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# On some hydrometeorological aspects of Narmada basin

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ABSTRACT. A study of some hydrometeorological aspects of Narmada Basin has been attempted. Monthly and annual normals of rainfall and of number of rainy days have been worked out for the basin from the respective normals for individual stations. Variability of monthly rainfall in the monsoon season (June-September) and of seasonal and annual rainfall have been obtained for 20 selected stations of the basin. Highest ever 24-hr rainfall amounts at important stations recorded upto 1960 have also been included. Climatological data of maximum and minimum temperatures and of relative humidity have been compiled and discussed.

All the major rainstorms for this basin during the period 1891-1968 have been studied by isohyetal method and their depth-duration curves obtained. Major rainstorms for the basin have been discussed in detail together with the synoptic situations responsible for them. Depth-area curves for various durations have also been drawn for major rainstorms and envelope curves obtained. Peak discharge at Garudeshwar gauge site on 6 August 1968 has been computed from the precedent precipitation in the basin.

## 1. Introduction

*Narmada* is the largest river of India amongst those falling in the Arabian Sea. It originates in the Amarkantak Plateau of Maikal range in Madhya Pradesh at an elevation of 1057 m above mean sea level. Flowing in a more or less westward direction the *Narmada* is joined by a large number of tributaries on its course and it falls in the Arabian Sea near Gulf of Cambay after traversing a distance of about 1300 km. The basin area of the *Narmada* upto Broach is roughly 96,500 sq. km of which 1,600 sq. km lies in Maharashtra State, 8,100 sq. km in Gujarat State and the rest in Madhya Pradesh.

The *Narmada* basin is east-west oriented and has its major portion confined to a relatively narrow width between Vindhya range to its north and Satpura range to its south. The basin is so located that its eastern portion generally starts receiving heavy rain under the influence of Bay storms/depressions while they are still over Orissa, and so that increasing areas of it come under their influence as they move west of Orissa within about the same latitudes as the basin itself. Storms/depressions which follow a due westward track have a comparatively greater influence in causing heavy rainfall and floods in the basin. The basin has, thus, a large water potential and any future river valley project in it is likely to have a great impact on the economy of the country in general and that of the region in particular.

Chief climatological features of rainfall, maximum and minimum temperatures and relative humidity, and the results of storm analysis for the basin presented in this paper will provide some of the basic hydrometeorological information required in the planning of a project in this basin.

## 2. Network of observatories in the Narmada Basin

In *Narmada* basin (upto Broach) there are 127 rain reporting stations, of which 9 full fledged observatories and 5 Hydrometeorological observatories are under the control of the India Meteorological Department; the remaining 113 are State raingauge stations. 5 of the Departmental observatories and 3 of the Hydrometeorological observatories in the basin are equipped with self recording raingauges. The density of network of raingauges in the basin works out to be one raingauge per 750 sq. km which, according to WMO standard, is considered to be slightly inadequate. The climatological data, like maximum and minimum temperatures, relative humidity etc are observed only at the Departmental observatories. The existing network of observatories and raingauge stations are shown in Fig. 1.

## 3. Rainfall and other climatological features on the Basin

Past records of rainfall, number of rainy days, maximum and minimum temperatures, relative humidity etc, have been compiled and discussed here.

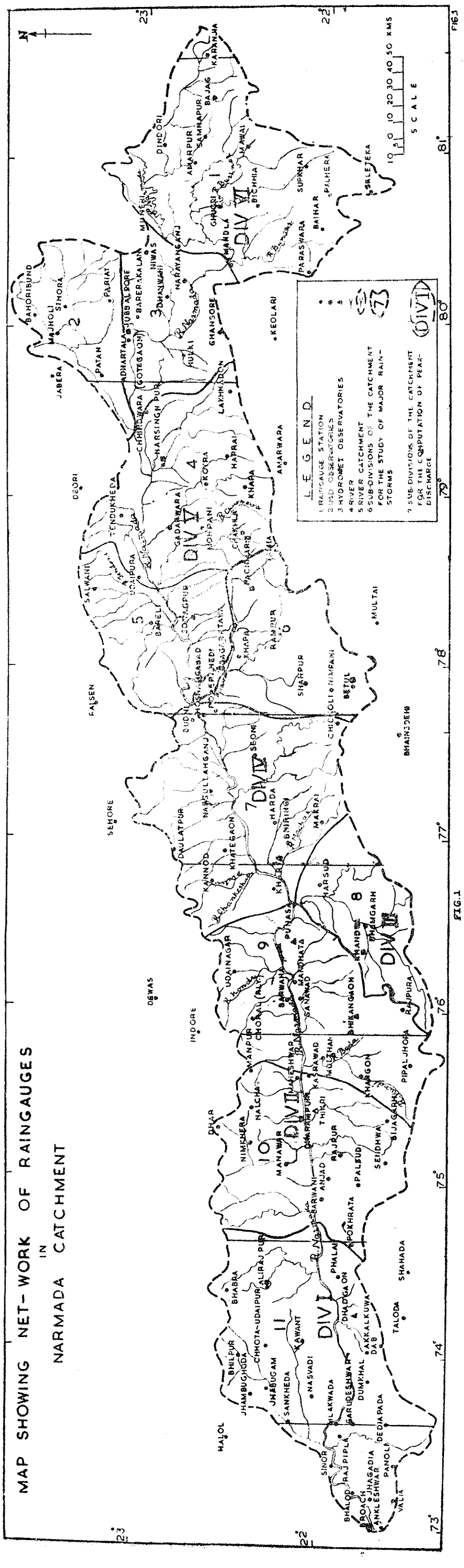


Fig. 1. Map showing network of raingauges in *Narmada* catchment

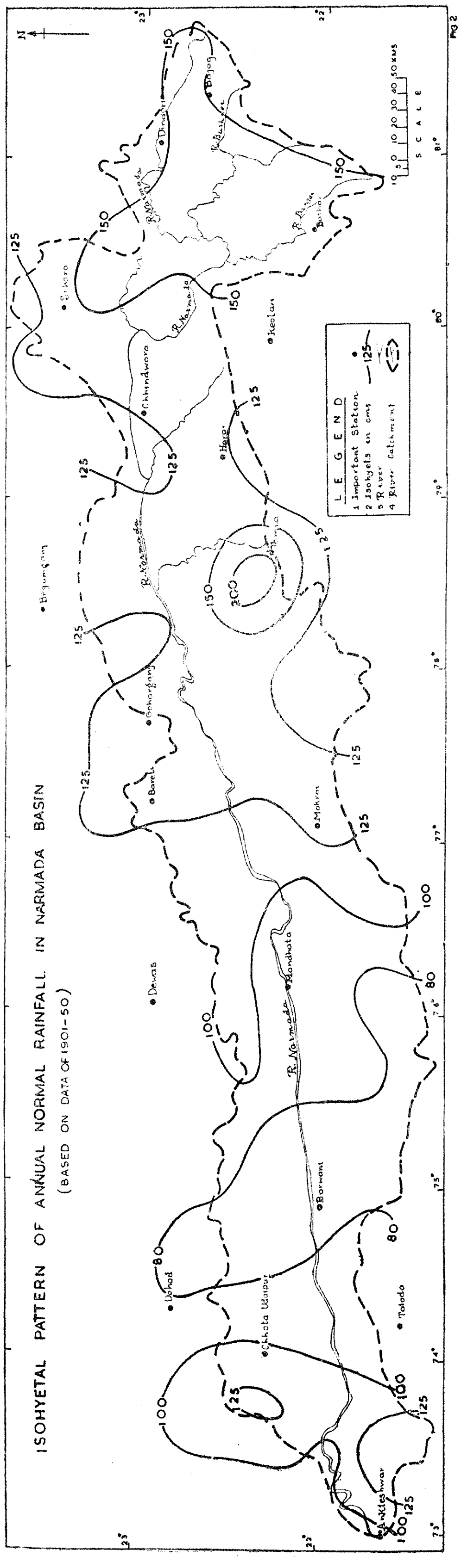


Fig. 2. Isohyetal pattern of annual normal rainfall in *Narmada* basin
(Based on data of 1901 to 1950)

### 3.1. *Rainfall*

3.1.1. *Average rainfall and average number of rainy days* — Monthly and annual averages of rainfall and of number of rainy days for the basin, worked out from the monthly normals of these elements (Mem. India met. Dep. 1962) at individual stations in the basin, are given in Table 1. It may be seen from this table that the average annual rainfall in the basin is about 125 cm. Major portions of this annual rainfall is received during southwest monsoon prevailing over this region from second week of June to the end of October. To be precise, 90 per cent of the annual rainfall is recorded during the months of June to September, whereas the months of July and August together account for about 60 per cent of the annual rainfall. The rainfall during the month of October is only 3 per cent of the annual whereas the remaining months, *i.e.*, November to May each receive about 1 per cent of the annual rainfall. Occurrence of more rainfall in the months of July and August than in June and September is firstly due to a comparatively higher frequency of Bay storms/depressions in these months which move over to the basin and secondly due to these storms/depressions having more westerly tracks affecting thereby a larger portion of the basin.

3.1.2. *Spatial distribution of rainfall* — The annual rainfall in the extreme eastern parts of the basin is of the order of 150 cm and it decreases gradually to the west to about 80 cm in the extreme western parts. The annual isohyetal pattern of the basin is shown in Fig. 2. Since 90 per cent of the annual rainfall occurs during the southwest monsoon season, the isohyetal pattern of monsoon period in the basin is similar to that of the annual.

3.1.3. *Highest daily rainfall amounts* — Statement of heaviest 24-hr rainfall for each of the monsoon months at 20 selected stations based on rainfall records upto 1960, along with the date of their record is given in Table 2. Such information may be useful for having a rough estimate of the probable maximum precipitation at any place in the basin.

3.1.4. *Rainfall variability* — Variability of monthly rainfall for the four monsoon months and of monsoon seasonal and annual rainfall at 20 selected stations have been computed as "per cent coefficient of variation" of the respective rainfall series; the coefficient of variation being defined as —

$$\text{C.V.} = \frac{\text{Standard Deviation of rainfall } (\sigma)}{\text{Mean rainfall } (m)}$$

Variability figures are presented in Table 3.

**TABLE 1**

**Monthly and annual averages of rainfall and of number of rainy days in the *Narmada* basin**

| | Av. rainfall (cm) | Av. No. of rainy days | Av. rainfall as percentage of the annual rainfall (nearest whole number) |
|---|---|---|---|
| Jan | 1·5 | 1·2 | 1 |
| Feb | 1·5 | 1·2 | 1 |
| Mar | 1·1 | 0·9 | 1 |
| Apr | 7.7 | 0·6 | 1 |
| May | 1·1 | 0·9 | 1 |
| Jun | 15·9 | 7·7 | 13 |
| Jul | 42·3 | 16·7 | 34 |
| Aug | 33·3 | 14·8 | 26 |
| Sep | 21·0 | 9·5 | 17 |
| Oct | 4·4 | 2·3 | 3 |
| Nov | 1·9 | 1·0 | 1 |
| Dec | 0·6 | 0·5 | 1 |
| Annual | 125·2 | 57·3 | 100 |

Some of the special features of the variability in the basin are —

*June* — The June rainfall in the *Narmada* basin is highly variable. The variability at individual stations of the basin ranges between 55 and 100 per cent. It is more than 70 per cent in the portions of basin lying in Gujarat and Maharashtra State and also in adjoining parts of Madhya Pradesh and between 55 to 70 per cent elsewhere.

*July* — The variability of July rainfall at individual stations in the basin ranges between 35 and 65 per cent suggesting thereby that July rainfall is more dependable than that of June. It is between 35 and 40 per cent in the eastern quarter of the basin and more than 50 per cent over Gujarat and Maharashtra portions of the catchment; and is between 40 and 50 per cent over the remaining parts.

*August* — Whereas the variability of August rainfall at individual stations in the basin is slightly different from the variability of July rainfall, the range of variability remains the same as for the latter month. In this month the variability is between 35 and 40 per cent, in the eastern half of the basin and between 50 and 65 per cent in the other half.

*September* — September rainfall in the basin is highly variable and its variability has some comparison with the variability of June rainfall. The range of variability is between about 55 and 95 per cent. The variability increases steadily towards west. Also for a given longitude the variability in this month generally increases towards north. It is more than 80 per cent in the portions of the basin belonging to Gujarat and Maharashtra

**TABLE 2**

**Highest 24-hr (observational day) rainfall at selected stations in Narmada catchment for monsoon months**

| Station | June | | July | | August | | September | |
|---|---|---|---|---|---|---|---|---|
| | Amt. (cm) | Date & Year | Amt. (cm) | Date & Year | Amt. (cm) | Date & Year | Amt. (cm) | Date & Year |
| Broach | 28·4 | 22, 1893 | *50·3* | *26, 1896* | 22·2 | 25, 1939 | 48·5 | 6, 1954 |
| Rajpipla | *51·7* | *28, 1913* | 34·6 | 26, 1896 | 30·1 | 5, 1942 | 28·4 | 3, 1913 |
| Chhota Udepur | 14·2 | 26, 1945 | 26·9 | 23, 1905 | 22·3 | 1, 1900 | *28·6* | *5, 1959* |
| Jabalpur | 18·5 | 16, 1882 | *34·3* | *30, 1915* | 32·1 | 20, 1923 | 25·2 | 20, 1926 |
| Mandla | 18·0 | 19, 1874 | *23·1* | *19, 1869* | 20·5 | 25, 1923 | 19·1 | 9, 1902 |
| Narayanganj | 16·1 | 22, 1928 | 23·5 | 30, 1915 | 16·3 | 25, 1923 | *23·8* | *20, 1926* |
| Dindori | *31·7* | *25, 1946* | 29·2 | 24, 1892 | 21·7 | 3, 1900 | 29·3 | 19, 1926 |
| Baihar | 15·0 | 20, 1870 | *28·5* | *14, 1875* | 22·4 | 6, 1911 | 16·3 | 21, 1926 |
| Hoshangabad | 17·9 | 21, 1895 | 23·9 | 6, 1898 | *29·4* | *23, 1919* | 20·7 | 16, 1950 |
| Pachmarhi | 20·2 | 16, 1916 | 33·8 | 15, 1882 | *45·9* | *2, 1913* | 35·0 | 23, 1932 |
| Harda | 25·3 | 21, 1896 | *29·6* | *3, 1930* | 23·9 | 31, 1939 | 20·1 | 4, 1876 |
| Lakhnadon | 21·2 | 20, 1893 | *25·3* | *5, 1898* | 24·1 | 26, 1872 | 23·1 | 8, 1904 |
| Narsimhapur | 33·8 | 27, 1875 | 21·3 | 16, 1939 | 22·9 | 16, 1867 | *42·2* | *7, 1891* |
| Mohpani | 17·6 | 21, 1893 | 28·7 | 1, 1930 | *35·0* | *2, 1913* | 29·7 | 7, 1891 |
| Khandwa | 15·3 | 27, 1940 | *24·1* | *13, 1927* | 20.3 | 22, 1957 | 21·9 | 15, 1959 |
| Betul | 16·3 | 29, 1877 | *26·0* | *3, 1930* | 22·6 | 1, 1944 | 17·5 | 3, 1876 |
| Manpur | 19·9 | 20, 1938 | 19·6 | 26, 1913 | 22·5 | 27, 1891 | *24·1* | *12, 1894* |
| Barwani | 14·3 | 15, 1927 | 15·0 | 12, 1927 | 15·8 | 16, 1944 | *21·6* | *15, 1959* |
| Dhar | 14·3 | 27, 1942 | 21·7 | 26, 1913 | 15·3 | 29, 1906 | *29·7* | *14, 1959* |
| Alirajpur | 10·3 | 7, 1925 | *25·9* | *23, 1939* | 24·1 | 11, 1933 | 22·1 | 30, 1954 |

Note—The figures in Italics are the highest ever 24-hr rainfall amounts and the dates of their record

States and also in the districts of Narsimhapur and Raisen in Central Madhya Pradesh. It is less than 70 per cent in the extreme east covering about one fifth of the basin area. In the remaining parts of the basin the variability is in the range of 70 to 80 per cent.

*Seasonal* (*June to September*) — The variability of seasonal rainfall in the basin ranges from 20 to about 40 per cent. It is more than 35 per cent only in a small portion of the basin in Gujarat and Maharashtra and is in the range of 20 to 35 per cent over the remaining parts of the basin.

*Annual* — The variability of annual rainfall in the basin, like that of the seasonal rainfall, is in the range of 20 to about 40 per cent and has almost the same space distribution as the variability of seasonal rainfall.

### 3.2. *Maximum and minimum temperature*

Monthly and annual mean daily maximum and mean daily minimum temperatures in respect of 7 climatological stations in the *Narmada* basin upto Broach, based on the data for the period 1931 to 1960, are given in Table 4 (a) and the highest maximum and lowest minimum temperatures are given in Table 4 (b). It may be seen from the former table that —

(*i*) April and May are the hottest months for this basin. Except for Pachmarhi, which is a hill station, the mean daily maximum temperature in the basin ranges roughly between 37°C and 40° C in April and between 39°C and 42°C in May.

(*ii*) Maximum temperature at individual stations in the basin in the month of June is appreciably lower than that in April and May. The range of mean daily maximum temperatures in this month at different stations, except for Pachmarhi, is roughly 35° to 38°C. The temperatures at individual stations are about 4°C lower in June than in April/May.

(*iii*) Mean daily maximum temperature in the month of July at individual stations, is about 6° to 7°C lower than that in the month of June. In July the mean daily maximum temperature at Pachmarhi is about 24·3°C and it lies between about 28° and 33°C at other stations.

(*iv*) Day temperatures fall slightly further in the month of August. From August to September, there is slight rise in temperatures. In the month of October there is a further rise in day temperatures.

(*v*) After October the day temperatures progressively fall and reach their lowest in the month of January with mean daily maximum temperatures ranging roughly between 25·5° and 31·5°C in this month. After January there is a progressive rise in day temperatures till they reach their highest in April/May.

(*vi*) Mean daily minimum temperatures in the basin are lowest in the month of December/January and increase progressively upto May. Afterwards, there is a continuous decrease in the mean daily minimum temperatures till December/January next.

### 3.3. *Relative humidity*

The monthly and annual mean relative humidity in respect of 7 observatory stations in the basin at both the hours of observations, *viz.*, at 0830 and 1730 IST are given in Table 5. It may be seen from this table that the relative humidity in the basin is highest, and of about the same order, in July, August and September, with its magnitude at individual stations ranging between 80 and 90 per cent at the morning hour of observation and between 65 and 90 per cent at the evening hour of observation in these months. Relative humidity in the month of October is between 65 and 80 per cent at the first hour of observation and between 40 and 60 per cent at the second hour. From November till January it is of about the same order with its magnitude at individual stations lying between 55 and 85 and between 30 and 50 per cent at the first and second hour of observations respectively. After January till April the relative humidity registers a progressive fall but the trend is reversed in May and June.

**TABLE 3**

**Coefficient of variability of monthly, seasonal (June-September and annual rainfall at selected stations in Narmada Basin**

(Percentage rainfall variability)

| | Jun | Jul | Aug | Sep | Seasonal (Monsoon) | Annual |
|---|---|---|---|---|---|---|
| Broach | 98 | 64 | 65 | 94 | 41 | 40 |
| Rajpipla | 92 | 63 | 64 | 90 | 42 | 42 |
| Chhota Udepur | 64 | 52 | 57 | 84 | 31 | 30 |
| Jabalpur | 67 | 39 | 44 | 72 | 23 | 23 |
| Mandla | 61 | 35 | 37 | 61 | 23 | 22 |
| Narayanganj | 59 | 35 | 36 | 67 | 23 | 22 |
| Dindori | 63 | 39 | 39 | 77 | 29 | 31 |
| Baihar | 57 | 34 | 34 | 57 | 21 | 22 |
| Hoshagabad | 71 | 41 | 45 | 73 | 28 | 27 |
| Pachmahri | 63 | 43 | 40 | 75 | 24 | 29 |
| Harda | 69 | 53 | 49 | 68 | 28 | 27 |
| Lakhnadon | 62 | 42 | 37 | 77 | 25 | 23 |
| Narsimhapur | 68 | 41 | 34 | 85 | 25 | 25 |
| Mohpani | 67 | 53 | 40 | 80 | 25 | 25 |
| Khandwa | 66 | 45 | 62 | 79 | 33 | 37 |
| Betul | 58 | 41 | 44 | 72 | 27 | 27 |
| Manpur | 70 | 50 | 55 | 74 | 26 | 34 |
| Barwani | 77 | 46 | 61 | 80 | 31 | 30 |
| Dhar | 63 | 42 | 53 | 76 | 32 | 33 |
| Alirajpur | 79 | 47 | 55 | 73 | 32 | 39 |

## 4. Storm studies for the basin

### 4.1. *Storm selection*

For the purpose of the storm study in the basin, the daily rainfall tables of India for the period 1891 onwards were examined and all such spells of rain during which a number of stations within the catchment and in the neighbourhood, recorded heavy rainfall on one or more of the days were picked out. Arithmetic average of rainfall in the basin was calculated for each of the selected dates. Of these, 34 spells of different durations which contributed at least 2·5 cm of average (arithmetic) rainfall in the basin on each day of its duration were then finally selected as rainstorms for their isohyetal analysis. The selected 34 rainstorms are listed in Table 6. It can be seen from this table that majority of the rainstorms are of 2-day duration and only a few have extended to longer durations.

TABLE 4 (a)

Narmada catchment—Mean maximum and mean minimum temperatures of different stations

| | | Broach | Jabalpur | Mandla | Hoshangabad | Panchmarhi | Khandwa | Betul |
|---|---|---|---|---|---|---|---|---|
| Jan | Max | 31·4 | 26·1 | 26·0 | 26·6 | 22·4 | 29·3 | 26·4 |
| | Min | 12·8 | 9·8 | 8·8 | 12·7 | 8·7 | 12·0 | 11·1 |
| Feb | Max | 34·3 | 28·9 | 29·3 | 29·8 | 24·7 | 31·9 | 29·8 |
| | Min | 14·9 | 11·4 | 10·1 | 14·3 | 10·4 | 13·6 | 12·5 |
| Mar | Max | 37·6 | 34·0 | 33·7 | 34·9 | 28·9 | 36·4 | 33·6 |
| | Min | 19·8 | 15·5 | 14·1 | 18·6 | 14·8 | 18·1 | 16·5 |
| Apr | Max | 40·0 | 38·5 | 37·9 | 39·3 | 33·4 | 40·2 | 37·0 |
| | Min | 23·7 | 20·5 | 19·1 | 23·5 | 20·1 | 23·9 | 21·1 |
| May | Max | 39·7 | 41·9 | 41·3 | 42·0 | 36·0 | 41·9 | 39·3 |
| | Min | 26·9 | 25·9 | 24·3 | 27·6 | 24·3 | 27·9 | 24·8 |
| Jun | Max | 35·4 | 37·6 | 37·5 | 37·6 | 31·4 | 37·5 | 35·0 |
| | Min | 26·9 | 26·4 | 25·3 | 26·6 | 22·5 | 26·2 | 24·4 |
| Jul | Max | 32·0 | 30·3 | 30·1 | 30·2 | 24·3 | 30·9 | 28·1 |
| | Min | 25·7 | 23·9 | 23·3 | 24·0 | 19·9 | 23·8 | 22·3 |
| Aug | Max | 31·1 | 29·5 | 29·2 | 29·2 | 23·8 | 29·9 | 26·9 |
| | Min | 25·1 | 23·6 | 23·1 | 23·5 | 19·6 | 23·2 | 21·7 |
| Sep | Max | 32·7 | 30·8 | 30·2 | 30·7 | 25·2 | 31·0 | 28·3 |
| | Min | 24·5 | 23·1 | 22·3 | 23·2 | 19·1 | 22·7 | 21·0 |
| Oct | Max | 35·9 | 31·4 | 30·5 | 32·1 | 26·2 | 33·4 | 29·3 |
| | Min | 22·1 | 18·4 | 17·6 | 19·5 | 14·8 | 18·9 | 17·2 |
| Nov | Max | 35·1 | 28·9 | 28·1 | 29·3 | 24·1 | 31·2 | 27·7 |
| | Min | 17·2 | 11·7 | 9·9 | 14·5 | 9·6 | 13·5 | 12·0 |
| Dec | Max | 23·0 | 26·9 | 26·6 | 27·7 | 22·8 | 29·6 | 27·0 |
| | Min | 14·0 | 9·0 | 7·8 | 12·3 | 7·5 | 11·2 | 10·3 |
| Annual | Max | 34·9 | 32·1 | 31·7 | 32·4 | 26·9 | 33·6 | 30·7 |
| | Min | 21·1 | 18·3 | 17·1 | 20·0 | 15·9 | 19·6 | 17·9 |

4.2. *Synoptic situations associated with rainstorms*

An examination of the synoptic situations associated with the rainstorms listed in Table 6 has revealed that all but a few of them were the result of Bay depressions moving westwards and that the remaining of them were caused either under general active monsoon conditions over Madhya Pradesh and Gujarat or under the influence of land depressions. The portion of the basin adjoining Gujarat coast receives heavy rainfall under the influence of Bay depressions when they are still centred over central parts of Madhya Pradesh between Long. 78°E and 82°E (Abbi *et al.* 1970). Eastern and central parts of the basin receive heavy rainfall under the influence of Bay depressions when they are still over Orissa and adjoining Madhya Pradesh. An important characteristic of Bay depressions that has a profound influence on the intensity and on the distribution of rainfall in the basin is the track followed by them. Bay depressions which follow a west to westnorthwest track, keeping Narmada basin in their southwestern sector are more potential in causing heavy rainfall and floods over the basin than the depressions following a more northerly track.

4.3. *Depth-duration envelope curve*

Daily average depths of rainfall obtained in the basin during each of the 34 rainstorms are also given in Table 6. Depth-duration curves for rainstorms of two-day and of longer durations are given in Fig. 3. The number against each curve in this figure refers to the serial number of the rainstorms as given in Table 6.

It may be seen that whereas depth-duration curve numbered 30, corresponding to the rainstorms of 8-9 September 1961 stands highest so far as 1 day depth is concerned, the curve numbered 21, corresponding to the rainstorm of 13-16 July 1944 envelopes depth-duration curves of all other rainstorms for 2-day and longer durations. The curve numbered 34 which corresponds to the rainstorm of 4-6 August 1968 follows very closely the curve for July 1944 rainstorms, particularly upto 2-day duration. The enveloping curve for durations from 1 to 4 day has been shown by dotted curves in the same figures. Enveloping depths for 1-day 2-day, 3-day and 4-day durations as read from the depth duration envelope curve are 8·8, 14·6, 18·8 and 22·9 cm respectively.

**TABLE 4 (b)**

**Narmada catchment—Highest and lowest minimum temperature (°C) with date of record**

| | | Broach | | Jabalpur | | Mandla | | Hoshangabad | | Pachmarhi | | Khandwa | | Betul | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Temp. (°C) | Date of record | Temp. (°C) | Date of record | Temp. (°C) | Date of record | Temp. (°C) | Date of record | Temp. (°C) | Date of record | Temp. (°C) | Date of record | Temp. (°C) | Date of record |
| Jan | H | 36·9 | 23 (1957) | 32·8 | 4D (1946) | 30·6 | 30 (1954) | 32·2 | 30 (1950) | 27·8 | 31 (1946) | 35·6 | 31 (1932) | 30·7 | 11 (1958) |
| | L | 5·6 | 10 (1954) | 1·1 | 7 (1946) | 0·6 | 25 (1954) | 3·3 | 15 (1935) | —1·1 | 16 (1935) | 1·7 | 7 (1946) | 2·8 | 24 (1943) |
| Feb | H | 42·8 | 28 (1953) | 37·2 | 24 (1953) | 35·6 | 24 (1953) | 37·8 | 28 (1953) | 31·7 | 28 (1953) | 38·9 | 28 (1953) | 37·2 | 27 (1953) |
| | L | 6·1 | 11 (1957) | 0·0 | 2 (1905) | 2·7 | 13 (1957) | 6·1 | 12 (1950) | —0·6 | 2 (1929) | 6·0 | 1 (1929) | 1·1 | 12 (1950) |
| Mar | H | 44·2 | 23 (1959) | 41·1 | 28 (1892) | 39·4 | 31 (1955) | 41·1 | 25 (1953) | 36·1 | 28 (1892) | 43·3 | 28 (1892) | 38·9 | 25 (1953) |
| | L | 11·5 | 6 (1957) | 3·3 | 4 (1898) | 7·8 | 1 (1957) | 10·6 | 10 (1935) | 3·3 | 1 (1906) | 6·1 | 4 (1898) | 8·2 | 23 (1960) |
| Apr | H | 45·6 | 30 (1956) | 45·0 | 29 (1942) | 43·2 | 25 (1958) | 45·2 | 27 (1958) | 40·0 | 30 (1942) | 46·1 | 27 (1896) | 42·6 | 26 (1958) |
| | L | 16·1 | 16 (1955) | 10·6 | 1 (1905) | 11·1 | 2 (1956) | 16·1 | 21 (1951) | 8·9 | 2 (1905) | 11·1 | 2 (1905) | 15·0 | 16 (1955) |
| May | H | 47·8 | 20 (1955) | 46·7 | 25 (1954) | 45·0 | 22 (1954) | 46·1 | 4D (1954) | 40·6 | 4D (1954) | 46·2 | 22 (1947) | 43·3 | 25 (1954) |
| | L | 21·2 | 6 (1957) | 17·2 | 5 (1937) | 16·2 | 9 (1960) | 20·0 | 1 (1947) | 15·0 | 10 (1933) | 17·2 | 3 (1881) | 19·2 | 7 (1957) |
| Jun | H | 44·4 | 6 (1953) | 46·1 | 2 (1889) | 44·4 | 17 (1958) | 45·6 | 7 (1953) | 40·6 | 2 (1889) | 46·1 | 1 (1923) | 42·2 | 7 (1953) |
| | L | 19·8 | 5 (1959) | 19·4 | 3 (1922) | 21·1 | 9 (1956) | 21·1 | 18 (1946) | 15·6 | 30 (1931) | 18·2 | 23 (1960) | 20·3 | 17 (1960) |
| Jul | H | 38·9 | 23 (1960) | 41·7 | 1 (1902) | 38·9 | 7 (1958) | 41·4 | 24 (1960) | 37·4 | 25 (1960) | 40·0 | 2 (1900) | 35·6 | 4 (1959) |
| | L | 22·7 | 14 (1959) | 20·6 | 17 (1930) | 20·8 | 11 (1959) | 18·9 | 23 (1951) | 16·1 | 15 (1941) | 20·0 | 12 (1941) | 19·3 | 13 (1959) |
| Aug | H | 35·6 | 30 (1954) | 35·0 | 7 (1954) | 33·6 | 25 (1958) | 35·6 | 27 (1950) | 30·0 | 11 (1899) | 39·4 | 29 (1951) | 32·2 | 24 (1950) |
| | L | 22·8 | 31 (1952) | 18·3 | 27 (1929) | 19·9 | 8 (1957) | 19·4 | 23 (1943) | 15·0 | 17 (1939) | 19·4 | 23 (1943) | 18·9 | 29 (1951) |
| Sep | H | 31·7 | 30 (1951) | 35·6 | 20 (1913) | 34·0 | 24 (1960) | 40·4 | 25 (1959) | 35·6 | 28 (1931) | 40·6 | 12 (1899) | 32·8 | 26 (1960) |
| | L | 21·1 | 17 (1957) | 16·7 | 30 (1899) | 17·4 | 30 (1957) | 17·8 | 29 (1942) | 12·8 | 30 (1940) | 17·8 | 29 (1942) | 16·9 | 30 (1960) |
| Oct | H | 41·7 | 13 (1951) | 36·7 | 21 (1941) | 35·0 | 4 (1951) | 37·2 | 24 (1951) | 31·7 | 4 (1920) | 40·6 | 6 (1899) | 33·4 | 19 (1957) |
| | L | 14·4 | 26 (1954) | 7·8 | 31 (1881) | 7·8 | 30 (1952) | 12·2 | 29 (1952) | 6·7 | 31 (1933) | 9·4 | 31 (1890) | 8·3 | 30 (1952) |
| Nov | H | 38·9 | 20 (1957) | 33·9 | 6 (1953) | 32·2 | 4 (1957) | 35·0 | 1 (1951) | 28·3 | 16 (1957) | 37·2 | 1 (1951) | 32·2 | 1 (1948) |
| | L | 10·9 | 29 (1960) | 3·9 | 12 (1889) | 3·9 | 30 (1953) | 3·9 | 23 (1952) | 2·2 | 20 (1912) | 6·1 | 25 (1939) | 5·6 | 29 (1956) |
| Dec | H | 37·2 | 8 (1952) | 32·8 | 12 (1941) | 31·2 | 28 (1960) | 32·3 | 17 (1959) | 27·8 | 11 (1941) | 34·4 | 1 (1896) | 30·6 | 18 (1952) |
| | L | 8·0 | 31 (1959) | 0·6 | 28 (1902) | 1·1 | 26 (1955) | 4·4 | 14 (1938) | —1·1 | 27 (1926) | 2·8 | 29 (1929) | 3·3 | 25 (1955) |
| Annual | H | 47·8 | | 46·7 | | 45·0 | | 46·1 | | 40·6 | | 46·2 | | 43·3 | |
| | L | 5·6 | | 0·0 | | 0·6 | | 3·3 | | —1·1 | | 1·7 | | 1·1 | |

H — Highest maximum temperature L — Lowest minimum temperature D — Days

TABLE 5

*Narmada* **Catchment—Mean relative humidity in per cent of different stations**

| | | Broach | Jabal-pur | Man-dla | Hoshan-gabad | Pach-marhi | Khan-dwa | Betul |
|---|---|---|---|---|---|---|---|---|
| Jan | I | 65 | 74 | 85 | 62 | 65 | 56 | 64 |
| | II | 29 | 43 | 45 | 37 | 49 | 29 | 37 |
| Feb | I | 56 | 64 | 74 | 51 | 54 | 44 | 46 |
| | II | 22 | 32 | 30 | 25 | 37 | 23 | 23 |
| Mar | I | 59 | 44 | 57 | 37 | 36 | 32 | 34 |
| | II | 21 | 23 | 24 | 17 | 25 | 17 | 20 |
| Apr | I | 59 | 30 | 43 | 28 | 29 | 29 | 31 |
| | II | 23 | 18 | 23 | 15 | 22 | 16 | 19 |
| May | I | 71 | 27 | 35 | 30 | 33 | 41 | 39 |
| | II | 37 | 17 | 21 | 17 | 23 | 18 | 21 |
| Jun | I | 79 | 57 | 64 | 62 | 68 | 66 | 70 |
| | II | 60 | 45 | 53 | 44 | 55 | 44 | 51 |
| Jul | I | 87 | 85 | 88 | 87 | 91 | 83 | 89 |
| | II | 74 | 79 | 79 | 78 | 87 | 71 | 78 |
| Aug | I | 89 | 87 | 88 | 89 | 92 | 84 | 91 |
| | II | 75 | 80 | 82 | 78 | 88 | 73 | 81 |
| Sep | I | 86 | 82 | 86 | 85 | 86 | 82 | 85 |
| | II | 63 | 71 | 75 | 70 | 82 | 66 | 75 |
| Oct | I | 74 | 73 | 82 | 69 | 64 | 64 | 69 |
| | II | 42 | 52 | 61 | 48 | 56 | 41 | 56 |
| Nov | I | 62 | 68 | 79 | 64 | 58 | 58 | 56 |
| | II | 30 | 44 | 46 | 38 | 50 | 35 | 42 |
| Dec | I | 66 | 72 | 84 | 62 | 65 | 58 | 63 |
| | II | 29 | 43 | 45 | 37 | 47 | 32 | 40 |
| Annual | I | 71 | 64 | 72 | 61 | 62 | 58 | 61 |
| | II | 42 | 46 | 49 | 42 | 52 | 39 | 45 |

I—Observations at 0830 IST II—Observations at 1730 IST

## 4.4. *Depth-area-duration analysis of heavy rainstorms*

For the purpose of knowing the maximum depths of rainfall actually recorded over areas of the basin, it is desirable that the rainfall in the basin associated with the rainstorms which have either contributed to the depth-duration envelope curve in Fig. 3, or have yielded very heavy rainfall over limited areas of the basin, be subjected to depth-area duration analysis with catchment as unit. This approach has been adopted since the basin lies in an identical rainfall regime and the storm centres generally lie in the basin. Necessary details and depth-area curves for the rainstorms of 13-16 July 1944 and 8-9 September 1961, which have contributed to the depth-duration envelope curve of the basin and for the rainstorms of 4-6 August 1968 which has contributed rainfall depths

TABLE 6

**Rainstorms and the associated daily rainfall averages (Isohyetals) for** *Narmada* **Basin**

| S. N. | Storm period | | | Daily catchment average rainfall (cm) 1st day | 2nd day | 3rd day | 4th day |
|---|---|---|---|---|---|---|---|
| 1 | 20-22 | Jan | 1893 | 4·0 | 4·9 | 3·7 | |
| 2 | 13 | Jul | 1894 | 3·2 | | | |
| 3 | 20-21 | Jul | 1894 | 2·8 | 4·4 | | |
| 4 | 25-26 | Jul | 1896 | 4·5 | 2·6 | | |
| 5 | 29 | Jul | 1896 | 4·7 | | | |
| 6 | 22-23 | Jul | 1905 | 4·8 | 4·3 | | |
| 7 | 5- 6 | Jul | 1910 | 4·9 | 4·3 | | |
| 8 | 4 | Aug | 1912 | 4·4 | | | |
| 9 | 20-21 | Aug | 1923 | 3·9 | 2·7 | | |
| 10 | 25-26 | Aug | 1923 | 4·1 | 3·9 | | |
| 11 | 19-21 | Sep | 1926 | 4·4 | 5·9 | 5·8 | |
| 12 | 13 | Jul | 1927 | 4·9 | | | |
| 19 | 2-3 | Jul | 1930 | 4·1 | 7·6 | | |
| 14 | 14-15 | Sep | 1933 | 2·3 | 5·1 | | |
| 15 | 29 | Jun | 1937 | 6·3 | | | |
| 16 | 20 | Jun | 1938 | 3·8 | | | |
| 17 | 20-21 | Aug | 1939 | 4·1 | 3·0 | | |
| 18 | 25 | Aug | 1939 | 2·3 | | | |
| 19 | 1-2 | Jul | 1941 | 3·3 | 4·1 | | |
| 20 | 4-5 | Aug | 1942 | 5·8 | 5·0 | | |
| 21 | 13-16 | Jul | 1944 | 4·2 | 6·3 | 8·3 | 4·1 |
| 22 | 17 | Aug | 1944 | 3·8 | | | |
| 23 | 21-22 | Aug | 1944 | 6·3 | 6·1 | | |
| 24 | 28 | Jun | 1945 | 4·8 | | | |
| 25 | 21-24 | Sep | 1945 | 2·5 | 3·0 | 3·3 | 4·1 |
| 26 | 15-16 | Sep | 1950 | 2·8 | 7·1 | | |
| 27 | 4- 5 | Aug | 1953 | 4·1 | 6·1 | | |
| 28 | 12-13 | Jul | 1959 | 4·3 | 6·6 | | |
| 29 | 14-15 | Sep | 1959 | 2·8 | 5·3 | | |
| 30 | 8-9 | Sep | 1961 | 3·1 | 8·8 | | |
| 31 | 15-16 | Sep | 1961 | 4·1 | 5·1 | | |
| 32 | 19-20 | Sep | 1962 | 4·4 | 5·6 | | |
| 33 | 12 | Aug | 1964 | 5·4 | | | |
| 34 | 4- 6 | Aug | 1968 | 2·9 | 7·6 | 6·9 | |

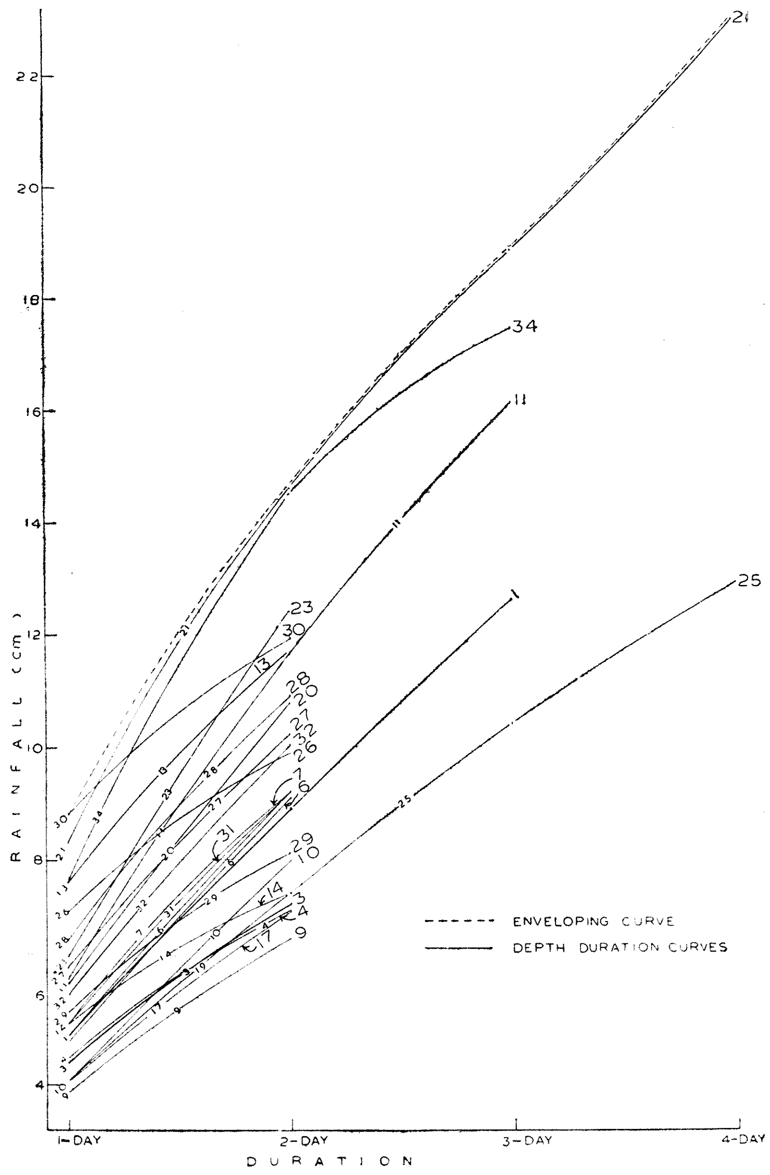


**Fig. 3. Depth-duration curves and their envelope**

comparable to those obtained from July 1944 rainstorm, have already been discussed (Pant *et al.* 1970). The rainstorms of 19-21 September 1926 and 2-3 July 1930 which caused higher rainfall concentration over some parts of the basin were caused under the influence of Bay depressions which had westerly to westnorth-westerly track. Their isohyetal patterns are shown in Figs. 5 (i), 5 (ii) and 6 respectively and their depth-area curves for durations of 1-day, 2-day and 3-day along with those for rainstorms of July 1944, September 1961 and August 1968 are given in Figs. 4(i-iii). The rainstorm of September 1926 was studied earlier by Raman and Dhar (1966) for its entire storm period (18-22) September 1929.

It is clarified that the depth-area-duration analysis with basin as unit, as adopted in the present study, should be viewed as distinctly different from the usual depth-area-duration analysis of rainfall which is conducted with storm as a unit. Whereas the former gives the spatial distribution of actual rainfall in the basin under study, the latter does so for the area covered within the peripherial isohyet of the rainstorm and is

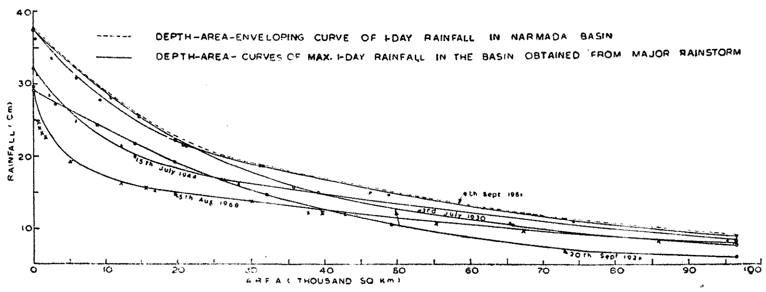


Fig. 4 (i). Depth-area curves of max. 1-day and their enveloping curve of *Narmada* basin

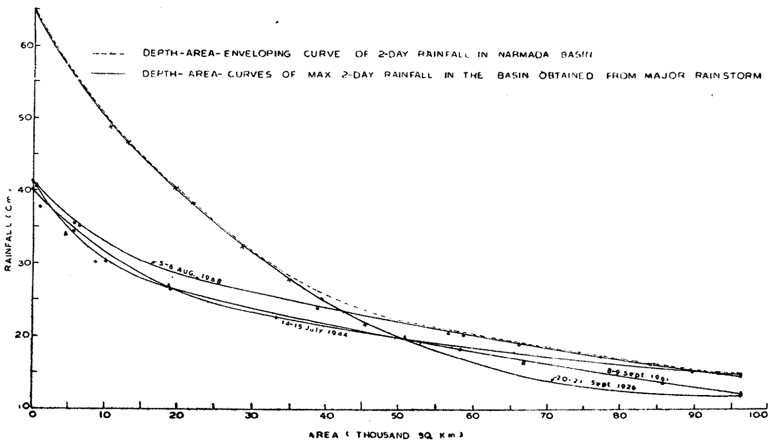


Fig. 4 (ii). Depth-area curves of max. 2-day and their enveloping curve for *Narmada* basin

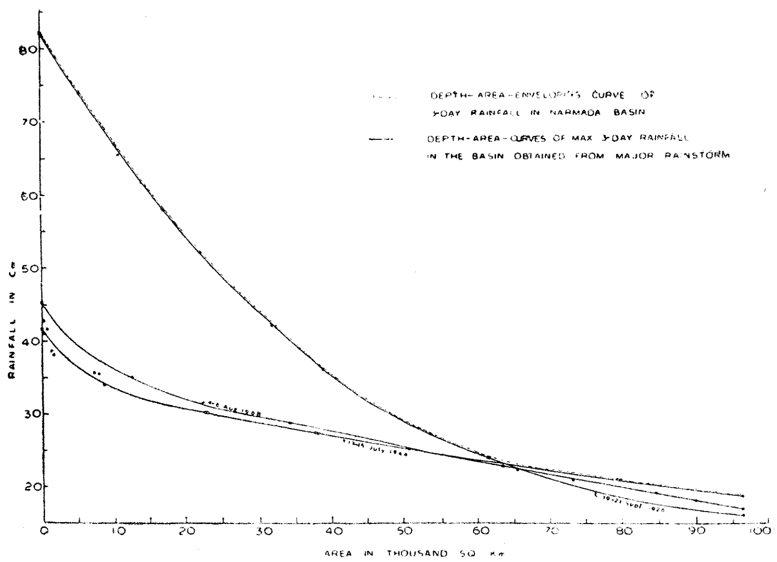


Fig. 4(iii). Depth-area curves of max. 3-day and their enveloping curve for *Narmada* basin

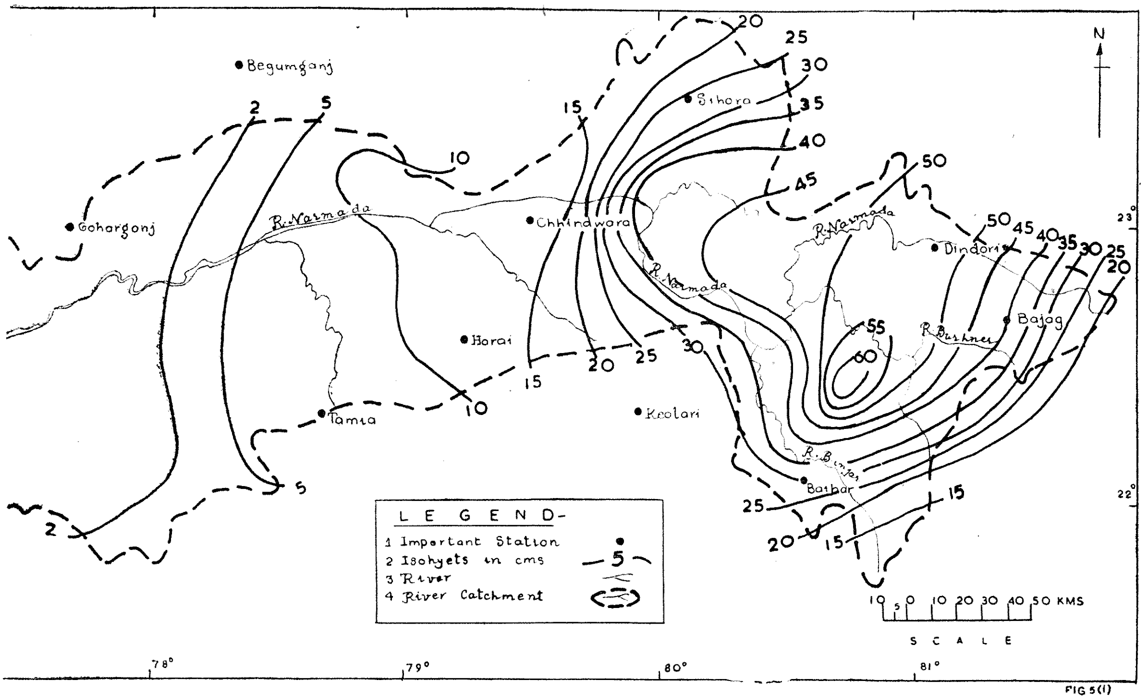


**Fig. 5(i). Isohyetal pattern for max. 2-day (20-21 Sep 1926) rainstorm in *Narmada* basin**

generally required to be done for the purpose of Storm Transposition.

#### 5. Depth-area-enveloping curves for different durations

The depth-area-enveloping curves for rainfall in different durations in the basin are shown by dotted lines in Figs. 4 (i-iii) along with depth-area-curves of major rainstorms for corresponding durations. It may be seen that the depth-area curves for the rainfall of 3 July 1930 and of 9 September 1961 determine the 1-day depth-area-enveloping curve of rainfall in the basin. Whereas the rainfall on 3 July has contributed the highest depths in the basin for areas upto 22,000 sq. km. The rainfall on 9 September has given highest depths for larger areas of the basin. The shape of the 2-day depth-area-enveloping curve is likewise determined for areas upto 42,000 sq. km by the depth-area curve of rainfall during 20-21 September 1926; for areas between 42,000 sq. km and 92,000 sq. km by the depth-area curve of the rainfall during 5-6 August 1968 and for larger areas of the basin by the depth-area curve of rainfall during 14-15 July 1944. The 3-day depth-area enveloping curve is formed by the depth-area curve of rainfall during 19-21 September 1926 for areas upto 64,000 sq. km and by the depth-area curve of rainfall during 13-15 July 1944 for larger areas. Since there are only two rainstorms which extended to 4-day duration, the depth-area-enveloping curve for this duration has not been drawn.

#### 6. Study of rainstorm yield over various sub-divisions of Narmada basin

For any river valley project in a basin, it is necessary to know the highest depths of rainfall on record over the area contributing the surface run-off at the project site. In order to get information regarding highest storm over its different parts, the *Narmada* basin has been divided into 11 sub-divisions as shown in Fig. 1. Each of these sub-divisions individually represents the catchment area of a major stream or of a group of streams which join the *Narmada* river. Their description is given in Table 7.

Rainstorms which have yielded abnormally high rainfall amounts over one or more of the sub-divisions of the basin have been analysed for their daily average rainfall depth contribution in the respective sub-divisions. The highest and second highest 1-day depths of rainfall recorded in each of the 11 sub-divisions, realised during the period 1891 onwards, are also given in Table 7. Average monthly rainfall in these sub-divisions have also been included in the same table.

#### 7. Peak discharge at Garudeshwar resulting from August 1968 rainstorm

Following the rainstorm of 4-6 August 1968, the flood hydrograph at Garudeshwar gauge site in *Narmada* basin reached a peak of 20·50 lakh

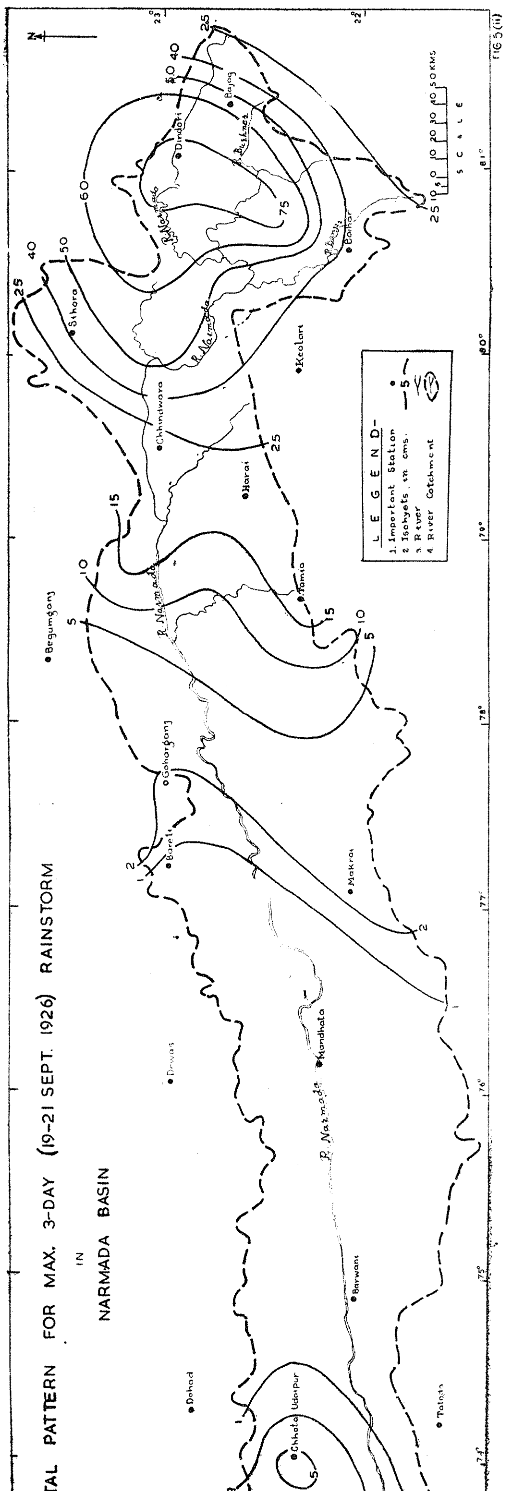


Fig. 5(ii). Isohyetal pattern of max. 3-day (19-21 Sep 1926) rainstorm in *Narmada* basin

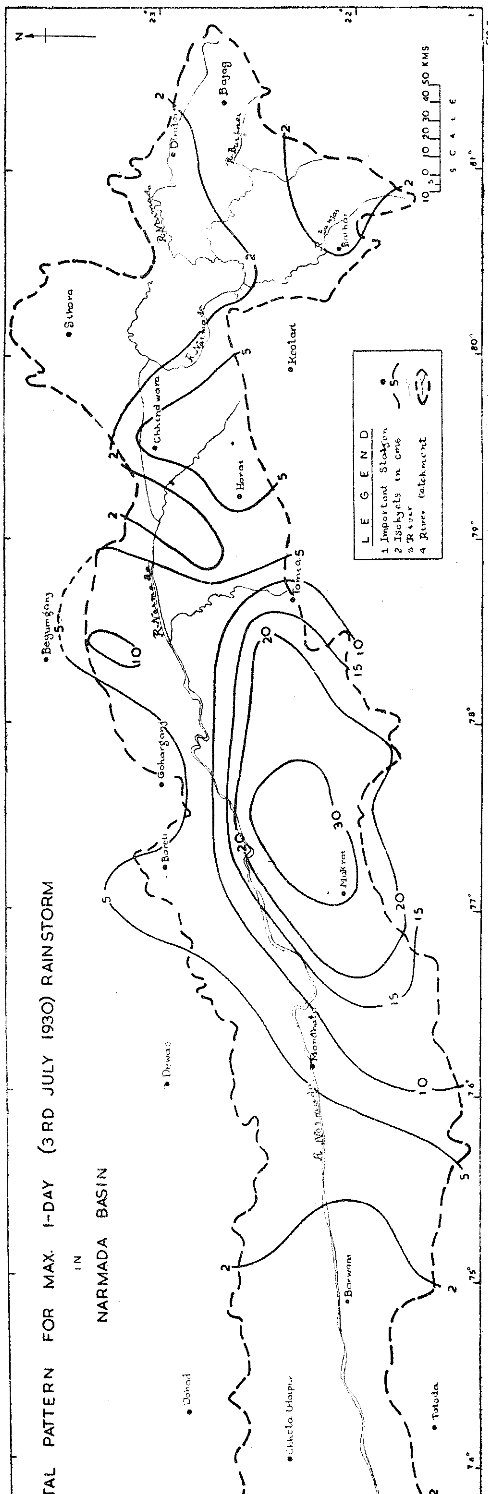


Fig. 6. Isohyetal pattern for max. 1-day (3 Jul 1930) rainstorm in *Narmada* basin

**TABLE 7**

**Sub-divisions of *Narmada* basin with their drainage area and the highest 1-day depths of rain actually recorded in each one of them**

| Sub-div. No | Description | Drainage area (sq. km) | Highest 1-day depth recorded: Amount (cm) | Highest 1-day depth recorded: Date | Second highest 1-day depth recorded: Amount (cm) | Second highest 1-day depth recorded: Date | Normal rainfall from 1 Jun to 30 Sep (cm) |
|---|---|---|---|---|---|---|---|
| 1 | Narmada upto Mandla | 12,800 | 22·9 | 21-9-1926 | 18·5 | 20-9-1926 | 135·8 |
| 2 | River Hiran upto its confluence with Narmada | 5,000 | 18·5 | 20-8-1923 | 16·3 | 21-9-1926 | 120·0 |
| 3 | Narmada between Mandla and confluence of Hiran with it (excluding river Hiran) | 5,500 | 18·5 | 20-9-1926 | 16·0 | 21-9-1926 | 122·1 |
| 4 | Narmada between the confluence of rivers Hiran and Dudhi (excluding river Hiran) | 9,500 | 18·8 | 4-8-1912 | 16·6 | 9-9-1961 | 117·5 |
| 5 | Narmada between the confluence of rivers Dhudi and Tawa (excluding river Tawa) | 6,300 | 12·6 | 9-9-1961 | 11·2 | 26-8-1923 | 116·2 |
| 6 | River Tawa upto its confluence with Narmada | 6,700 | 27·7 | 9-9-1961 | 21·1 | 15-9-1961 | 122·2 |
| 7 | Narmada between confluence of rivers Tawa and Chhota Tawa (excluding rivers Tawa and Chhota Tawa) | 12,100 | 18·8 | 13-7-1959 & 15-7-1944 | 17·5 | 3-7-1930 | 110·3 |
| 8 | River Chhota Tawa upto its confluence with Narmada | 5,200 | 16·0 | 15-7-1944 | 15·5 | 21-8-1944 | 86·3 |
| 9 | Narmada from confluence of river Chhota Tawa to Maheswar | 10,000 | 12·2 | 12-7-1959 | 10·9 | 20-6-1938 | 82·6 |
| 10 | Narmada from Maheswar to the confluence of river Goi | 9,600 | 18·0 | 15-9-1959 | 9·9 | 6-8-1968 | 70·1 |
| 11 | Narmada from confluence of river Goi to Broach | 13,800 | 19·6 | 5-8-1942 | 19·3 | 24-9-1945 | 95·5 |

**TABLE 8**

**Computation of expected Peak Discharge at Garudeshwar**

Adopted Storage Factor ($K$)$=0·70$, Date of Maximum Discharge : 6 August 1968

Run-off due to precedent precipitation

| Date | Div. No. | Area (sq. miles) | Average rain-fall (Inches) | Mutiply-ing factor | Expected rainfall* ($10^6$ cu. ft) |
|---|---|---|---|---|---|
| 1-8-1968 | VI | 8735 | $0·9\ K^5$ | 0·17 | 3105 |
| 2-8-1968 | V | 9208 | $0·8\ K^4$ | 0·24 | 4110 |
| 3-8-1968 | IV | 4181 | $1·5\ K^3$ | 0·34 | 4954 |
| 4-8-1968 | III | 5233 | $1.6\ K^2$ | 0·49 | 9528 |
| 5-8-1968 | II | 5156 | $3·7\ K^1$ | 0.70 | 31022 |
| 6-8-1968 | I | 3968 | $5·2\ K^0$ | 1·00 | 47936 |

*These are expected contributions of rainfall to volume of discharge at Garudeshwar on 6 Aug 1968

(1) Total expected contribution of precedent rainfall to volume of discharge at Garudeshwar on 6 August1968$=100655\times10^6$ cu. ft.

(2) Total expected contribution of precedent rainfall to volume of discharge at Garudeshwar on 11 September 1961$=55899\times10^6$† cu. ft.

Ratio of (1) and (2) above $=1·83$

This implies that expected contribution of precedent rainfall to volume of discharge on 6 August 1968 is 1·83 times the expected contribution of precedent rainfall to volume of discharge on 11 September 1961.

Since recorded peak discharge (base flow separated) on 11 September 1961 was $1100\times10^3$ cusecs, expected peak discharge (base flow separated) on 6 Aug 1968 $=1·83\times1100\times10^3$ cusecs $=19·8$ lakh cusecs.

†Figures taken from Banerji and Manton (*Indian J. Met. Geophys.*, **17**, Spl. No, p. 302)

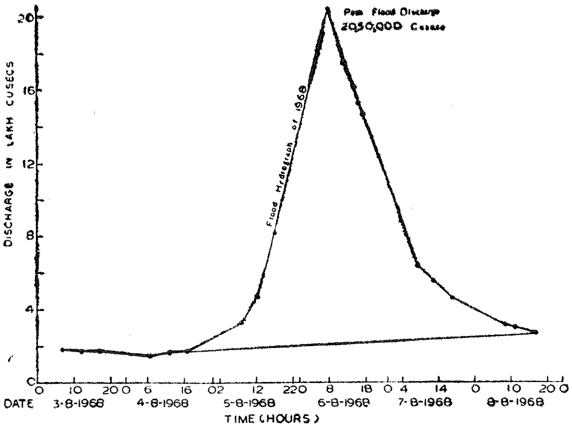


**Fig. 7.** ***Narmada*** **basin flood hydrograph at Garudeshwar gauge site**

cusecs on 6 August which is the highest so far recorded and is, to be specific, 5·05 lakh cusecs higher than the previous highest peak discharge recorded on 17 September 1961. The flood hydrograph is shown in Fig. 7.* Separating the base flow of about 1·80 lakh cusecs, a net discharge of 18·70 lakh cusecs was thus caused by rainfall run-off.

The discharge on 6 August 1968 has been estimated (Banerji and Mantan 1966) from the precedent precipitation in the basin during the period 1 to 6 August 1968. However, since the rainstorm of August 1968 occurred in mid-monsoon season a storage factor of 0·70 has been adopted in place of 0·75 recommended for the September rainstorm. Detailed computations are given in Table 8. The estimated peak discharge (base flow separated) works out to be 19·8 lakh cusecs as against the recorded peak discharge of 18·70 lakh cusecs (base flow separated). The estimate is thus about 6 per cent higher than the recorded value.

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*Taken from International Hydrological Decade News Letter No. 2 October 1968, published by the Indian National Committee for the International Hydrological Decade, CSIR, New Delhi