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A comparative hydrometeorological study of the historical floods in the *Yamuna* river

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सार – दिल्ली में यमुना में सितम्बर 1978 में आई रिकार्ड बाढ़ पूर्ववर्ती 1924, 1947 एवं 1976 में आई भीषण बाढ़ों के सभी आंकड़ों को पार कर गई। इस भीषण बाढ़ में भारी जन, धन की हानि हुई।

इस शोध पत्र में बाढ़ को उत्पन्न करने वाली वर्षा और उससे संबद्ध सिनॉप्टिक परिस्थितियों का विस्तार से विश्लेषण किया गया है।

ABSTRACT. An all time record flood occurred in the *Yamuna* river in September 1978 in Delhi surpassing the previous major floods of 1924, 1947 and 1976. This record flood caused colossal loss to life and property.

The present study deals with a detailed analysis of rainfall resulting in the floods and the associated synoptic situations.

1. Introduction

The river *Yamuna* had floods of high intensity in the past. The flood in October 1924 was considered at that time to be one of the worst floods in living memory. The exceptionally heavy rains in the river catchment during the four days from 27 to 30 September and consequent floods caused tremendous destruction of life and property. It was estimated that a peak discharge of about 5.0 lakh cusecs (14150 cumecs) passed down Tajewala Headworks on 28 September. Some of this water was apparently lost before reaching Delhi and had caused very severe damage due to local inundation in Ambala and Karnal districts. The peak gauge of 205.77 m asl (675.1 ft) was recorded at Delhi Railway Bridge on 2 October 1924. But for this loss the river level could be higher than what was recorded.

The next major flood occurred in September 1947. This flood was caused by a spell of heavy rain from 23 to 28 September. The peak discharge at the Tajewala Headworks was 5.63 lakh cusecs (15930 cumecs). The peak gauge at Delhi Railway Bridge was 206.01 m (675.9 ft) on 29 September 1947. This was more than the level in 1924 and the discharge at Tajewala Headworks was also comparatively greater. In 1947 also all the flood water did not reach Delhi Railway Bridge from Tajewala Headworks.

Delhi experienced unprecedented flood in August 1976 when the river level at Delhi Railway Bridge surpassed all earlier values. The level recorded was 206.70 m (678.1 ft) on 22 August 1976, *i.e.*, 1.87 m above the danger level of 204.83 m (672.0 ft). This flood which exceeded all previous records was caused due to heavy rain in the catchment from 18 to 20 August. As estimated by Central Flood Forecasting Division, New Delhi the peak discharge of 1.76 lakh cusecs (4978 cumecs) occurred at Kalanaur on 19 August, the peak discharge at Tajewala Headworks being 2.88 lakh cusecs (8150 cumecs) at 1700 IST on the same day. The peak discharge at Delhi Railway Bridge was estimated as 1.53 lakh cusecs (4335 cumecs) at 1230 IST on 22 August. The water level at Delhi Railway Bridge crossed the danger level of 204.83 m at 1130 IST on 19 August. The peak level of 206.70 m was recorded at 1230 IST on 22 August. It fell below the danger mark at 1730 IST on 25 August.

The all time record flood, however, occurred in September 1978 when the river level at Delhi Railway Bridge reached an unprecedented value

TABLE 1

Total rainfall (mm) Upper Yamuna Catchment

Station	1924	1947	1976	1978
Solan	—	—	52.4	146.5
Kotkhai	—	304.0	23.4	395.0
Chakrata	435.0	370.6	203.8	270.2
Chopal	—	—	80.5	339.5
Simla	281.9	257.2	49.7	158.6
Mussoorie	597.5	—	151.8	234.0
Paonta	—	—	5.1	348.1
Jubbal	—	—	0.0	306.0
Dak Pathar	—	—	151.5	253.0
Tajewala	—	—	250.0	414.1
Dadupur	421.6	632.8	381.0	386.0
Naya Shahr	495.3	481.3	2.0	341.0
Kalsia	622.3	409.1	240.4	295.9
Jateon Barrage	—	—	—	482.4
Koti	—	—	—	391.1
Pachhad	—	—	—	396.5

TABLE 2

Total rainfall (mm) Lower Yamuna Catchment

Station	1924	1947	1976	1978
Indri	—	—	257.8	—
Saharanpur	311.4	347.2	202.0	—
Ghaziabad	206.8	—	66.2	424.7
Nakur	248.1	226.5	134.0	269.0
Panipat	—	134.9	79.3	137.1
Sonepat	250.4	—	22.7	325.9
Narela	—	—	81.0	145.0
Mawi	—	—	99.7	207.9
Kutana	—	—	38.2	92.3
Kalanaur	—	—	202.6	329.4
Badaut	—	—	196.8	—
New Delhi (Safdarjung)	207.3	71.1	36.0	242.4
Yamuna Nagar	—	—	216.0	—
Muzaffarnagar	272.9	179.1	62.0	290.7
Kaukhera	286.2	283.7	164.0	236.0
Salampur	257.3	259.1	8.0	167.0
Baghpat	246.9	156.2	—	258.0
Budhana	237.5	73.8	—	208.0
Hindon	—	—	—	273.7
Karnal	—	260.7	—	108.0
New Delhi (Palam)	—	—	—	224.1
Saharanpur (Irrigation Deptt.)	—	—	—	397.0
Saharanpur (IAF)	—	—	—	386.4

TABLE 3

Daily Arithmetic Mean (mm) Upper Yamuna Catchment

Date	Arithmetic mean (mm)	Date	Arithmetic mean (mm)
27 Sep'24	35.8	17 Aug'76	13.3
28 Sep'24	134.7	18 Aug'76	22.9
29 Sep'24	182.1	19 Aug'76	14.9
30 Sep'24	156.7	20 Aug'76	27.3
1 Oct'24	25.7	21 Aug'76	2.1
23 Sep'47	37.5	31 Aug'78	33.3
24 Sep'47	40.6	1 Sep'78	56.5
25 Sep'47	129.9	2 Sep'78	64.9
26 Sep'47	167.0	3 Sep'78	167.6
27 Sep'47	72.3	4 Sep'78	17.9
28 Sep'47	6.0		

TABLE 4

Daily Arithmetic mean (mm) Lower Yamuna Catchment

Date	Arithmetic mean (mm)	Date	Arithmetic mean (mm)
27 Sep'24	1.6	17 Aug'76	7.9
28 Sep'24	68.7	18 Aug'76	46.8
29 Sep'24	77.5	19 Aug'76	112.2
30 Sep'24	125.4	20 Aug'76	8.5
1 Oct'24	—	21 Aug'76	0.5
23 Sep'47	30.8	31 Aug'78	0.0
24 Sep'47	22.8	1 Sep '78	74.5
25 Sep'47	78.6	2 Sep '78	133.2
26 Sep'47	34.6	3 Sep '78	40.2
27 Sep'47	47.4	4 Sep '78	2.1
28 Sep'47	26.6		

TABLE 5

Isohyetal average depth of rainfall (cm)

Upper Yamuna Catchment

	1924	1947	1976	1978
	27 Sep to 1 Oct	23 to 28 Oct	19 & 20 Aug	31 Aug to 3 Sep
One-day	10.4	11.1	9.8	11.7
Two-day	20.9	19.7	12.4	18.6
Three-day	29.8	23.6	—	22.8
Four-day	34.5	27.3	—	26.5
Five-day	35.4	29.1	—	—

of 207.49 m asl (+ 2.66 m) on 6 September. Needless to mention that the floods of such magnitudes disrupted rail and road traffic, inundated parts of the capital, submerged many villages around, resulted in loss of life and property and brought immense suffering to a large number of people.

This record flood occurred due to heavy rainfall in the catchment from 31 August to 3 September 1978. According to Haryana Irrigation Department there was a peak discharge of 7.10 lakh cusecs (20100 cumecs) at Tajewala Headworks between 0300 and 0400 IST on 3 September. Central Flood Forecasting Division, New Delhi estimated a peak discharge of 8.65 lakh cusecs (24500 cumecs) at Kalanaur between 1030 and 1430 IST on 3 September. According to Abbi (1980) the peak discharge as reproduced by the Sacramento model was 6.7 lakh cusecs at Kalanaur on 3rd morning of September 1978. The peak discharge estimated by other authorities at Wazirabad Barrage, Delhi Railway Bridge, Yamuna Barrage and Okhla Wier varied from 2.20 to 3.00 lakh cusecs (6226 to 8490 cumecs) on 6 September. The water level at Delhi Railway Bridge crossed the danger level of 204.83 m at 2030 IST on 1 September. An all time record peak level of 207.49 m (680.74 ft) was recorded at 0030 IST on 6th. The water level fell below the danger mark at 1430 IST on 10 September.

2. Physiographic features

The *Yamuna* river rises from Jamanotri springs in the Western Himalayas. It flows in a southwesterly direction upto Tajewala. Thereafter it flows in a southerly direction upto Delhi Railway Bridge. Keeping in view the orography, the catchment is divided in two parts (1) the upper catchment from source to Kalanaur and (2) the lower catchment from Kalanaur to Delhi Railway Bridge. The upper catchment comprises parts of Himachal Pradesh and of the hills of west Uttar Pradesh. The lower catchment consists of parts of the plains of west Uttar Pradesh and Harayana. The catchment comes under the influence of monsoon lows and depressions from the Bay of Bengal and the Arabian Sea which are responsible for spells of heavy rainfall.

3. Raingauge network

The present study has been made on the basis of rainfall recorded at raingauge stations lying in and around the catchment.

There are 21 recording raingauges in the whole catchment, 14 of them in the upper catchment and 7 in the lower catchment.

4. Rainfall analysis

The total rainfall (mm) recorded by raingauge stations lying in the Upper Yamuna Catchment areas during the flood periods are given in Table 1 in respect of the historical floods of 1924, 1947, 1976 and 1978. The total rainfall (mm) recorded by raingauge stations in the lower catchment areas during the relevant flood periods are given in Table 2 in respect of the above mentioned floods. These floods were caused by significant amount of rainfall from 27 September to 1 October 1924, 23 to 27 September 1947, 18 to 20 August 1976 and 31 August to 3 September 1978.

5. Rainstorm

The criterion for the purpose of storm selection has been taken as an arithmetic average of at least 2.5 cm of daily rainfall in the catchment (Abbi *et al.* 1970).

5.1. *Daily Arithmetic Mean*

5.1.1. *Upper Catchment*

The daily arithmetic mean of the rainfall data of the stations lying in the upper catchment is given in Table 3.

Table 3 shows that in 1924 there was a rainstorm of five days, *viz.*, 27 September to 1 October and in 1947 a rainstorm of four days from 23 to 27 September. There was a rainstorm of two days, *viz.*, on 19 and 20 August in the year 1976 and of four days, *i.e.*, from 31 August to 3 September in 1978.

5.1.2. *Lower Catchment*

Table 4 shows the daily arithmetic mean of rainfall of the stations lying in the lower catchment.

It is seen from Table 4 that in 1924 there was a rainstorm of three days from 28 to 30 September and in 1947 a rainstorm of four days from 25 to 28 September (following a one day storm of 23). The values of daily arithmetic mean shows that in 1976 there was a rainstorm of two days on 18 and 19 August and in 1978 there was a rainstorm of three days from 1 to 3 September.

5.2. *Isohyetal Daily Mean*

5.2.1. *Upper Catchment*

Fig. 1 shows the isohyetal analysis of the accumulated rainfall of 27 September to 1 October 1924. In this figure a maximum of more than 60 cm of rain lies southeast of Tajewala. Another maximum of more than 56 cm of rain lies over Ambari. Isohyetal average depth of rainfall on 29 September was 10.4 cm. Isohyetal average depths of accumulated rain on 29 and 30 September, 28 to 30 September and 27 to 30 September were 20.9, 29.8 and 34.5 cm respectively and the isohyetal average depth of accumulated rainfall from 27 September to 1 October was 35.4 cm.

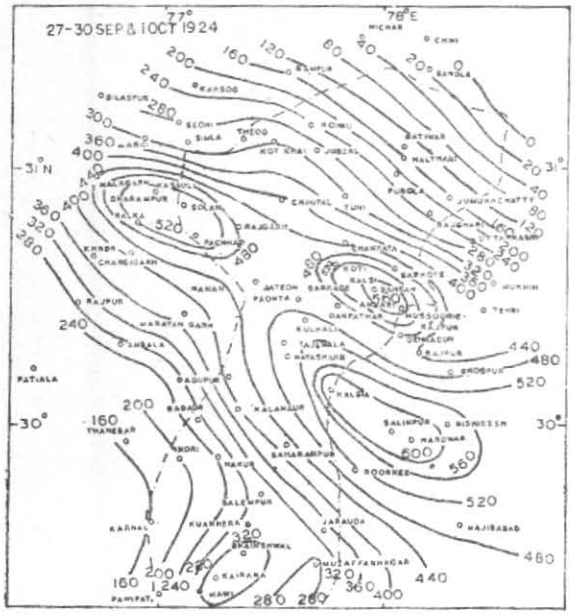

Fig. 1. Isohyetal analysis of accumulated rainfall (mm) on 27-30 Sep & 1 Oct 1924

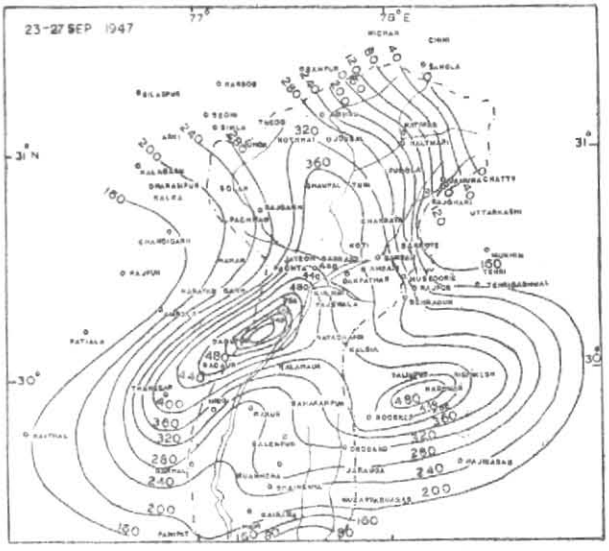

Fig. 2. Isohyetal analysis of accumulated rainfall (mm) on 23-27 Sep 1947

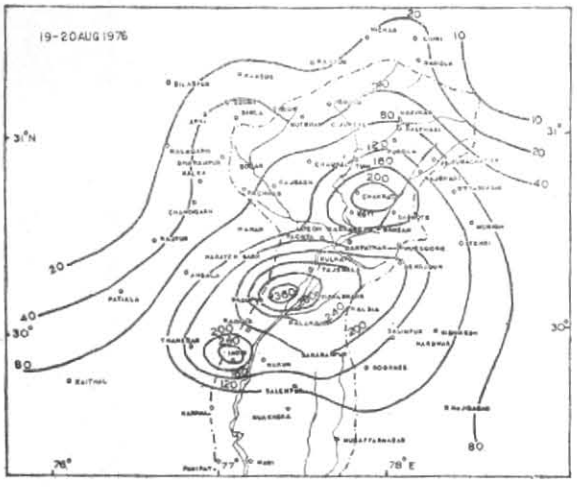

Fig. 3. Isohyetal analysis of accumulated rainfall (mm) on 19-20 August 1976

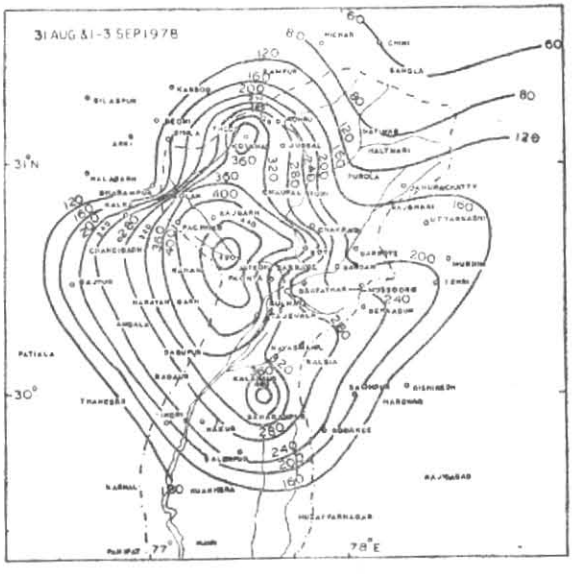

Fig. 4. Isohyetal analysis of accumulated rainfall (mm) on 31 August, 1-3 September 1978

TABLE 6

Isohyetal average depth of rainfall (cm) Lower Yamuna Catchment

	1924 28 to 30 Sep	1947 25 to 28 Sep	1976 18 and 19 Aug	1978 1 to 3 Sep
One-day	11.8	8.9	9.7	8.9
Two-day	18.9	12.4	14.9	18.5
Three-day	25.7	18.1	—	19.3
Four-day	—	20.2	—	—

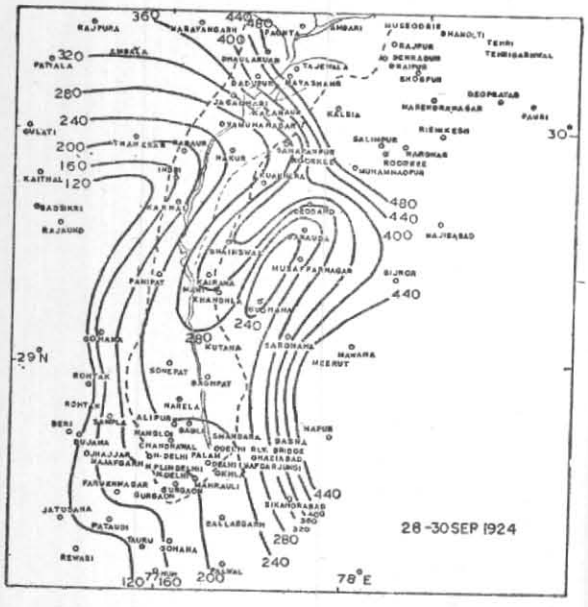

Fig. 5. Isohyetal analysis of the accumulated rainfall (mm) on 28-30 September 1924

Fig. 6. Isohyetal analysis of the accumulated rainfall (mm) on 25-28 September 1947

Fig. 2 shows the isohyetal analysis of the accumulated rainfall of 23 to 27 September 1947. In this figure a maximum of more than 72 cm of rain lies at Dadupur, southwest of Tajewala. Isohyetal average depth of rainfall on 26 September was 11.1 cm. Isohyetal average depth of accumulated rainfall on 25 and 26 September, 25 to 27 September and 24 to 27 September were 19.7, 23.6 and 27.3 cm respectively and the isohyetal average depth of accumulated rainfall from 23 to 27 September was 29.1 cm.

Fig. 3 shows the isohyetal analysis of the accumulated rainfall of 19 and 20 August 1976. In this figure a maximum of more than 36 cm of rainfall lies southwest of Tajewala. Another maximum of more than 20 cm lies over Chakrata. Isohyetal average depth of rainfall on 19 August was 9.8 cm and isohyetal average depth of accumulated rainfall on 19 and 20 August was 12.4 cm.

Fig. 4 shows the isohyetal analysis of four day accumulated rainfall from 31 August to 3 September 1978. A maximum of more than 48 cm of rainfall lies over Jateon Barrage. Another maximum of more than 36 cm of rainfall lies over Kotkhai. During this rainstorm one day maximum isohyetal average depth of rainfall was 11.7 cm on 3 September, two day maximum isohyetal average depth of accumulated rainfall on 2 and 3 September was 18.6 cm, three day maximum depth of accumulated rainfall from 1 to 3 September was 22.8 cm and four day maximum depth of accumulated rainfall from 31 August to 3 September was 26.5 cm.

Isohyetal average depths of rainfall (in cm) for 1, 2, 3, 4 and 5 days are given in Table 5 for all the 4 floods.

5.2.2. *Lower Catchment*

The isohyetal analysis of the accumulated rainfall of 28 to 30 September 1924 is depicted in Fig. 5. This shows that a maximum of more than 16 cm of rainfall lies over Mawi. There is a continuous increase of rainfall northwards from Kutana. Isohyetal average depth of rainfall on 30 September was 11.8 cm and the isohyetal depths of accumulated rainfall on 29 and 30 September and 28 to 30 September were 18.9 and 25.7 cm respectively.

Fig. 6 shows the isohyetal analysis of the accumulated rainfall of 25 to 28 September 1947. In this a maximum of more than 24 cm lies over Karnal. There is a continuous increase of rainfall northwards from Delhi. Isohyetal average depth of rainfall on 25 September was 8.9 cm. The isohyetal average depths of accumulated rainfall on 25 and 26 September, 25 to 27 September and 25 to 28 September were 12.4, 18.1 and 20.2 cm respectively.

The isohyetal analysis of the accumulated rainfall of 18 and 19 August 1976 is depicted in Fig. 7, which shows a maximum of more than 24 cm of rainfall over Indri, another maximum of more than 16 cm of rainfall lies over Mawi. The third maximum of more than 16 cm of rain lies over Delhi. There is continuous increase of rainfall northwards from Kutana. Isohyetal average depth of rainfall on 19 August was 9.7 cm and isohyetal average depth of accumulated rainfall on 18 and 19 was 14.9 cm.

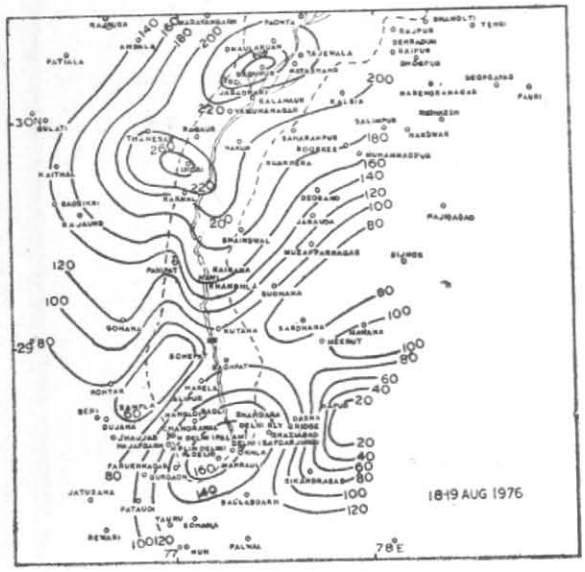

Fig. 7. Isohyetal analysis of accumulated rainfall (mm) on 18 and 19 August 1976

TABLE 7

Maximum Average Depth of Rainfall (cm) Upper Yamuna Catchment — One-Day

Area (sq. km)	1924 29 Sep	1947 26 Sep	1976 19 Aug	1978 3 Sep
500	22.6	27.7	27.7	20.0
1000	20.4	25.0	25.0	21.4
1500	18.6	21.7	21.9	21.2
2000	17.5	19.9	19.9	21.0
2500	16.9	19.4	19.4	20.6
3000	16.5	19.1	15.9	19.9
3500	16.1	18.7	14.0	19.1
4000	15.7	18.3	12.4	18.3
4500	15.1	17.7	11.2	17.7
5000	14.5	17.1	10.0	17.3
5500	13.7	16.3	9.2	16.7
6000	13.0	15.3	8.4	16.0
6500	12.2	14.1	7.9	15.1
7000	11.4	12.4	7.4	14.2
7500	10.6	10.6	6.9	12.8
8000	9.6	8.7	6.6	10.9
8500	8.6	6.8	6.3	8.8
9000	7.0	4.8	5.9	7.3
9500	5.9	2.8	5.5	6.0
10000	4.1	0.8	5.0	4.5
10500	1.4	—	4.6	3.4
11000	—	—	4.0	2.4
11500	—	—	3.4	1.6
12000	—	—	2.8	0.5
12500	—	—	2.0	—

TABLE 8

Maximum Average Depth of Rainfall (cm) Upper Yamuna Catchment — Two-Day

Area (sq. km)	1924 29 & 30 Sep	1947 25 & 26 Sep	1976 19 & 20 Aug	1978 2 & 3 Sep
500	40.7	42.5	32.3	31.1
1000	37.6	39.3	30.2	30.2
1500	35.6	36.5	27.5	29.4
2000	34.3	34.5	22.5	28.7
2500	33.4	33.0	20.1	28.1
3000	32.7	31.7	18.8	27.5
3500	31.9	30.7	17.6	27.1
4000	31.1	29.5	16.6	26.6
4500	30.1	28.6	15.7	26.0
5000	29.0	27.6	14.8	25.2
5500	27.7	26.5	14.0	24.2
6000	26.3	25.2	13.2	23.0
6500	24.7	23.7	12.4	21.7
7000	22.9	22.0	11.6	20.4
7500	21.0	20.0	10.8	19.1
8000	18.9	17.8	10.0	17.8
8500	16.7	15.5	9.4	16.4
9000	14.5	12.9	8.6	15.0
9500	12.1	9.8	7.9	13.7
10000	9.8	6.0	7.1	12.2
10500	7.6	0.5	6.3	11.0
11000	5.7	—	5.5	10.0
11500	3.9	—	4.6	9.1
12000	2.1	—	3.8	8.1
12500	0.4	—	2.9	7.0

TABLE 9

Maximum Average Depth of Rainfall (cm) Upper Yamuna Catchment — Three-Day

Area (sq. km)	1924 28, 29 & 30 Sep	1947 25, 26 & 27 Sep	1978 1, 2 & 3 Sep
500	53.3	45.2	39.9
1000	52.2	43.0	38.5
1500	51.7	41.4	37.5
2000	51.4	40.3	36.8
2500	50.9	39.3	35.7
3000	50.3	38.2	33.8
3500	49.2	37.0	32.7
4000	47.0	35.6	31.9
4500	44.7	33.8	31.3
5000	42.2	31.7	30.5
5500	39.3	29.6	29.1

TABLE 9 (*contd*)

Area (sq. km)	1924 28, 29 & 30 Sep	1947 25, 26 & 27 Sep	1978 1, 2 & 3 Sep
6000	36.4	27.5	27.4
6500	33.0	25.5	25.2
7000	29.4	23.6	23.6
7500	25.3	22.3	22.3
8000	21.0	21.4	21.0
8500	18.2	20.4	19.2
9000	16.1	18.9	16.6
9500	14.0	16.0	14.3
10000	12.0	11.9	12.7
10500	9.9	7.4	11.5
11000	7.8	1.9	10.4
11500	5.6	0.7	9.3
12000	3.4	0.3	8.2
12500	1.1	—	7.0

TABLE 10

Maximum Average Depth of Rainfall (cm)
Upper Yamuna Catchment — Four-Day

Area (sq. km)	1924 27, 28, 29 &30 Sep	1947 24, 25, 26 & 27 Sep	1978 31 Aug, 1, 2 & 3 Sep
500	55.0	49.0	46.6
1000	53.7	44.0	44.9
1500	53.1	42.5	42.1
2000	52.7	41.5	41.4
2500	52.0	40.5	39.8
3000	51.3	39.4	38.2
3500	50.4	38.3	36.7
4000	49.3	37.2	35.6
4500	48.0	36.1	34.6
5000	46.4	34.9	33.3
5500	44.3	33.7	31.8
6000	42.5	32.4	30.1
6500	40.7	31.1	28.5
7000	38.8	29.7	26.8
7500	36.4	28.3	25.2
8000	33.7	26.8	23.6
8500	30.4	25.1	21.9
9000	27.0	23.1	20.4
9500	23.2	20.6	18.9
10000	18.6	17.4	17.4
10500	16.0	13.6	16.0
11000	12.7	10.6	14.5
11500	9.2	7.4	12.9
12000	5.6	3.2	11.2
12500	1.8	—	9.5

TABLE 11

Maximum Average Depth of Rainfall (cm)
Upper Yamuna Catchment — Five-Day

Area (sq. km)	1924 27, 28, 29, 30 Sep and 1 Oct	1947 23, 24, 25, 26 and 27 Sep
500	59.0	55.2
1000	55.4	49.2
1500	53.9	45.4
2000	53.0	43.3
2500	52.3	42.0
3000	51.4	40.9
3500	50.6	40.0
4000	49.7	38.9
4500	48.7	37.9
5000	47.4	36.8
5500	46.0	35.8
6000	44.4	34.4
6500	42.2	33.1
7000	39.8	31.8
7500	37.3	30.4
8000	35.2	28.8
8500	32.0	27.1
9000	28.8	25.4
9500	26.1	23.8
10000	22.0	21.2
10500	18.0	17.0
11000	14.3	12.4
11500	10.6	9.8
12000	7.0	5.6
12500	3.0	1.8

TABLE 12

Maximum Average Depth of Rainfall (cm)
Lower Yamuna Catchment — One-Day

Area (sq. km)	1924 30 Sep	1947 25 Sep	1976 19 Aug	1978 2 Sep
500	16.8	14.5	21.5	16.5
1000	15.5	13.3	19.7	15.6
1500	14.6	12.3	17.9	14.7
2000	13.9	11.4	15.7	13.3
2500	13.3	10.7	12.7	11.3
3000	12.8	10.0	9.5	10.3
3500	12.3	9.3	6.9	9.7
4000	11.7	8.5	5.2	9.1
4500	11.1	7.7	4.3	8.3
5000	10.3	6.8	3.6	7.4
5500	9.5	5.8	3.1	6.3
6000	8.7	4.5	2.3	5.0
6500	—	2.8	—	3.5

TABLE 13

Maximum Average Depth of Rainfall (cm) Lower Yamuna Catchment — Two-Day

Area (sq. km)	1924 29 & 30 Sep	1947 25 & 26 Sep	1976 18&19 Aug	1978 1 & 2 Sep
500	25.4	19.6	23.7	28.4
1000	24.2	16.0	22.8	25.6
1500	23.2	14.0	21.8	23.8
2000	22.4	13.1	20.6	21.8
2500	21.8	13.0	19.0	19.4
3000	21.5	12.8	17.2	18.4
3500	21.1	12.7	15.2	18.0
4000	20.5	12.4	13.1	18.0
4500	19.7	11.8	11.5	17.8
5000	18.6	11.0	10.6	17.2
5500	17.4	9.6	9.3	16.3
6000	15.2	7.6	6.8	13.4
6500	—	—	4.5	—

TABLE 14

Maximum Average Depth of Rainfall (cm) Lower Yamuna Catchment — Three-Day

Area (sq. km)	1924 28, 29 & 30 Sep	1947 25, 26 & 27 Sep	1978 1,2, & 3 Sep
500	34.0	31.2	31.2
1000	31.1	27.0	28.2
1500	29.8	23.8	26.2
2000	29.2	21.6	24.3
2500	28.7	20.6	22.8
3000	27.9	18.5	21.4
3500	27.3	18.0	19.6
4000	26.6	17.7	18.1
4500	25.8	17.0	17.3
5000	24.7	15.9	16.2
5500	23.2	14.2	14.6
6000	20.8	11.9	12.0
6500	—	—	9.5

The isohyetal analysis of the accumulated rainfall from 1 to 3 September 1978 is shown Fig. 8. A maximum of more than 36 cm of rainfall lies northeast of Ghaziabad. The other maximum of more than 28 cm lies over Muzaffarnagar. In this rainstorm one day maximum isohyetal average depth of rainfall was 8.9 cm on 2 September, two day maximum isohyetal average depth of accumulated rainfall of 1 and 2 September was 18.5 cm and three days maximum isohyetal average depth of accumulated rainfall from 1 to 3 September was 19.3 cm.

Isohyetal average depths of rainfall in cm for 1, 2, 3 and 4 days are given in Table 6 for all the 4 floods.

TABLE 15

Maximum Average Depth of Rainfall (cm) Lower Yamuna Catchment — Four-Day

Area (sq. km)	1947 25,26,27 & 28 Sep	Area (sq. km)	1947 25-28 Sep
500	32.2	4000	18.7
1000	29.3	4500	17.8
1500	27.5	5000	16.8
2000	26.0	5500	15.0
2500	23.7	6000	12.0
3000	21.6	6500	—
3500	20.0		

5.3. *Depth-Area-Duration Curves*

5.3.1. *Upper Catchment*

Depth area duration curves for the upper catchment have been plotted and maximum rainfall depths for various standard areas have been read out from these curves. These are given in Table 7 for 1 day, in Table 8 for 2 days, in Table 9 for 3 days, in Table 10 for 4 days and in Table 11 for 5 days.

5.3.2. *Lower Catchment*

Depth area duration curves for the lower catchment have been plotted and maximum rainfall depths for various standard areas have been read out from these curves. These are given in Table 12 for 1 day, in Table 13 for 2 days, in Table 14 for 3 days and in Table 15 for 4 days.

6. Significant synoptic features

6.1. *Flood of September/October 1924*

The synoptic situation responsible for this flood are enumerated below :

A depression formed on 24 September in the southwest Bay of Bengal with its centre near Lat. 11 deg. N, Long. 83 deg. E. It crossed the Coromandal coast (now Tamil Nadu coast) near Nellore on the morning of 25th. Traversing in a northwesterly direction across the Peninsula it was centred near about Ahmednagar on 27th and near Surat on the morning of 28th. Thereafter it recurved in a northeasterly direction and passed through east Rajputana on 29th. It caused very heavy rain in the northwest of Uttar Pradesh and the adjacent districts of Punjab (now Haryana). The depression broke up over Simla-Kumaon hills on 30th and caused heavy rain in the region between Delhi and the Kumaon hills.

Fig. 8. Isohyetal analysis of accumulated rainfall (mm) on 1-3 September 1978

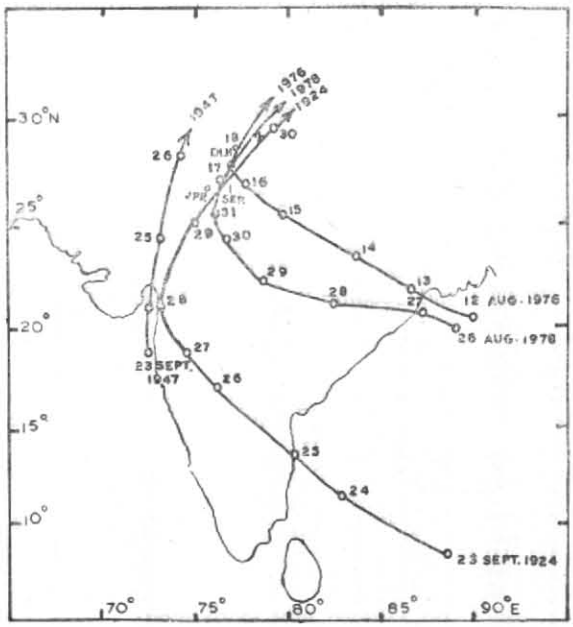

Fig. 9. Tracks of depressions/cyclonic storms responsible for major floods in *Yamuna*

6.2. *Floods of September 1947*

This flood was caused by a spell of heavy rain from 23 to 28 September in association with an Arabian Sea depression.

By the evening of 22nd a deep depression had formed in the Arabian Sea. This was centred in the morning of 23rd about 50 miles southwest of Bombay. It crossed the coast near Surat in the early hours of 24th. After crossing the coast the depression weakened and continued to move northnortheastwards. It lay between Ahmedabad and Udaipur on 25th and was centred above 50 miles east of Bikaner at 0800 IST on 26th. Thereafter, it weakened further and moved away towards the Punjab on 27th and got filled up over the Punjab hills.

6.3. *Flood of August 1976*

The synoptic situations responsible for this flood are enumerated below:

6.3.1. On 15 August 1976 a well marked low pressure area lay over south Uttar Pradesh and adjoining north Madhya Pradesh. The next day it concentrated into a depression and lay over east Rajasthan and southwest Uttar Pradesh with its centre just to the west of Agra. It remained practically stationary till 17th, but concentrated into a deep depression with its centre between Alwar and Mathura. Moving in a northerly direction under the influence of a trough in the westerlies (described in 6.3.3 below) it further intensified into a cyclonic storm and lay in the morning of 18th, with its centre just to the north of Delhi. The same evening it weakened into a depression which lay over northwest Uttar Pradesh with its centre between Roorkee and Meerut. On 19th it further weakened into a low pressure area over northwest Uttar Pradesh and broke up over the hills of west Uttar Pradesh on 20th. The track of the depression/cyclonic storm is shown in Fig. 9.

6.3.2. On 18 August a western disturbance was located over northwest Rajasthan and adjoining north Pakistan as an upper air cyclonic circulation extending upto 4.5 km a.s.l. On 19th it lay over north Pakistan and adjoining Jammu & Kashmir as an upper air cyclonic circulation between 700 and 400 mb. On 20th it lay over north Pakistan as an upper air cyclonic circulation extending upto 500 mb tilting northwards with height.

6.3.3. On 16 August a trough in the westerlies lay between 500 and 200 mb with its axis roughly along Long. 70 deg. E, north of Lat. 30 deg. N. It persisted over the same region on 17th. On 18th its axis lay along Long. 73 deg. E, north of Lat. 32 deg. N. It moved away eastwards across Western Himalayas on 19th.

6.4. *Flood of September 1978*

The relevant synoptic situations which caused this flood are given below:

6.4.1. On 30 August a depression was located over southeast Rajasthan and adjoining northwest Madhya Pradesh with its centre about 50 km southeast of Jhalawar. Moving northnorthwestwards it was centred 60 km north of Kota on 31st. Recurving northnortheastwards it intensified into a deep depression and was centred close to

Meerut on 2 September. Thereafter, it weakened rapidly and lay as an upper air cyclonic circulation extending upto 2.1 km a.s.l. over northwest Uttar Pradesh on 3rd. It became unimportant on the following day. The depression track is shown in Fig. 9.

6.4.2. On 1 September a trough in westerlies lay between 500 and 200 mb with its axis roughly along Long. 69 deg. E, north of Lat. 30 deg. N, tilting eastwards with height. It moved eastwards and became unimportant on 3rd.

7. Discussion

7.1. Out of the 4 historical floods studied three, *viz.*, 1924, 1947 and 1978 occurred in September and one, *viz.*, 1976 in August. Thus all the major floods have occurred in August and September. Johri and Veeraraghavan (1976) had mentioned that during the 75 years period from 1900 to 1974, 22 of the 27, *i.e.*, 81 per cent peak floods in the *Yamuna* occurred in the months of August and September.

7.2. The floods of 1924, 1976 and 1978 occurred due to heavy rainfall in the catchment associated with a depression from the Bay of Bengal. In each of these cases the depression after reaching east Rajasthan recurved northeastwards, moved over the catchment and finally broke up over the hills of Himachal Pradesh and of west Uttar Pradesh. The flood of 1947 was caused due to heavy rainfall in the catchment associated with a depression from the Arabian Sea, aided by the passage eastwards of a western disturbance across north India.

7.3. In 1924 the line of advance of the depression was practically perpendicular to the line of the Himalayas and the humid southerly current in the eastern semi-circle of the depression fed both from the Bay and the Arabian Sea was being continuously faced up against the same part of the Himalayas, namely the Simla-Kumaon hills. This resulted in exceptionally heavy and continuous rain there as well as in the adjacent plains from 27 to 29 September.

7.4. The amount of rainfall for the storm duration were as follows :

Year of flood	*Upper catchment*	*Lower catchment*
1924	>60 cm	>30 <35 cm
1947	>60 cm	>30 <35 cm
1976	>35 <40 cm	<30 cm
1978	>45 <50 cm	>40 cm

In 1924 and 1947 considerable water was apparently lost due to local inundation before reaching Delhi. In the year 1976 the amount of rainfall for the storm duration was less than 40 cm in the upper catchment and less than 30 cm in the lower catchment. The peak gauge at Delhi Railway Bridge was, however, the highest ever recorded till that year. This was so because the antecedent precipitation index was more that year and the saturated soil could not absorb enough water and most of the rainfall had flown as the surface run-off. In 1978 the amount of rainfall for the storm duration was less than that in the remaining three years but it was more in the lower catchment. This shows that the rainfall in the lower catchment also contributes significantly to the flood gauge.

7.5. The duration of the rainstorms in the four floods years 1924, 1947, 1976 and 1978 were 5, 4, 2, and 4 days respectively in the upper catchment and 3, 4, 2, and 3 days respectively in the lower catchment.

7.6. The maximum average depth in the upper and lower catchments in the four years for 1, 2, 3, 4 and 5 days are given in Tables 5 and 6.

8. Concluding remarks

8.1. All the major floods have occurred in the *Yamuna* river at Delhi in August and September.

8.2. The floods occur due to heavy rainfall in the upper and lower catchments associated with a depression from the Bay of Bengal or Arabian Sea recurving towards northeast from east Rajasthan, the rainfall in the lower catchment also contributing significantly to the flood peak. The amount of rainfall for the storm duration is greater than 50 cm in the upper catchment and greater than 30 cm in the lower catchment. A higher antecedent precipitation index, however, reduces the quantity of rainfall required for a major flood to greater than 35 cm.

8.3. The duration of the rainstorms is generally 4 to 5 days in the upper catchment and 3 to 4 days in the lower catchment but it can be as low as 2 days in both catchments if soil is earlier saturated.

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