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A study of Rainfall and Floods in the Yamuna Catchment (up to Delhi)

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1. Introduction

The Yamuna which has been described in the Vedas (Burrard 1934) as one of the seven branches of the Ganga (Sapta-Sindhavas), drains the Punjab-Kumaon Himalayas from Simla in the northwest to Mussoorie in the southeast. In its Himalayan reach, its catchment lies between the two great Himalayan rivers, the Sutlej and the Ganga. The Sutlej drains the Punjab Himalayas to its north and west, while the Ganga drains the Kumaon Himalayas to its east. The Yamuna debouches into the plains near about Faizabad in the Saharanpur district (west U. P.) after piercing the Siwalik hills. About two miles downstream from this place is the Tajewala Headworks in the Punjab wherefrom the Western Yamuna Canal takes off. The Eastern Yamuna Canal also takes off near about this place on the U. P. side. From Tajewala onwards, Yamuna flows in a southerly direction upto Okhla Headworks near Delhi. From the point of view of terrain, the whole catchment upto Delhi (Okhla) can broadly be divided into two main reaches, *viz.*, the Himalayan reach from the source to Tajewala and the plains reach from Tajewala to Okhla.

2. The Himalayan reach

In this reach, the Yamuna has two important tributaries, *viz.*, the Tons and the Giri. The main river (*i.e.*, the Yamuna) rises from the glaciers of the Bunderpunch (20,720 ft), north of the Jamnotri hot springs. After flowing a distance of about 100 miles in a southwesterly direction, the Yamuna is joined by its principal tributary, the Tons, from the north at a point about 2 miles downstream of Kalsi. As the Tons drains a larger catchment area, it carries a greater volume of water than the main river Yamuna. From the west another important tributary, the Giri, joins the main river two miles upstream of Paonta. The total catchment area of its fan-shaped Himalayan reach is about 4300 sq. miles. If the 22 principal Himalayan rivers from the Indus in the west to the Brahmauputra in the east are arranged according to the size of the Himalayan areas they drain, the Yamuna occupies the 18th position in the list (Burrard 1934).

3. The Plains reach

In this reach, about 10 miles upstream of Delhi, the Yamuna acts as a boundary between the two states of U. P. and the Punjab. After debouching into the plains, it flows through a level country for a distance of about 155 miles from Tajewala to Okhla. In this reach, the slope of this river is about 1·3 feet per mile and the total catchment area of this ribbon-shaped reach is about 3300 sq. miles. During the flood season, it is this reach which is subjected to maximum inundation and flooding. The river has no major tributaries in this reach.

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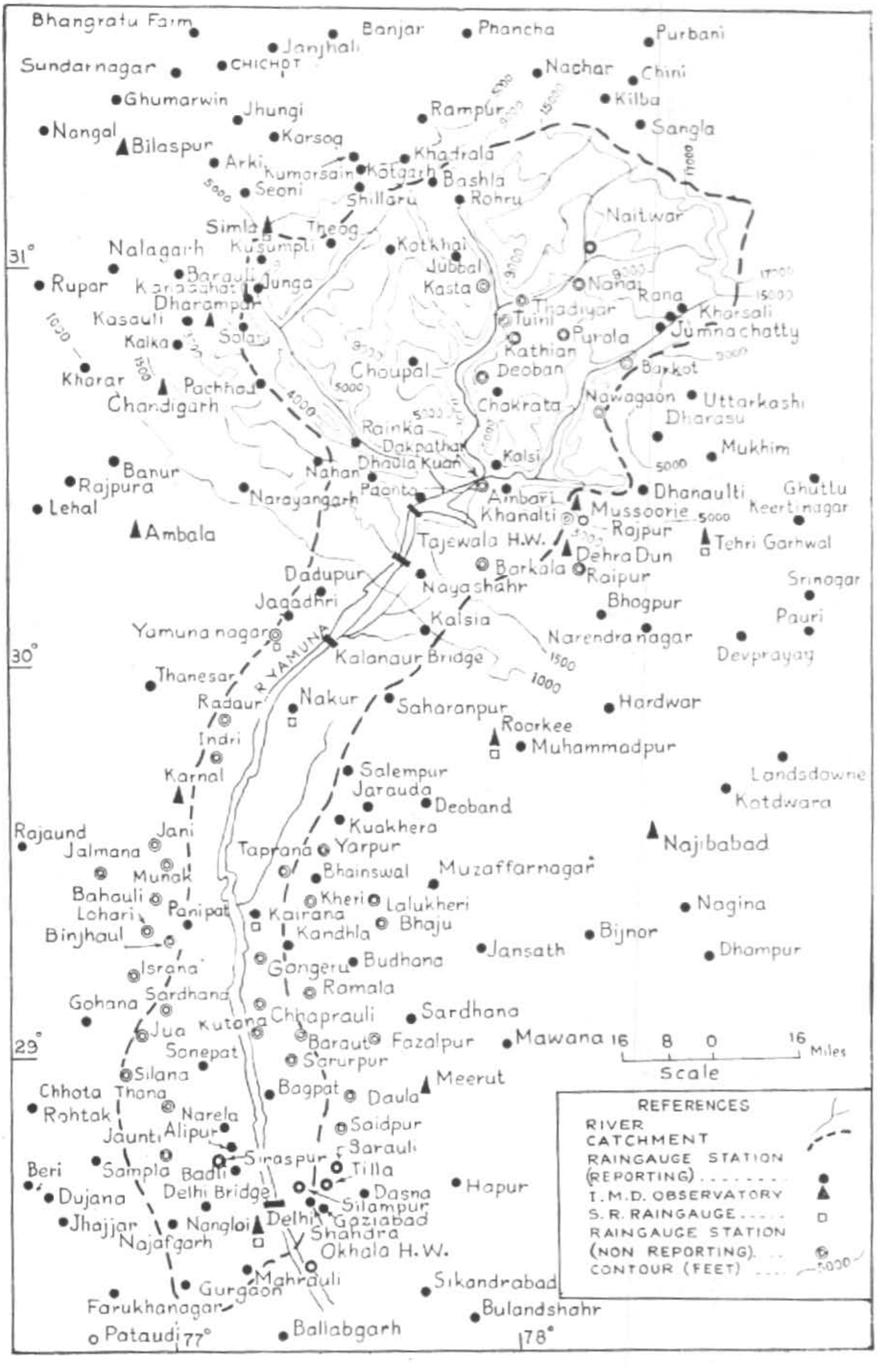

Fig. 1. Raingauge stations in Yamuna Catchment

4. Onset and withdrawal of monsoon

Normally, monsoon sets in over the upper reach, by about the end of the third week of June, while in the lower reach, it sets in a few days later, *i.e.*, by about the middle of the fourth week of June. Monsoon, normally, withdraws from this region by about the middle or third week of September, and October is generally a dry month for this region. Examination of past rainfall data has, however, shown that there have been instances in the past when heavy spells of rainfall were received in and near the Yamuna catchment towards the end of September or even upto the middle of October. These spells of heavy rain occurred in association with the late monsoon depressions which originate either in the Bay of Bengal or the Arabian Sea. These spells of heavy rain were received practically at the close of the monsoon season when the catchment was almost saturated and the river was nearly full and consequently heavy floods occurred in the lower reaches. The late September Floods of 1900, 1914, 1933, 1947 and the October Floods of 1924, 1955 and 1956 were caused by factors similar to the above.

5. Raingauge network (ordinary and self-recording)

The total number of existing reporting (ordinary) raingauge stations in the Yamuna catchment (upto Okhla) is 41. A map of the catchment showing raingauge stations in and around the catchment is given at Fig. 1. Out of 41 reporting raingauges, 20 are located in the upper or the Himalayan reach and the remaining 21 in the plains or the lower reach between Tajewala and Okhla. Five out of the 20 raingauge stations in the upper catchment, *viz.*, Chakrata, Ambari, Mussoorie, Simla and Kotkhai have daily rainfall data available in the printed rainfall tables since 1891. The data for the remaining 15 raingauge stations (mostly located in Himachal Pradesh) are available only after 1951.

In addition to the existing reporting raingauge stations, there are a fairly good number of non-reporting stations maintained by the Forests and Irrigation Departments of the respective States of U. P. and Punjab. Locations of some of these stations have been shown in the raingauge map at Fig. 1. The total number of raingauge stations upto Okhla, both reporting and non-reporting, are 66 for a total catchment area of 7600 sq. miles. Thus the density of raingauges works out to one raingauge for every 115 sq. miles in the Yamuna catchment compared to one raingauge for every 250 sq. miles in U. S. A. (U. S. Weath. Bur. 1960). However, the network of raingauges in the upper catchment requires to be considerably strengthened as the existing raingauges are not uniformly distributed. It is seen from the raingauge map of the catchment (Fig. 1) that certain portions of the catchment, *viz.*, (*i*) north-eastern part of the upper catchment to the east of Pabar and Rupin rivers, (*ii*) part of the catchment between the Giri and Tons rivers, and (*iii*) in the lower reach, part of the catchment between Nakur and Kairana stations, are not well represented by raingauge stations. These areas require to be covered by the installation of additional raingauges.

There are six S. R. raingauges in the whole catchment at the following places—

Upper catchment—Simla; Lower catchment—(1) Nakur, (2) Kairana, (3) New Delhi, (4) Karnal, and (5) Yamuna Nagar.

Excepting the S. R. raingauge at New Delhi the rest have been installed very recently. The one at Simla is functioning since 1956 while the other four in the lower catchment were installed during 1959-60. Apart from Simla, which is located in the north-western corner of the upper catchment, there are no S. R. raingauge stations in the upper reach. It is thus evident that there is a necessity for establishing a few S. R. raingauges in this reach.

6. Mean monthly and annual rainfall

As already stated, rainfall data of 75 per cent of the reporting raingauge stations

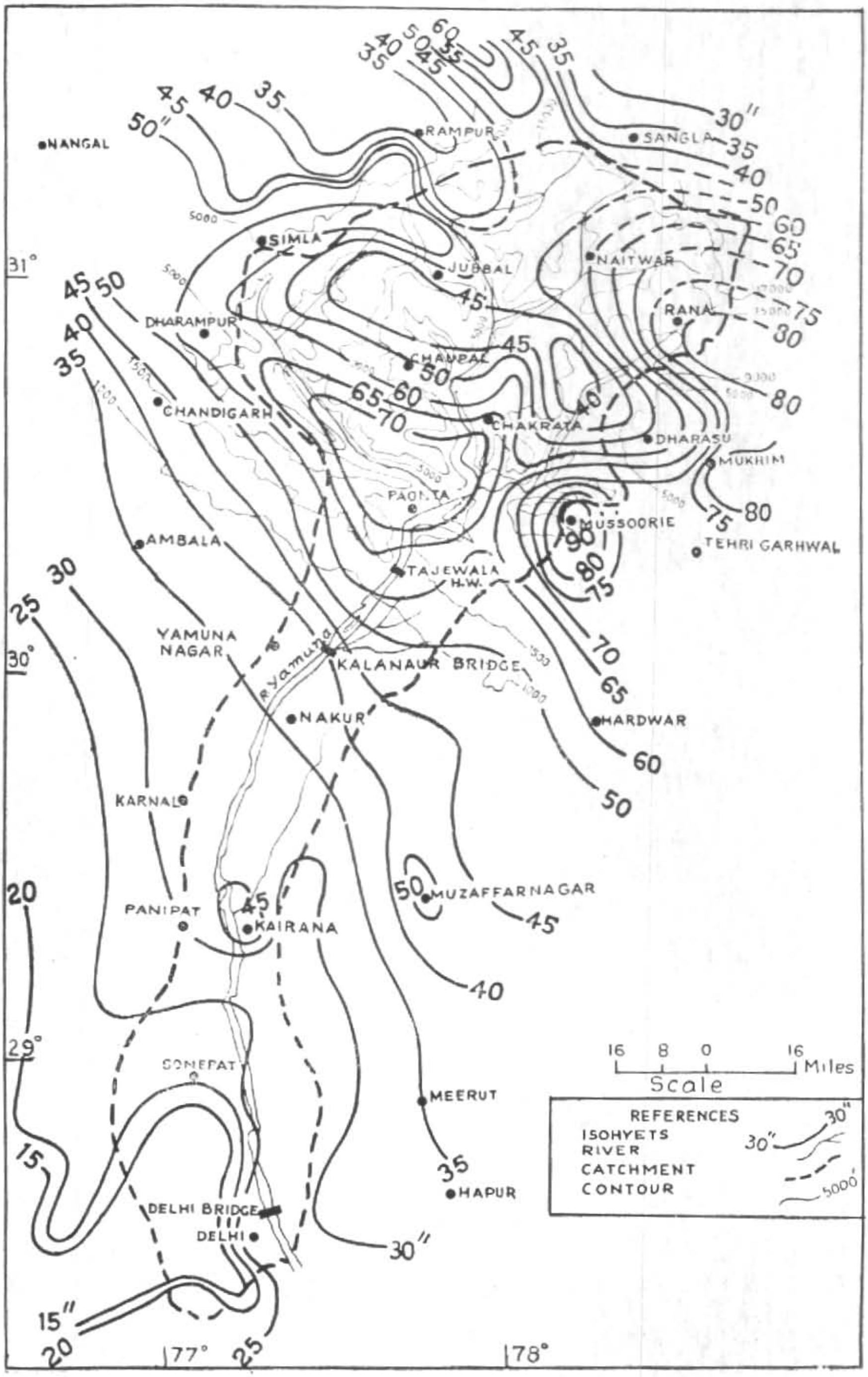

Fig. 2. Mean annual isohyets (1951—1958) of Yamuna Catchment

in the upper catchment are available from 1951 only. As such, calculation of mean monthly values of rainfall for the whole catchment (upto Okhla) was done for the period 1951-58 making use of the monthly totals of rainfall for all raingauges in and around the catchment. As the data after 1958 have not yet been published in respect of all the state raingauges, this study could not be undertaken for the data beyond 1958. On the basis of all available data and utilising the data of some of the forest non-reporting raingauges in the upper catchment, mean monthly and mean annual values of rainfall were calculated by the isohyetal method for the upper, lower and the whole catchment. In view of the mountainous terrain of the upper catchment, rainfall data of individual raingauge stations in and around the catchment were plotted on base maps showing height contours. The guiding principles summarised by Satakopan (1951) were kept in view while drawing isohyets. Special attention was paid to the variation of rainfall with orography and the normal isohyetal pattern of the surrounding areas was also taken into consideration. Consistency of the mean monthly isohyetal maps was also checked with the mean annual isohyetal map and wherever necessary, isohyets were adjusted. In cases where the network of raingauge stations were not adequate, isohyets have been drawn in dotted lines to indicate that these are not based on recorded data. Weighted mean monthly and annual rainfall values were then calculated by planimetering the individual monthly and annual isohyetal maps. The mean annual isohyetal map of the catchment is given in Fig. 2. The mean monthly and annual values of rainfall based on 8 years' data are given in Table 1.

The mean monthly values obtained by isohyetal method (*vide* Table 1) have been further checked with the values obtained by the arithmetic average method and it has been seen that the values more or less tally as can be seen from Table 2.

From Table 1 it can be seen that July and August are the principal rainy months during which more than 51 per cent of the annual precipitation is received.

TABLE 1

Mean monthly and annual values of rainfall (inches) (1951-58)

	Upper catchment	Lower catchment	Whole catchment
Jan	4·3	1·4	3·0
Feb	2·1	0·8	1·5
Mar	2·9	0·7	1·9
Apr	1·5	0·2	0·9
May	2·2	0·4	1·4
Jun	3·6	2·2	3·0
Jul	13·9	8·4	11·4
Aug	14·2	10·2	12·4
Sep	6·7	4·9	5·9
Oct	4·1	2·7	3·4
Nov	0·4	0·3	0·3
Dec	1·5	0·3	1·0
Annual	57·4	32·5	46·1

Catchment rainfall of individual months during each year was also calculated separately for the period 1951-58 by arithmetic average method. On the basis of this data, cumulative rainfall curves (January to December) for each year were separately drawn. These curves are shown in Fig. 3. From these curves it can be seen that during the period 1951-58, 1956 was the year of maximum rainfall, while 1951 was the year of minimum rainfall for the Yamuna catchment. The highest and the lowest values of catchment rainfall for the four flood-months of July to October have also been worked out and the values are given in Table 3.

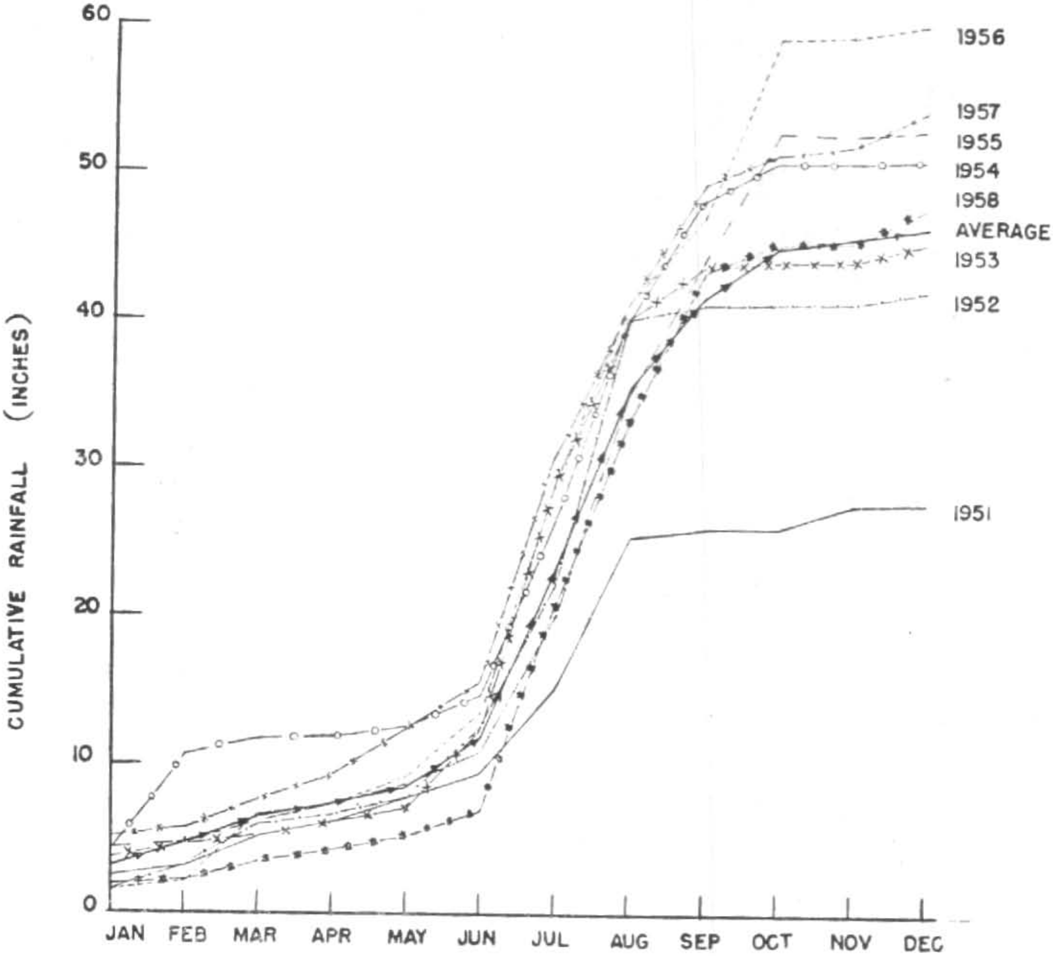

Fig. 3. Cumulative rainfall for the Yamuna Catchment (1951—58)

7. Highest 24-hour rainfall values

From the available printed daily rainfall records since 1891, the highest 24-hour rainfall values recorded at each raingauge station inside the catchment during the flood-months of July to October, and also for a year as a whole, were picked up and are given in Table 4. On examining this table, it will be seen that in the Yamuna catchment the highest recorded rainfall of 17·50 inches in 24 hours was recorded at the canal raingauge station at Dadupur (13 miles downstream of Tajewala) on 2 July 1956. If recorded rainfall data of earlier years are also examined, (*i.e.*, earlier than 1891) it is likely that one may come across heavier falls of rain in 24 hours at some stations. While examining daily rainfall data of the period 1875-1885, Blanford (1889) found that Delhi (lower Yamuna catchment) had recorded exceptionally heavy falls of 19·5″ and 12·0″ in 24 hours on 9 September 1875 and 18 September 1878 respectively.

TABLE 2

Mean rainfall (inches) for the whole catchment

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Isohyetal method	3·0	1·5	1·9	0·9	1·4	3·0	11·4	12·4	5·9	3·4	0·3	1·0	46·1
Arithmetic average method	3·0	1·5	2·0	0·9	1·4	3·2	12·0	12·4	6·0	3·6	0·3	0·9	47·2

TABLE 3

Highest and lowest values of Catchment rainfall (1951-58)

	Highest catchment rainfall (in.)	Percentage departure from mean monthly/ annual rainfall	Lowest catchment rainfall (in.)	Percentage departure from mean monthly/ annual rainfall
July	16·6 (1953)	+46	5·7 (1951)	—50
August	17·9 (1952)	+44	9·4 (1957)	—24
September	9·8 (1958)	+66	0·4 (1951)	—93
October	12·1 (1956)	+256	0·1 (1952)	—97
Annual	60·0 (1956)	+30	27·7 (1951)	—40

The number of occasions of heavy falls of rain of more than 5 inches and more than 10 inches in 24 hours at each raingauge station for the period for which the data are available are shown in Cols. 14 and 15 respectively of Table 4. From a perusal of this table, it will be seen that for rainfall amounts of 5 inches and above in 24 hours, Mussoorie has the highest frequency, *i.e.*, 102 occasions in a period of 70 years. For rainfall amounts of 10 inches and above in 24 hours, Ambari, a raingauge station near the Siwalik hills inside the catchment, has the highest frequency of 5 occasions in the same period.

8. Past floods in the Yamuna

For this study, all the peak floods which occurred in each year during the period 1900 to 1960 were noted. Table 5 shows the year, date and month of peak floods in each year when the gauge at Delhi Railway Bridge crossed the danger level of R. L. 672·0 ft during the above period.

It will be seen from the peak gauges given in Table 5 that the danger level (*i.e.*, R. L. 672·0 feet) was exceeded on 17 occasions during the sixty-year period. Table 5 also shows that the months of August and September are the chief flood producing months for the Yamuna river. Rarely floods have occurred in July, which is one of the two principal rainy months of this region. In the month of October, some major floods have occurred in the past especially after the monsoon had withdrawn from this region.

TABLE 4

Highest rainfall in 24 hours at raingauge stations inside the Yamuna Catchment

Station	Period of availability of data	JULY		AUGUST		SEPTEMBER		OCTOBER		ANNUAL		Rainfall frequency	
		Date	Amount (in.)	Date	Amount (in.)	Date	Amount (in.)	Date	Amount (in.)	Date	Amount (in.)	5" and above	10" and above
Mussoorie	1891—1960	17-7-01	8·0	30-8-36	11·8	29-9-24	10·2	27-10-17	5·3	30-8-36	11·8	102	4
Ambari	,,	17-7-09	11·2	21-8-43	11·4	4-9-36	8·0	27-10-17	4·7	21-8-43	11·4	82	5
Kalsia	1892—1960	1-7-95	7·6	9-8-42	12·7	30-9-24	10·5	12-10-56	4·9	9-8-42	12·7	41	2
Nayashahr	1891—1960	2-7-56	11·0	9-8-42	8·3	30-9-24	10·0	12-10-56	7·0	2-7-56	11·0	46	2
Saharanpur	,,	2-7-95	10·5	7-8-91	8·6	15-9-57	9·2	12-10-56	6·4	2-7-95	10·5	21	1
Nakur	,,	2-7-95	11·5	2-8-08	7·4	8-9-12	7·8	27-10-17	6·5	2-7-95	11·5	22	1
Kairana	,,	19-7-12	6·5	3-8-34	5·7	8-9-12	10·8	9-10-56	5·6	8-9-12	10·8	27	1
Kandhla	1891—1959	15-7-00	7·0	13-8-50	7·0	19-9-33	11·0	9-10-56	5·5	19-9-33	11·0	22	1
Baghpat	1891—1960	29-7-20	5·7	21-8-52	12·4	8-9-12	8·1	2-10-10	5·4	21-8-52	12·4	10	1
Chakrata	,,	21-7-03	6·2	14-8-03	9.1	29-9-24	7·1	9-10-56	7·5	14-8-03	9·1	28	—
Karnal	,,	16-7-00	7·7	21-8-52	10·6	13-9-05	6·9	9-10-56	5·1	21-8-52	10·6	20	1
Panipat	,,	29-7-20	5·1	2-8-08	7·5	19-9-33	10·0	9-10-56	4·9	19-9-33	10·0	14	1
Sonepat	,,	22-7-57	8·0	6-8-91	6·0	19-9-33	10·1	2-10-10	5·0	19-9-33	10·1	13	1
Jagadhri	1891—1959	6-7-09	7·6	2-8-08	11·3	19-9-14	7·0	27-10-17	4·7	2-8-08	11·3	24	1
Dadupur	1891—1960	2-7-56	17·5	13-8-21	12·1	26-9-47	12·0	27-10-17	7·0	2-7-56	17·5	47	4
Gurgaon	,,	27-7-56	6·9	5-8-91	10·2	28-9-11	9·3	2-10-10	6·9	5-8-91	10·2	9	1
Mehrauli	1891—1912 } 1942—1959 }	12-7-44	5·4	6-8-91	5·1	28-9-11	7·0	2-10-10	6·5	28-9-11	7·0	10	—
Delhi	1891—1912 } 1942—1960 }	21-7-58	10·5	6-8-91	7·1	16-9-04	6·9	1-10-54	6·8	21-7-58	10·5	11	1
Nagloi	1942—1959	22-7-58	5·8	28-8-46	2·5	1-9-44	3·0	5-10-44	1·3	22-7-58	5·8	1	—
Badli	1942—1960	12-7-60	4·7	11-8-53	4·0	11-9-60 } 1-9-44 }	3·4	11-10-56	5·3	11-10-56	5·3	1	—
Alipur	1942—1959	21-7-50	5·0	26-8-52	2·7	16-9-45	4·1	5-10-44	2·8	21-7-50	5·0	1	—
Narela	1942—1960	21-7-50	5·7	21-8-60	5·2	15-9-47	7·3	5-10-44	3·5	15-9-47	7·3	3	—
Shahadara	1942—1959	20-7-49	4·0	16-8-42	3·0	4-9-44	5·1	5-10-44	2·5	4-9-44	5·1	1	—
Najafgarh	1942—1960	9-7-55	4·2	21-8-47	3·0	28-9-55	4·5	1-10-54	5·5	1-10-54	5·5	1	—
Kandaghat	1952—1959	25-7-57	3·1	14-8-54	5·1	26-9-54	5·3	12-10-56	5·6	12-10-56	5·6	3	—
Simla	1891—1960	20-7-22	6·6	6-8-91	10·7	26-9-47	4·3	8-10-27	2·9	6-8-91	10·7	13	1
Dhaula Kuan	1952—1960	18-7-57	6·9	2-8-53	8·5	27-9-54	3·7	11-10-56	4·9	2-8-53	8·5	11	—
Paonta	1951—1960	26-7-56	8·9	22-8-51	8·2	8-9-59	5·2	12-10-56	8·8	26-7-56	8·9	15	—
Rainka	,,	26-7-57	5·7	8-8-54	8·4	7-9-54	9·2	12-10-56	9·7	12-10-56	9·7	10	—
Pachhad	1951—1959	30-7-58	4·7	22-8-58	9·0	26-9-54	4·4	12-10-56	6·1	22-8-58	9·0	7	—
Solan	1951—1960	14-7-52	4·5	21-8-51	10·4	26-9-54	6·0	12-10-56	2·6	21-8-51	10·4	3	1

TABLE 4 *(contd)*

Station	Period of availability of data	JULY Date	JULY Amount (in.)	AUGUST Date	AUGUST Amount (in.)	SEPTEMBER Date	SEPTEMBER Amount (in.)	OCTOBER Date	OCTOBER Amount (in.)	ANNUAL Date	ANNUAL Amount (in.)	Rainfall frequency 5″ and above	Rainfall frequency 10″ and above
Junga	1951—1960	14-7-58	5·0	16-8-54	5·3	26-9-54	4·0	12-10-56	3·0	16-8-54	5·3	2	—
Kusumpti	1951—1959	9-7-54	3·7	8-8-53	3·2	27-9-54	3·4	12-10-56	2·3	9-7-54	3·7	—	—
Theog	1958—1960	6-7-59	3·0	2-8-59	1·8	1-9-60	1·4	27-10-59	0·9	6-7-59	3·0	—	—
Rohru	1951—1959	6-7-59	2·3	19-8-52	2·4	26-9-54	2·7	4-10-55	4·4	4-10-55	4·4	—	—
Bashlâ	,,	15-7-58	5·8	21-8-51	3·2	26-9-54	4·1	4-10-55	5·1	15-7-58	5·8	2	—
Kotkhai	1891—1960	1-7-14	7·2	14-8-03	4·9	25-9-47	5·3	26-10-17	4·0	1-7-14	7·2	3	—
Jubbal	1951—1960	16-7-54	2·1	19-8-52	3·0	14-9-57	2·8	3-10-55	4·2	3-10-55	4·2	—	—
Chopal	1951—1960	5-7-59	3·1	21-8-51	3·1	14-9-57	3·7	12-10-56	4·9	12-10-56	4·9	—	—
Rana	,,	15-7-57	3·7	11-8-53	3·9	7-9-55	2·6	2-10-54	2·3	11-8-53	3·9	—	—
Jamuna Chatty	,,	12-7-57	5·7	22-8-51	5·5	8-9-55	2·3	9-10-56	3·2	12-7-57	5·7	2	—
Kharsali	,,	15-7-57	4·0	22-8-51	3·3	27-9-55	3·3	9-10-56	5·1	9-10-56	5·1	1	—
Thadiyar	1952—1960	12-7-53 28-7-53 17-7-58	3·5	8-8-54	4·0	3-9-57	3·5	12-10-56	3·5	8-8-54	4·0	—	—
Naitwar	,,	23-7-52	2·7	1-8-52	3·6	8-9-59	2·7	11-10-56	3·0	1-8-52	3·6	—	—
Nanai	,,	18-7-55	3·2	9-8-55	3·3	29-9-56	2·5	4-10-55	3·4	4-10-55	3·4	—	—
Kasta	,,	14-7-57	4·0	10-8-57	2·2	25-9-54 26-9-54	2·2	11-10-56	3·6	14-7-57	4·0	—	—
Deoban	1940—1958	19-7-43	5·5	17-8-45	6·4	24-9-47	6·0	8-10-56	6·7	8-10-56	6·7	6	—
Barkala	1950—1960	20-7-54	6·7	4-8-52	11·1	26-9-54	5·4	12-10-56	2·9	4-8-52	11·1	9	1

NOTE—Daily monsoon rainfall data from July to September 1961, in respect of raingauge stations mentioned in the above table were examined subsequently. It was noticed that in the case of following raingauage stations in the catchment the highest 24-hour rainfall values mentioned above were exceeded on the dates given below—

Station	Month (date)	Highest 24-hour rainfall value (inches)
Narela	July (17th)	6·4
Badli	July (17th)	8·1
Panipat	July (30th)	7·5
New Delhi	August (2nd)	7·3
Chopal	August (8th)	3·4

TABLE 5

Year	Date	Peak gauge at Delhi Rly. Bridge R.L. (ft)
1900	21 Sep	672·8
1902	21 Jul	672·7
1908	4 Aug	673·1
1914	23 Sep	672·5
1924	2 Oct	675·1
1932	13 Sep	672·4
1933	23 Sep	672·5
1937	20 Sep	672·0
1942	16 Aug	673·0
1943	19 Aug	672·3
1947	29 Sep	675·9
1948	27 Aug	672·0
1952	25 Aug	672·2
1955	9 Oct	675·5
1956	15 Oct	677·3
1957	18 Sep	672·8
1958	8 Aug	672·8

NOTE—This table is based on the gauge data obtained from the Northern Railway authorities and has been checked with the data obtained from other sources

9. Attendant meteorological situations responsible for floods in the Yamuna

Meteorological situations responsible for the worst floods in the Yamuna in October 1924, September 1947, October 1955 and October 1956, when the gauge at Delhi Railway Bridge stood above R. L. 675·0 feet (*i.e.*, 3 feet above the danger level) are described here in detail. The meteorological situations associated with the other medium floods (*i.e.*, when the gauge at the Delhi Railway Bridge was between R. L. 672 and 675 ft) are described rather briefly in the following paragraphs.

10. Flood producing meteorological situations

Floods are normally caused by the incidence of heavy rain in short periods over a river basin. The meteorological situations that cause heavy rainfall are described in a note submitted by the Meteorological Department to the High Level Committee on Floods (1957). The chief flood producing situations are briefly mentioned below—

(*i*) *Monsoon depressions*—They cause incidence of heavy rain along their track during their travel in the interior of the country with a high concentration of rainfall being received in the southwestern sector of the depression,

(*ii*) *Heavy rainfall due to orographic lifting*—When moist currents are made to rise abruptly over mountain barriers during a period of active monsoon, and

(*iii*) *"Breaks" in the monsoon*—Heavy rain caused over the central and eastern Himalayas due to shifting of the axis of the seasonal monsoon trough to the foot of the Himalayas.

In the light of above three flood producing factors, the attendant meteorological situations responsible for the peak floods in the Yamuna mentioned in Table 5 have been studied in this note. As a result of this study, it has been observed that floods in the Yamuna have never been caused by the setting in of "Breaks" in the monsoon. On the other hand, floods have generally been caused by the incidence of heavy rainfall associated with the monsoon depressions either from the Bay of Bengal or the Arabian Sea. The peak floods of July 1902, September 1914, October 1924, September 1933, September 1937, August 1943, September 1947, August 1948, October 1955, October 1956, and September 1957 were mainly caused by monsoon depressions breaking over the

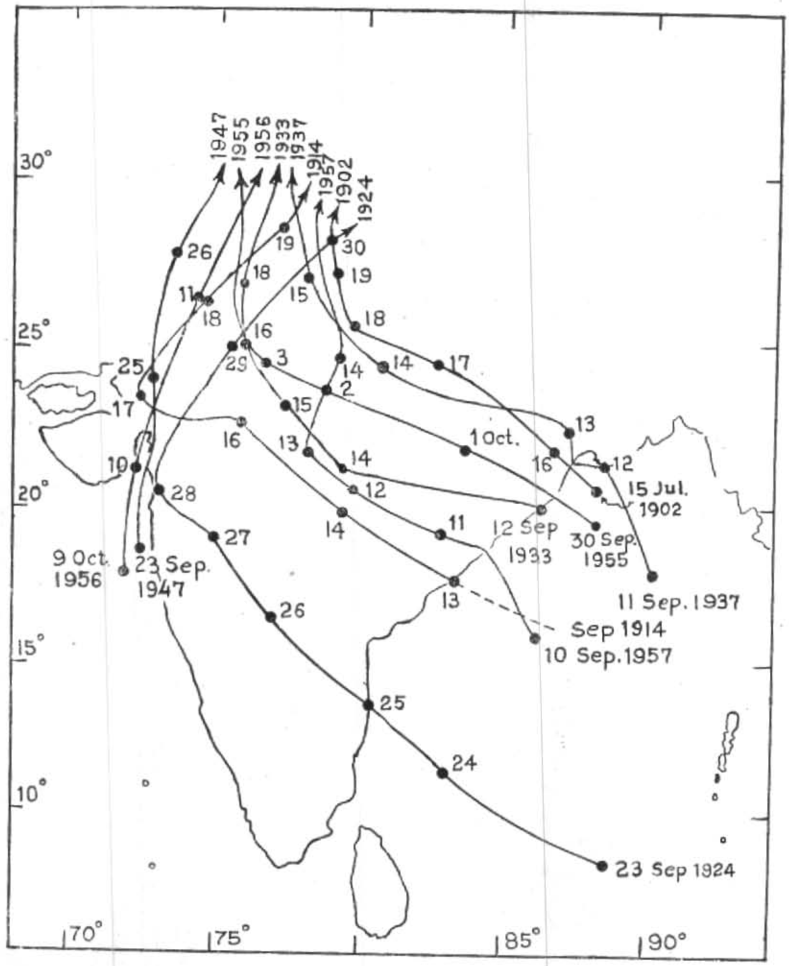

Fig. 4. Tracks of some important depressions responsible for floods in Yamuna River

Punjab-Kumaon hills or depressions getting filled up over the plains of north Punjab and/or northwest U.P. Storm tracks of some of the important depressions which have been responsible for floods in the Yamuna are given in Fig. 4. In other years, floods have been caused by the vigorous inflow of moisture into the region by the strengthening of the monsoon current. Sometimes passage of depressions or low pressure areas in the southern latitudes have been responsible for the strengthening of the monsoon current over the region. The floods in September 1900, August 1908, August 1942, August 1952 and August 1958 were caused by the meteorological situations similar to the above.

It is well-known that the activity of monsoon over northwest U. P. and adjoining Punjab gets enhanced with the passage of westerly waves across extreme north India during the monsoon months. This has been corroborated by Malurkar (1950), Mooley (1957) and other workers. If at the time of approaching depression or when the vigorous inflow of moisture is taking place over the region, a westerly wave happens to pass eastwards across the Punjab-Kumaon hills, the rainfall experienced is exceptionally heavy due to moist currents being pulled up over the hilly terrain. In the recent years, the floods in the Yamuna in October 1955, October 1956, September 1957 were also associated with the eastward passage of active westerly waves through Kashmir and Punjab Himalayas when depressions were heading towards the Punjab-Kumaon hills. As a result of syncronization of westerly waves with the filling up of depressions over the Punjab-Kumaon hills, exceptionally heavy rain was received in the upper half of the catchment.

11. Analysis of the major floods in the Yamuna

From Table 5, it can be seen that major floods occurred in the Yamuna in October 1924, September 1947, October. 1955 and October 1956. Meteorological situations associated with these floods are described in the following paragraphs. Table 7 shows the total rainfall amounts of 10 inches and above recorded at reporting raingauge stations inside the catchment, during these storm periods.

(*i*) *Flood of October 1924*—The October 1924 flood in the Yamuna is considered to be one of the worst floods in the living memory. The abnormally heavy rains and consequent unprecedented floods caused tremendous destruction of life and property both in west U. P. and the Punjab. Hundreds of persons, thousands of head of cattle and a large number of houses were washed away in the adjoining districts of Dehra Dun, Saharanpur Ambala and Karnal. Considerable damage was also caused to the eastern and western canal systems, Tajewala Headworks, rail and road communications in the adjoining districts of U. P. and Punjab.

This flood was caused by exceptionally heavy rains which continued for nearly four days from 27 to 30 September. This unusually heavy spell of rain was caused by the Bay depression which crossed the Coromondal coast near Nellore on the morning of 25 September. Traversing across the Peninsula in a northwesterly direction, it was centered near about Surat on the morning of the 28th. Thereafter it recurved in a northeasterly direction and passed through east Rajasthan on the 29th and broke up over the Simla—Kumaon hills on the 30th, giving exceptionally heavy continuous rain during the last four days of the month. According to the *Indian Weather Review* (1924), "the advance of storms from the Bay into U. P. in the month of September or October is by no means an uncommon occurrence; but this disturbance was peculiar in that it was an unusually intense disturbance, and further its line of advance for three days was practically perpendicular to the line of the Himalayas, so that heavy rainfall associated with it, instead of being distributed along different hill tracts on succeeding days, fell for three successive days in one region". From depth-area-duration analysis of this storm, Parthasarthy (1958) has found the centre of this storm at a place about 40 miles east of Roorkee where nearly 30 inches of rain was recorded during the period 27 to 30 September.

It has been estimated that a peak discharge of about 5·0 lakh cusecs passed down Tajewala Headworks on 28 September and Paonta, 14 miles upstream of Tajewala recorded the highest gauge of R. L. 1267 ft (a rise of 43 ft) on the same day. The peak gauge of R. L. 675·1 ft (3·1 ft above danger level) was recorded at Delhi Railway Bridge on 2 October 1924.

(*ii*) *Flood of September 1947*—If Tajewala discharges and Kalanaur gauges are taken into consideration, the September 1947 flood may be regarded as the record flood for the Yamuna. The peak discharge of 5·63 lakh cusecs was recorded at the Tajewala Headworks on 27 September and the corresponding peak gauge at Kalanaur Railway Bridge, 24 miles downstream of Tajewala, was R. L. 883·7 ft on the same date.

TABLE 6

Spell of rain (Oct. 1956 flood)	Date	Weighted rainfall over the whole catchment (inches)	Corresponding gauges at Kalanaur Railway Bridge R.L.(ft)	Corresponding gauges at Delhi Railway Bridge with 3 days lag R.L. (ft)	Remarks
1st Spell	8-10-56	1·08	869·10	671·4 (11 Oct)	Actual dates in the case of Delhi Rly. Bridge gauges are given in brackets
,,	9-10-56	3·33	*876·00*	672·2 (12 Oct)	
,,	10-10-56	0·83	874·50	672·6 (13 Oct)	
2nd Spell	11-10-56	2·05	873·80	673·3 (14 Oct)	
,,	12-10-56	2·51	*880·00*	*677·3* (15 Oct)	
,,	13-10-56	0·92	877·00	677·8 (16 Oct)	
,,	14-10-56	0·28	874·80	675·8 (17 Oct)	

TABLE 7

Peak flood date at Delhi Railway Bridge	Storm period	Total rainfall (inches) recorded at raingauge stations inside the Yamuna catchment during the storm periods—cases of 10 inches and above
2-10-24	27 to 30 Sep	Kalsi 24·0, Mussoorie, 22·1, Nayashahr 19·5, Ambari 17·0, Dadupur 16·6, Chakrata 16·0, Kairana 13·0, Kotkhai 12·6, Kandhla 12·5, Saharanpur 12·3, Jagadhri 11·7, Panipat 11·4, Karnal 11·3, Simla 11·1
29-9-47	23 to 28 Sep	Dadupur 29·1, Nayashahr 19·3, Kandhla 17·7, Kalsia 16·4, Saharanpur 14·9, Chakrata 14·7, Ambari 14·5, Jagadhri 13·1, Kotkhai 12·0, Mussoorie 11·4, Nakur 11·3, Karnal 10·5, Simla 10·2
9-10-55	2 to 6 Oct	Pachhad 14·9, Chopal 14·0, Rainka 13·9, Chakrata 11·7, Dadupur 10·7, Jubbal 10·5, Kotkhai 10·1
15-10-56	8 to 14 Oct	Nayashahr 21·7, Rainka 20·2, Pachhad 18·9, Paonta 18·7, Chakrata 18·2, Chopal 16·3, Dadupur 15·6, Badli 15·4, Kalsia 13·7 Dhaula Kuan 13·2, Saharanpur 13·1, Jubbal 12·8, Bashla 11·6, Kairana 10·5

This flood was caused by a spell of heavy rain from 23 to 28 September in association with an Arabian Sea depression. The rainfall over the Punjab-Kumaon hills was very heavy on 25 and 26 September. The depression was formed on the 23rd, 50 miles southwest of Bombay. It crossed coast near Surat in the early hours of 24th. After crossing the coast, it weakened and continued to move northnortheastwards. It lay between Ahmedabad and Udaipur on the 25th and was centred 50 miles east of Bikaner on the 26th. Thereafter, it weakened further and moved away towards the Punjab on the 27th and got filled up over the Punjab hills.

The heavy rains and consequent floods in the rivers of the Punjab and west U. P. came in the wake of the partition of the country and caused untold hardships to the stranded refugees. Road and rail communications in the east Punjab and west U. P. remained disrupted for a number of days. The peak gauge at Delhi Railway Bridge was R. L. 675·9 ft (*i.e.*, 3·9 ft above the danger mark) on 29 September 1947.

(*iii*) *Flood of October 1955*—The spell of heavy rain which resulted in a major flood in the Yamuna in 1955 commenced from 2 October and lasted till 6 October. During this flood, a peak discharge of 4·67 lakh cusecs was recorded at Tajewala on 4 October and the corresponding peak gauge of R. L. 675·5 ft (3·5 ft above danger level) was recorded on the 9th at Delhi Railway Bridge.

The heavy rain occurred in association with a cyclonic storm from the Bay of Bengal which crossed the Orissa coast near Chandbali on the night of 30 September. It weakened into a deep depression after crossing the coast and moved northwestwards. It was centered near Raigarh in east Madhya Pradesh on 1 October. Thereafter, it moved westnorthwest and was centered near Jhalawar on the 3rd where it remained practically stationary till the 4th evening and got strengthened as a result of the feed of fresh monsoon air from the Arabian Sea. Under the influence of a deep westerly wave moving eastwards over Kashmir by this time, it moved northwards over the plains of the Punjab on the 5th and broke up against the Punjab hills on the 6th. Under the combined effect of the depression and the westerly wave, monsoon was vigorous over the region. Due to heavy rains in the Punjab and northwest U.P. practically all the rivers of this region were in high floods causing large scale disruption of rail and road communications and inundation of thousands of villages and damage to cash crops worth crores of rupees.

The centre of this rain storm was near Batala in the Punjab (Parthasarthy 1958). The daily weighted rainfall over the Yamuna catchment for this storm was calculated by the isohyetal method. Daily rainfall depths during this storm over the whole catchment are given below—

Date	Rainfall depth (inches)
2-10-55	0·65
3-10-55	1·56
4-10-55	2·57
5-10-55	1·61
6-10-55	0·80

From the above, it is evident that the rainfall over the Yamuna catchment was quite heavy on 4 October, when the depression was near about Jhalawar in the southeast Rajasthan.

(*iv*) *Flood of October 1956*—During this flood the highest recorded gauge of R.L. 677·3 ft (5·3 ft above the danger level) was recorded at Delhi Railway Bridge on 15 October at about 2200 IST. From a perusal of the daily gauge data of Delhi Railway Bridge, it is also seen that the Yamuna remained above danger level for nearly seven days from 12 to 18 October. The corresponding peak discharge at Tajewala was 4·50 lakh cusecs on 12 October.

The flood was caused by two spells of very heavy rain in quick succession during the period 8 to 14 October. The occurrence of heavy rainfall during the above period (*i.e.*, 8 to 14 October) has been attributed by Bose (1958) to the following three meteorological factors.

(*i*) The orientation of the axis of the extended seasonal trough of low pressure in the south Bay of Bengal and the Arbian Sea in a southeast-northwest direction instead of in east-west direction;

(*ii*) The passage of a low from the east Bay of Bengal along the above axis and the formation of a depression in the northeast Arabian Sea off Bombay; and

(*iii*) The eastward passage across Punjab and Kashmir of two active westerly waves in quick succession.

The first two factors maintained the flow of very moist air from the Bay of Bengal and the Arabian Sea into the region. The passage of two active westerly waves between 6 and 9 October across Punjab pulled up and squeezed the moist air over the Punjab-Kumaon hills and caused the first spell of heavy rains over the catchment between 8 and 10 October. The second spell of heavy rain occurred from 11 to 14 October in association with the passage of the Arabian Sea depression towards the Punjab hills. This depression after crossing the coast between Surat and Bhavnagar on the 10th rapidly moved northeastwards. It was centred near Jaipur on the 11th and finally broke up against the Punjab hills on 12th and 13th causing very heavy rains in the region.

The daily weighted rainfall over the whole catchment was worked out for the two storm spells, by the isohyetal method and weighted rainfall amounts are given in Table 6 along with the corresponding Kalanaur and Delhi gauges with three days lag. Table 6 shows that corresponding to two rain spells over the Yamuna catchment, there were two distinct flood peaks at Kalanaur Railway Bridge on 9 and 12 October, but at Delhi Railway Bridge, there was only one peak on the 15th. Perhaps, the first peak at Kalanaur Railway Bridge got smoothened out during its travel of about 120 miles to Delhi.

12. Rainfall distribution over the Yamuna catchment during monsoon depressions

Yamuna catchment (upto Delhi) runs in a north-south direction. Monsoon depressions either from the Bay of Bengal or the Arabian Sea heading towards the Punjab-Kumaon hills move over this region generally in the opposite direction, *i.e.*, opposite to the flow of the river. From a study of the rainfall distribution over this region caused by the depression of September 1924, Ramamurthy (1958) observed that heavy rain commenced over the hills and sub-montane regions evenwhen the depression centre was far away (about 700 miles in the case of September 1924 depression). The distribution of rainfall associated with the depressions of October 1955 and October 1956 was also studied for the upper and lower Yamuna catchments, respectively, when the depression centres were far away from the catchment. Table 8 shows the distribution of rainfall over the two parts of the catchment with respect to the depression centres.

From Table 8 it is seen that when the depression was far away, the upper catchment was affected first and received a good amount of rainfall in contrast to the lower catchment. Also, even when the depression was approaching the lower catchment from a southerly direction, the upper catchment continued to receive heavier rainfall. Such a situation may cause abnormally heavy floods in the lower reaches, if the flood wave travelling down from the upper catchment synchronises with the heavy rainfall in the lower reaches.

13. Rainfall analysis of October 1955 and October 1956 storms

October 1955 and October 1956 rain storms were analysed with the help of daily isohyetal

TABLE 8

	October 1955 storm					October 1956 storm			
	2nd	3rd	4th	5th	6th	11th	12th	13th	14th
Position of the centre of depression 24 hrs earlier*	Near Raigarh in east M.P.	Near Sagar in west M.P.	Near Jhalawar in Rajasthan	Stationary near Jhalawar	Over Punjab	Over Gulf of Cambay between Surat and Bhavnagar	Over north-east Rajasthan near Jaipur	Over Punjab hills	Residual trough of low pressure over Punjab
Weighted rainfall (in.) over the upper (Himalayan) catchment	1·1	2·6	2·8	2·0	0·8	2·7	3·1	1·0	0·5
Weighted rainfall (in.) over the lower (Plains) catchment	0·1	0·3	2·3	1·2	0·7	0·3	1·8	0·8	0·0

*Since rainfall recorded is of previous 24 hours

TABLE 9

Storm periods	Max. one-day (inch)	Max. two-day (inch)	Max. three-day (inch)	Max. four-day (inch)
2—6 Oct 1955	2·6	4·2	5·7	6·5
8—10 Oct 1956	3·3	4·4	5·2	—
11—14 Oct 1956	2·5	4·6	5·5	5·8

maps of the respective storm periods. The total storm isohyetal maps for October 1955 and October 1956 storms are given in Figs. 5 and 6. In the preparation of these isohyetal maps, daily storm rainfall data of some of the non-reporting forest raingauge stations in the upper catchment were obtained from the U.P. Forest authorities and utilized in drawing daily isohyetal maps. As in the case of mean monthly and annual isohyets, the storm isohyetal maps were also drawn after taking into account the orography of the catchment and storm rainfall isohyets of the surrounding regions. The weighted rainfall depths for different durations of maximum one-day, maximum two-day etc of each storm were then calculated and the same are given in Table 9.

The maximum depths obtained above have been plotted as depth-duration curves in

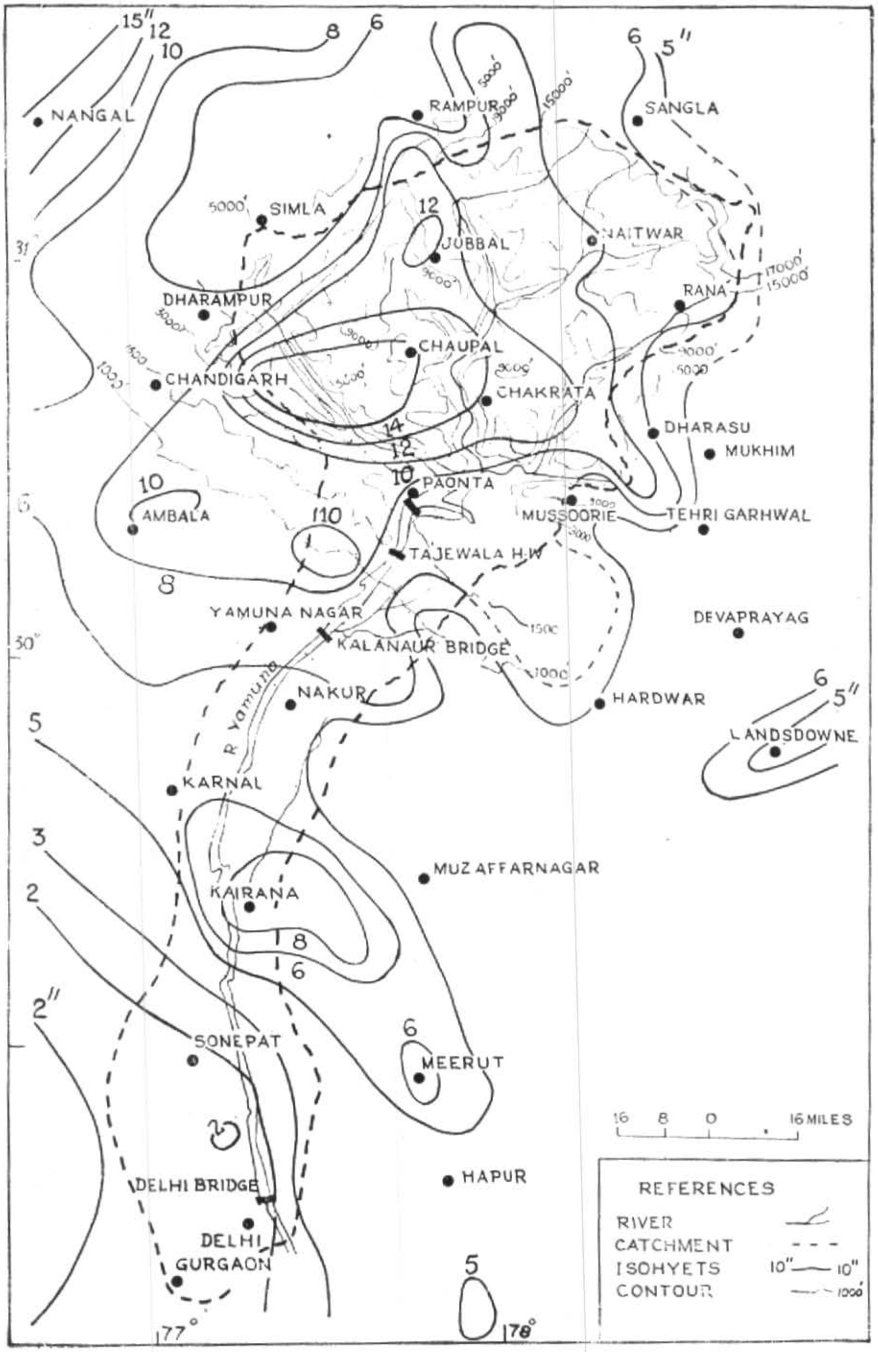

Fig. 5. Yamuna Catchment—total storm isohyets (2—6 October 1955)

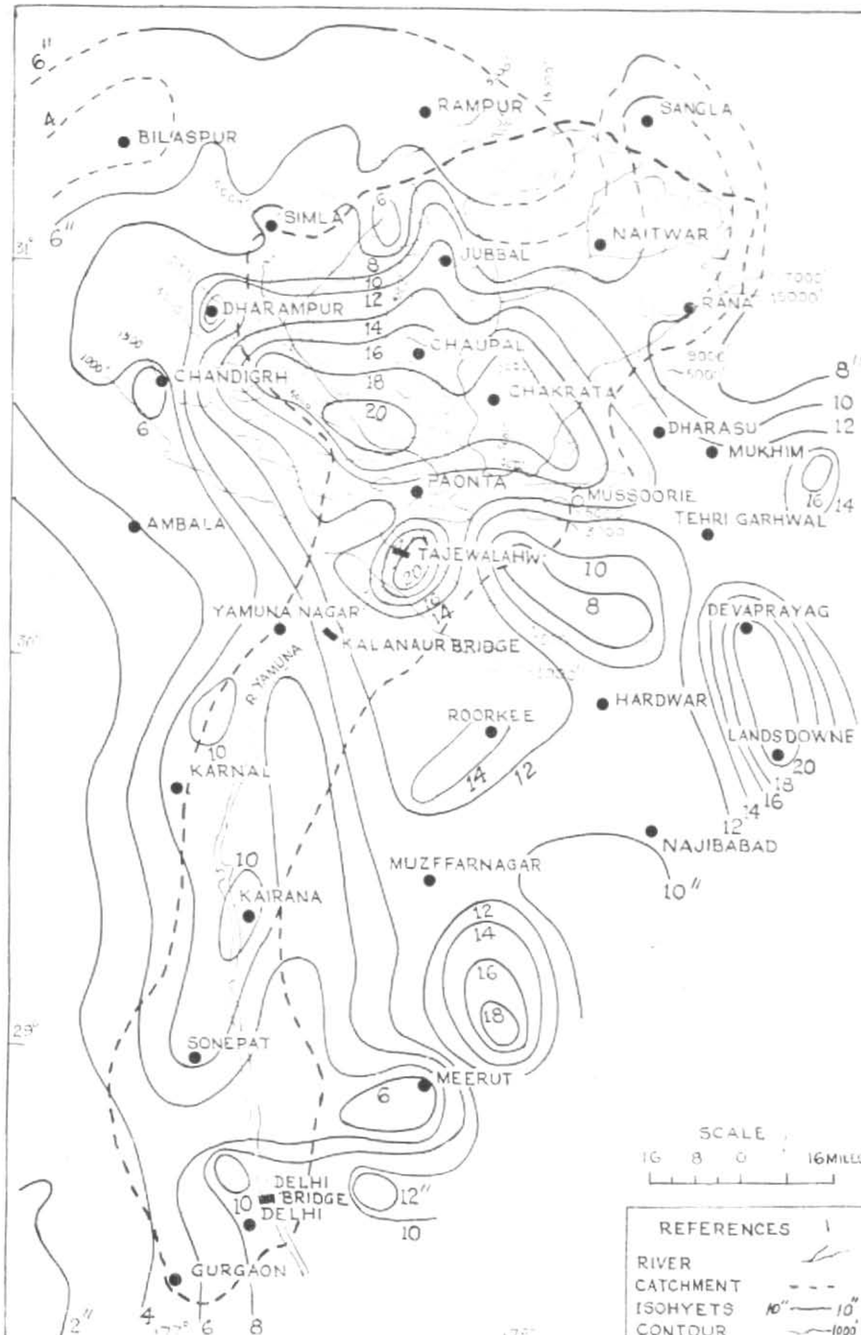

Fig. 6. Yamuna Catchment—total storm isohyets (8—14 October 1956)

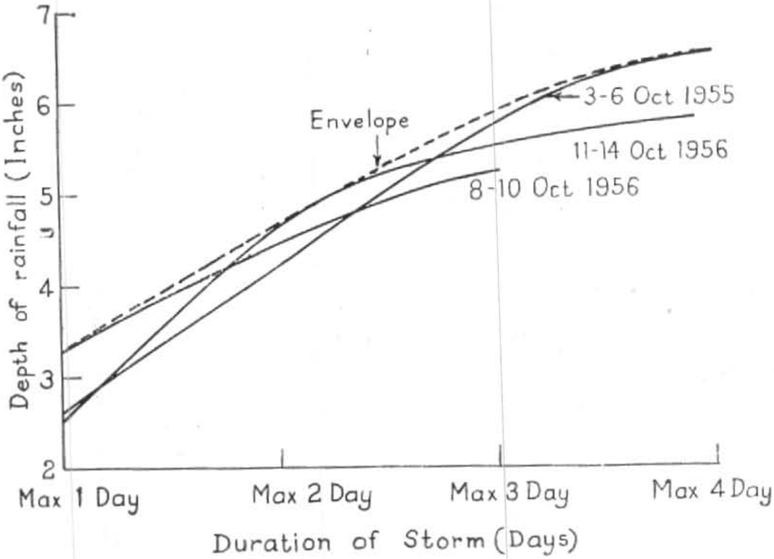

Fig 7. Depth-duration curves for Yamuna Catchment (upto Okhla)

Fig. 7. From the envelope curve, maximum depths for the whole catchment have been obtained for different durations and are given below—

Max. one-day — 3·3 inches
Max. two-day — 4·6 inches
Max. three-day — 5·8 inches
Max. four-day — 6·5 inches

The above maximum depths are based on the study of 3 major storms only and cannot, therefore, be taken as design depths of rainfall for this catchment. It is likely that higher depths of rainfall may be obtained if other major storms of September 1924 and September 1947 are also examined. This study could not be undertaken as the daily rainfall data of a majority of raingauge stations in the upper catchment are not available prior to 1951. Maximum rainfall depths obtained from depth-area-duration curves prepared by Parthasarthy (1958) for 1924 west U.P. storm and 1955 Punjab storm cannot be applied to this catchment because of the rugged topography of the upper catchment. For similar reasons, it is not advisable to apply the storm transposition technique to this catchment for obtaining design depths of rainfall.

14. Conclusions

From the above study, the following can be concluded—

1. Mean annual rainfall of the whole catchment (upto Okhla) is about 46 inches. July and August are the principal rainy months during which about 51 per cent of the annual rainfall is received. Examination of past rainfall data of the period 1951—58 has also shown that 1956 and 1951 were the years of maximum and minimum rainfall for the catchment respectively. The percentage departures of the maximum and minimum values from the mean annual are of the order of +30 and —40 respectively.

2. August and September are the chief flood producing months. Floods rarely occur in July, but some major floods have occurred upto the middle of October after the monsoon had withdrawn from this region.

3. Floods do not occur in the Yamuna with the setting in of "Breaks" in the monsoon. The majority of floods are associated with

monsoon and post-monsoon depressions breaking up over Punjab-Kumaon hills. A few floods have also occurred due to strong monsoon activity over the region.

If at the time of breaking up of a depression or during the period of active monsoon over the region, a westerly wave happens to pass eastwards across the Punjab-Kashsmir hills, exceptionally heavy rain occurs over the catchment.

5. Even when monsoon depressions heading towards Punjab-Kumaon hills are far away from the catchment, the upper catchment gets affected first and begins to receive heavy rain.

6. To obtain design rainfall of the catchment, it is necessary to analyse the major storms of September 1924, September 1947, October 1955 and October 1956 by depth-duration method. The upper catchment being hilly, the depth-area-duration or storm transposition analysis of these storms will not give correct depths of rainfall for various durations.

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