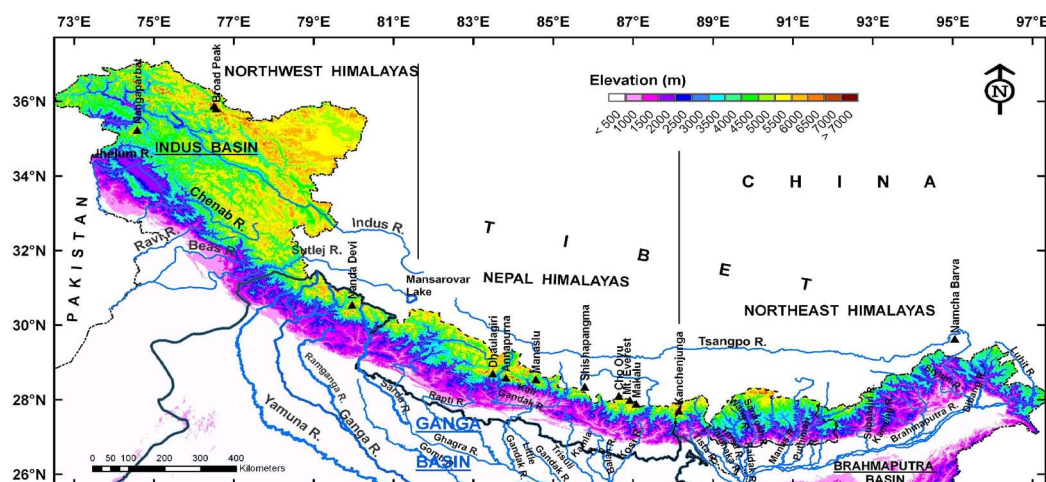


Figure 1: Digital Elevation Map of the Himalayas showing 3 main sections, Elevation and River systems.

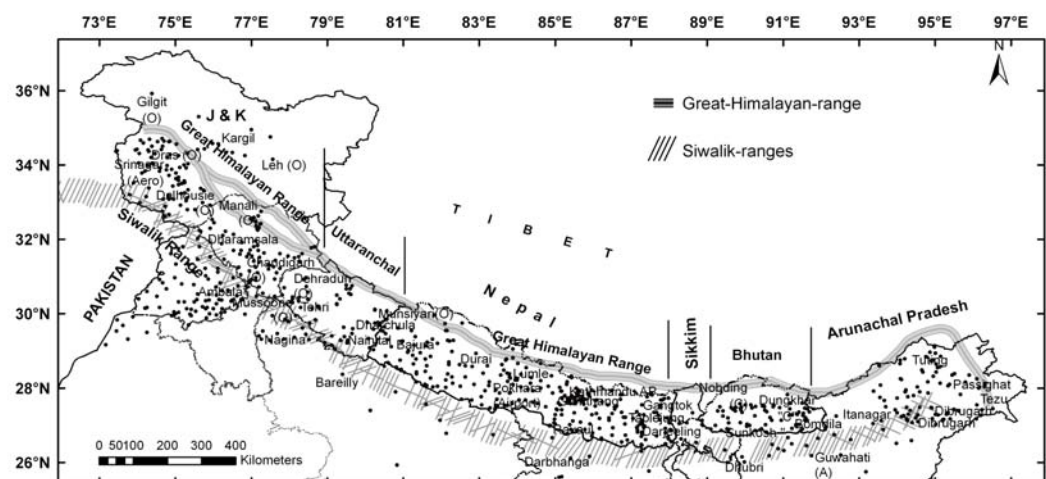


Figure 2: Map of the Himalayan region showing different sections and present network of rainfall stations.

extreme northeastern part of Lohit and Debang basins in India, still there are practically no precipitation measuring stations.

In the NW Himalayas, daily rainfall data of more than 200 stations, whose elevations vary from 300 to 4100 m a.s.l, and the data from the adjoining plains numbering about 350 stations, were used for the period 1875 to 2010.

The rainfall and flood data for these two regions were collected from the following sources:

1. Various publications of India Meteorological Department (IMD) viz. Monthly, Seasonal and Annual Reports, Daily rainfall summary, Weekly Rainfall Report, etc. and the data from National Climate Data Centre (NCDC), IMD, Pune.

2. Rainfall records from the Project Authorities such as National Thermal Power Corporation (NTPC), National Hydro-electric Power Corporation (NHPC), Central Water Commission (CWC), New Delhi.

3. Rainfall volumes at Indian Institute of Tropical Meteorology (IITM), Pune since 1871.

4. The Rainfall Registration Authorities and Forest Departments of Punjab, Haryana, Himachal Pradesh, Uttarakhand (formerly Uttaranchal) and J&K states.

5. Bhutan Meteorological Centre (1989-2005).

Flood data

6. Relevant flood data of Indian rivers were collected mainly from Central Water Commission (CWC), New Delhi for the period 1986-2010.

In Central or Nepal Himalayas, before 1947, there was only one meteorological observatory in the Indian Embassy complex at Katmandu (1324m) the capital of Nepal. In connection with the Kosi High Dam Project and Flood Control Projects of the Govt. of India, more than 100 meteorological stations were started by IMD throughout the Nepal with the permission of the Nepal Govt. From early sixties Nepal Meteorological Service (NMS) augmented this network by adding more stations and at present there are about 270 meteorological stations (Figure 2) whose data are available for varying periods, from 10 to 50 years or so. Using these data, International

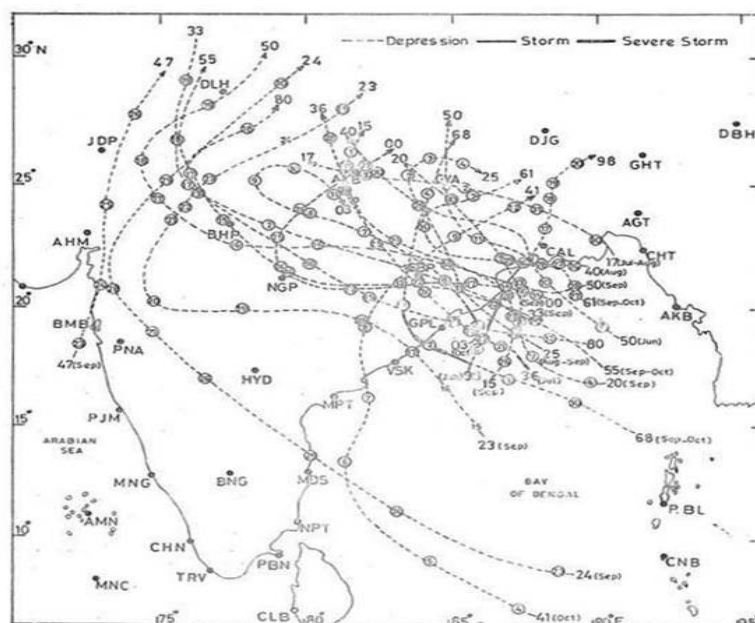


Figure 3: Recurring Cyclonic disturbances which cause heavy rainfall to the foot-hills of the Himalayas.

Methodology

Estimations of maximum average rain depths from analysis of severe rainstorms over a basin are normally made by the following methods considering the orography, nature and size of the basin/catchment, the data period and its suitability- a) Depth-Duration (DD) Method, b) Depth-Area-Duration (DAD) Method and c) Storm Transposition (ST) Technique. The main objective of all these methods is to estimate the maximum possible rain depths, which a basin may experience in future. All the above methods are well documented in various publications [10-15]. Severe rainstorms considered in this study broadly satisfy the criteria used by the authors in their several studies on severe rainstorms of India [16-20].

A flood is generally defined as a relatively high stage of a river at a given gauge/discharge (G/D) site. It has been defined by various people in different ways but in India, a river is said to be in flood when it crosses the Danger Level (DL) at a given G/D site on a river. The DLs at each G/D sites are fixed by State Engineers in consultation with CWC Engineers.

Besides the orography, the meteorological situations which are mainly responsible for causing heavy rainfall over the Himalayan region are as follows:

Normally, the southwest monsoon starts withdrawing from the northwest and adjoining regions of India from 15 September, it gets revived again in association with a Bay of Bengal / Arabian Sea depressions which move towards NW region and interacting with western disturbances cause exceptionally heavy rainfall especially in J&K, sub- Himalayan regions of Himachal Pradesh, Punjab and Uttarakhand Himalayas.

The periodic movement of Western Disturbances (WD) that originate from extra-tropics in the Mediterranean and Caspian seas

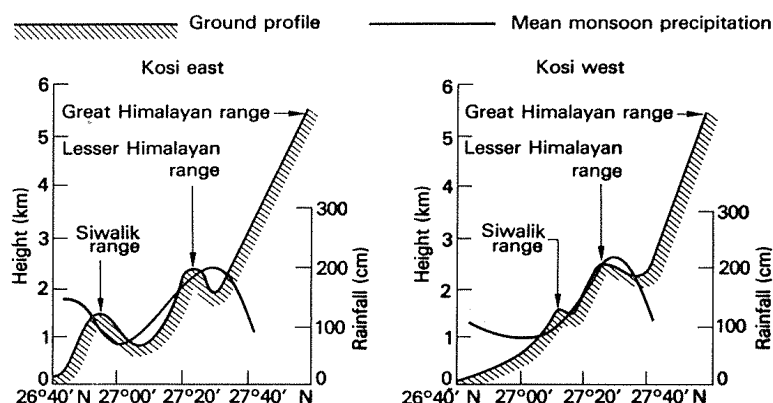


Figure 4: A schematic representation of the mean monsoon precipitation across the Kosi Himalayas in Nepal.

and travel through extreme north Indian region give rainfall/snowfall and chilly weather conditions. On an average 5-7 WD move over the northwestern region of India during the winter months [1]. An equal number of induced lows form to their south and move east and northeastward give heavy to very heavy rains over the plains of Punjab, Haryana, and Uttar Pradesh. Similarly, upper air troughs in the westerlies over extreme north of Arunachal Pradesh, cause heavy rainfall over the NE region.

Shifting of the axis of the monsoon trough to the foot-hills of the Himalayas from north Indian plains (known as 'break monsoon situation'), cause very heavy rainfall in the eastern and central Himalayas. Break situations mostly occur during the monsoon months of July and August and occasionally in September and caused very heavy rainfall on about 65% of occasions causing serious flooding in the rivers of these regions [21]. This particular meteorological situation in combination with orography of the Himalayas and occasionally with the passage of WD along the Himalayas is responsible for causing copious amounts of rainfall in the Himalayan catchments while the plains in the downstream reaches of these river basins receive practically no rainfall.

Apart from the above, the following factors also play an important role in augmenting rainfall and thereby floods in the river basins of the Himalayas:

- Indiscriminate destruction of forest and vegetal cover in the upper reaches of a river,
- Deposition of silt washed down from bare and poorly covered hill slopes in the upper reaches of a river,
- Man-made obstructions to the free flow of rivers like bridges, embankments, etc.,
- Improper agricultural practices like shifting cultivation etc. and
- Failure of dams and artificial lakes created by advancing glacier tongues or landslides.

Effect of altitude on precipitation climatology of the Himalayas

The Climate of Himalayas is said to be of Alpine nature, e.g. the altitude in the Central or Nepal Himalayas varies from 60m in the

south at Terai (Foothills of the Himalayas) to 8848m at Mt. Everest in the north within a short distance of 90km to 120km which cause variation in climate. It gets colder as the elevation increases and gets warmer and wetter as the elevation decreases. As a result, the climate in general changes in the different Himalayan sections rather quickly which may lead to sudden occurrences of cloud bursts, high winds, snowstorms, etc, resulting in quick floods, which makes the climate over the region quite unpredictable and at times dangerous too.

The Himalayan ranges from some sort of a barrier for the southwest monsoon (hereafter called as 'monsoon') winds from crossing over to Tibet, thereby causing heavy to very heavy rainfall in the foothills and the adjoining plains of India to its south [22-23]. Studies [24-26] carried out on variation of rainfall with height in Nepal Himalayas showed that rainfall is maximum near the outer Himalayas, i.e. foot-hills and a second maximum of rainfall is obtained near about the middle Himalayas at a height of about 2400m asl. Thereafter, rainfall decreases sharply as one proceeds northwards to higher elevations till the Great Himalayan Range is reached (Figure 4).

At meso-scale, the rainfall is highly influenced by local orography. Precipitation in general increases from low land valleys to higher mountain slopes up to certain heights. The windward slope gets more precipitation than the leeward side. It is also showed [27] using the precipitation data of seven stations in southern Tibet, that there is a reduction of 25% to 30% in precipitation in southern Tibet side compared to windward side of Nepal Himalayas.

Ladakh, region which is situated on the lee side of the western part of the Himalayas, monsoon activity in this region is very weak, e.g. the mean annual precipitation of Leh station is hardly 93 mm which is less than one-fourth of what is received in Lhasa, the capital of Tibet [28]. Whereas stations located in the Pir Panjal ranges receive far greater rainfall, because these stations lie to the windward side of monsoon disturbances and the Pir Panjal range traps most of the moisture from the monsoon currents, on account of orographic lifting. However, these monsoon currents get denuded of their moisture by the time they cross the 3000 to 4000 m high Pir Panjal range and stations located to the lee side of the range receive very less rainfall [29].

Met. Sub-divisions of India in the eastern Himalayas receive the highest normal annual and monsoon rainfall and as one move along

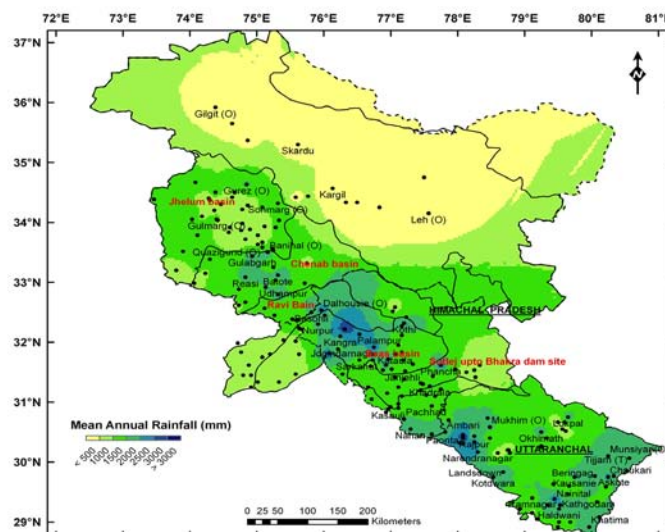


Figure 5: Spatial distribution of mean annual rainfall over the NW Himalayas.

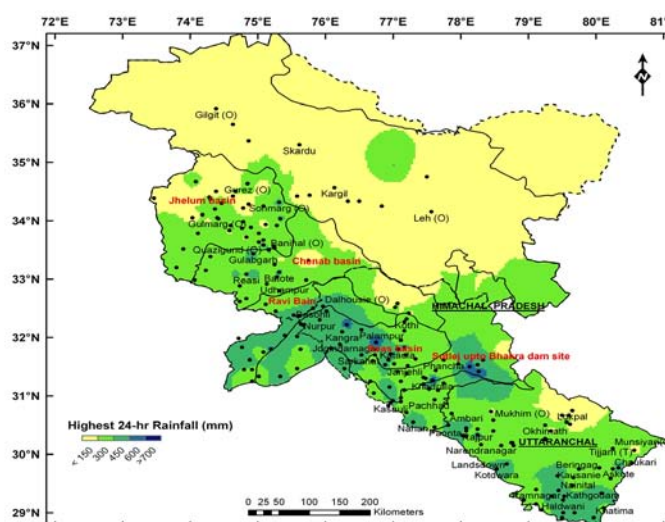


Figure 6: Spatial distribution of highest 24-hr rainfall over the NW Himalayas.

the Himalayan ranges from east to west, the rainfall decreases sharply [30]. In the interior of the Himalayas, monsoon rainfall is much less compared to the plain areas and in the first few frontal ranges of the Himalayas. In addition to this, heavy rainfall does not occur in a continuous spell as seen over the plain foothill Himalayan regions but there can be sudden falls of heavy rain within a short duration of 3-4 hours to a long duration of 10-14 hours.

In the Himalayan region, snow generally accumulates in the winter months (October to March) and sometimes during summer months (April to May). The snow that always remains throughout the year is considered as permanent snow. To delineate the snowfed and rainfed catchment areas over any Himalayan river basin with reference to permanent snowline, requires extensive analysis and use of satellite data representing the status in non- monsoon period probably during Feb.-Mar. and during monsoon period from Jul. to Sept. and hence it requires a separate study [31]. However an EL 4000m (Figure 5) may approximately be considered as the permanent snowline over

the Himalayan region as per the suggestion from experts/Research Scientists who have vast experience about the Himalayan region.

Considering the altitudinal aspect, a good number of studies [32-35,22,24,36,21,37-39] have been carried out on different aspects of Himalayan climatology and rainfall distribution due to heavy rainfalls. These studies emphasized that such studies are very important for planning, design and operation of water resources and hydro-electric power projects in the region.

In the following three sections rainfall characteristics and associated flood disasters over the three major sections of the Himalayas have been described.

Northwest (NW) Himalayas (India)

The NW Himalayan region considered in the present study extends over most of the hill states of the northwestern Indian region viz. J&K, Himachal Pradesh, Himalayan parts of Punjab-Haryana comprising of the Indus river basin (India) and Uttarakhand state

Table 1: Mean monthly, seasonal and annual rainfall mm for Individual catchments in the NW Himalayas.

Months/Seasons	Mean Rainfall mm for the catchments				
	Sutlej *	Beas	Ravi & Chenab	Jhelum	Indus #
January	90.9	79.8	104.8	91.4	21.2
February	82.4	81.9	119.5	109.4	21.2
March	86.6	91.8	129.9	139.5	36.7
April	53.9	59.4	97.2	122.5	26.1
May	64.6	56.3	60.8	91.1	21.0
June	104.1	119.0	76.0	60.5	8.5
July	262.6	421.1	267.9	91.9	12.2
August	234.2	415.7	276.3	92.3	14.5
September	124.6	180.0	124.0	57.1	10.6
October	37.8	42.6	34.3	40.8	6.0
November	15.3	15.6	21.0	27.1	4.2
December	42.6	38.8	59.5	51.9	11.1
Winter Dec.-Mar.	302.5	292.3	413.7	392.2	90.2
Spring/Summer Apr.-Jun.	222.5	234.7	233.9	274.1	55.6
SW Monsoon Jul.-Sept.	621.4	1016.8	668.2	184.2	26.7
Autumn Oct.-Nov.	53.1	58.2	55.3	120.0	20.8
Annual	1199.5	1601.9	1371.1	975.6	193.4
SW monsoon as % of Annual	52	63	49	19	14

Table 2: Highest 24-hr rainfall mm >400 mm recording stations in NW Himalayas.

Station Name	Highest 24-hr rainfall mm	Date of Occurrence
Kilba	609.6	27.12.1958
Sangla	558.8	21.12.1958
Arki	416.6	12.08.1963
Barauli	418.6	21.08.1901
Nahan	561.3	14.08.1910
Dharamsala	530.0	25.07.1967
Jogindarnagar	600.0	14.08.1996
Kataula	413.0	08.07.1957
Batala	474.5	05.10.1955
Malikpur	410.0	26.09.1988
Dalhousie O	409.0	09.09.1966
Qazigund O	432.3	23.08.1905
Kaladhungi	413.0	10.07.1970
Haldwani	413.0	11.07.1970
Askote	404.2	28.07.1968
Kharsali O	400.0	15.09.1963
Dehradun O	487.0	25.07.1966
Mussoorie O	440.0	19.08.1890
Khadrala	762.0	28.01.1968

(India) (Figures 1&2). The Indus river system in India consists of the main river Indus and its major tributaries, the Jhelum, the Chenab, the Ravi, the Beas and the Sutlej from the east. The entire Indus basin lying in Tibet (China), India, Pakistan and Afghanistan extends over

an area of about 1154,500 sq. km. The present study is restricted to the drainage area (about 321,290 sq. km) lying in India which is nearly 9.8% of the total geographical area of the India. The upper part of the basin lying in J&K and Himachal Pradesh is mostly mountainous and criss-crossed by narrow valleys.

The northern side of the western Himalayas, also known as the 'trans-Himalayan belt', is a region of barren, arid, frigid, and wind-blown wastelands. Similarly, the upper Indus catchment which falls in the Ladakh region is located in the worst arid region of India due to lack of precipitation. However, the climate to the south is typically monsoonal lasting for just two months or so (mid July to September). The upper portion of the region receives good rainfall during the winter season due to the passage of WD (Section 4). As such, bulk of precipitation occurs during the winter season in Kashmir valley especially in Jhelum river catchment, Ladakh region, Himachal Pradesh and Uttarakhand. Any heavy rainfall for duration of 1 to 2 days can cause serious floods over the region.

The mean annual rainfall over the entire NW Himalayas (Table 1 and Figure 6) broadly range from about 193 mm (14%) for the Indus basin in the extreme north to 1602 mm (63%) for the Beas basin to south. The maximum annual rainfall of 3097mm was recorded at Dharamsala (Lower) (Himachal Pradesh) and least at Khalatse (50mm) (Ladakh). Uttarakhand and Himachal Pradesh sub-division experience about 66% to 67% whereas J&K sub-division receives only 43% of annual rainfall during the monsoon season [30].

Rainfall recorded at individual stations showed that Badrinath (Uttarakhand) experienced monsoon rainfall of about 94% whereas Leh and Gilgit experienced 40% and 10% respectively. Maximum number of stations (49) recorded highest 24-hr rainfall in the month of July followed by August (40), September (35), December (16) and January (12). Table 2 gives the list of stations recording highest 24-hr rainfall >400mm and spatial distribution is shown in Figure 7.

As a part of CWC Project, on the basis of 1901 to 2005 rainfall data, severe rainstorms were analyzed by DD method over the five

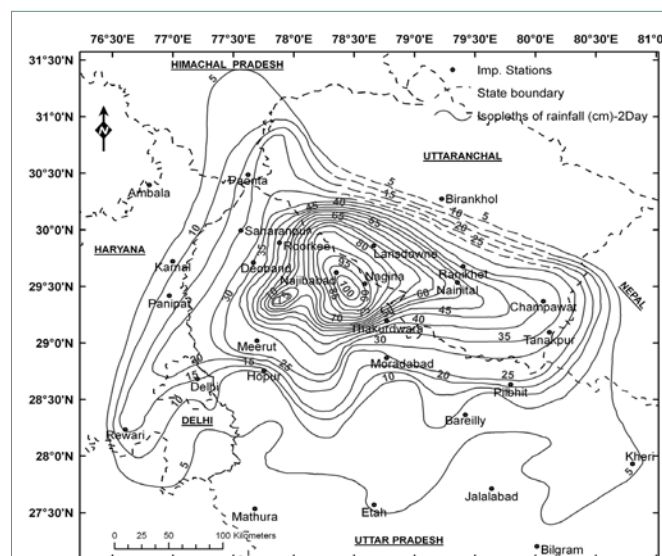
**Figure 7:** 2-day isohyetal pattern of 17-18 Sept. 1880 rainstorm over Uttarakhand and neighbourhood.

Table 3: SPS and PMP raindepths over different catchments of the Indus basin.

	Name of the catchment	SPS raindepths mm for			PMP raindepths mm		
		1-day	2-day	3-day	1-day	2-day	3-day
1	Sutlej upto	102	140	172	122	168	191
	Bhakra dam	24/9/1988	24-25/9/1988	10-12/7/1993			
	site	MMF: 1.20 24-26/9/1988		1.11 10-12/7/1993			
2	Beas	192	328	358	250	420	458
		5/10/1955	4-5/10/1955	3-5/10/1955			
		MMF: 1.28 3-5/10/1955					
3	Ravi	169	323	333	216	413	426
		5/10/1955	4-5/10/1955	3-5/10/1955			
		MMF: 1.28 3-5/10/1955					
4	Chenab	95	187	246	114	224	295
		24/9/1988	24-25/9/1988	24-26/9/1988			
		MMF: 1.20 24-26/9/1988					
5	Jhelum	83	131	170	106	168	218
		1/9/1928	1-2/9/1928	31/8-2/9/1928			
		MMF: 1.28 31/8 – 2/9/1928					

Table 4: Estimates of point PMP and return periods at selected stations in the upper Indus basin in India up to Pakistan boundary.

No.	Station	PMP mm			Estimates of maximum rainfall mm for Return period of					
		Point			1000-yr			5000-yr		
		1-day	2-day	3-day	1-day	2-day	3-day	1-day	2-day	3-day
1.	Leh	69	73	91	52	68	75	62	81	89
2.	Skardu O	97	122	143	78	117	127	92	139	150
3.	Kargil	169	216	256	145	214	245	172	257	294
4.	Dras	176	270	344	159	279	343	189	332	410
5.	Gilgit	108	125	156	85	120	137	101	143	163

Table 5: Distribution of most severe rainstorms during 1875 to 2010.

Period	1875-1900	1901-1925	1926-1950	1951-1975	1976-2000
Severe Rainstorm	17-18 Sept. 1880	28-30 Sept. 1924	26-27 Sept. 1947	3-5 Oct. 1955	24-26 Sept. 1988

individual catchments of the Indus basin (India) [40] and their estimated results of Standard Project Storm (SPS) and Probable Maximum Precipitation (PMP) raindepths are given in Table 3. Considering the physiographic features of the Indus catchment in the extreme north and due to lack of sufficient precipitation data for available stations, it's not correct to carry out any rainstorm analysis over this region to derive the PMP design raindepths. However, by considering precipitation data of stations for relatively longer period (>50 years), point PMP estimated by Hershfield [41-42] statistical method are given in Table 4 for rough use.

Analysis of daily rainfall data of about 200 stations from 1875 to 2010 [43], showed that there are five most severe rainstorms which occurred over and near this region in the past. If the entire period is divided into 25-year sub-periods it is seen that each sub-period has recorded one severe rainstorm (Table 5) except during the present period of 2001 to 2010. DAD analysis of these rainstorms showed that these severe rainstorms occurred over more than 100,000 sq.km of area. However, their DAD raindepths for standard areas up to

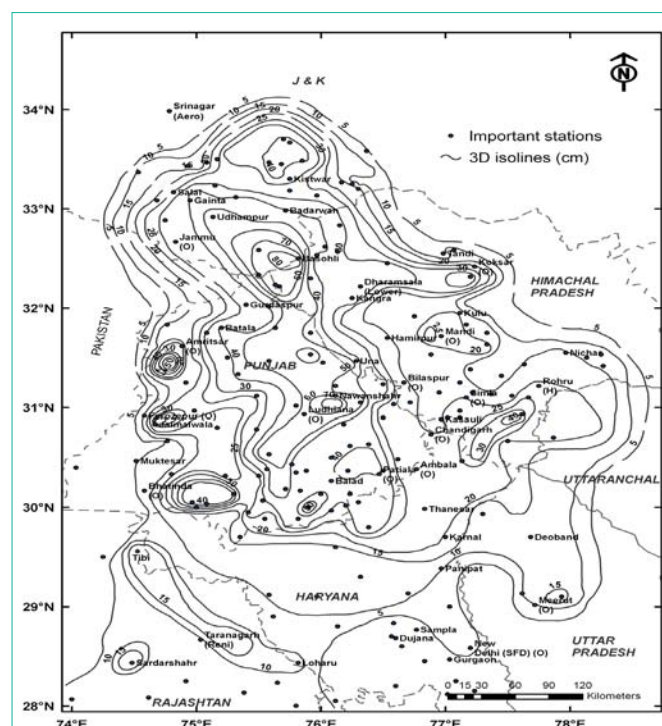
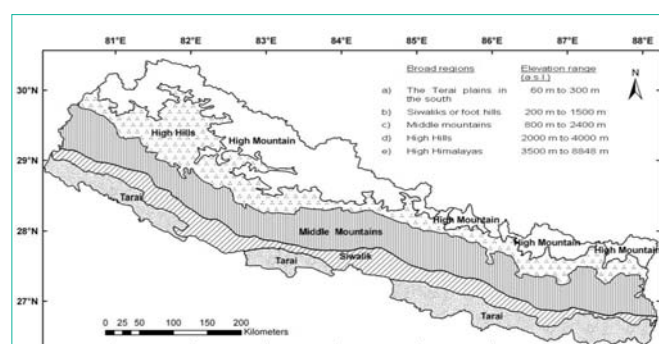
50,000sq.kms are given in Table 6 for comparison. Table 6 shows that 17-18 Sept., 1880 rainstorm (Figure 8) occurred over and near the plains of Uttarakhand state is definitely much severe for 1 and 2-day durations than all the other 3-day duration rainstorms, whereas Sept., 1988 rainstorm (Figure 9) occurred over the entire Indus basin covering more than 2 lakhs sq.km area caused serious floods in the major river basins.

The severe rainstorms that occur over this region normally lead to peak floods in the Yamuna River. All time record floods occurred in Aug. 1976, Sept. 1978 and Sept. 1988 [32,44,45,39]. During Sept. 1988 flood; the Yamuna River crossed the DL at 204.83m at Delhi Rly. Bridge and touched the maximum level of 206.92m on 27 Sept.1988 [39].

Usually, the western Himalayan region experiences the cloud burst events (Table 7) during the monsoon season in association with the strong monsoon circulation or the interaction of monsoon circulation with the mid-latitude westerly systems. The orography of the region plays a dominant role by increasing the convection and

Table 6: Average raindepths cm for 1, 2 and 3-day durations of most severe rainstorms.

Rainstorm	Storm Centre	Point	Area in hundreds of sq.km							
			1	5	10	20	50	100	200	500
24/9/1988	Nawanshahr	51.4	51.0	49.0	46.9	43.4	37.0	31.8	27.6	20.6
	Jullundur									
24-25/9/1988	Nawanshahr	64.9	63.3	59.5	56.2	52.0	45.3	42.8	38.8	31.5
	Jullundur									
24-26/9/1988	Basohli	81.1	80.9	79.7	78.0	74.7	66.2	62.0	54.1	41.5
	Kathua									
5/10/1955	Aliwal	49.5	48.0	45.7	45.0	43.8	40.5	35.5	28.9	19.9
	Ambala									
4-5/10/1955	Batala	69.1	67.7	65.5	63.5	61.2	55.7	51.0	43.8	32.5
	Gurdaspur									
3-5/10/1955	Batala	82.6	81.0	75.3	69.7	63.9	58.4	53.4	47.2	38.4
	Gurdaspur									
26/9/1947	Dadupur	30.5	29.9	28.6	27.3	26.0	23.5	20.8	17.7	14.9
	Ambala									
26-27/9/1947	Dadupur	40.6	40.4	39.1	38.4	37.1	34.2	30.8	25.8	21.0
	Ambala									
25-27/9/1947	Dadupur	56.3	55.3	51.0	48.4	45.8	42.4	38.2	32.6	26.8
	Ambala									
29/9/1924	Lansdowne	35.1	34.9	33.8	32.9	31.0	27.1	25.0	23.0	18.5
	Garhwal Himalayas									
28-29/9/1924	Lansdowne	59.4	58.2	57.1	56.0	54.0	49.5	44.5	38.8	33.8
	Garhwal Himalayas									
28-30/9/1924	Lansdowne	77.5	76.8	75.5	74.0	70.9	63.5	55.8	49.0	41.0
	Garhwal Himalayas									
18/9/1880	Nagina	82.3	82.0	80.0	77.5	73.6	62.8	51.5	40.5	26.3
	Bijnor									
17-18/9/1880	Nagina	104.1	103.5	100.0	99.1	95.9	86.8	76.8	63.0	41.4
	Bijnor									

**Figure 8:** 3-day Isohyetal pattern of 24-26 Sept. 1988 rainstorm over the NW Himalayas.**Figure 9:** Broad topographic regions of Nepal and their elevations.

hence the intensity of cloudburst causing heavy landslides, flash floods and loss of human lives.

However Laddakh region of J&K is not known to be frequently affected by this type of phenomena. It is a cold desert and average rainfall for the month of August is 14.5mm only. The highest rainfall ever recorded over Leh during 24 hours has been 51.3mm (22 Aug.1933). A series of cloudbursts have been reported near Leh in J&K around 0130–0200 hours IST on 6th Aug., 2010 leading to flash flood and mud slides over the region causing huge loss of lives and properties [46].

Central or Nepal Himalayas

The Central or Nepal Himalayas extends along the Himalayan

Table 7: Recent events of cloudbursts in the NW Himalayas.

Date of occurrence of cloudburst	Regions affected
15 Aug. 1997	Simla district, Himachal Pradesh
17 Aug. 1998	Kumaun division of Uttarakhand
16 Jul. 2003	Kullu, Himachal Pradesh
6 Jul. 2004	Alaknanda river in Chamoli district, Uttarakhand
16 Aug. 2007	Himachal Pradesh
7 Aug. 2009	Munsyari, Pithorgarh district. of Uttarakhand
6 Aug. 2010	Leh, Ladakh region of J&K
15 Sept. 2010	Almora district of Uttarakhand
9 Jun. 2011	Near Jammu
20 Jul. 2011	Upper Manali region, Himachal Pradesh
4 Aug. 2012	Chamoli district of Uttarakhand

ranges for 885km and its width from north to south varies from 145km to 248km (Figure 1). The Himalayan altitude varies in the Nepal from 60m asl at Jhapa, the easternmost district in the south to more than 8848m asl at Mt. Everest in the north. The rugged topography is mainly responsible for producing different climates ranging from sub-tropical in the south to Alpine type in the north of the Nepal Himalayas. Therefore, entire Nepal has been divided into the five broad regions (Figure 9) from south to north with increasing altitudes [47,48]. Most of the rainfall stations (i.e.50) are located in the 100 to 200 m altitudinal range and 30 stations in the range of 1300- 1400 m.

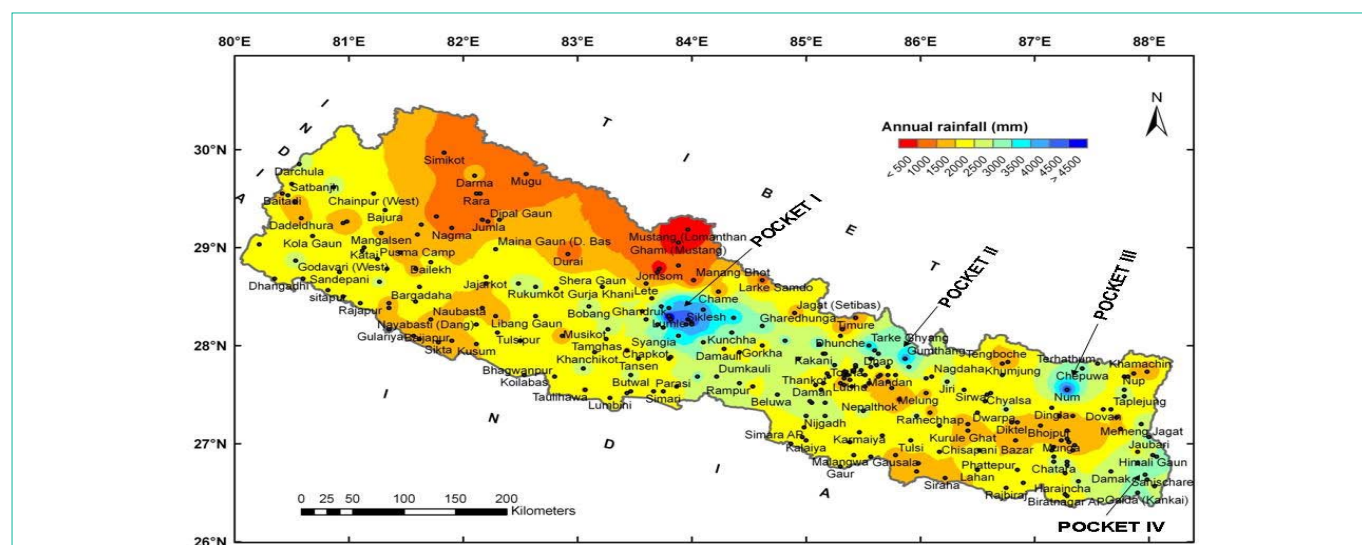
Although rainfall data of Nepal are not readily available for a long period of years, studies [25,49,50,27,51,26,53,54] carried out for different sections of Nepal Himalayas showed that monsoon (June to September) is the main rainy season of this region during which 80% of the annual rainfall is received. The annual precipitation received in Everest–Kanchenjunga region (altitude 3000m to 4000m) in Nepal is barely 1000mm [50]. According to IMD's study [55] the Khumbu glacier (5000m to 6000m) at the foot of the Everest peak on the Nepal side receives precipitation of about 450mm.

Towards the north, as one approach nearer the Great Himalayan Range, precipitation decreases and is of the order of 1000mm to 2000mm in the eastern half and in western half it is 1000mm to 1500mm or even <500mm excluding the southeastern and middle region which receive rainfall in the range of 1500mm to 2500mm. However, pockets of heavy precipitation (>3500mm) are located in the middle part of the Nepal (Figure 10) on the windward (southern) side of the Great Himalayan range:

a) Pocket I: It is located in the south of 7km high Annapurna range in central Nepal about 40 to 50km south of the range in the upper Pokhara valley. This is the heaviest pocket of rainfall within the Central Himalayas [49,51,26] (Figure 10) as far as present records are concerned. In the valley, good number of stations, viz. Pokhara (827m), Lumle (1740m), Bhadaure Deurali (1600m) Lamachaur (1070m), Khudi Bazar (823m), etc. recorded >4000 mm of annual rainfall.

b) Pocket II: It is located to the south of Langtang Himalayan range which is just northeast of Kathmandu valley (1324m) and almost quite close to the Kodari pass which connects central Nepal with Tibet (Figure 10) receiving monsoon and annual rainfall >4000mm. A couple of stations viz. Chautara (1660m), Gumthang (2000 m), Sarmathang (2625m) have recorded annual rainfall of the order of 4000 mm. The 7km high Langtang Himalayan range, acts as a barrier to the moist winds from the south, thereby causing them to shed most of their moisture before crossing the range [26].

c) Pocket III: This pocket lies south of the high Himalayan range connecting Kanchenjunga (8598m) and Everest (8848m) peaks. Stations in this pocket like Num (1676m) and Chepuwa (2591m) have recorded rainfall in the range of 2500mm to 4200mm. The rainfall distribution around the two highest peaks, viz. Mt. Everest and Kanchenjunga [50] showed that the Kanchenjunga region receives greater rainfall than the Everest region. As one approach these two peaks from the south, rainfall decreases rapidly because moisture is shed on the Himalayan ranges to the south. Chepuwa station which lies midway between these two regions, south of the Great Himalayan

**Figure 10:** Spatial distribution of mean Annual rainfall mm over Nepal Central Himalayas.



Nepal has three major river systems (Figure 12) viz. a) The Karnali or Ghagra, b) The Narayani or Gandak, c) The Kosi or Sapta Kosi, each having numerous tributaries flow south towards the Terai plains and joins the mighty Ganga River in the Indo-Gangetic states of Uttar Pradesh and Bihar in north India. All these rivers have their head waters in the high Himalayan glaciers and snow fields and during the

Station	District	High. 24-hr rainfall mm	Date of Occurrence
Parasi	Nawalparasi	495.0	03/08/1998
Musikot	Gulmi	503.0	29/07/1960
Hetaunda N.F.I.	Makwanpur	456.8	31/07/2003
Tistung *	Makwanpur	540.0	20/07/1993
Gumthang	Sindhupalchok	505.0	25/08/1968
Hariharpur Gadhi	Sindhuli	482.5	20/07/1993
Anarmani Birta	Jhapa	473.0	10/10/1959

Floods in Nepal result from heavy rainfall, snowmelt, glacier lake outburst, landslide dam outburst, or a combination of two or more of them [56] e.g. heavy rainfalls of 27-30 Sept. 1981, in 1902/03, 19-22 Jul. 1993 over Bagmati, 28 Sept-7 Oct. 1968 over east Rapti. Floods of 1964, 1981 and 1984 in the Sunkosi River are some events in the eastern region. Similar studies on floods occurred in different parts of the Nepal and damage caused during 1968 to 2000 [57,58,8,59-61] and a brief history of floods in Kathmandu Valley for the period of 1988 to 2002 [62] have highlighted the severity of rainfall and floods in these regions.



Figure 12: Location of three major river basins of Nepal Himalayas.

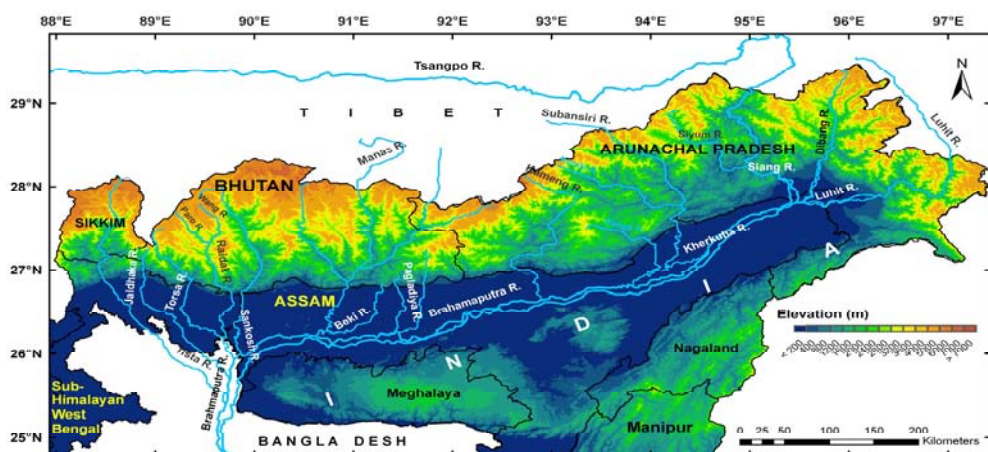


Figure 13: Physiographic map of NE Himalayas showing Brahmaputra river system.

In the recent past, heavy rainfalls of 21-26 Jul., 2002, 30-31 Jul. 2003, 26 Jul. 2004 caused record rainfall in the Bagmati catchment affecting eastern and mid region of the Kathmandu valley [63]. The heavy rainfalls of 4-16 Oct. 2009 affected 14 districts in the mid and far west regions of Nepal. Latest heavy rainfalls of 5-7 May 2012 over the Pokhara valley resulted in blockage of Seti River due to landslide and accumulated water caused flash flood around Mt. Annapurna and neighbourhood. This shows that natural disasters associated with extreme weather events are widely distributed in Nepal and show an increasing trend [63].

Northeast (NE) Himalayas (India, Bhutan)

Northeast Himalayan region comprises of the major portions of Sikkim, Sub-Himalayan West Bengal, and Arunachal Pradesh, Assam in the Indian sub-continent and Bhutan forming the major Brahmaputra river system. The Brahmaputra river originates at an elevation of about 5300m in the Kailash range and known by the name of Yarlung-Tsangpo and flows for about 1625km eastwards almost parallel to the Great Himalayan range on its northern side. In eastern Tibet, the river

flows around the snow-capped massif of Namche Burwa (7,756m) and the Gyala Peri and enters into Arunachal Pradesh at Kepang La above Tuting station as river Siang (also called Dihang) (Figure 13).

Two more Himalayan tributaries, Dibang and Lohit join the Siang River in Sadiya sub-division of Tinsukhia district and it is from this confluence that the river takes the mighty form and is called as 'Brahmaputra' (Figure 14). This region of the eastern Himalayas in Arunachal Pradesh receives heavy rainfall generating 70% flow of the Brahmaputra River during the SW monsoon months of mid-May to mid-October, resulting in tremendous death and destruction. After flowing through the Assam Valley up to the Goalpara town, river takes a southern course and enters Bangladesh. In the extreme west of the NE Himalayas, the Teesta (or Tista) river originates in the glaciers of the Sikkim Himalayas and joins the Brahmaputra River in Bangladesh.

Next to Sikkim, Bhutan is situated in the NE Himalayas and it stretches over 340 km in length from west to east and 170km from north to south with an approx. area 38394 sq.km. The terrain is mostly rugged and mountainous with elevations ranging from 200m

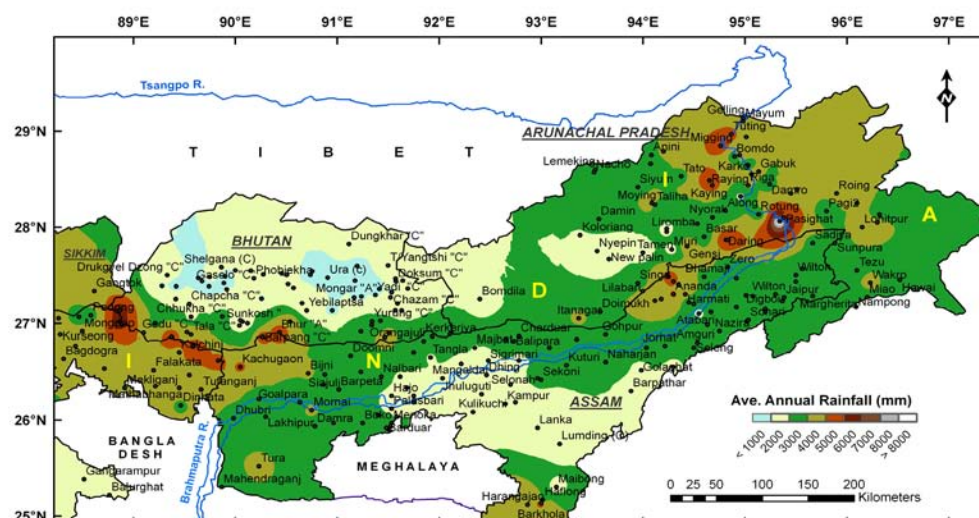


Figure 14: Average annual rainfall mm distribution over the NE Himalayan region.

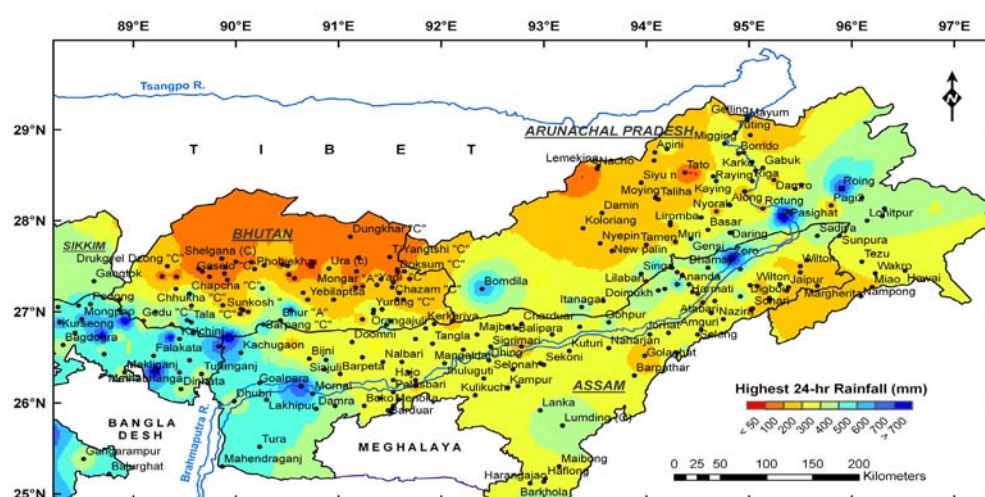


Figure 15: Spatial distribution of highest 24-hr rainfall mm over the NE Himalayan region.

to >7000m asl (Figure 15) within a distance of less than 175 km. About 21% of the total land, above 4,200m asl is covered by the snow, glaciers and glacial lakes. The variation of the climate is extremely dependent on the altitude. The Manas is the largest river system of Bhutan, acts as a trans-boundary river in the Himalayan foothills between southern Bhutan and India.

Besides monsoonal rainfall during June to September, there is considerable thunderstorm activity in May in NE Himalayan region and the rainfall caused by these thunderstorms (about 33.8 cm, [64,65] is comparable in magnitude to the rainfall of any of the monsoon months. Therefore, in the present study monsoon period is considered from May to October for this region.

The catchment of Brahmaputra and its tributaries in India receive very heavy rainfall ranging from 1100mm to 6400mm a year [66]. Most of the run-off in the river is contributed by heavy rainfall of about 5100 to 6400mm in the Abor and Mishmi hills in Arunachal Pradesh and 2500 to 5100mm by the Brahmaputra basin. The basin in

India receives a mean annual rainfall of 2300mm and its catchment in northeast (i.e. Arunachal Pradesh) receives 4100mm of rainfall/year [67,68]. Rainfall in the NE Himalayan sector amounts to 5000mm/year with lower ranges receiving more than the higher ranges (6350mm or more) [67,68] causing frequent flood ravages in the Assam Valley, e.g., Dibrugarh (a station at the head of the Assam Valley) in the eastern part receives annual rainfall of the order of 2850mm whereas Pasighat, located at foot hills of the eastern Himalayas in Arunachal Pradesh receives 5070 mm of annual rainfall. Tuting station located further high up in the Himalayas (Siang basin) receives rainfall of about 2740mm annually [67,68].

The mean annual rainfall of 267 stations (India) (1901 to 2005) is of the order of 2444.3mm. The spatial distribution of annual rainfall over the NE Himalayas (Figure 16) shows that zone of the highest rainfall is located just near the foot hills of the Himalayas. Rainfall decreases sharply with the increase in elevation towards the higher ranges of the Himalayas northwards. 5 stations viz. Buxa, Pasighat

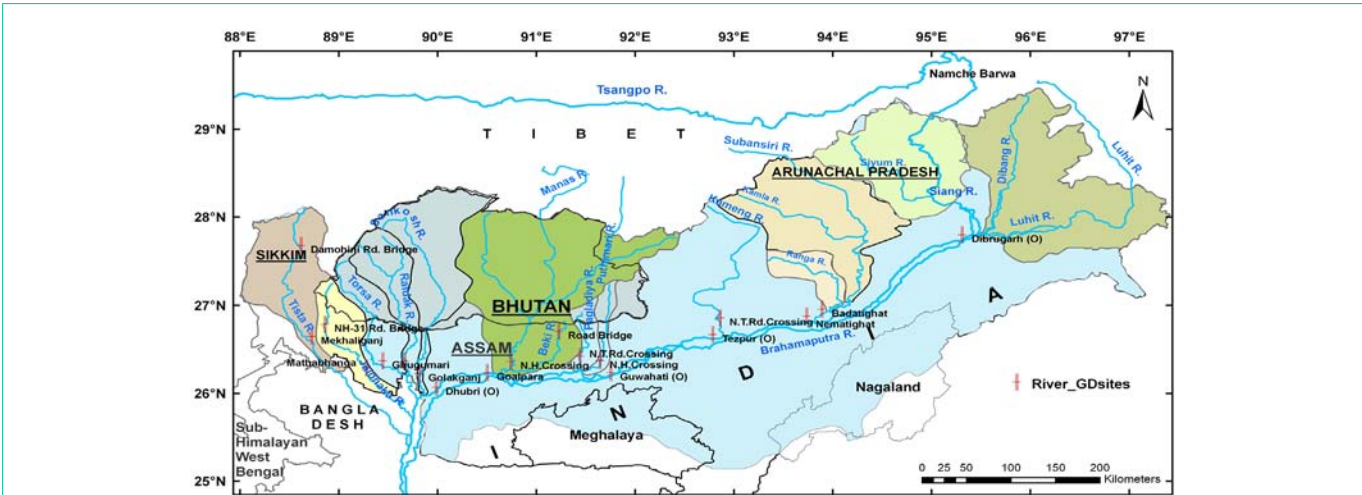


Figure 16: Major river basins of the NE Himalayas showing G/D sites on the rivers in India.

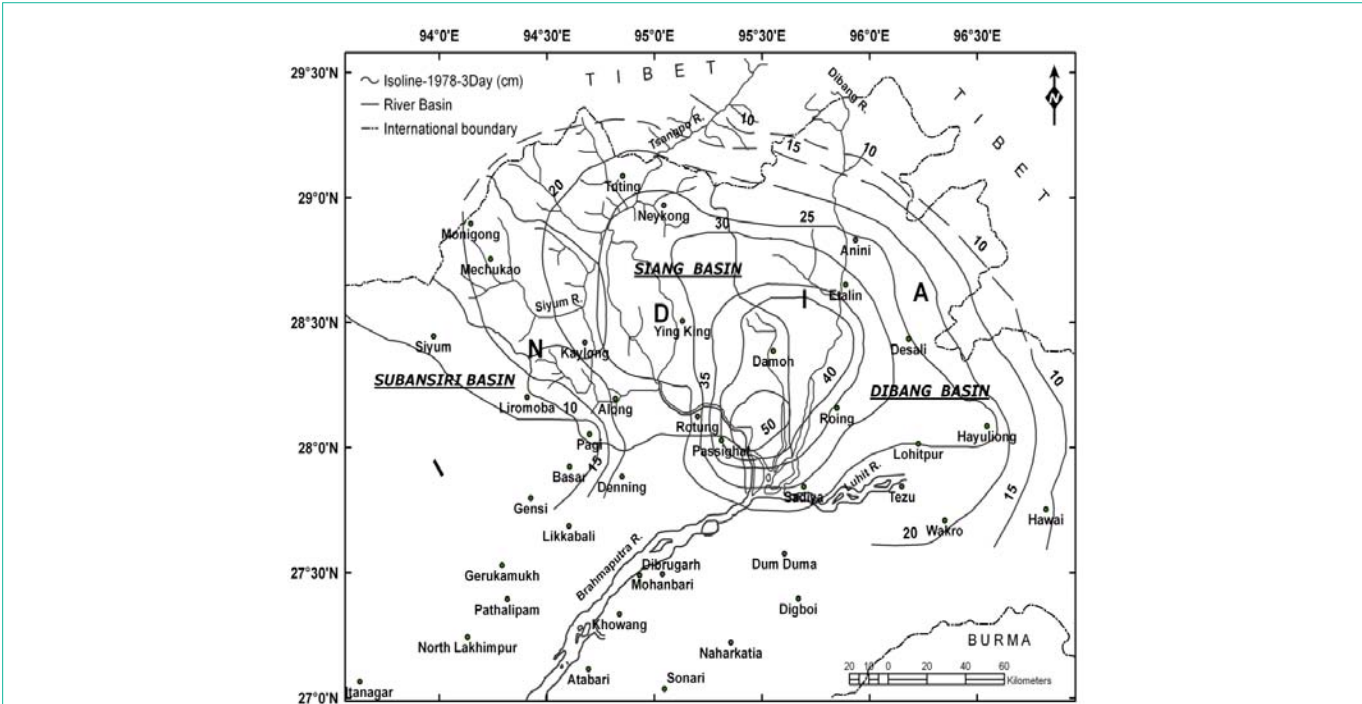


Figure 17: 3-day 21-23 Jun isohyetal pattern of 1978 rainstorm over the Siang basin.

Table 9: Mean annual and seasonal rainfall mm of the major river basins in NE Himalayas.

No.	Major river basins	Catch. Area Sq.km	Average Rainfall mm			Season rainfall as % of annual	
			Jun.-Sept.	May- Oct.	Annual	Jun.- Sept.	May- Oct.
1	Entire Siang basin	14039	1725.0	2395.0	3024.0	57	79
2	Subansiri	24116	1164.0	1450.0	1844.0	63	79
3	Puthimari and Pagladiya	3380	1629.8	2088.2	2434.4	67	86
4	Manas Bhutan	18300	938.2	1144.0	1349.8	70	85
	Manas India	23050	1799.9	2331.1	2637.9	68	88
	Manas Entire	41350	1070.7	1326.6	1548.0	69	86
5	Torsa, Raidak, Sankosh	21810	1815.5	2206.4	2461.2	74	90
6	Teesta India	10155	2323.6	2747.4	3009.2	77	91

Table 10: Highest 24-hr rainfall mm > 500 mm recording stations in NE Himalayas.

Stations	NE Himalayan region	24-hr highest rainfall mm	Date of Occurrence
Mathabhanga H	Sub-Himalayan West Bengal	800.6	13.08.1990
Darjeeling O	"	504.4	31.07.1995
Kurseong	"	640.0	05.10.1968
Mongpoo	"	546.1	12.06.1950
Buxa	"	538.5	08.06.1921
Hasimara H	"	790.6	21.07.1993
Kumargram H	"	657.5	21.07.1993
Nagarkata H	"	805.3	06.08.1990
Neora H	"	802.4	26.05.1990
Malda O	"	567.5	28.09.1995
Raiganj H	"	680.0	11.07.1999
Gedu "C"	Bhutan	520.0	03.08.2000
Surey "C"	"	611.6	02.08.2000
Ananda	Northeast India	600.0	20.08.1979
Bomdila	"	570.2	11.06.1976
NorthLakh	"	508.0	22.09.1956
Passighat A	"	912.4	28.07.1911
Roing	"	745.0	16.08.1977
Zero	"	800.0	16.09.1987
Goalpara	"	712.1	08.06.1970
Jamduar	"	805.5	07.09.1976

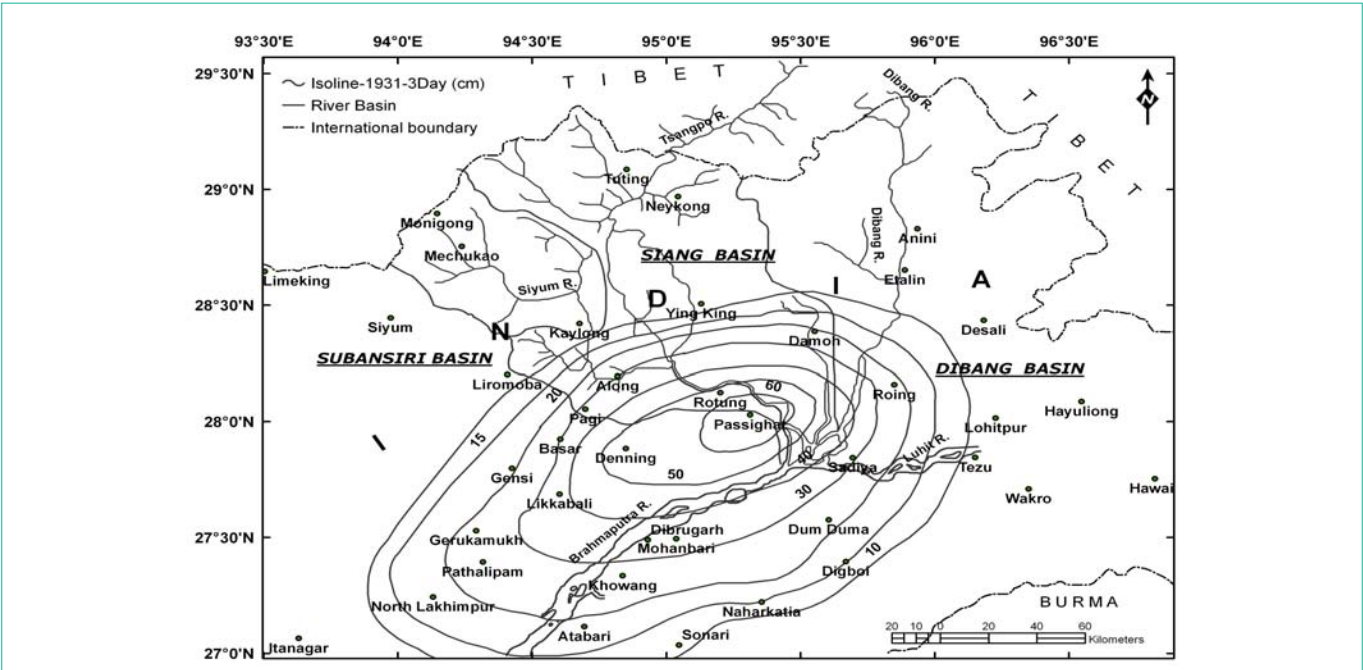


Figure 18: 3-day 24-26 Jun. isohyetal pattern of 1931 rainstorm.

and Denning (India) and Sipsoo and Tendu (Bhutan) recorded >5000mm of average annual rainfall. 17 stations recorded more than 4000mm of annual rainfall. The mean annual and seasonal rainfall for the 6 major river basins in NE Himalayas (Figure 17) is given in Table 9. Due to the altitude of some individual stations in this region

also, there are pockets of high and low rainfall around these stations. Pasighat (AP) (India) and Sipsoo (Bhutan) recorded the highest mean annual rainfall of 8972mm and 5866mm [69] respectively. Average annual precipitation of Bhutan is 1679mm and 70% of it occurs in monsoon months [69]. The central and northern parts of Bhutan

Table 11: Comparison of SPS and PMP estimates obtained by different methods over Siang and Subansiri basins.

Design rain depths mm for	Siang basin			Subansiri basin		
	1-day	2-day	3-day	1-day	2-day	3-day
SPS by DD method	100	180	233	67	119	135
PMP by DD method	122	220	284	80	143	162
Rainstorm considered	21-23 June, 1978 MMF = 1.22			12-14 Jul. 1985 MMF = 1.20		
SPS by DAD method	133	220	273	83	155	198
PMP by DAD method	179	297	369	112	209	267
Rainstorm considered	24-26 June, 1931 rainstorm MMF = 1.35 IMD, 1988					
PMP by Statistical method Point PMP	287	396	545	179	246	369

Note: Depth-Duration DD method Depth-Area-Duration DAD method

receive relatively less rainfall.

The highest 24-hr rainfall recorded by the stations range from 36mm at Gyetsha (C), Bhutan to 912.4mm at Pasighat in Arunachal Pradesh, India. 71 stations recorded highest rain amount during the rainy season of July, 37 stations each in June and August and 25 stations in the September month. Most of the stations recorded highest 24-hr rainfall of the magnitude 200mm to 300mm (Figure 15). There are pockets of highest 24-hr rainfall, located mostly in the extreme northeast and western region of the NE Himalayas. In the northern part of the Bhutan there are less number of stations and have recorded highest 24-hr rainfall <50 mm. 21 stations (Table 10) recorded highest 24-hr rainfall >500mm. These stations lie close to the foot hills of the Himalayas to the windward side.

The entire NE Himalayan region consists of six major river systems (Figure 17) which are the sub-basins of the main Brahmaputra river system. These river systems have their origin in the glaciers at high altitude Himalayas. Each one has numerous tributaries which drain the Himalayan mountain slopes from north to south and mostly from the 'V' shape drainage structure. Flowing to the south they join the Brahmaputra River in India and Bangladesh. All these rivers during

the monsoon months of June to September are in high floods due to heavy rainfall in their respective catchments.

In the past 9-12 Aug., 1902 and 18-21 Jun., 1934 are the most severe rainstorms occurred over this region [64]. Both these rainstorms were caused by the northward shifting of the eastern end of the monsoon trough (i.e. 'Break'). The average raindepths caused by these two rainstorms over 67,700sq.km of an area for 4-day duration were 300 mm and 280 mm respectively with the Mawsynram as the centre of the rainstorm. 1-day extreme point rainfall (or PMP) using Hershifeld's statistical technique [42] over the Assam Valley varied from 300 to 750mm [70]. By using the same technique, but using a longer and more up-to-date network of stations data, the IITM, Pune [71] found the extreme point rainfall varying between 400 to 800 mm.

The rainstorm analysis [72,73] over NE Himalayas revealed that 21-23 Jun., 1978 rainstorm (Figure 18) over the entire Siang basin and 12-14 Jul., 1985 over the Subansiri basin have yielded highest raindepths by DD method for 1, 2 and 3-day durations and these are referred to as SPS raindepths. These SPS raindepths were then moisture maximized with a suitable Moisture Maximization Factor (MMF) to obtain PMP raindepths (Table 11). Similarly, using long

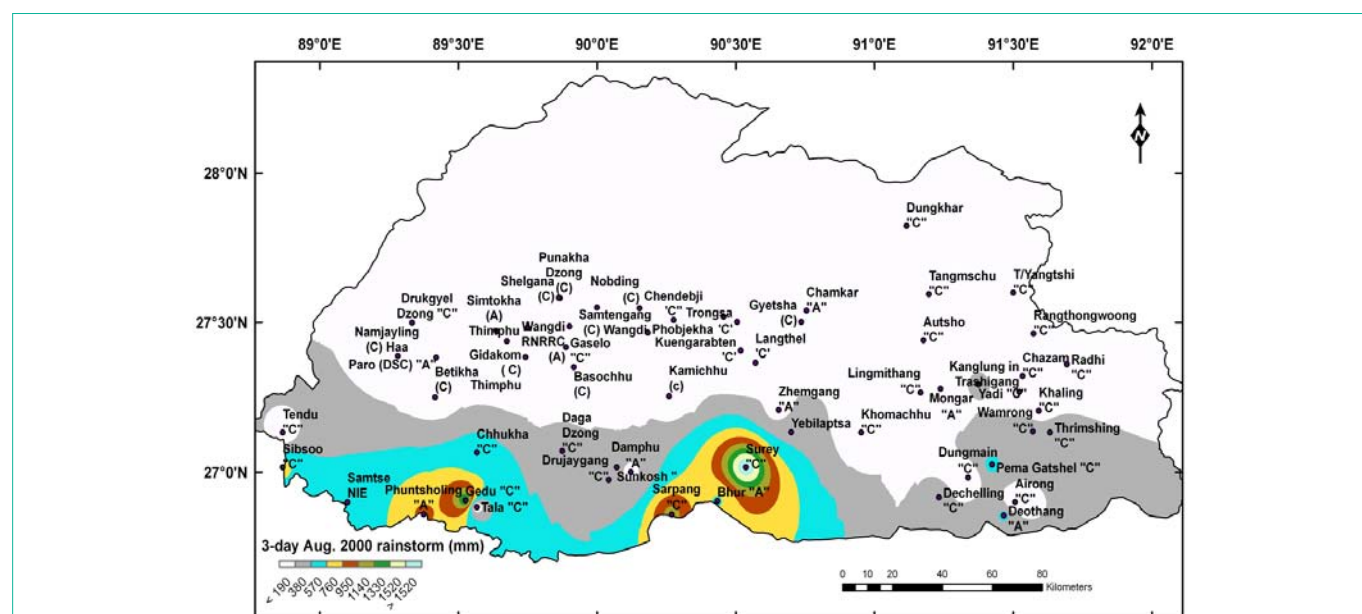
**Figure 19:** 3-day spatial distribution of 2-4 Aug. 2000 rainstorm over Bhutan.

Table 12: Average raindepths mm for severe rainstorm for Manas basin in Bhutan.

Rainstorm	Average Raindepths mm for		
	1-day	2-day	3-day
11-13 Jul. 1996	50.9 13/7 Pema Gatshel "C"	93.5 12-13/7 Pema Gatshel "C"	112.2 Pema Gatshel "C"
5-7 Jul. 1998	44.7 7/7 Dungmain "C"	76.1 6-7/7 Dungmain "C"	101.8 Dungmain "C"
18-20 Oct. 1999	42.2 19/10 Yebilaptsa	73.8 19-20/10 Chendebeji "C"	96.1 Chendebeji "C"
2-4 Aug. 2000	59.7 3/8 Surey "C"	118.3 2-3/8 Surey "C"	159.8 Surey "C"

Note: Figs. in brackets indicate the date of occurrence and centre of the rainstorm

period daily rainfall data, severe rainstorms were selected for DAD analysis. Of all the severe rainstorms, 24-26 Jun., 1931 rainstorm (Figure 19) produced highest raindepths for 1, 2 and 3-day durations over and near these two basins. As the region is highly mountainous, rainstorm transposition has not been carried out. But by applying suitable elevation correction (EC) factor to envelope DAD raindepths, SPS raindepths were obtained. PMP was evaluated by applying appropriate MMF to SPS raindepths (Table 11).

Using Hershfield statistical technique [41,42] estimates of PMP for all stations in and around the two basins were made based on available rainfall data for 1 to 3-day durations (Table 11). However, it may be mentioned here that estimation of any statistical parameter should be based upon long period data series, i.e. > 30 years. Since the length of rainfall records for stations in the Subansiri and Siang basins are rather short, the above PMP estimates may be considered as the tentative and are subjective to change as and when more rainfall data becomes available in the study region.

Manas basin, which is a trans-boundary catchment of Bhutan and Assam (India) has experienced 6 to 7 rainstorms in the recent past, of which 11-13 Jul., 1996, 5-7 Jul., 1998, 18- 20 Oct., 1999 and 2-4 Aug., 2000 rainstorms were found to be the most severe one and their average raindepths are given in Table 12 for 1, 2 and 3-day durations. The 3-day spatial distribution of 2-4 Aug. 2000 rainstorms is shown in Figure 20. The most noteworthy heavy rain spells experienced over the sub-Himalayan West Bengal-Sikkim section are 11-13 June 1950 and 3-5 October 1968 (Figure 20) [74].

By considering the orography of the region, Depth-Duration (DD) analysis is the most suitable technique applicable for rainfall analysis of the region. SPS raindepths obtained from the DD analysis and PMP derived from maximization of SPS values would have been the most appropriate ones to use for any hydrology purposes.

Flood studies [35,75,70,24,76,77,79,23,78,80-87] over the Brahmaputra basin showed that frequency of floods are quite high in the rivers of northeast India. The highest flood deviation recorded by different (G/D) sites at these rivers (Table 13) during the period of 1986 to 2010 showed that rivers, Jibareilly, Manas and Teesta recorded highest flood deviation more than 10.0m during the last 25 years.

Although Bhutan does not have comprehensive precipitation data, on the available data it was observed that the eastern and southern foothill regions of Bhutan, which have intensively dissected terrains with deeply eroded, steep and closely spaced gullies, gorges and river valleys, often experience floods caused by heavy rainfall. A noteworthy flash flood of 2004 affected six eastern Dzongkhags, of which Trashigang, Trashiyangtse and Samdrup Jongkhar were the most affected areas with damages to property and livestock.

Conclusion

At present, the enormous water resources of the Ganga and Brahmaputra river are not fully utilized and practically most of its flood waters is running waste into the Bay of Bengal through Bangladesh after causing enormous damage by way of ravaging floods in north and northeast India, Nepal and Bangladesh. Though there is not much scope for increasing irrigation facilities in the Assam valley beyond a certain limit due to lack of proper storage sites especially in the main Brahmaputra river and some of its tributaries, but there is enormous potential for hydropower generation in this region especially at the "Great Bend" of the Dihang river when it enters India from Tibet and in some of its tributaries. The Brahmaputra Board in their Report on Dihang Project [88] stated that most of the hydropower potential of India is concentrated in the Brahmaputra basin, out of which, more than 80% lies in the Siang and the Subansiri river basins. A realistic assessment of this vast water resource is most

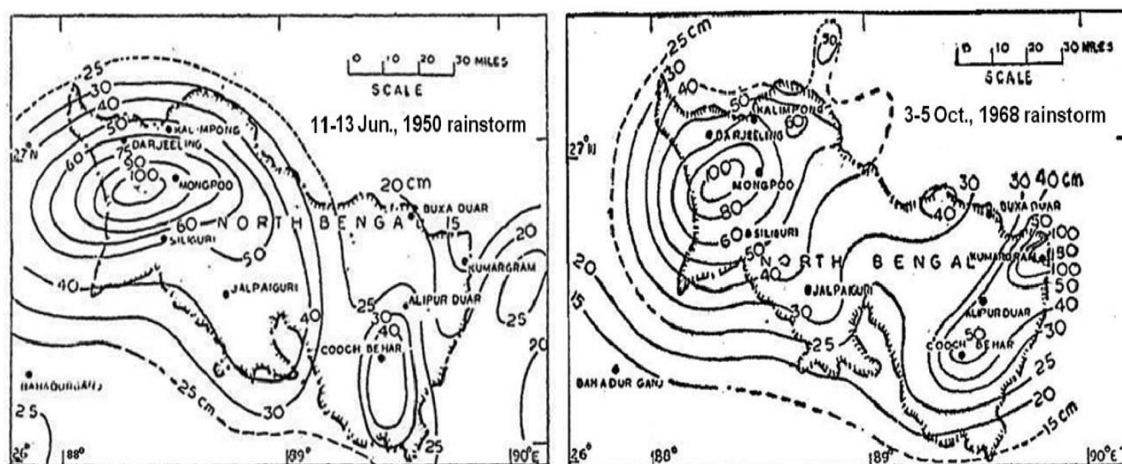
**Figure 20:** 3-day isohyetal cm map of 1950 and 1968 rainstorm over northern region of sub-Himalayan West Bengal.

Table 13: Highest flood deviations recorded at G/D sites on the Brahmaputra and its tributaries 1986-2010.

	River	Gauge/ Discharge Site	Danger Level m	Highest Deviation m	Date of Occurrence
a	Main Brahmaputra river :				
1	Brahmaputra	Dibrugarh	104.24	2.24	03/09/1998
		Nematighat	85.04	2.33	11/07/1991
		Tezpur	65.23	1.36	27/08/1988
		Guwahati	49.68	2.55	08/08/2000
		Goalpara	36.27	1.16	31/08/1954
		Dhubri	28.62	1.74	28/08/1988
b	Northern tributaries of the Brahmaputra river :				
2	Subansiri	Badatighat	82.53	4.31	28/06/1972
3	Jaibareilly	N.T.Rd. Crossing	77.00	12.22	22/09/2010
4	Putthimari	N.H.Crossing	51.81	4.65	20/06/1993
5	Pagladiya	N.T.Rd.Crossing	52.75	2.72	08/07/2004
6	Manas	N.H.Crossing	47.56	11.03	13/07/1984
7	Beki	N.H.Crossing	45.10	1.10	04/08/2000
		Road Bridge	44.38	1.78	04/08/2000
c	Rivers joining the Brahmaputra in Bangla Desh :				
8	Raidak	Tufanganj	35.30	1.06	21/07/1993
9	Torsa	Ghugumari Cooch Behar	40.41	1.05	03/08/2000
10	Jaldhaka	Nagarkata	185.60	7.75	1954
11	Teesta	Anderson Bridge	210.50	18.10	04/10/1968
		Coronation Bridge	149.40	10.65	10/1968

essential to plan optimum utilization of water available in these basins.

Similar is the case with the Kosi, the Gandak and the Karnali basin in Nepal. All this has to be tapped fully for the proper development in the coming years. This, of course, can be done with the full cooperation between India, Nepal, Bhutan and Bangladesh so far as the developments of water resources projects of this region are concerned.

Acknowledgement

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