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Devastating rainstorm of June-2013 in Uttarakhand

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सार – उत्तराखंड राज्य अपनी स्थलाकृति के कारण बाढ़ और भूस्खलन की चपेट में आ जाता है। उत्तराखंड राज्य और उसके आसपास के राज्यों में 15-18 जून, 2013 के दौरान भारी से अत्यधिक भारी वर्षा हुई। इस तूफानी वर्षा का महत्व इसलिए है क्योंकि इसी के वजह से भीषण बाढ़, भूस्खलन, हजारों की संख्या में जानमाल आदि की क्षति हुई। इस अवधि के दौरान उत्तराखंड राज्य और उसके आसपास के राज्यों जैसे:- हिमाचल प्रदेश, हरियाणा और पंजाब में भी अत्यधिक भारी वर्षा (एक दिन में 24.5 से.मी. से अधिक) के साथ भारी वर्षा के होने की रिपोर्ट दर्ज की गई। उत्तराखंड का अधिकांश भाग वृहत्तर हिमालयी क्षेत्र में आता है। बाढ़ से बचने के लिए हाइड्रोलिक संरचनाओं के रूप में जल भंडारण करना इसका एक उपाय है। हाइड्रोलिक संरचनाओं के बनाने की योजना एवं डिजाइनिंग के लिए डिजाइन स्टॉर्म का आकलन तथा बाढ़ के डिजाइन से संबंधित मौलिक जानकारियों को आकलित करना प्रमुख है। डिज़ाइन तूफान का आकलन करने के लिए उन सभी क्षेत्रों या उसके आसपास के क्षेत्रों जहाँ भारी तूफानी वर्षा की घटना घटती है उनका विश्लेषण किया गया है। इस शोध पत्र में विस्तृत क्षेत्र में हुई इस तूफानी वर्षा और अन्य भारी तूफानी वर्षा का उस क्षेत्र में हाइड्रॉलिक संरचनाओं के डिज़ाइन तूफान का परिकलन करने के उद्देश्य से विश्लेषण किया गया है। जून 2013 में हुई इस तूफानी वर्षा की तुलना इतिहास में इससे पहले 28-30 सितम्बर, 1924 में लैंसडाउन में हुई भारी तूफानी वर्षा से की गई है। इनकी परस्पर तुलना से यह पता चला कि जून 2013 में हुई तूफानी वर्षा की मात्रा सितम्बर 1924 में लैंसडाउन में हुई वर्षा से ज्यादा थी। जो 1 दिन की अवधि में 5000 वर्ग कि.मी. में थी। जबकि DAD के आकलन के अनुसार सितम्बर 1924 में दो और तीन दिनों की अवधि में हुई तूफानी वर्षा की मात्रा जून 2013 की तूफानी वर्षा से काफी अधिक थी और यह 20,000 वर्ग कि.मी. के क्षेत्र में थी।

ABSTRACT. The state of Uttarakhand is prone to floods and landslides due to its topographic location. The state of Uttarakhand and neighbouring states experienced heavy to very heavy rainfall during 15-18 June, 2013. The analysis of this rainstorm is important because it caused severe floods, landslides, loss of thousands of lives, property etc. During this period, many stations reported very heavy rainfall with a few extremely heavy rainfall (more than 24.5 cm in a day) in Uttarakhand and also in the neighbouring states of Himachal Pradesh, Haryana and Punjab. Most part of the state of Uttarakhand lies in the Greater Himalayan region. For safety from floods, one of the methods is to store water in hydraulic structures. For planning and designing of hydraulic structures, the estimation of design storm is the primary and the basic input for the computation of design flood. In the estimation of design storm, all the heavy rainstorms occurred over or near the area have to be analysed. In this paper, this rainstorm and other heavy rainstorms over a wide area has been analysed for the purpose of computation of Design storm estimates of hydraulic structures in that area. The rainstorm of June 2013 is compared with the earlier historical heaviest rainstorm of 28^{th} to 30^{th} September, 1924 at Lansdowne and it is observed that the rainstorm of June 2013 has contributed more rainfall than the rainstorm of September 1924 rainstorm for an area up to 5000 km^2 for 1-day duration, while the DAD estimates for two day and three duration of rainstorm of September 1924 are higher than the rainstorm of June 2013 for area up to 20,000 km^2.

Key words – Rainstorm, Heavy rainfall, Uttarakhand, PMP, GIS.

1. Introduction

The state of Uttarakhand lies in the northern part of India and most part of the state lies in the Greater Himalayan region. The region is renowned for its natural beauty, as well as pilgrimage sites which dot the upper reaches of the hills. Millions of pilgrims visited the famous worship places namely, Kedarnath, Badrinath, Gangotri, Yamunotri and Hemkund Sahib every year. Uttarakhand has a total area of 53,484 km^2, 93% of area is covered by mountains and 64% is covered by forest. It is geographically fragile and highly eco-sensitive and hence prone to natural disasters including floods and landslides in almost every monsoon season. Two largest rivers, Ganges and Yamuna, originate in the glaciers of Uttarakhand, where they are fed by myriad lakes, glacial

TABLE 1

Station wise 1-day highest recorded Rainfall along with date (upto 2012)

S. No.	Station Name	District Name	1-Day highest recorded rainfall (mm)	Date	S. No.	Station Name	District Name	1-Day highest recorded rainfall (mm)	Date
1.	Almora	Almora	223	29 Sep 1924	30.	P. Nagar A	Nainital	193	19 Aug 2003
2.	Chaubattia	Almora	120	15 Sep 1972	31.	Ramnagar	Nainital	291	14 Oct 1985
3.	Ranikhet	Almora	351	16 Jun 1970	32.	Rudrapur	Nainital	307	25 Jul 1907
4.	Badrinath	Chamoli	121	4 Jul 1958	33.	Bironkhol	PauriGarhwal	255	29 Sep 1924
5.	Chamoli	Chamoli	120	11 Aug 1983	34.	Kotdwara	PauriGarhwal	274	23 Aug 1922
6.	Ghangaria	Chamoli	136	25 Dec 1985	35.	Landsdown	PauriGarhwal	323	29 Sep 1924
7.	Joshimath	Chamoli	273	21 Jul 1970	36.	Pauri	PauriGarhwal	309	5 Aug 1982
8.	Karnaprayag	Chamoli	250	10 May 1971	37.	Srinagar	PauriGarhwal	135	29 Sep 1924
9.	Lokapa	Chamoli	158	23 Mar 1967	38.	Deoprayag	Tehri-Garhwal	216	9 Oct 1956
10.	Okhimath	Chamoli	208	8 Aug 1925	39.	Dhanolti	Tehri-Garhwal	188	17 Jul 1972
11.	Rudraprayag	Chamoli	300	20 May 2005	40.	Keertinagar	Tehri-Garhwal	311	31 May 1971
12.	Tapoban	Chamoli	191	27 Jul 1952	41.	Mukhim	Tehri-Garhwal	450	5 Sep 1995
13.	Bhogpur	Dehra Dun	307	17 Aug 1921	42.	Narendranagar	Tehri-Garhwal	272	31 Jul 1955
14.	Dehra Dun	Dehra Dun	487	25 Jul 1966	43.	Tehri	Tehri-Garhwal	195	12 Dec 1957
15.	Mussoorie	Dehra Dun	317	5 Aug 1964	44.	Tehri-Garhwal	Tehri-Garhwal	151	9 Oct 1956
16.	Hardwar	Hardwar	356	13 Aug 1910	45.	Barkote	Uttar-Kashi	152	25 Sep 1988
17.	Roorkee	Hardwar	258	15 Sep 1957	46.	Bhatwari	Uttar-Kashi	300	15 Jul 1985
18.	Bazpur	Nainital	299	21 Jul 1954	47.	Dunda	Uttar-Kashi	150	14 Aug 1982
19.	Gadarpur	Nainital	274	5 Jul 1950	48.	Maneri(G)	Uttar-Kashi	350	22 Jan 1985
20.	Haldwani	Nainital	413	11 Jul 1970	49.	Naitwar	Uttar-Kashi	210	10 Feb 1986
21.	Kaladhungi	Nainital	413	10 Jul 1970	50.	Purola	Uttar-Kashi	127	17 Oct 1998
22.	Kashipur	Nainital	315	2 Oct 1954	51.	Uttar Kashi	Uttar-Kashi	150	20 Aug 1988
23.	Kathgodam	Nainital	283	12 Jul 1949	52.	Ambari	Dehra Dun	318	2 Aug 1907
24.	Khatima	Nainital	406	15 Sep 1972	53.	Chakrata Kalsi	Dehra Dun	229	4 Feb 1926
25.	Kilpuri	Nainital	285	19 Jun 1916	54.	Dakpathar	Dehra Dun	485	20 May 1986
26.	Mukteshwar	Nainital	255	18 Sep 1914	55.	Haripur	Dehra Dun	265	3 Aug 2001
27.	Nagla	Nainital	326	20 Sep 1922	56.	Koti	Dehra Dun	215	20 Jul 1982
28.	Nainital	Nainital	399	24 Aug 1927	57.	Tiuni	Dehra Dun	122	27 Jun 2001
29.	Pantnagar	Nainital	203	5 Jul 1988	58.	Rajgarhi	Uttar-Kashi	370	28 May 1971

melts and streams. In the monsoon season 2013, there was an exceptional disaster occurred in Uttarakhand associated with widespread heavy rainfall. The description of this event is mentioned in the Monsoon report 2013 of IMD (2014). The onset of monsoon in the state was relatively early, resulting in heavy to very heavy rainfall in and around the state from 15th to 18th June 2013. Various factors, namely prolonged and wide spread heavy rains, high melting rate of glaciers during the period and snow fall prior to rainfall in the region had resulted in abnormally high discharge in all major rivers in the state. Heavy rainfall events are not rare in this region but during this period devastating floods were occurred which caused thousands of deaths and destruction to property. In

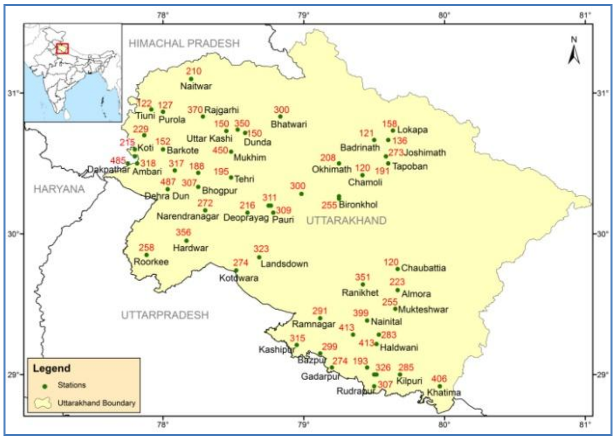

Fig. 1. 1-day highest rainfall (mm) of stations in Uttarakhand

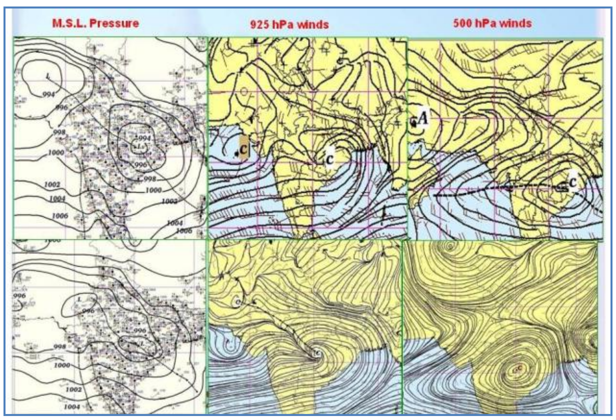

Fig. 2. Synoptic charts for 14th & 15th June, 2013

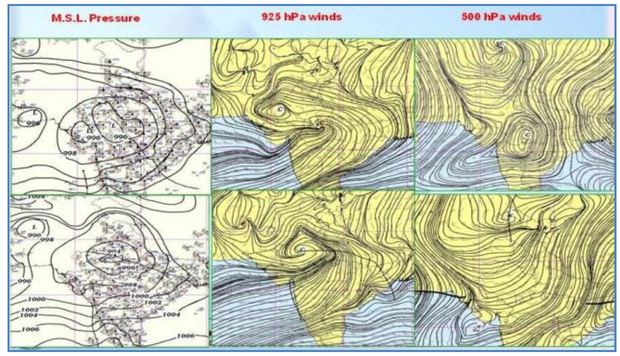

Fig. 3. Synoptic charts for 16th & 17th June, 2013

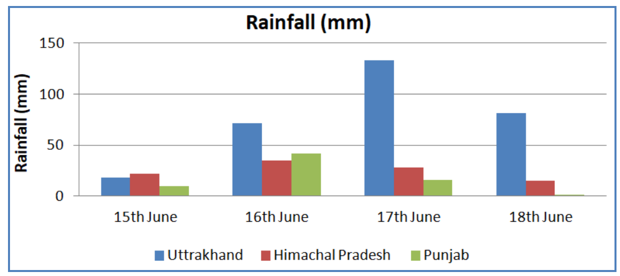

Fig. 4. Daily average Rainfall during 15th to 18th June over 3 states

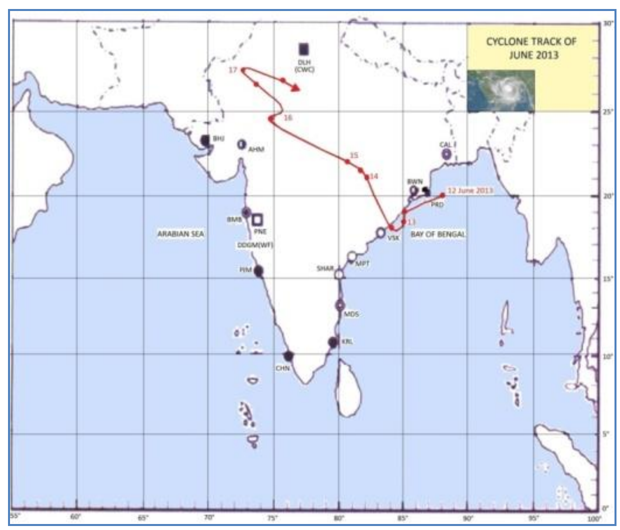

Fig. 5. Track of June 2013 Storm

addition to rainfall, the local anthropogenic factors like deforestation, slope cutting, construction in river bank etc. also contributed in the devastating flood peaks. Such activities are largely related to extensive and growing pilgrimage and tourist in the state.

The hydraulic structures like dam etc. also provide safety against floods. In the June 2013 rainstorm, the Tehri dam actually observed the flood wave of Bhagirathi river, a tributary of Ganga, on 16th June, thereby mitigating downstream flood damage. For safety from floods, more structures can be constructed and for the designing of new hydraulic structures or for reviewing existing structures, the design storm estimates are required to compute the contribution of floods from the catchment areas above that structure to minimise the risk.The design storm estimates consist of highest rain depth magnitudes in the form of standard project storms (SPS) and probable maximum precipitation (PMP) from the analysis of severe rainstorms, and the time distribution. Dube *et al*. (2005) have listed the extreme weather events over India in the last 100 years. Ramaswamy (1987) has studied the meteorological aspects of severe floods in India during the period 1923-1979 and mentioned the heavy rainstorm of 28-30 September, 1924 over Uttarakhand. Many authors have computed design estimates for different projects/ basins/zones. Kulkarni *et al*. (2010) have computed zonal estimation of PMP over Krishna basin in peninsular India. Nandargi and Dhar (2012) have studied the extreme rainfall events over the northwest Himalayas during 1875-2010. They have mentioned that 5 heavy rainstorm events

TABLE 2

State-wise average rainfall

State	Average Rainfall (mm)			
	15th June	16th June	17th June	18th June
Uttarakhand	17.8	71.7	133.3	81.4
Himachal Pradesh	22.0	35.0	27.8	15.4
Punjab	9.7	41.9	15.5	1.1

TABLE 3

Stations recorded 100 mm or more rainfall

Date	Stations Recorded 100 mm or more Rainfall
15th June, 2013	State: Himachal Pradesh : Nagrota Surian 120
	State: Punjab : Kapurthala 100
	State: Uttar Pradesh : Thakudwara 140
16th June, 2013	State: Haryana : Jagadhari 105
	State: Himachal Pradesh : Paonta 180, Renuka/Adhau 140
	State: Punjab : Balachaur 121, Muktsar 124
	State: Uttarakahnd : Barkot 113, Dehradun 220, Deoprayag 130, Dunda 118, Hardwar 108, Jakholi 121, Kosani (U Prob) 105, Mussoorie 137, Purola 165, Tehri 122, Tehri (Cwc) 124, Uttarkashi 129, Uttarkashi (Cwc) 122
17th June, 2013	State: Haryana : Bilaspur 270, Chhachhrauli 271, Jagadhari 261
	State: Himachal Pradesh : Kalpa 194, Paonta 405, Renuka/Dadhau 149, Sangraha 113
	State: Uttarakhand : Bageshwar(Thmo) 161, Dehradun 370, Deoprayag 163, Dunda 185, Haldwani 200, Hardwar 218, Jakholi 108, Joshimath 114, Kosani (U Prob) 205, Mukteshwar 237, Mussoorie 155, Nainital 176, Roorkee 147, Tehri 169, Tehri (Cwc) 168, Tharali 173, Uttarkashi 162, Uttarkashi (Cwc) 207
	State: Uttar Pradesh : Anupshahr 138, Dhaurahara 100, Harpur 163, Kheri Lakhimpur 114, Mawana 100, Meerut 116, Nakur 153, Saharanpur 204, Sawayajpur 140
18th June, 2013	State: Uttarakhand : Almora 100, Bambasa 230, Chamoli 100, Haldwani 278, Mukteshwar 183, Nainital 170, Pantanagar 113, Pithoragarh 117, Ranikhet(G) 120
	State: Uttar Pradesh : Ayodhya 103, Baheri 237, Bansi Cwc 205, Champawat 222, Elgin Bridge 115, Gorakhpur 105, Kaiserganj 130, Laharpur 125, Nagina 120, Palliakalan, Thakurdwara 127

occurred over NW Himalayas and 1 out of these 5 events occurred over Uttarakhand. The method of computation of design storm estimates is described in detail in WMO No. 1045 (2009). In this paper, the design storm estimates has been computed for very heavy rainstorms over Uttarakhand.

TABLE 4

DAD estimates (cm)

Area (sq. km)	1-day (17 June, 2013)	2-day (16-17 June, 2013)	3-day (16-18 June, 2013)	3-day (15-17 June, 2013)
Max. point value (25 sq km)	40.5	59.0	61.3	64.4
500	39.5	57.3	60.2	63.2
1000	38.5	55.5	59.0	62.2
2000	36.7	52.4	57.1	59.6
5000	32.4	45.2	52.7	53.0
10000	26.9	38.3	46.5	44.5
20000	21.4	31.0	38.5	35.6

2. Data used

The daily historical rainfall data from the year 1901 to 2014 of about 150 stations in and around Uttarakhand have been used in selection of heavy rainfall rainstorms over the area. The 1-day highest ever recorded rainfall at different stations in Uttarakhand are given in Table 1 and also shown in Fig. 1. The nine self recording raingauge stations *viz*., Bageshwar, Devprayag, Gangolihat, Jakholi, Pati, Srinagar, Tharali and Rishikesh and hourly rainfall data from 36 AWS and ARG stations located in and around Uttarakhand have been used to analyze the short duration (1-hr, 3-hr and 6-hr) rainstorms as well as time distribution curves.

3. Methodology

The huge devastation occurred in Uttarakhand during the period 15th to 18th June, 2013. The rainstorm of June 2013 has been analysed and compared with the earlier historical rainstorms occurred over that area. The synoptic situation, spatial distribution, DAD analysis, MAF and time distribution curves corresponding to the heavy rainstorms are discussed in the following paragraphs. In the hilly region, rainstorms are not transposed from plain to hills or from one hilly region to another due to non homogeneous regions. Normally, design estimates are computed based on the DAD analysis subjected to suitably applicable altitude correction factor.

3.1. *Synoptic system responsible for the rainstorm of 15-18 June, 2013*

The main features which are responsible for the heavy to very heavy monsoon rainfall during 15-18 June, 2013 over Uttarakhand is due to strong interaction between an oncoming trough in the westerly in association

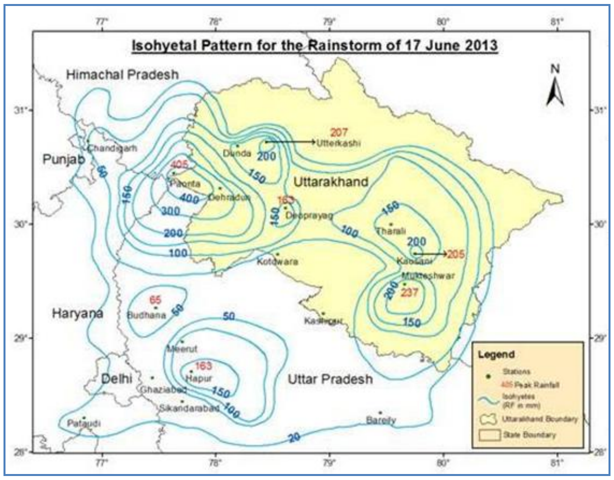

Fig. 6. Isohyetal pattern of the rainstorm of 17th June, 2013

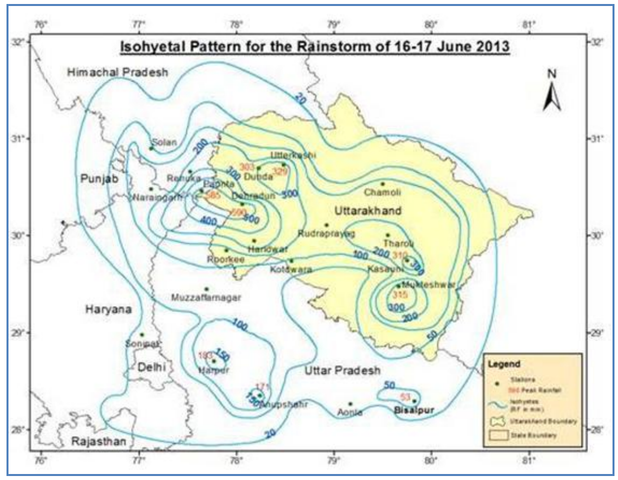

Fig. 7. Isohyetal pattern for the rainstorm of 16-17 June, 2013

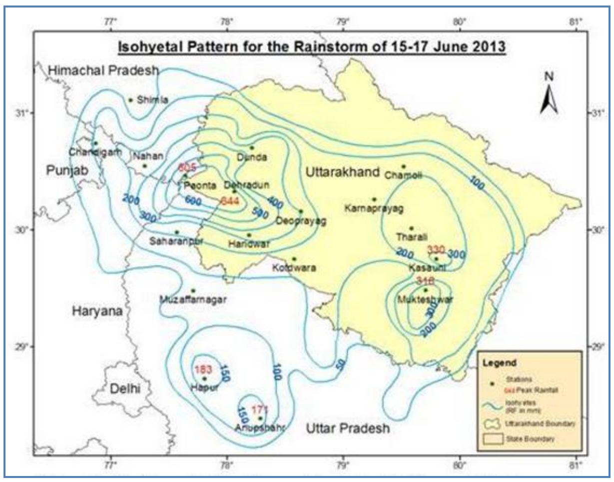

Fig. 8. Isohyetal pattern of the rainstorm of 15-17 June, 2013

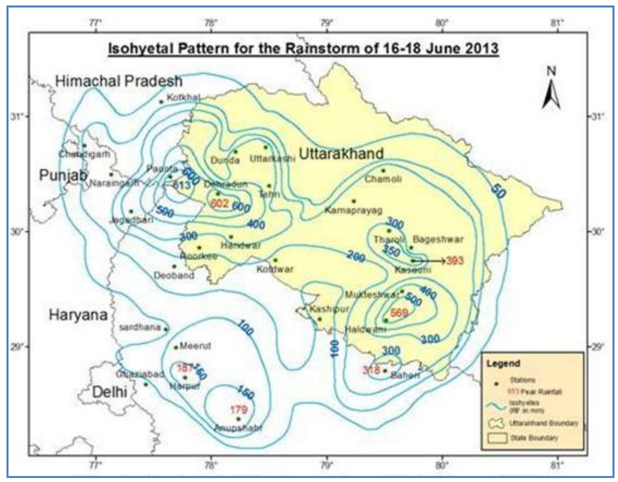

Fig. 9. Isohyetal pattern of the rainstorm of 16-18 June, 2013

with western disturbance and the strong south easterly monsoon wind flow in association with a monsoon low pressure system over the North Indian region. A monsoon low pressure area formed over northwest Bay of Bengal on 12th June, 2013. The monsoon low had a west-northwestward movement and migrated from Odisha to Vidarbha between 13th and 15th June and to west Madhya Pradesh on 16th June and reached up to northeast Rajasthan and Haryana on 18th June, 2013. The western disturbance also moves across north India from west to east during the period. This results into development of lower tropospheric wind convergence over the Uttarakhand and neighbouring regions. This, with strong orographic effect due to high terrain when coupled by the strong moisture feeding from both the Arabian Sea and Bay of Bengal triggered heavy rainfall activity, over the North Indian region as shown in Figs. 2 & 3. The episode was unique in that, the line of convergence of the two weather systems was nearly stationary for hours at a time, resulting in huge amount of accumulated rainfall over parts of North India causing widespread rain. The state wise average daily rainfall occurred during 15-18 June, 2013 is given in Table 2 and in Fig. 4. The track of this system causing unexpected rainfall is given in Fig. 5.

It can be seen from Table 2 that during this period of 15-18 June, 2013, the maximum rainfall occurred over Uttarakhand State and resulting in heavy floods.

3.2. *Spatial distribution of June-2013 rainstorm*

The rainfall of the stations of this rainstorm is subjected to isohyetal analysis by taking storm as a unit for 1-day (17th June), 2-day (16-17 June) and 3-day (15-17 June) & 3-day (16-18 June) cumulative rainfall. The station wise rainfall in respect of the stations recorded rainfall 100 mm or more in one day of this rainstorm is

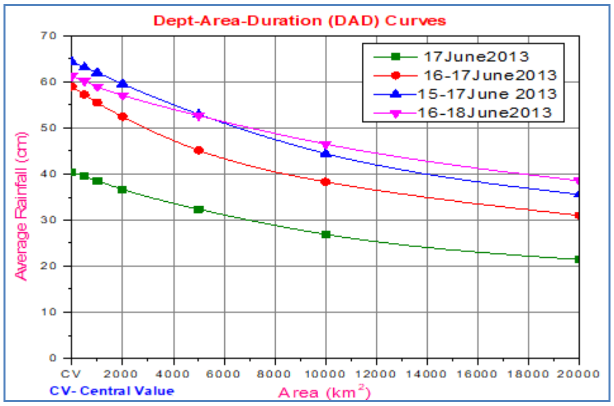

Fig. 10. Depth area duration curve for rainstorm of June, 2013

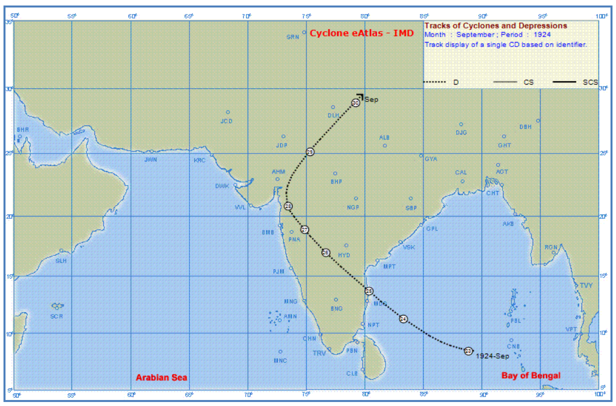

Fig. 11. Track of Sept, 1924 Storm

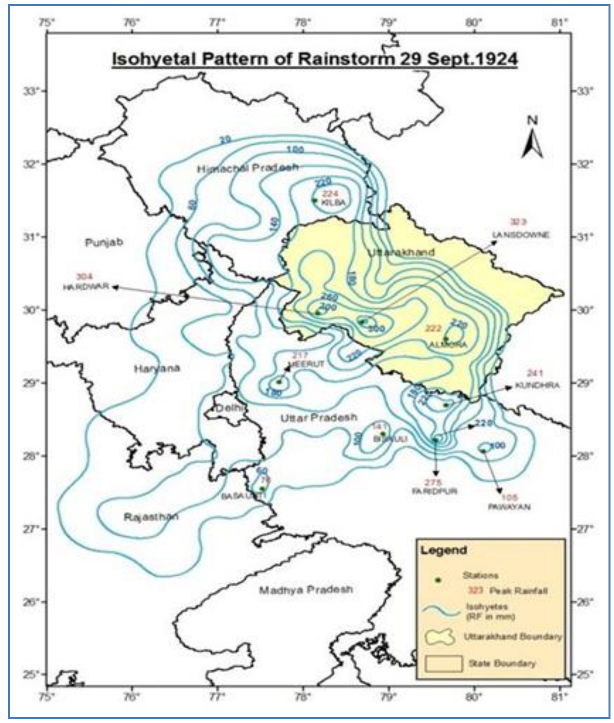

Fig. 12. Isohyetal pattern for 29th September, 1924 rainstorm

given in Table 3. The isohyetal patterns for one day, two day and three day durations are given in Figs 6, 7, 8 & 9 respectively. The Depth Area Duration (DAD) values for different areas (upto 20,000 km^2) are derived and the corresponding rain depths are given in Table 4 and DAD Curves for 1-day, 2-day and 3-day durations are given in Fig. 10. It can be seen that the 3-day rainfall values are higher for 15-17th June, 2013 rainstorm up to 5500 km^2 and beyond that the rainfall values are higher for 16-18th June, 2013 rainstorm.

It is also seen that the rainfall distribution is wide spread in most of the part of Uttarakhand but the center of the storm has been shifting from Paonta (H.P.) to Dehradun for different duration of rainstorms. The one day storm center on 17th June was at Paonta, two day storm of 16-17th June was centered at Dehradun, three day storm of 15-17th June was centered at Dehradun and three day storm of 16-18th June was again centered at Paonta.

3.3. *Comparison with the historical rainstorm prior to 2013*

The heavy rainstorms prior to 2013 were selected and analysed. It is found that the rainstorm of 28th to 30th September, 1924 is the heaviest rainstorm. This rainstorm is compared with the June 2013 rainstorm.

3.3.1. *Synoptic situation of rainstorm of 28-30 September, 1924 at Lansdowne*

The rainstorm of 28-30 September, 1924 occurred over the upper Ganga and Yamuna catchments was a result of a depression of 23-30 September, 1924. It formed near the Andaman Sea on the morning of 23 September and passed through Maharashtra on 27th September. Thereafter, the depression moved north-northwest and then north. It subsequently curved to northeast and dissipated over the lower Himalayan hills causing exceptionally heavy and continuous rain there as well as over the adjacent areas from 28 to 30 September. The track of the depression is given in Fig. 11.

Under its influence, the heaviest rainfall occurred over the upper Ganga catchment during 28-30 September. The area under the storm recorded 1-day maximum rainfall on 29th September, 2-day maximum rainfall for 28-29 September and 3-day maximum rainfall for 28-30 September. The centre of the rainstorm was located at Lansdowne (29.83° N, 78.68° E) in Uttarakhand, which recorded 323 mm, 594 mm and 774 mm of rainfall in 1, 2 and 3-days rainstorm respectively. The isohyetal pattern of the rainstorms with centre at Lansdowne of 1 day, 2 day and 3 day rainstorms are given in (Figs. 12-14).

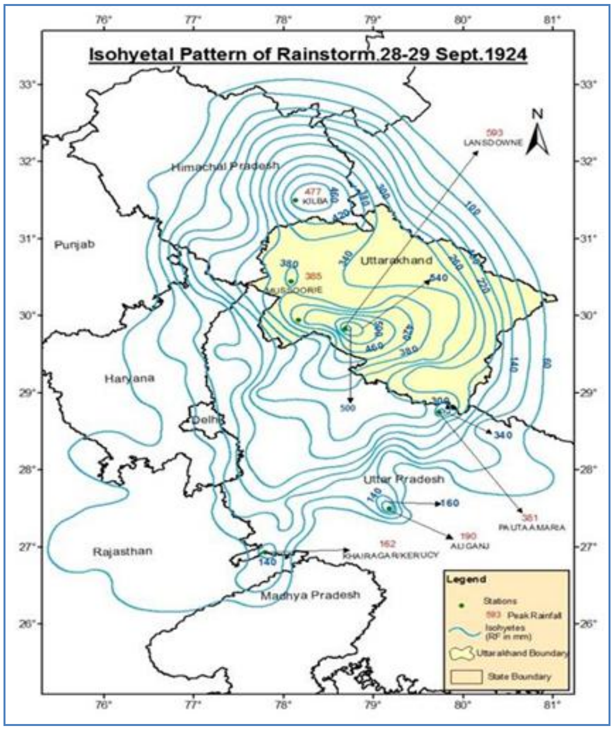

Fig. 13. Isohyetal pattern for 28-29 September, 1924 rainstorm

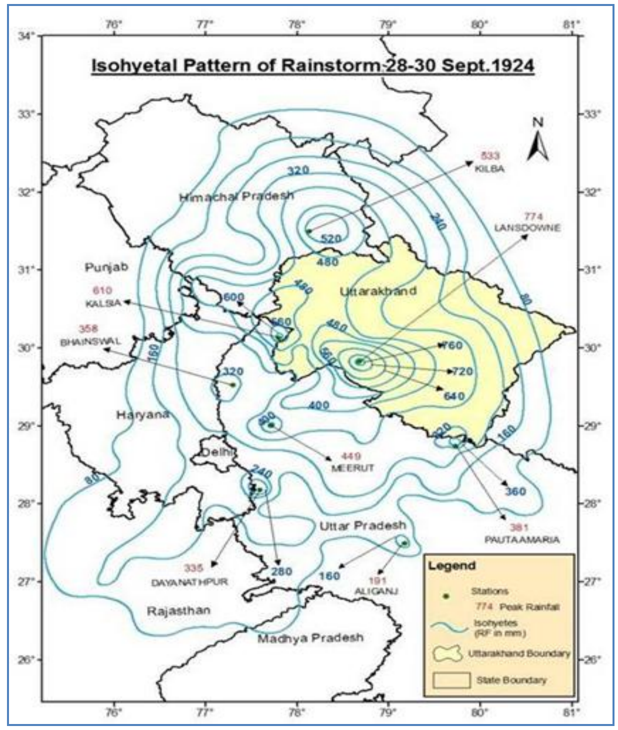

Fig. 14. Isohyetal pattern for 28-30 September, 1924 rainstorm

3.3.2 *Spatial distribution of rainstorm of 28-30 September, 1924 at Lansdowne*

The rainfall of the stations of this rainstorm is subjected to isohyetal analysis by taking storm as a unit for 1-day (28^{th} September), 2-day (28-29 September) and 3-day (28-30 September) cumulative rainfall. The Depth Area Duration (DAD) values for different areas (up to 20,000 km^2) are derived.

3.3.3. *Comparison of two heavy rainstorms*

The results of DAD analysis of the rainstorm of June-2013 at Poanta/Dehradun are compared with the historical rainstorm of 28-30 September, 1924 at Lansdowne. The comparative study is given in Table 5.The study revealed that for one day duration, the rainstorm of June-2013 contributed more rainfall than the rainstorm of Sept-1924 up to an area of 5000 km^2 but after 5000 sq km DAD values of September 1924 storm are higher than the storm of June 2013. However, for 2day and 3 day durations, the rainfall contributions of September-1924 rainstorm are higher for any area.

3.4. *Moisture adjustment factor (MAF)*

The moisture adjustment is a ratio of the perceptible water corresponding to the maximum persistent dew point temperature of the station which is representative of the storm to the perceptible water corresponding to the persistent dew point temperature during the storm period. The 1-day maximum persisting dew point temperatures for stations have been taken from IMD (2000). The Moisture Adjustment Factor for the rainstorm of June, 2013 is of the order of 1.33 which is computed on the basis of dew point temperature of Dehradun whereas it is 1.57 for the rainstorm of September 1924 computed on the basis of dew point temperature of Roorkee station.

3.5. *Time distribution of June 2013 storm rainfall*

The temporal distribution of rainfall is an important component of a design storm. Normally 3-hourly time distribution of 24-hour and 48-hour rainfall meets most of the requirements of design engineers. Here nine self recording raingauge stations *viz*., Bageshwar, Devprayag, Gangolihat, Jakholi, Pati, Srinagar, Tharali and Rishikesh for which continuous rainfall data for this rainstorm of June-2013 is available, have been selected for computing time distribution.

Time distribution analysis 24-hour and 48-hour rainstorms at each station are carried out separately on the basis of 3 consecutive clock hour duration rainfall data in respect of each rainstorm. In each rainstorm any 3-hour

TABLE 5

Comparative values of Depth Area Duration (DAD) values (cm)

Area (sq.km)	1-day		2-day		3-day	
	17 June, 2013	29 Sept, 1924	16-17 June, 2013	28-29 Sept, 1924	16-18 June, 2013	28-30 Sept, 1924
Point Value	40.5	32.3	59.0	59.3	61.3	77.4
500	39.5	32.1	57.3	58.8	60.2	76.6
1000	38.5	31.2	55.5	57.5	59.0	75.8
2000	36.5	30.1	52.4	52.5	57.1	68.8
5000	32.4	29.7	45.2	51.2	52.7	67.2
10000	26.9	27.9	38.3	46.8	46.5	61.2
20000	21.4	25.6	31.0	42.4	38.5	54.1

TABLE 6(a)

Time distribution for 24-storm rainfall

Hours	3	6	9	12	15	18	21	24
Average	28	45	57	67	77	85	93	100
Envelope	38	62	80	88	94	98	99	100

TABLE 6(b)

Time distribution for 48-storm rainfall

Hours	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	48
Average	18	28	37	46	53	59	65	70	75	79	83	87	91	95	98	100
Envelope	23	35	45	45	65	72	77	82	86	90	93	96	98	99	100	100

TABLE 7

Areal Reduction Factor (ARF) for 1 hour, 3-hours and 6-hours rainstorm

Area	1-Hour			3-Hours			6-Hours		
	AVG RF (mm)	ARF	% Reduction Factor	AVG RF (mm)	ARF	% Reduction Factor	AVG RF (mm)	ARF	% Reduction Factor
1000	44.9	0.64	35.8	110.7	0.76	24.1	123.5	0.85	15.4
2000	38.1	0.54	45.6	96.3	0.66	34	112.2	0.77	23.1
3000	33.3	0.48	52.5	86.9	0.59	40.5	102.2	0.7	30
4000	29.8	0.43	57.4	80.1	0.55	45.2	95	0.65	34.9
5000	27	0.39	61.4	73.7	0.5	49.6	87.8	0.6	39.9
6000	25.3	0.36	63.8	68.2	0.47	53.3	81.4	0.56	44.2
7000	23.9	0.34	65.8	63.6	0.44	56.4	76.9	0.53	47.3
8000	22.5	0.32	67.8	60.2	0.41	58.8	72.4	0.5	50.4
9000	21.1	0.3	69.8	56.8	0.39	61.1	67.9	0.46	53.5
10000	20	0.29	71.5	53.4	0.37	63.4	64.4	0.44	55.9

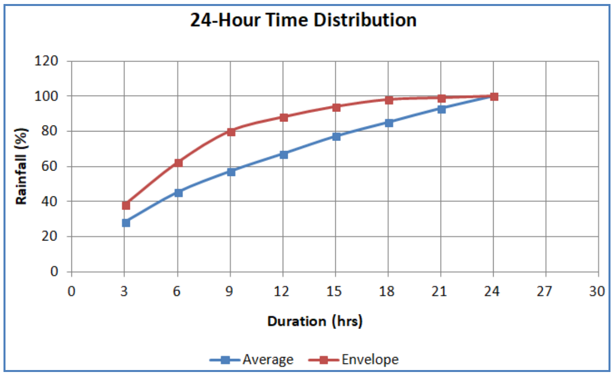

Fig. 15. Time distribution curve for 24-hour rainstorm

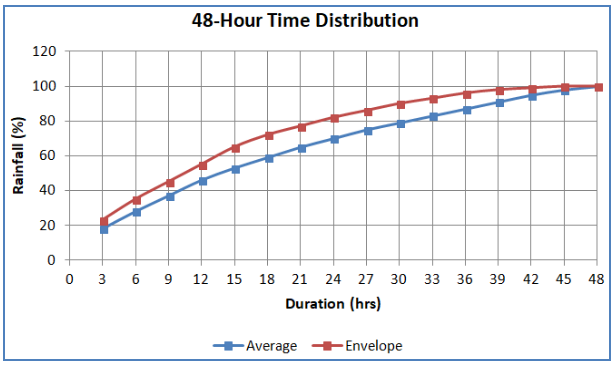

Fig. 16. Time distribution curve for 48-hour rainstorm

duration in which maximum rainfall is recorded, has been selected. This maximum rainfall value of each rainstorm is expressed as percentage of 24-hour and 48-hour rainfall value as the case may be. The procedure is followed for obtaining corresponding percentage ratios for 6-hour, 9-hour, … , 24-hour durations for 24-hour storm and same procedure is followed in respect of 48-hopur storms. The percentage values thus estimated for each duration and for each rainstorm are plotted against duration are calculated and time distribution curves (enveloping and average) are prepared for each duration. The corresponding percentage values (average and envelope) for 24-hour and 48 hour rainstorm are given in Tables 6(a&b) respectively and 24-hour and 48-hour average and envelope time distribution curves are shown in Figs. 15 and 16 respectively.

3.6. *Short duration rainstorms*

The unprecedented floods in Uttarakhand during this period were due to combination of few factors *viz.*, heavy to very heavy rainfall, occurrence of fresh snow prior to heavy rainfall which melted rapidly due to heavy rainfall, high melting rate of glacier during the period, steep slopes etc. In such cases analysis of short duration rainstorms is also important. Generally it is difficult to get short

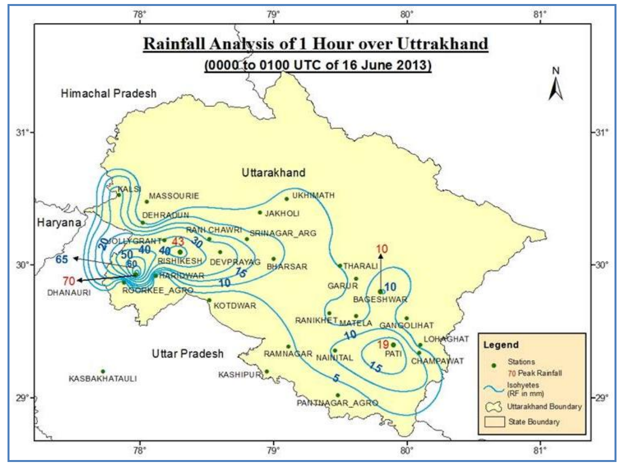

Fig. 17. Analysis of 1-hour rainstorm

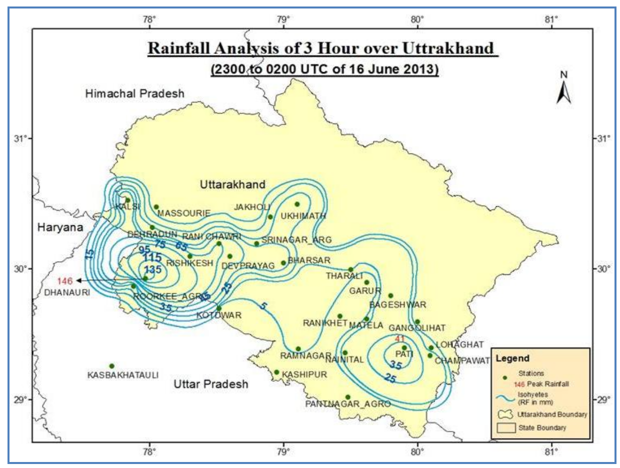

Fig. 18. Analysis of 3-hour rainstorm

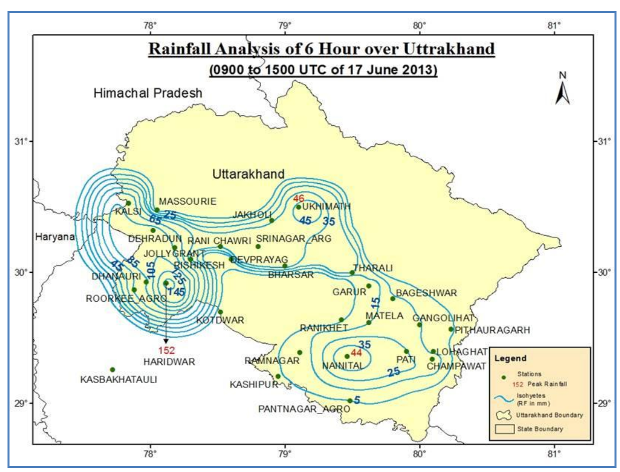

Fig. 19. Analysis of 6-hour rainstorm

duration rainfall data, especially in hilly region. The hourly rainfall data of 36 AWS/ARG stations were used to analyse short duration rainstorm. With the available data, 1, 3 and 6 hours rainstorms were analysed and shown in Figs. 17-19. The centre of rainstorms for 1 hr (0000 to 0100 UTC of 16.6.2013) and 3 hours (2300 to 0200 UTC of 16.6.2013) is at Dhanuri whereas the centre of 6 hours (0900 to 1500 UTC ending on 17.6.2013) rainstorm is at Haridwar with central values of 70, 146 and 152 mm. The Depth Area Duration (DAD), Areal Reduction Factors (ARF) and average percentage reduction factors for 1, 3 and 6 hour rainstorms are given in Table 7. It is observed that there is a decrease in percentage reduction factor when we move from 1 hr to 6 hr rainstorm. The percentage reduction factors for 1, 3 and 6 hr rainstorms at 1000 sq km are 35.8, 24.1 and 15.4 respectively where as at 5000 sq km these are 61.4, 49.6 and 39.9 respectively. It can also be seen that concentration of 1 hr rainstorm is confined to smaller area as compared to 3 hr and 6 hr rainstorms. This inference is based on the available hourly data from AWS/ARG stations of rainstorm of 15 to 18 June, 2013.

4. Conclusion

The state of Uttarakhand is prone to floods and landslides. Every year million of pilgrims visited this state. For safety from floods, more structures may be constructed and for the designing of new hydraulic structures or for reviewing existing structures, the design storm estimates are required to compute the contribution of floods from the catchments above that structure to minimise risk. In June, 2013, huge devastation occurred in Uttarakhand due to very heavy rainfall, early onset of monsoon that lead to melting of late snowfall and glaciated Lake Outburst. Few stations in Uttarakhand crossed earlier recorded 1-day highest rainfall during this period. There are two historical heavy and widespread rainstorms occurred over Uttarakhand, rainstorms of June, 2013 and September, 1924. The DAD values for 1-day duration for the rainstorm of June 2013 are higher than the DAD values for the rainstorm of September, 1924 up to 5000 sq. km area. Beyond 5000 sq. km, the 1-day DAD values for the rainstorm of September, 1924 are higher. For 2-day and 3-day rainstorms, the DAD values of the rainstorm of September, 1924 are higher. Therefore, for construction of hydraulic structures in this region, design flood may be estimated from the PMP values computed based on the historical rainstorms of either September, 1924 or June, 2013 dependent on the project area under consideration. If the catchment area of any hydraulic structure is less than 5000 sq. km, then design flood may be computed on the basis of PMP estimates based on June 2013 rainstorm and for hydraulic structure having area more than 5000 sq. km, then design flood may be computed on the basis of PMP estimates based on September, 1924 rainstorm. The necessary action to control floods due to local anthropogenic factors like deforestation, slope cutting, river bank construction etc. may be taken by the concerned authorities.

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