A Study of Heavy Rainfall of 8–10 June, 1991 over Maharashtra, India

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Received January 14, 1994; revised March 11, 1994

ABSTRACT

A low pressure system from the southwest Bay of Bengal between 8–10 June, 1991 brought heavy and continuous rainfall over different parts of Maharashtra. This 3–day heavy rainspell over Maharashtra has been analysed to assess its magnitudes of point as well as areal rainfall. The analysis showed that there were 74 stations which received 3–day total rainfall during 8–10 June exceeding their respective normal June rainfall. The areal raindepths obtained from the rainstorm of June, 1991 have been compared with similar data of past severe rainstorms of the region which showed that June, 1991 rainstorm yielded higher magnitudes of raindepths upto certain size of areas. A relationship has also been developed between point to areal rainfall of this rainstorm for 1–3 day durations for obtaining areal raindepths.

Key words: Heavy rainfall, Raindepth, Point rainfall, Areal rainfall

I. INTRODUCTION

During the onset phase of the southwest monsoon over the Maharashtra state in early June, 1991 heavy rainfall were reported by many stations during 4 to 11 June due to the passage of a low pressure system, persistence of a cyclonic circulation extending upto mid–tropospheric level and a trough along west coast between Maharashtra–Goa–Karnataka regions. Rainfall was, however, found to be very heavy during 8 to 10 June, 1991. This heavy rainfall claimed 74 human lives and disrupted rail and road communications over different parts of the Maharashtra state for a number of days.

Considering the incidence of heavy rainfall experienced by many stations over Maharashtra during 8–10 June, 1991, an attempt has been made in the present study to analyse this heaviest 3–day rainfall episode and present the salient features of the analysis so that the information given in this study may be useful to various agencies dealing with planning and designing of water resources projects in this state.

II. RAINFALL DATA USED

i) Daily rainfall data of state raingauge stations numbering 260 distributed uniformly over different parts of Maharashtra state were collected from the Agriculture Department, Pune for the period 5 to 11 June, 1991.

ii) The following information has also been obtained from the Weather Central, IMD, Pune:

a) Rainfall data of 5 to 11 June for 15 observatory stations in and around the Maharashtra state, b) Surface pressure charts of 8 to 10 June, 1991 at 3 UTC and c) Upper wind charts of 8 to 10 June at 500 hPa at 3 UTC.

iii) The INSAT–1 D cloud pictures over Indian region for the period 7 to 10 June have

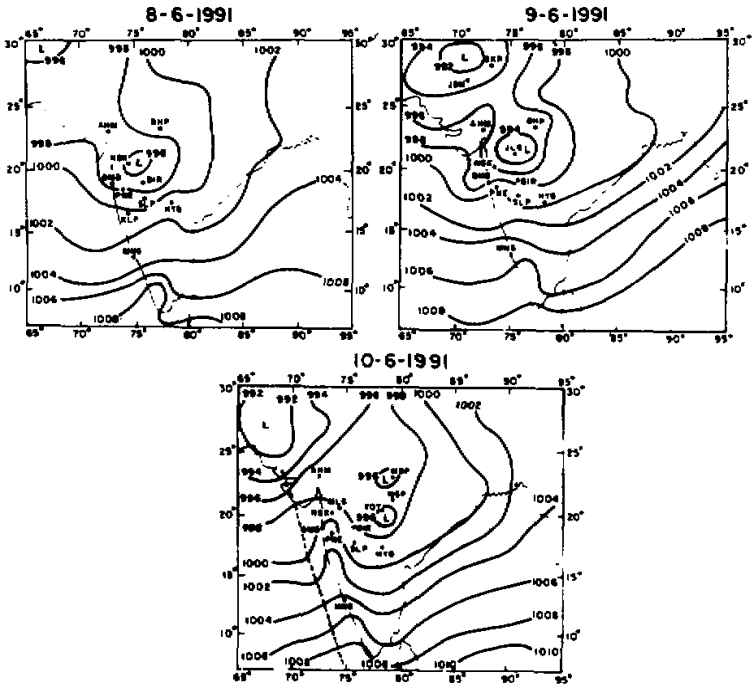

Fig. 1. Surface pressure charts at 3 U.T.C. of 8,9 and 10 June, 1991.

been obtained from the DGM's Office, IMD, N. Delhi.

The rainfall data mentioned above have been used as the basic input for the analysis of the present study.

III. METEOROLOGICAL SITUATIONS RESPONSIBLE FOR CAUSING HEAVY RAINFALL DURING 8 TO 10 JUNE, 1991 OVER MAHARASHTRA

The following meteorological situations were found to be responsible for causing heavy rainfall over Maharashtra state during 8 to 10 June:

i) A low pressure system originating from the southwest Bay of Bengal moved through the Maharashtra state whose centre was located at different positions over the state on different days. The position of this low pressure area over the state can be seen from the surface pressure charts of 8, 9 and 10 June, 1991 at 3 UTC (see Fig. 1).

A cyclonic circulation extending upto mid–tropospheric level was persisting over the state during all the 3–day period of 8 to 10 June. This mid–tropospheric cyclonic circulation is shown on the 500 hPa upper wind charts of 8, 9 and 10 June (see Fig. 2). It seems that the low pressure system may be considered as a reflection or downward penetration of the mid–tropospheric cyclonic circulation and

ii) A trough along Maharashtra–Goa–Karnataka coasts was positioned on 10 June. This trough off the west coast can be seen in Fig. 1.

The above meteorological situations resulted in formation of dense rain bearing cloud over the region of the state which caused heavy rainfall during 8 to 10 June. INSAT–1D

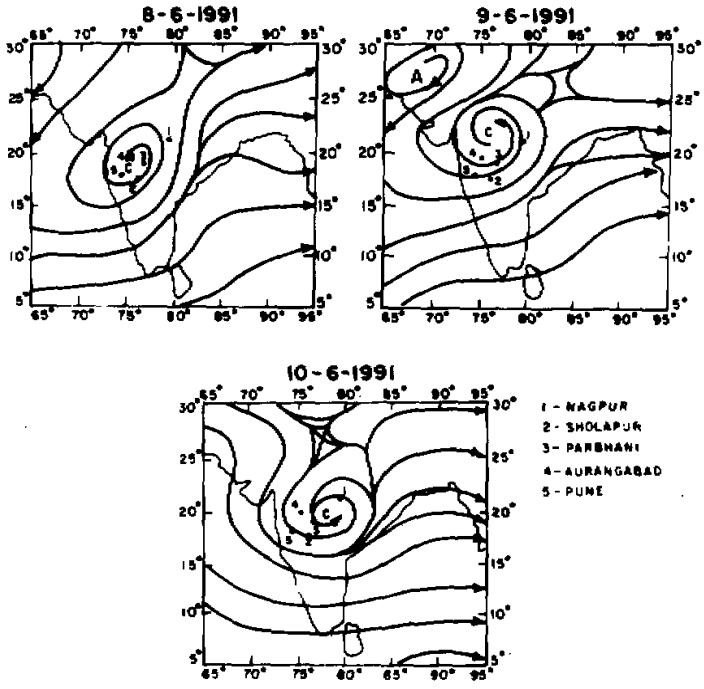

Fig. 2. *500 hPa upper wind charts of 8,9 and 10 June, 1991.*

satellite cloud pictures of 7 to 10 June (Figs. 3 a,d) show clearly the overcast clouds over the Maharashtra region on these days.

IV. RAINFALL CLIMATOLOGY OF MAHARASHTRA

The state of Maharashtra situated south of 22°N experiences extremes of rainfall during the monsoon months of June to September ranging from more than 600 cm over the Ghats to less than 50 cm in Madhya Maharashtra. The southwest monsoon normally sets in over Konkan by 8 June (Rao, 1976), covers the entire state by about 12 to 13 June and withdraws by early half of the second week of October. The monsoonal rainfall of heavy to very heavy nature over the state are generally found to be associated with meteorological situations like i) the passage of depressions / cyclonic storms from the Bay of Bengal or the Arabian Sea, ii) passage of low pressure systems across the state and iii) active monsoon conditions. The mean monthly rainfall and number of rainy days based on 80 years (1891 to 1970) rainfall (Kulkarni, 1991) data of stations in the 4 meteorological sub–divisions of Maharashtra for the monsoon months and the season as a whole are given in Table 1.

From Table 1 it is seen that July and August months are the principal rainy months over the state.

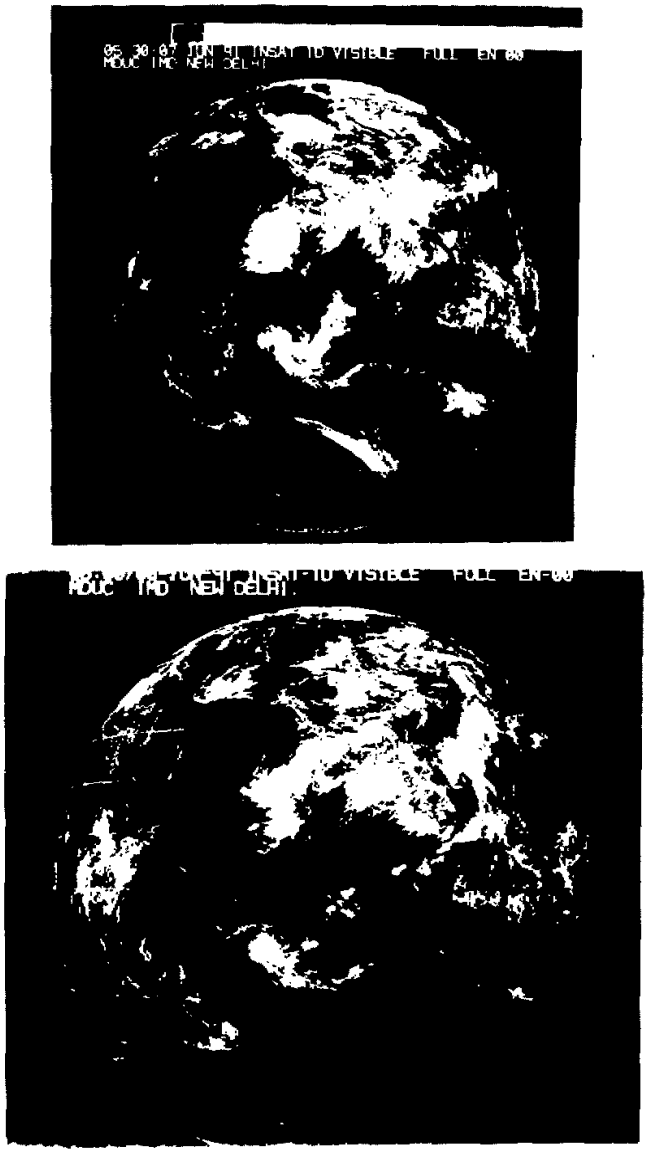

Fig. 3 a and b. INSAT–1D Satellite cloud patterns showing the dense overcast over Maharashtra associated with the passage of low pressure system of 7 to 8 June, 1991.

V. RAINFALL DISTRIBUTION ASSOCIATED WITH THE RAINSPELL OF 8–10 JUNE, 1991

1. *Observed Heaviest Rainfall during 8–10 June*

Meteorological situations as mentioned in Section III above caused heavy rainfall over different parts of Maharashtra during 8 to 10 June. Stations which received 3–day (8 to 10

June) total rainfall of 70 cm or more from the Konkan region and 30 cm or more in 3 days for stations from Madhya Maharashtra, Marathwada and Vidarbha regions are shown in Table 2. This table shows that there were 7 stations in the Konkan region which received 70 cm or more rainfall in the 3–day period while there were 9 stations from the Madhya Maharashtra, 4 stations from the Marathwada and 1 station from the Vidarbha region which received 30 cm or more rainfall in 3 days.

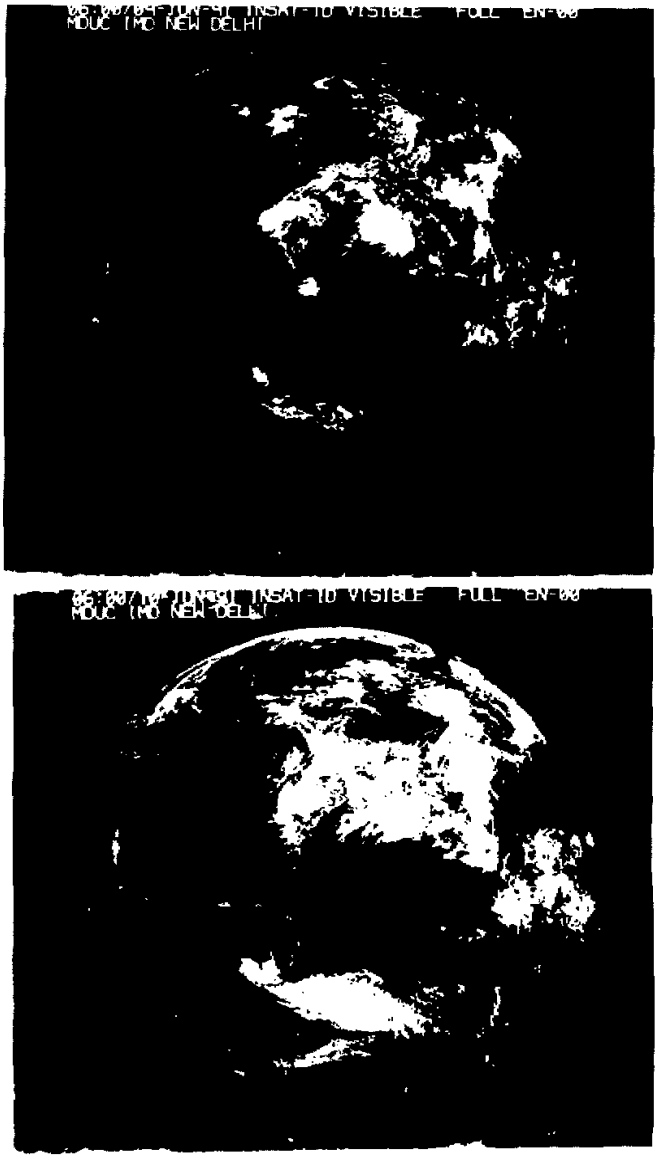

Fig. 3 c and d. INSAT–1D satellite cloud patterns showing the dense overcast over Maharashtra associated with the passage of low pressure system of 9 and 10 June, 1991.

Table 1. Monthly Normal Rainfall (cm) of June to September and Number of Rainy Days for 4 Meteorological Sub–divisions of Maharashtra (1891–1970)

Sub–division	Jun. (cm)	Jul. (cm)	Aug. (cm)	Sept. (cm)	Jun. to Sept. (cm)
Konkan	64.3 (16.5)	109.7 (25.9)	67.0 (16.6)	35.5 (19.9)	276.5
Madhya Maharashtra	16.1 (7.6)	31.3 (12.4)	31.0 (9.7)	16.9 (8.3)	95.3
Marathwada	14.3 (7.7)	19.3 (11.3)	16.6 (9.5)	19.9 (8.9)	70.1
Vidarbha	16.4 (8.6)	32.5 (15.2)	25.5 (12.2)	19.0 (9.2)	93.4

Note: Figures in brackets are number of rainy days.

Table 2. List of Stations Which Have Recorded 3–day Total Rainfall of 70 cm or More in Konkan and >30 cm for Stations in Other Sub–divisions of Maharashtra

Sr. No.	Name of the station	Rainfall (cm) 8/6	9/6	10/6	Total 3–day rainfall (cm)	100–year 1–day rainfall (cm)
	Sub–division: Konkan (3–day total rainfall>70 cm)					
1.	Devrukh	30.3	47.8	17.1	95.2	35.8
2.	Mandangad	45.3	31.4	15.4	92.1	42.1
3.	Dapoli	7.6	28.3	35.7	71.6	33.2
4.	Mhasala	21.2	37.5	24.5	83.2	–
5.	Murud	18.0	36.2	28.8	83.0	–
6.	Alibag	21.4	35.2	37.7	94.3	39.4
7.	Bombay (Colaba)	12.8	39.7	47.8	100.3	43.4
	Sub–divisions: Madhya Maharashtra, Vidarbha, Marathwada (3–day total rainfall>30 cm)					
8.	Igatpuri	5.7	32.2	3.9	41.8	40.5
9.	Chalisgaon	5.6	16.4	8.2	30.2	18.5
10.	Bhor	10.0	14.8	6.9	31.7	19.1
11.	Lonavala	20.3	18.7	18.3	57.3	51.7
12.	Purandar	11.9	11.5	7.0	30.4	–
13.	Medha	10.6	17.5	4.0	32.1	17.2
14.	Mahabaleshwar	12.4	38.9	6.9	58.2	–
15.	Roti	10.0	12.5	7.5	30.0	22.3
16.	Shahuvadi	14.5	12.1	7.4	34.0	–
17.	Radhanagari	14.6	11.3	4.5	30.4	34.1
18.	Gaganbavada	8.0	24.6	12.6	45.2	41.1
19.	Aurangabad	8.6	9.5	13.9	32.0	19.8
20.	Chikhalthana	3.9	15.7	11.1	30.7	–
21.	Khuldabad	2.2	22.6	23.1	47.9	–

Note: Underlined rainfall values show that 1–day heaviest rainfall of the station has exceeded its 100–year 1–day rainfall.

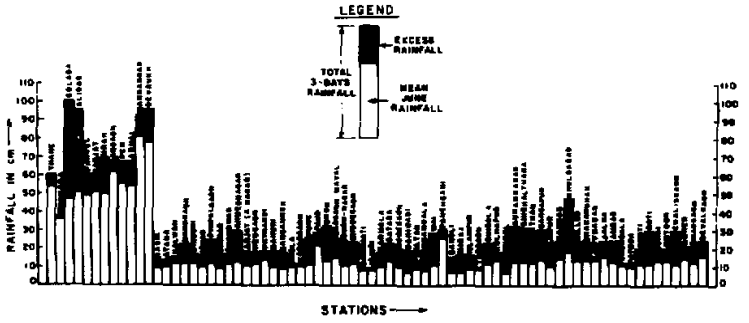

Fig. 4. Histogram shows mean June rainfall (cm) and three–day total rainfall (8–10 June, 1991).

The highest 1–day rainfall of 47.8 cm (see Table 2) was recorded at two stations viz. Bombay (Colaba) on 10 June and Devrukh, a station in the Ratnagiri district on 9 June respectively. The 2–day and 3–day heaviest rainfall was recorded at Bombay (Colaba) which were 87.5 cm (9–10 June) and 100.3 cm (8–10 June) respectively.

Highest 1–day rainfall of stations given in Table 2 have been compared with their respective estimated 100–year 1–day maximum rainfall (Dhar et al., 1980; Rakhecha et al, 1992). It is seen from Table 2 that the highest 1–day rainfall of 5 stations during 8–10 June have exceeded their respective 100–year 1–day rainfall.

2. *3–Day Total Point Rainfall and Their Comparison with Normal June Rainfall*

Normal June rainfall of stations in Maharashtra was extracted from the normal rainfall publication (IMD, 1962) and the same have been compared with their respective 3–day total rainfall received during 8–10 June, 1991 in order to see whether the 3–day rainfall at these stations have surpassed their normal June rainfall. Stations which received 3–day (8–10 June) total rainfall more than their respective normal June rainfall have been picked out. Fig. 4 shows the rainfall of these stations which received 3–day rainfall more than their respective June normal rainfall, alongwith the 3–day total rainfall and their corresponding mean June rainfall with the help of histograms. The shaded part in the histogram shows the extent of excess rainfall eaceived by the stations in 3 days as against its normal June rainfall. This Fig. shows that there were as many as 74 stations over different parts of Maharashtra which received 3–day rainfall more than their respective normal June rainfall. Among these 74 stations, 12 stations were from the Konkan region, 40 stations from the Madhya Maharashtra, 18 stations from the Marathwada and 4 stations from the Vidarbha region. It was also seen that among these 74 stations, there were 16 such stations which received twice or more than their respective normal June rainfall just in the 3–day period of 8–10 June (see Fig. 4). It is also seen that there were maximum number of stations from the low rainfall belts of Madhya Maharashtra and Marathwada regions which have exceeded their normal June rainfall during this 3–day period.

3. *Depth–Area–Duration (DAD) Analysis of 8–10 June, 1991*

The rainstorm of 8–10 June, 1991 has been analysed by DAD method for maximum 1, 2 and 3–day following the procedure as laid down in WMO (1969) and IMD (1972) manuals on Hydrometeorological analysis of rainstorms. The purpose of DAD analysis of a rainstorm

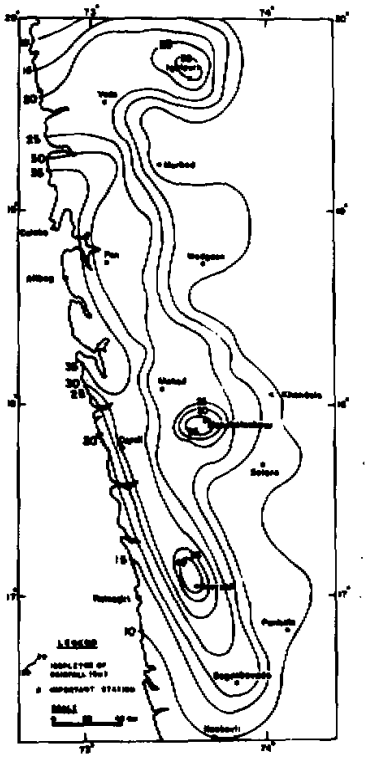

Fig. 5. Isohyetal pattern of one–day (9 June, 1991) rainstorm cell along the coastal region of Maharashtra.

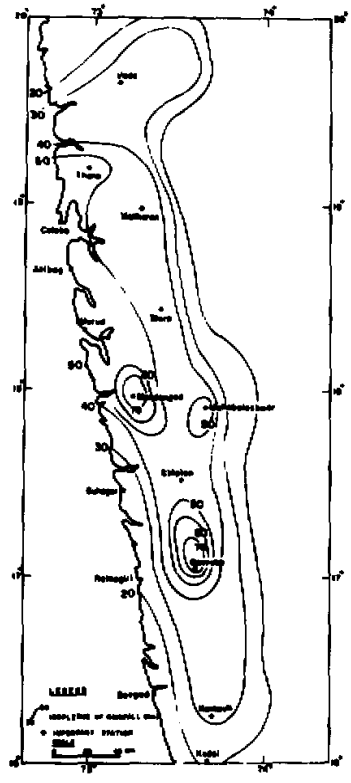

Fig. 6. Isohyetal pattern of two–day (8–9 June, 1991) rainstorm cell along the coastal region of Maharashtra.

is to work out its average raindepths over different size of areas yielded by that rainstorm in a specified interval of time. Such areal raindepths are often used for planning and designing of water resources projects of the region concerned.

On large scale base maps showing all raingauge stations and contour heights, rainfall data of 8 to 10 June for maximum 1,2 and 3–day durations were plotted separately and isohyets at suitable intervals were drawn by interpolation between stations rainfall values and thus isohyetal maps were prepared.

It was seen that there were two separate cells of the June, 1991 rainstorm, one cell over the plains in the Marathwada region and other along the coastal region. Figs. 5 to 9 show the isohyetal patterns of 1,2 and 3–day durations of this rainstorm over plains as well as over the coastal region. The centre of this rainstorm cell along the coast for 1–day (9 June) and 2–day (8–9 June) was at Devrukh (Lat. 17°03′, long 73°27′) which recorded rainfall of 47.8 cm and 78.1 cm respectively (see Figs. 5 & 6). Figs. 7 & 8 show the isohyetal patterns of this rainstorm cell over the plains with centre at Khuldabad (Lat, 20°01′, Long. 75°11′) which recorded

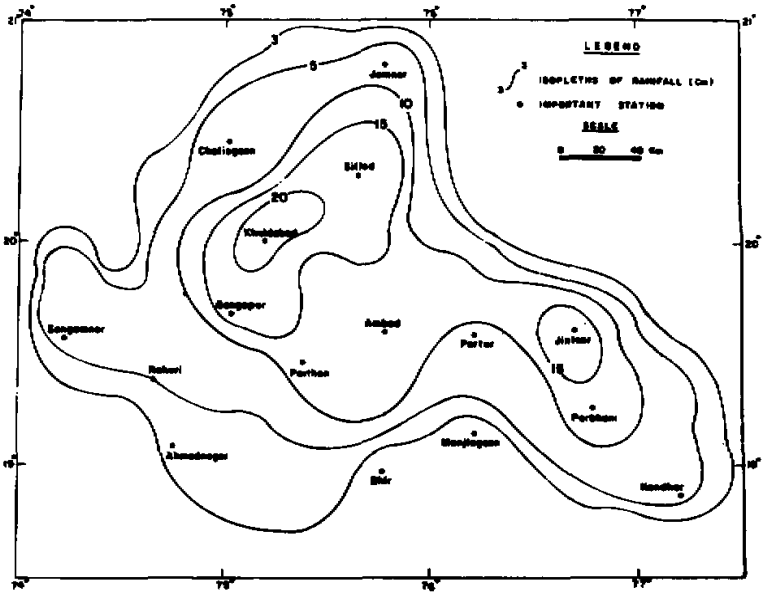

Fig. 7. Isohyetal pattern of one-day (10 June, 1991) rainstorm cell over the plains of Maharashtra.

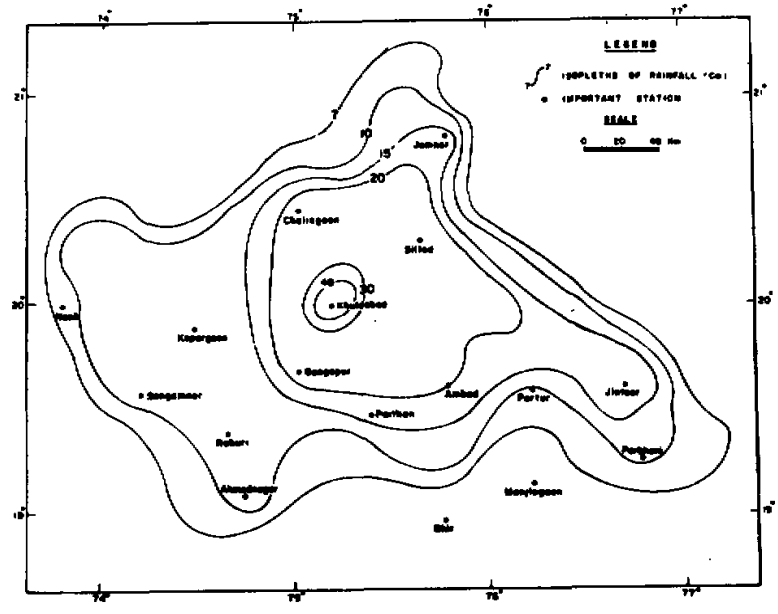

Fig. 8. Isohyetal pattern of two-day (9–10 June, 1991) rainstorm cell over the plains of Maharashtra.

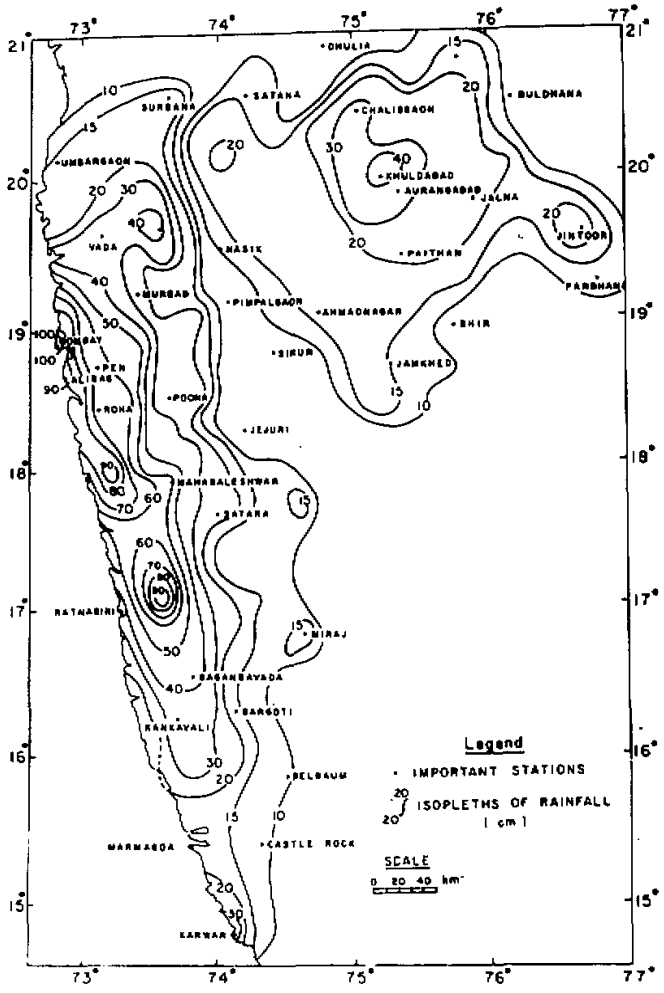

Fig. 9. Isohyetal pattern of 3–day rainstorm of 8–10 June, 1991 over Maharashtra.

1–day (10 June) and 2–day (9–10 June) rainfall of 23.1 cm and 45.6 cm respectively. Fig. 9 shows the 3–day rainstorm patterns with two separate cells. The 3–day rain centre for the coastal cell was at Bombay (Colaba) which recorded 100.3 cm of rainfall while over the plains it was over Khuldabad which recorded rainfall of 47.9 cm.

All the above isohyetal maps have been analysed by DAD technique. Average raindepths obtained for different durations over different size areas upto 50.000 km^2 have been worked out and the same are given in Tables 3 and 4.

It may be worth mentioning that Kulkarni et al. (1991) while analysing the severe rainstorm of 23–25 July, 1989 over Maharashtra had also found two separate cells similar to June, 1991 rainstorm. The DAD values of June, 1991 rainstorm cell along the coastal region have been compared with DAD data of 23–25 July, 1989 rainstorm (coastal cell) with centre at Bhira and 1–3 July, 1941 rainstorm over north Konkan–south Gujarat with centre at

Dharampur (see Table 3). From Table 3 it is seen that the DAD values of June, 1991 rainstorm were higher than those of 3–day July, 1989 rainstorm upto an area of 20,000 km^2. It is, however, seen that the magnitudes of raindepths of June, 1991 rainstorm were much less when compared with similar raindepths of 1–3 July, 1941, the most severe rainstorm of India (Dhar et al, 1984). The July, 1941 rainstorm is the most severe rainstorm in India and its areal raindepths have been exceeded the raindepths of severe rainstorms of tropical USA and Australia (Dhar et. al., 1984). The DAD values of June, 1991 rainstorm cell over the plains have been compared with DAD values obtained from the 23–25 July, 1989 rainstorm cell over the plains with centre at Bhir (see Table 4). From Table 4, it can be seen that 2–day and 3–day raindepths of June, 1991 rainstorm were higher than those of July, 1989 rainstorm upto an area of 2000 km^2 and 3000 km^2 respectively. From a perusal of the comparison of DAD data of severe rainstorms given in Tables 3 and 4, it can be said that although the June, 1991 rainstorm is not the most severe one but it may be considered as one of the severe rainstorms over the Maharashtra state.

Table 3. Comparison of 1,2 and 3–day DAD Statistics (cm) of Severe Rainstorms over the Coastal Region of Maharashtra

Areas	1–3 July, 1941			23–25 July, 1989			8–19 June, 1991		
(km^2)	1–day	2–day	3–day	1–day	2–day	3–day	1–day	2–day	3–day
	2	2–3	1–3	24	23–24	23–25	9	8–9	8–10
Point	98.8	127.0	144.8	71.3	74.9	95.7	47.8	78.1	100.2
100	96.5	126.0	142.0	66.0	74.0	94.0	46.0	76.0	98.0
200	94.0	124.5	141.0	61.0	73.0	91.0	44.0	74.0	97.0
500	90.4	122.5	138.0	52.5	72.2	86.0	43.0	68.0	93.0
1,000	84.5	118.0	133.5	47.0	71.0	83.5	41.0	65.0	90.0
3,000	71.7	105.0	123.5	38.2	64.5	76.0	37.5	59.0	82.0
5,000	65.0	97.0	117.0	35.2	59.7	71.0	35.0	56.0	77.0
10,000	53.5	83.2	104.5	32.0	52.5	64.0	32.0	52.0	70.0
20,000	42.5	66.0	86.0	28.0	46.5	56.2	27.5	45.5	58.5
30,000	36.0	55.5	75.5	25.0	41.7	51.0	24.5	39.5	50.5
40,000	31.0	48.0	66.5	–	38.2	46.0	20.5	34.0	45.0
50,000	27.5	43.0	59.0	–	34.9	42.0	18.0	29.5	40.0

VI. RELATIONSHIP BETWEEN POINT TO AREAL RAINFALL FOR ESTIMATING AREAL RAINDEPTHS FROM POINT RAINFALL

The isohyetal patterns of the rainstorm show that the maximum rainfall intensity is at its centre and outside this rain intensity gradually decreases. Maximum rainfall at the centre of the rainstorm appears to bear a definite relationship to the average amount of rainfall inside the area enclosed by an isohyet. Dhar and Bhattacharya (1977) have developed a non–linear mathematical relationship which relates point rainfall of a rainstorm to areal rainfall by considering all the major rainstorms which occurred in different parts of north India by considering rainfall data of 80–year period. Similar relationship has been obtained for June, 1991 rainstorm by considering 4 recent rainstorms (i.e. 23–25 July, 1989; 22–23 August, 1990; 8–10 June, 1991 and 2–3 September, 1992) over Maharashtra. The relationship can be expressed as

$$\overline{P} = P_m \cdot \overline{e}^{k \cdot A^n} \quad ,$$

where $\overline{P}$ is the average rainfall over an area A, P_m is the maximum point rainfall experienced in the rainstorm area and k and n are constants whose values vary with the duration of a rainstorm.

Process of obtaining the average rainfall $(\overline{P})$

$$\overline{P} = P_m \cdot \overline{e}^{kA^n} \quad .$$

$$\text{Let} \quad Y = \frac{\overline{P}}{P_m} = \overline{e}^{kA^n} \quad .$$

It can be written as

$$\frac{P_m}{\overline{P}} = e^{kA^n} \quad .$$

Taking logs both sides

$$\log_{10} \frac{P_m}{\overline{P}} = kA^n \log_{10} e \quad .$$

Again taking logs both sides

$$\log_{10} \log_{10} \frac{P_m}{\overline{P}} = \log_{10} k \log_{10} e + n \log_{10} A \quad .$$

Let us suppose

$$\log_{10} k \log_{10} e = a \quad ,$$

$$\log_{10} \log_{10} \frac{P_m}{\overline{P}} = a + n \log A \quad .$$

$$\text{By plotting} \quad \log_{10} \log_{10} \frac{P_m}{\overline{P}} \forall_s \log_{10} A \quad ,$$

we get straight line. By finding the slope, the constants a and n are calculated, by knowing the values of a and n, the value of k is determined.

By substituting the values of k and n for different areas (A), the average rainfall $(\overline{P})$ is calculated for 1,2 and 3–day duration.

The depth–area model of 1,2 and 3–day rainstorm of June, 1991 patterns which occurred over the coastal region and that over the plains have been obtained separately and the same are reproduced as below:

For castal area region:

$$1-\text{day} \quad \overline{P}_1 = P_{m1} e^{-0.0369(A)^{0.52}} \quad ,$$

$$2-\text{day} \quad \overline{P}_2 = P_{m2} e^{-0.0097(A)^{0.42}} \quad ,$$

$$3-\text{day} \quad \overline{P}_3 = P_{m3} e^{-0.0003(A)^{0.78}} \quad .$$

For plain area region:

$$1-\text{day} \quad \overline{P}_1 = P_{m1} e^{-0.000233(A)^{0.80}} \quad ,$$

$$2-\text{day} \quad \overline{P}_2 = P_{m2} e^{-0.000232(A)^{0.87}} \quad ,$$

$$3-\text{day} \quad \overline{P}_3 = P_{m3} e^{-0.000217(A)^{0.85}} \quad .$$

The above relationships can be used to convert the rainstorms central rainfall to areal rainfall. Raindepths obtained by using the above relationships for 1,2 and 3–day durations of June, 1991 rainstorm cell over the coastal region are found to be in close agreement with those obtained by DAD technique up to an area of 10,000 km^2. These relationships, however, hold good upto an area of 5000 km^2 for the raindepths obtained from this rainstorm cell over the plains. Table 5 shows comparison of DAD values obtained by actual analysis and by the model technique for 3–day rainstorm of 8–10 June, 1991.

Table 4. Comparison of 1,2 and 3–day Raindepths (cm) of 8–10 June, 1991 Rainstorm and 23–25 July, 1989 Rainstorm over Maharashtra Plains

Areas	23–25 July, 1989			8–10 June, 1991		
	Centre: Bhir			Centre: Khuldabad		
(km^2)	1–day	2–day	3–day	1–day	2–day	3–day
	24	23–24	23–25	10	9–10	8–10
Point	34.6	38.0	39.2	23.1	45.6	47.9
100	33.5	37.9	39.1	22.9	45.0	47.5
200	32.8	37.8	39.0	22.7	44.7	47.0
500	31.9	37.8	38.9	22.5	42.2	44.0
1,000	28.6	37.4	38.8	21.8	38.0	42.5
3,000	22.9	36.7	38.1	20.0	34.5	38.1
5,000	20.7	36.0	37.5	18.8	32.0	35.3
10,000	18.6	34.6	36.1	16.8	27.0	31.3
20,000	17.0	32.3	33.7	14.0	22.0	26.3
30,000	16.3	30.4	31.7	12.1	19.0	23.7
40,000	15.8	28.9	29.8	10.5	17.0	21.7
50,000	15.3	27.5	28.3	9.4	15.0	21.0

Table 5. Comparison of DAD Values Obtained by Actual Analysis and by the Model for 3–day Rainstorm of 8–10 June, 1991

Areas	Coastal storm		Plain area storm	
(km^2)	DAD values Actual (cm)	DAD values by Model (cm)	DAD values Actual (cm)	DAD values by Model (cm)
Point	100.2	100.2	47.9	47.9
100	99.0	99.1	47.5	47.4
200	98.0	98.3	46.8	47.0
500	95.0	96.4	44.0	45.9
1,000	92.0	93.8	42.4	44.3
3,000	83.0	85.8	38.0	39.4
5,000	77.0	79.6	35.4	35.4
10,000	68.0	67.5	31.5	27.7

VII. SUMMARY AND CONCLUSIONS

From the foregoing the following facts emerged from the present study:

i) The heavy rainfall over different parts of Maharashtra during 8–10 June, 1991 was caused

due to the meteorological situations i.e. passage of a low pressure system, persistance of mid–tropospheric cyclonic circulation and a trough off the west coast between Maharashtra–Goa–Karnataka.

ii) There were 74 stations over the Maharashtra state which received 3–day total rainfall during 8–10 June, more than their respective normal June rainfall. 15 such stations received twice or more than their corresponding normal June rainfall during these 3 days.

iii) The 3–day (8–19 June) total rainfall at Bombay (Coloba) of 100 cm has established a new record for 3–day duration for this station.

iV) Comparison of DAD values of June, 1991 rainstorm with other past severe rainstorms has shown that the 2 and 3–day rainstorm of June, 1991 has yielded higher raindepths than those obtained from July, 1989 rainstorm upto certain size of areas. However, raindepths of July, 1941 rainstorm were much higher than those of June, 1991.

V) A relationship each for durations of 1,2 and 3–day has been developed between point to areal rainfall for obtaining areal raindepths from central point rainfall for the rainstorm patterns over the coastal region and the patterns over the plain. The ralationship applicable for the coastal region holds reasonably good upto an area of 10,000 km^2 while the relationship for the plains can give good estimate upto 5,000 km^2 area.

Authors are grateful to Dr.R.N.Keshavmurty, Director, Indian Institute of Tropical Meteorology, Pune for his keen interest in the hydrometeorological studies and to Dr.G.B.Pant, Deputy Director who reviewed the manuscript. Authors are also thankful to Dr.O.N.Dhar, Emeritus Scientist for his valuable suggestions for the improvement of this paper. Rainfall data used in this study were obtained from the Agriculture Department, Pune and Weather Central, IMD, Pune–5 for which authors are also thankful to them. The INSAT–1D cloud pictures over the Indian region for the period 7–10 June, 1991 used in our study have been obtained from the DGM's Office, New Delhi for which the authors are highly thankful. Thanks are also due to Miss Shobha Nandargi for typing the manuscript.

REFERENCES

Dhar, O.N., and Bhattacharya, B. K. (1977), Relationships between central rainfall and its areal extent for severemost rainstorms of north Indian plains, *Irrigation and Power*, Vol.28, No.2.

Dhar, O.N.Kulkarni, A.K. and Rakhecha, P.R. (1980), Maximum 1–day point rainfall estimation for north Indian plains using district average ratios, *J. of Pure & Applied Geophysics*, Switzerland, **118**: Part 3.

Dhar, O. N., Kulkarni, A.K. and Mandal, B. N. (1984), The most severe rainstorm over India—a brief appraisal, *Hydrological Sciences Journal*, Vol.29, No.12.

India Meteorological Department (1962), Monthly and annual normals of rainfall and number of rainy days, *Memoirs* **31**: Part 3, IMD publication.

India Meteorological Department (1972), *Manual of Hydrometeorology*, Part I, IMD Publication.

Kulkarni, A.K., Mandal, B.N. and Sangam, R.B. (1991), Analysis of severe rainstorm of 23–25 July, 1989 over northern half of the Indian peninsula, *Trans. Instt. of Indian Geographers*, Vol.13, No.1.

Kulkarni, B.D. (1991), Hydrometeorological studies of Maharashtra rainfall, M.Sc. thesis, Poona University.

Rao, Y.P (1976), Southwest Monsoons, Meteorological Monograph, Synoptic Meteorology, No.1, IMD Publication.

Rakhecha, P.R., Mandal, B.N., Kulkarni, A.K. and Deshpande, N.R. (1992), Probability of one–day maximum rainfall events over different river basins of Maharashtra, *Journal of IAH*, Roorkee, Vol.XIV, No.4.

World Meteorological Organization, Geneva (1969), *Manual for Depth–Area–Duration analysis of storm precipitation*, WMO No.237, TP 129.