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Articles

AN OPTIMUM ASSESSMENT OF RAINFALL DATA IN THE CATCHMENTS OF BETWA AND KEN RIVERS : THE BUNDELKHAND REGION

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Rainfall, a basic input parameter in hydrological studies, has been analyzed most intensively, but as an isolated event. Even there exists a single emphasis either on data network or on its temporal and seasonal behaviour. The present study, therefore, attempts to analyse the optimality of data record in all aspects, which become important in the regions lacking in adequate agricultural developments like Bundelkhand. In this region, drainage basins of the Betwa and Ken rivers are considered for comparing published climatic data record, although available till the period 1901-50 only. An analysis of this limited record clearly reflects the spatial coverage of rain-gauge network. It was found to be far below the optimum standard laid down by World Meteorological Organization. Even when variability of rainfall is considered, the situation, although referring to old period, remains bleak. The spatial coverage of optimum number of rain-gauge has also been suggested based on Theissen polygon and isohyetal method of mean basin rainfall estimation. The optimality of temporal record, however, confirms to normal behaviour. But, there exists large variation in terms of length of rainfall record maintained at rain-gauge level. The seasonal behaviour of rainfall analysed through isohyetal maps and harmonic analysis provides useful clue to the water resources planner.

INTRODUCTION

The question, how much water a region has, will have to be, first of all, answered by knowing the amount of water that falls into the region. The question therefore, starts with rainfall regime. Rainfall constitutes the backbone of any hydrological investigation such as storm analysis. depth-area duration studies, flood designs, etc. (Mutreja, 1986). It also holds the key to develop and manage water resources, particularly in the field of agriculture and water supply. As the description of rainfall characteristics depends upon distribution of rain-gauge, accuracy and precision of their record, therefore quantitative analysis of data becomes essential to determine its optimality. Hence, spatial, temporal and seasonal behaviour of rainfall is tested here for their normality.

REVIEW OF LITERATURE

Various methods have been employed to estimate mean basin rainfall ranging from simple arithmetic method to isohyetal, Thiessen polygon and mathematical methods using determinants and matrices. The utility of these methods is important to analyse the spatial distribution of network and to suggest their optimum location. An examination of space variations of daily precipitation over the Sleepers Rivers Watersheds in Northern Vermont revealed that the correlation fields about a control gauges and dependent on inter-station distance and azimuth, daily rainfall amount; and the season of the year (Hendrik and Comere, 1970). Other components like cost and time involved, uncertainty of hydrological phenomena and length of record have also been considered to emphasize multiple use of data (Moss, Thomas and Gilroy, 1985). In an another assessment of hydrologial data network in the case of Brunei Darussalem, it was revealed that the greater preponderance of gauges in the coastal plains with very few stations in the remorter parts of the interior poses difficulty in the accurate inventory and planning of water resources (Chaun, 1992). In India, very few studies have concentrated on distributional network of rain-gauges, however, the need to extend the work related to optimality of data has been stressed in a study on Dhansiri basin (Goswami and Bora, 1993). The optimum requirement of each zone was determined through isohyetal mapping. The location of proposed rain-gauging stations was attempted in another study on the Mahanadi river (Prasad, 1995).

In the analysis of temporal variations, the importance of spatial coverage of data set has been very well exemplified by a statistical geographer, Gregory (1986). According to him, a data set representing the whole country like India is valuable in terms of causative studies on the macro-scale, but significant difference in terms of temporal correlation, overall spatial pattern, drought occurrence and characteristics exist among "All India" data set and sub-divisional meteorological station in particular. For prediction of rainfall or any other parameter of climate, long-term (1901-85) local level data when analysed on monthly and weekly basis for the Pune city revealed the inadequacy of methods like smoothed time series for discerning and predicting any definite climatic trend. Therefore, methods like autocorrelation, cross correlation and multiple correlation were employed to develop models for rainfall prediction (Gadgil, Gore and Gupte, 1986). A very simple presentation of various aspects of rainfall like distribution, intensity, variability and frequency in the drought prone area of Cuddapah district of Andhra Pradesh also described the micro-level temporal pattern

(Penchalaiah and Ramanaiah, 1992).

To determine the optimum character of rainfall, its seasonal behaviour has been analysed by approximating it with harmonic wave. A detailed illustration of harmonic method was, first of all, presented by Conrad and Pollak (1954). Since then, it has been applied to a variety of cyclic phenomena. A special mention may be made of the harmonic analysis of annual rainfall over the United States of America (Horn and Bryson, 1960). They have replicated the entire precipiation curve for Madison, Wisconsin by adding six harmonic terms and have prepared maps to show the relative importance of various harmonics. In India, several meteorologists and hydrometeo-rologists have used the harmonic method to analyse cyclic variations in climatic elements. The spatial variations in rainfall periodicitiy have been further used to demarcate climatic divide in Assam (Kalita and Sharma, 1993).

Thus, most of the studies in India concentrate on temporal aspects of rainfall. Starting from empirical descriptions, rainfall analysis has achieved a status of modelling, particularly in the fields of prediction, and estimation of frequency and intensity of rainfall. The areal estimation of rainfall, however, could not still be give due importance in many countries of the world because of uneven distribution of rain-gauges.

OBJECTIVES

The objectives of the study are : (i) to assess the optimality of rain-gauge network and to estimate mean basin rainfall; (ii) to analyse the optimum or normal character of temporal data; and (iii) to analyse the seasonal behaviour of rainfall.

THE STUDY AREA

A geologically and historically distinct region "Bundelkhand" has been selected for this study. The boundaries of the region as defined by Singh have been extended for the entire basin of the Betwa and Ken rivers, the southernmost tributaries of the Yamuna river. The region extends from 22°50′ North to 26°0′ North latitudes and 77°10′. East to 80°36′ East longitudes. It covers (including parts) five districts of Uttar Pradesh (Jalaun, Jhansi, Lalitpur, Hamirpur and Banda) and fifteen districts of Madhya Pradesh (Datia, Chhatarpur, Tikamgarh, Panna, Sagar, Vidisha, Damoh, Satna, Raisen, Jabalpur, Narsinghpur, Guna, Shivpuri, Bhopal and Sehore).

The study area is strategically located as it falls in the transitional zone of rainfall (75 to 125 cm). Geology, in addition to its own central Bundelkhand massif, forms the intermediate zone between northern alluvial plains of the Yamuna river and central Vindhyan plateau. Dissected relief, badlands, ephemeral and non-perennial stream along with deforestation activities have accentuated the problems of soil erosion as is evident from large-scale silting of Matatila Reservoir on the Betwa river. Recurrence of famines and absence of major dams have necessitated the scientific study on water resource potential, which begins with rainfall.

DATA SOURCE

The data for the study is based on secondary source like various publications of Indian Meteorological Department (IMD) which include Climate of Uttar Pradesh (1989) and Madhya Pradesh (1981). These atlas-cum-statistical summaries provide state and district-wise details of average rainfall data. Location of rain-gauge is determined with the help of Survey of India toposheets and Rainfall Atlas of India, by IMD. IMD data quoted in National Water Development Agency's publications is also used.

METHODOLOGY

To assess optimality of rain-gauge network, a comparison is made, first, with the standards laid down by World Meteorological Organization (Table 1).

Table 1
Recommended Minimum Density of Precipitation Station Network

S. No.	Physiographic unit	Minimum density (Km2/gauge) for non-recording gauges
1.	Coastal	900
2.	Mountainous	250
3.	Interior plains	575
4.	Hilly/Undulating regions	575
5.	Small Islands and Urban areas	25
6.	Arid/polar zones	10,000

Source: World Meteorological Organisation (1994) *Guide to Hydrological Practices*. WMO No.168, 5th Edition.

These densities assume uniform influence area of rain-gauge which may not be the case in reality. Therefore, the formula, proposed by Indian Standards Institution and later on adopted by Subramanya, Bora and Goswami and Prasad estimates the optimum number of rain-gauge based on variability of rainfall, i.e.

$$N = \left(\frac{C_v \times 100}{\epsilon} \right)^2 \quad \text{.... Eq. (1)}$$

where, N = optimum number of rain-gauge
Cv = coefficient of variation
ϵ = desired degree of percent of error in the estimation of mean basin rainfall, usually, taken as 5% or 10%.

To determine optimum number of rain-gauge required for good areal estimation of normal rainfall, another formula proposed by McCulloh is used. It is expressed by the relation:

$$N = \frac{C_V'}{10} \times N_0 \quad \text{.... Eq. (2)}$$

where, C_V = coefficient of variation above 5%
N_0 = existing number of rain-gauge

Here, mean rainfall is calculated, first, by arithmetic method and then, by drawing Thiessen polygons and isohyetes because optimality should exist not only with regard to their number but also with respect to their spatial extent. These means are calculated according to the following simple formulae:

$$P_M = \frac{P_1+P_2 ...+P_n}{N} \qquad P_T = \frac{a_1P_1+a_2P_2+...+1_nP_n}{A} \qquad P_I = \frac{a_1P_{z1}+a2P_{z2}+...+A_nP_{zn}}{A}$$

... Eq. (3)

where,

P_M, P_T and P_I	=	arithmetic mean, Thiessen polygon weighted mean and isohyetal mean respectively
P_1, P_2 ... P_3	=	mean precipitation amount recorded at each rain gauge
P_{z1}, P_{z2} .. P_{zn}	=	mean precipitation of each isohyetal zone
a_1, a_2 ... a_n	=	influence area of gauge
N	=	total number of existing rain-gauge
A	=	total drainage basin area.

To test the temporal behaviour of rainfall, empirical frequency of rainfall is fitted to normal probability distribution (i.e. the mean time in years for the mth largest value among annual maxima series of length N to be exceeded once on an average). It may be written as :

Recurrence interval (T) = (N+1)/m
where, N = length of record (80 years)
m = rank

The probability, i.e. the relative frequency of values being equal to or greater than marked values is, then, given by the reciprocal of recurrence interval and *vice-versa*.

$$\therefore \quad p(R \text{ £ } r) = 1/T = m/(N+1) \quad \text{... Eq. (4)}$$

$$\text{or} \quad p(X \text{ £ } x) = (m/81) \times 100\%$$

The best fit of the distribution is determined statistically by χ^2-test and graphically by *normal arithmetic probability paper*. For the best fitted distribution line, confidence bands are also drawn to determine the range of maximum and minimum rainfall.

The seasonal behavior of rainfall is described by drawing isohyets for the monsoon, pre-monsoon and post-monsoon season. The periodic character of rainfall is analysed by harmonic method. Here, monthly precipitation series is obtained/ reproduced by adding six harmonic terms of Fourier series (Horn and Bryson, 1960) using the following equation for sine curve :

$$Y = a_o + a_1 \sin(30^\circ \tau + \phi 1) + a_2 \sin(60o\ \tau + \phi 2) + \ldots a_6 \sin(360^\circ \tau + \phi 6) \quad \text{... Eq. (5)}$$

If we expand the above equation and substitute

$p_1 = a1\sin\phi 1$, $p_2 = a_2 \sin\phi_2 \ldots$

$q_1 = a_1 \cos\phi_1$, $q_2 = a_2 \cos\phi_2 \ldots$

Then equation (5) becomes

$$Y = a_0 + \sum_{k=1}^{6} \{p_k \cos kx + q_l \sin kx\} \quad \text{... Eq. (6)}$$

Thus, equation (6) is used in harmonic analysis of rainfall. The harmonic term can be determined objectively by phase angle (ϕ) = $\tan^{-1}(p_k/q_k)$ and amplitude $(a_k) = \sqrt{p_k^2 + q_k^2}$ with the help of Fourier coefficients (p_k and q_k) as shown below:

$$p_k = \frac{1}{6} \sum_{\tau=0}^{11} m_\tau \cos 30^\circ k\tau, \qquad q_k = \frac{1}{6} \sum_{\tau=0}^{11} m_\tau \cos 30^\circ k\tau,$$

where, k = number of harmonic term 1, 2, ... 6

$x = \frac{2\pi}{T}$ or $\omega\tau$ represents the time angle with w as angular frequency, *i.e.* time period (T) to cover its one cycle covering the interval 2π.

here, T = total length of the period investigated (i.e. 12 months for the yearly rainfall)

and τ = 0, 1, 2, ..., (n-1) observation points (i.e. individual months starting from 0, 1, ..., 11).

m_τ = mean monthly precipitation for months.

a_o = mean annual precipitation

Further, percentage contribution of the kth harmonic to the total variance representing monthly fluctuations is calculated in order to determine the number of significant terms as:

$$Vk = (a_k^2/2S_m^2) \times 100\% \quad \text{...Eq.(7)}$$

where, $S(\text{Variance}) = \frac{\sum (m_\tau - m_x)^2}{N}$

with $m\tau$ = mean monthly rainfall values

m_x = mean annual rainfall

For comparing amplitude and phase angle of different harmonic waves, a harmonic dial is constructed which is a simple and useful graphical method for comparing simultaneously the amplitude and the phase angle of periodic or quasi-periodic phenomena of the same period in a polar coordinate system. In order to check dial, the time of maximum (tm) oscillation can be computed directly by equating argument of the sine term to its maximum and minimum value, i.e.

$$kx = \phi k = 90^\circ$$

or, $$k\,30^\circ t_m + \phi k = 90^\circ + 2\pi, \text{ if } \phi k > 90^\circ \quad \text{... Eq. (8)}$$

where, k is the number of the harmonic term.

RESULTS AND DISCUSSIONS

Optimality of Rain-Gauge

Preliminary investigations of the spatial network of rain-gauge revealed that there were about 75 rain-gauges in the study region, 45 in the Betwa basin and 30 in the Ken basin (Fig. 1). They cover 50-year period between 1901-50 as the published climatological record was available only for this period. Out of these, only 37 stations cover the entire length of fifty-year record. Therefore, only those stations, established before 1920, are selected because of the normal requirement of, at least, 30 observation points for statistical analysis. These 47 stations constitute about 62.7% of the total rain-gauge in the region. The average density of rain-gauge network, thus, works out to be 1542 Km^2 for the stations having sufficient long-term record. This density reduces to 976 Km^2 per station even if all the 75 rain-gauges are considered. But is this rain-gauge network adequate enough to provide reasonable estimates of basin rainfall?

According to modern WMO standards, minimum density of 575 Km2 per gauge is required in the interior plains and undulating or hilly regions like Bundelkhand (Table 1). The existing density of rain-gauge network does not reach this optimum standard. To attain the desired level of optimality there should be, at least, 127 rain-gauges, i.e.

$$\text{Optimum number of rain-gauge} = \frac{\text{Total drainage area}}{\text{Minimum density per gauge}}$$

$$= \frac{73{,}395}{576} \approx 127$$

The spatial distribution of this optimum network can be shown by drawing circles of equal radii. But, these circles will leave interstitial space between adjacent rows and columns. Entire space will come under the influence area of all the rain-gauging stations if, hexagons are drawn (Fig.2).

Before making this uniform recommendations for the establishment of new rain-gauge, other aspects like variability of mean basin rainfall are to be considered.

Therefore, the formula given in equation (1) is used to determine the optimum number of rain-gauge as :

$$N = \left(\frac{18.66 \times 100}{5}\right)^2 \approx 14$$

Here, mean = 1029.20 and

$$\text{Standard deviation } (\sigma) = \sqrt{\frac{\Sigma(\cdot\cdot\ \cdot)^2}{47-1}} = 192.23$$

This estimated optimum number of rain-gauge is, in fact, not even the half of the existing ones (47). The difference arises due to lower coefficient of variation calculated on the basis of normal annual rainfall data. Hence, the inference that existing number of rain-gauge is higher than the optimum level does not reflect the true status and thereby shows the inapplicability of the formula (equation 1) to the normal data having relatively lesser actual deviation from mean. Therefore, McCulloh formula (equation 2) is used to estimate optimum number of rain-gauge. Accordingly,

$$(N = (\frac{8.66}{10})^2 \times 46 \approx 160$$

Thus, optimum number of rain-gauge at 10% level of error in the estimation of coefficient of variation would approximately be 160, which is little less than the four times of the existing number of rain-gauges that have sufficient long-term record. On the other hand, the optimum number is more than the WMO recommended network of 127 gauges. It is because of higher value of Cv during non-monsoon months. Thus, an estimation of optimum number of rain-gauge depends not on the total number of existing gauge, but on the level of coefficient of variation. Therefore, to determine the variability of mean rainfall, best estimates for its areal measurement are required first.

MEAN BASIN RAINFALL:

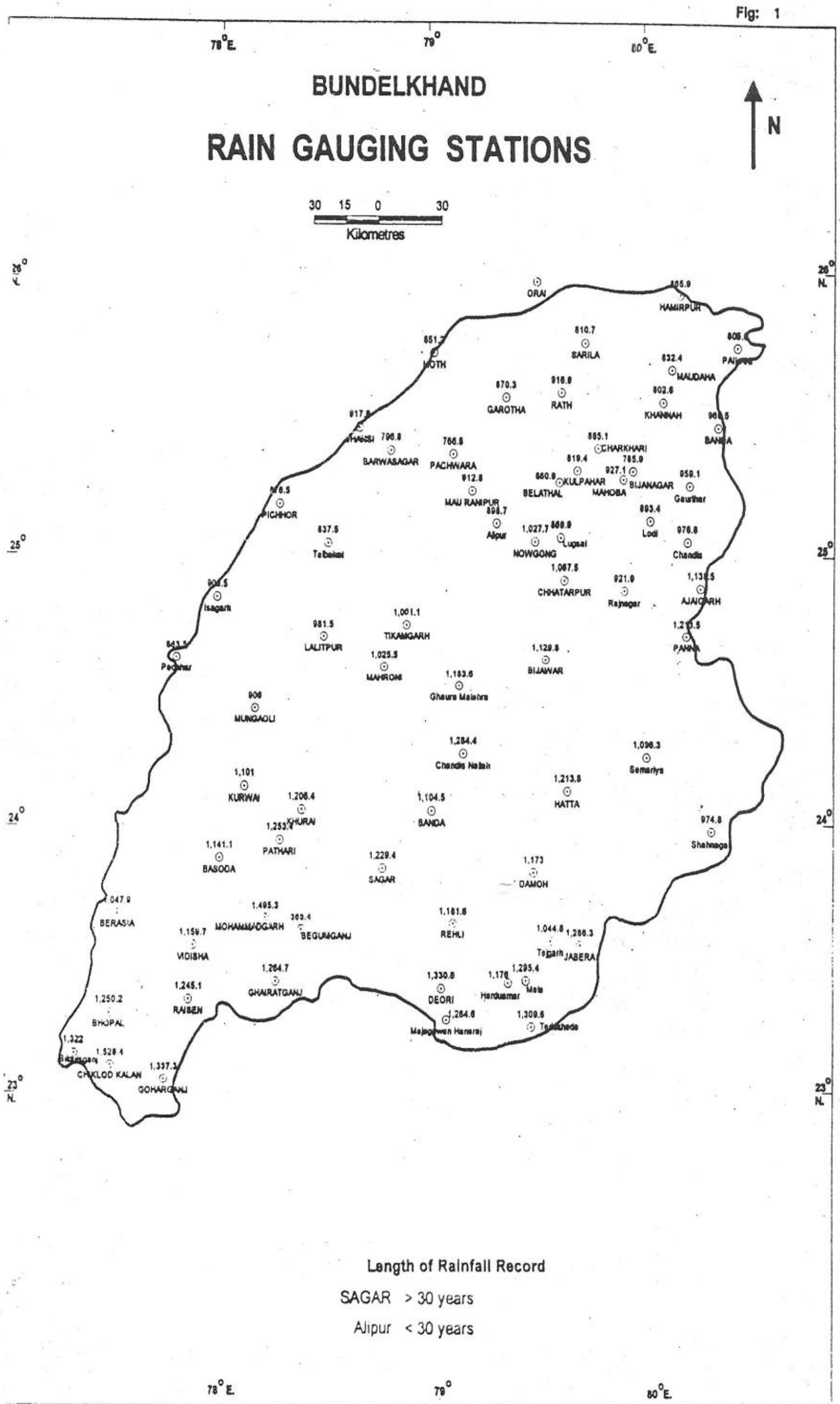
a) Arithmetic method

The arithmetic average as used in the previous section puts the mean annual rainfall in the Bundelkhand region as 1029 mm. But, this approach provides reasonable estimates if the gauges are distributed uniformly and the topography is flat which, except for the northern region, is not found in abundance in the study area. Other commonly used methods are Theissen polygons and isohyets. Besides, these methods provide clear insight into spatial distribution of rain-gauge and, thus, may prove to be helpful in designing an optimum network.

b) Theissen Polygon Method

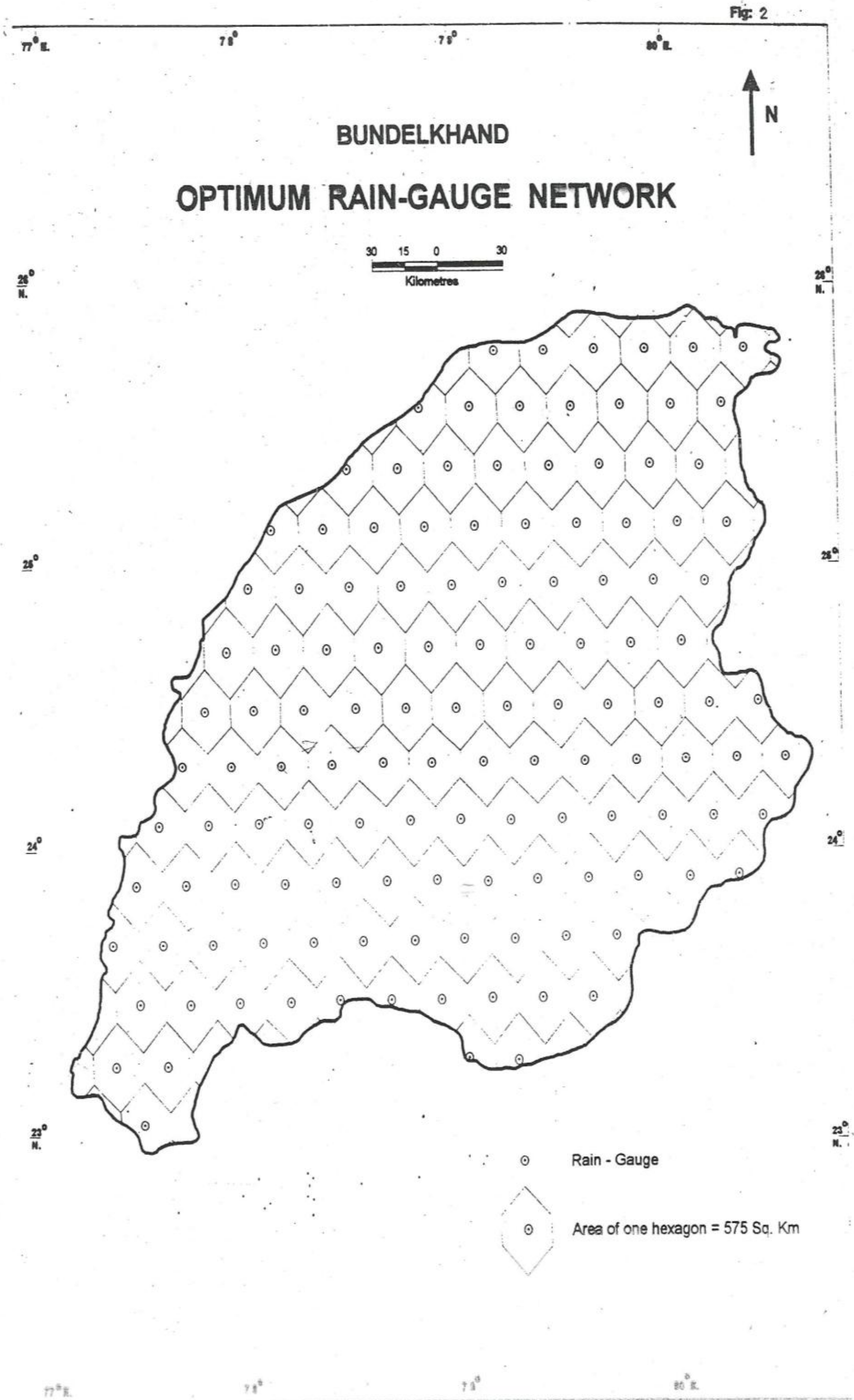
The spatial extent of rain gauge influence area is clearly reflected by drawing polygons around each rain-gauge for which computation are given in Table 2.

Fig: 1



Source : Based on data from Government of India, Indian Meteorological Department (1981) Climate of Madhya Pradesh; (1989) Uttar Pradesh; and Rainfall Atlas of India.

Fig: 2



Source : Based on Recommendations by World Meteorological Organization (1995) Guide to Hydrological Practices. WMO No. 168. 5th edition.

Table 2
Mean Annual Rainfall and Influence Area of Rain-Gauge by Theissen Polygon Method

S. No.	Rain-gauging station	Influence area (km^2) of a polygon	Rainfall (mm)	S. No.	Rain-guaging station	Influence area (km^2) of a polygon	Rainfall (mm)
1	Jhansi	423.8	917.6	28.	Hatta	3,884.0	1,213.8
2.	Moth	811.7	851.2	29.	Jabera	1,812.0	1,286.3
3.	Garotha	1,321.0	870.3	30.	Raisen	1,442.0	1,245.1
4.	Mau	1,561.0	912.8	31.	Begumganj	1,825.0	1,368.4
5.	Lalitpur	2,065.0	981.5	32.	Kaliakheri	1,502.0	1,337.3
6.	Mahroni	2,301.0	1,025.5	33.	Panna	2,551.0	1,213.5
7.	Pachwara	829.2	766.5	34	Ajaigarh	1,309.0	1,139.5
8.	Barwasagar	1,575.0	796.8	35.	Chhatarpur	1,531.0	1,067.5
9.	Banda	908.3	969.5	36.	Bijawar	3,212.0	1,129.8
10.	Pailani	659.0	805.6	37.	Nowgong	1,277.0	1,027.7
11.	Hamirpur	618.3	865.9	38.	Pichhore	2,053.0	876.5
12.	Rath	1,282.0	916.9	39.	Vidisha	1,109.0	1,159.7
13.	Maudaha	813.4	832.4	40.	Basoda	1,831.0	1,141.1
14.	Kulpahar	407.4	819.4	41.	Kurwai	1,664.0	1,101.0
15.	Mohoba	752.3	927.1	42.	Pathari`	766.0	1,253.4
16.	Khannah	809.5	802.6	43.	Mohhamadgarh	1,116.0	1,495.3
17.	Sarila	1,282.0	810.7	44.	Banda	2,949.0	1,104.5
18.	Charkhari	535.7	885.1	45.	Berasia	2,090.0	1,047.9
19.	Belathal	794.0	860.9	46.	Orai	442.1	724.9
20.	Bijanagar	840.4	785.9	47.	Kalpi	76.8	859.9
21.	Tikamgarh	2,544.0	1,001.1	48.	Badausa	97.2	901.5
22.	Mungaoli	3,227.0	906.0	49.	Nagod	1,479.0	1,097.0
23.	Sagar	1,818.0	1,229.4	50.	Murwara	1,609.0	1,220.0
24.	Khurai	1,708.0	1,206.4	51.	Sihora	297.5	1,320.3
25.	Rehli	1,709.0	1,181.6	52.	Patan	680.8	1,279.8
26.	Deori	2,023.0	1,330.6	53.	Ichhawar	463.3	1,242.1
27.	Damoh	1,866.0	1,173.0	54.	Guna	122.7	1,098.5

Source : Computed from (i) Government of India, Indian Meteorological Department. *Rainfall Atlas of India*; (ii) Government of India, Indian Meteorological Department (1989) *Climate of Uttar Pradesh* and (1983) *Climate of Madhya Pradesh.*

Substituting the respective values from Table 2, mean precipitation is computed at

$$p = \frac{80{,}520{,}666.60\ mm.km^2}{74{,}631.40\ km^2} = 1078.91\ mm$$

If these polygons drawn in Fig. 3 are compared with the optimum-sized hexagons having an uniform influence areal each comprising a fractional value of 7.936 x

10-3 (Fig. 2), then large variations are found in their size. Rain-gauging stations with lower annual rainfall values have smaller influence area towards the Bundelkhand plains, whereas moderate to large-size polygons are found in the central Bundelkhand upland and plateau region. Polygons with a comparable optimum size occur in the hilly region specially towards the headwater regions of the Betwa river. This distorted distribution of rain-gauge can be explained by the overall development in the region. Agricultural intensity in the plains may be attributed to establishment of more rain-gauges there, reflecting the demand for accurate measurement of rainfall in their vicinity. The rugged and inaccessible terrain in the middle course of the river, besides the low level of development, has resulted in a relatively large-size polygons. However, with the development of irrigation in the region, new stations have been installed in Madhya Pradesh which is evident from the total network of rain-gauge even during 1950's.

Table 3
Estimation of Mean Annual Rainfall by Isohyetal Method

Isohyetal zone		Mean rainfall between isohyets (mm)	Deviation from assumed mean (a=1050)d	Area enclosed between isohyets (km²)	Fractions of total area	Existing rain-guage	Proposed rain guage	Additional rain-guage
I	700-800	750	-3	1,952.20	0.026769	3	4	1
II	800-900	850	-2	13,230.00	0.167701	11	27	16
III	900-1000	950	-1	10,689.20	0.146573	7	23	16
IV	1000-1100	1050	0	11,810.00	0.161942	8	26	20
V	1100-1200	1150	+1	20,990.70	0.287830	7	46	38
VI	1200-1300	1250	+2	9,564.11	0.131145	3	21	14
VII	1300-1400	1350	+3	5,255.20	0.072061	1	12	9
VIII	1400-1500	1450	+4	436.10	0.005990	1	1	0
Total				73,927.51	1.0000	46	160	114

Source : Fig. 4.4 op cit.

Fig. 5 : Monsoon Rainfall at Bijawar (1901-80)

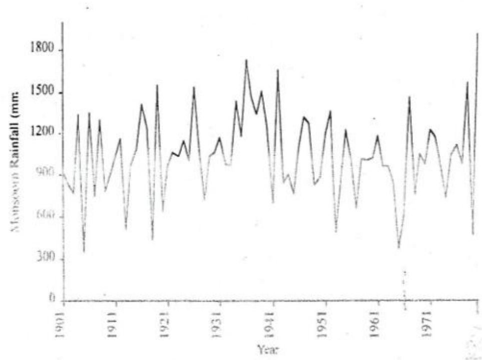
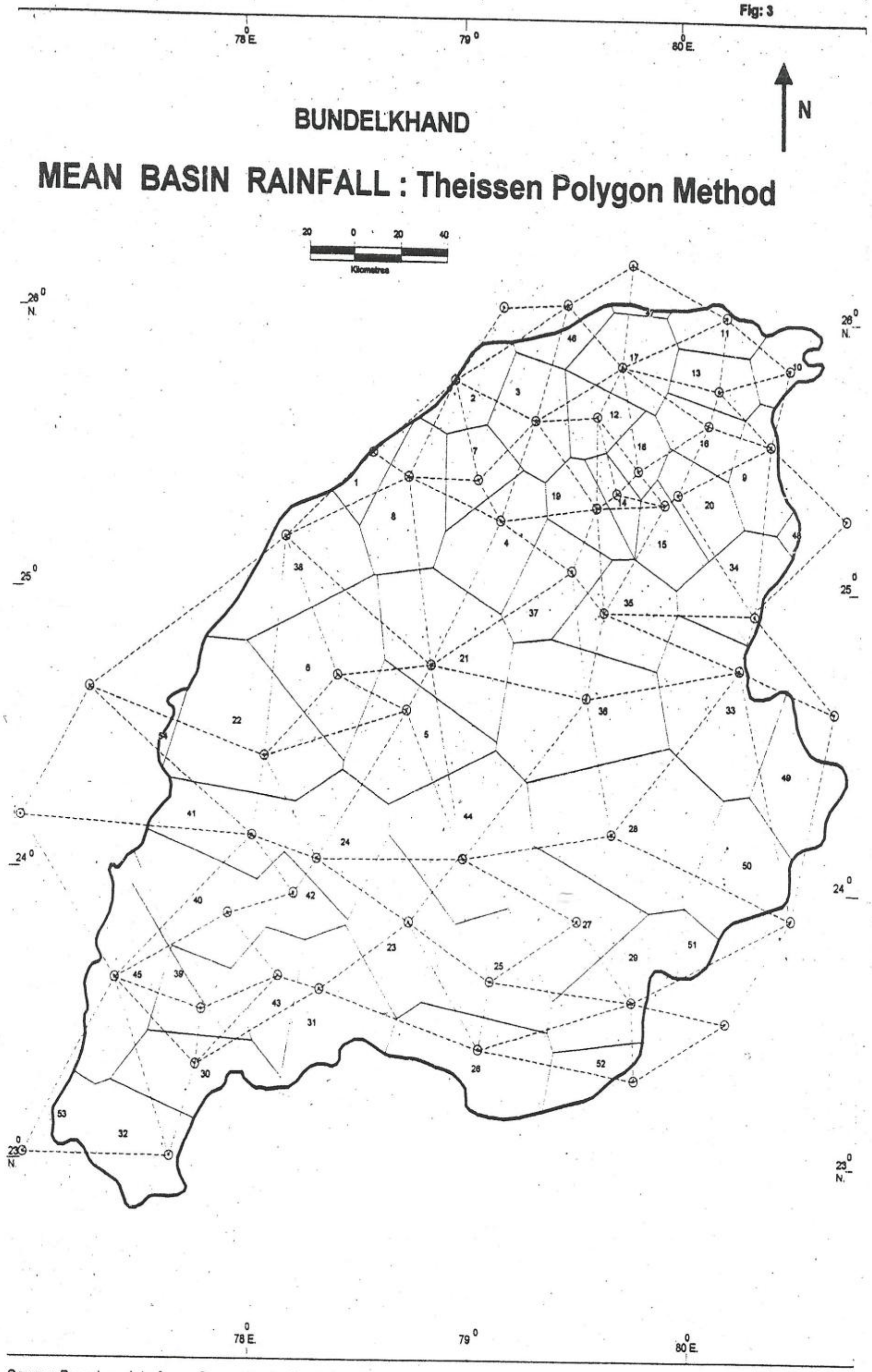
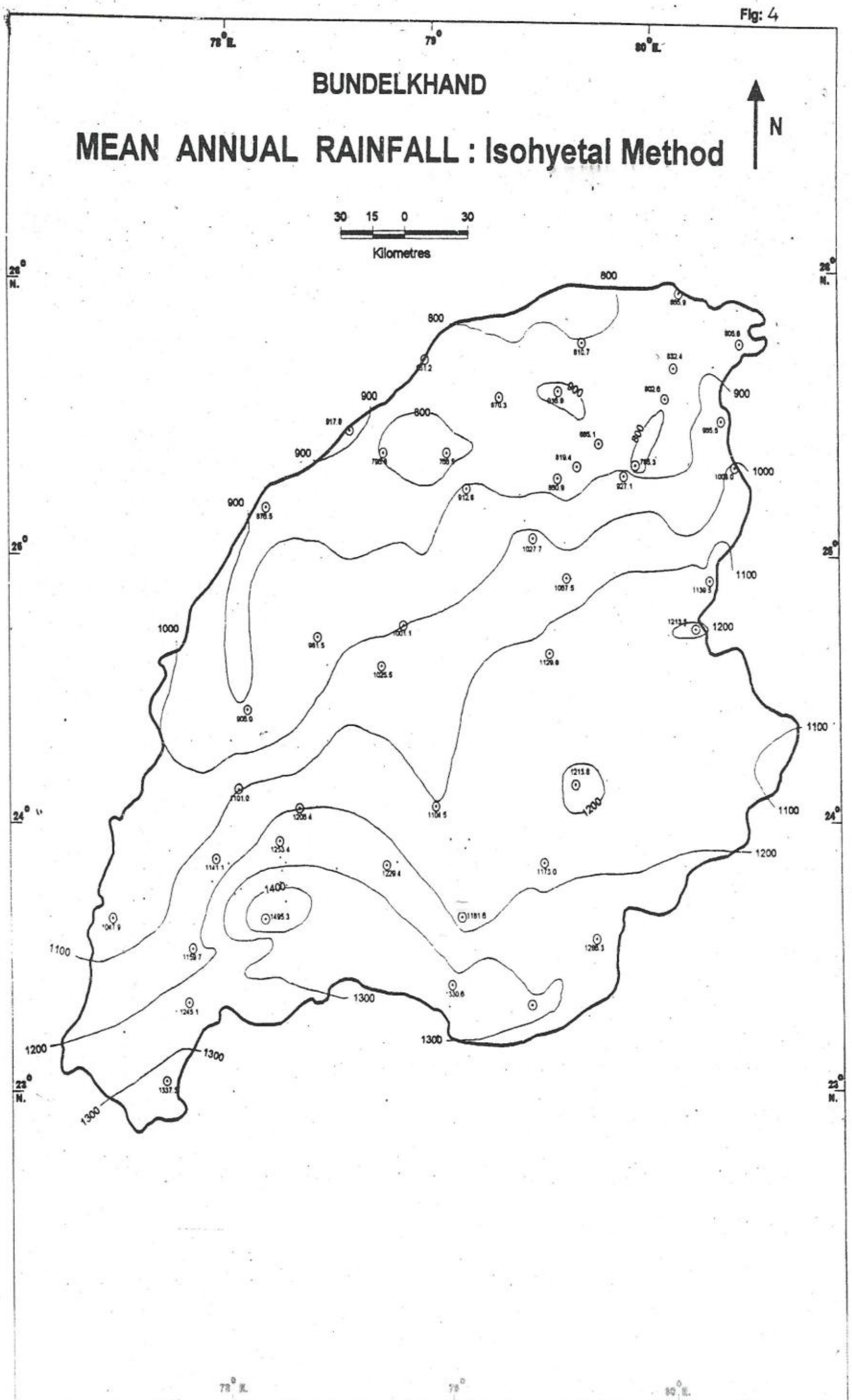


Fig: 3



Source: Based on data from: Government of India (1981), Indian Meterological Department, Climate of Madhya Pradesh and Uttar Pradesh

Fig: 4



Source : Based on data from Government of India, Indian Meteorological Department (1983) Climate of Madhya Pradesh and (1989) Uttar Pradesh; (1972) Rainfall Atlas of India

Isohyetal Method

Isohyetal average is obtained by contouring precipitation values (Fig. 4). The precipitation values weighted by the fractional area between the contours are, then, summed to obtain the isohyetal average precipitation for the basin (Table 3).

$$R = a + \frac{\Sigma A_m d}{N} . i$$

$$R = 1050 + \frac{14,623.12}{73,927.51} \times 100$$

$$= 1050 + 19.78$$

$$= 1069.78 \text{ mm}$$

This slightly lesser value of isohyetal mean does not differ significantly from the mean calculated by Theissen polygon method. But, both the methods result in higher mean rainfall than the one by arithmetic method. The significance of isohyetal method lies in the spatial distribution of proposed rain-gauge. On the basis of area enclosed, the proposed number of rain-gauge for each isohyetal zone has been estimated. Table 3 shows that the isohyetal zone VIII requires no additional rain-gauge as it already has one rain-gauge that equals the optimum number estimated for it. In rest of the zones, 114 additional rain-gauges, being maximum in the central isohyetal zones that fall under plateau region, are required so as to make up for the desired number.

While making recommendations for 114 additional rain-gauges in zones I to VII, other existing rain-gauges which have lesser period of record may be incorporated in extending the existing network in order to reduce time and cost expenses. Moreover, the existing network being analysed here is based on data till 1960 only. In 1999, after a gap of 39 years, some new stations might have already been installed and many more would have completed sufficient time-period to provide normal figures. Thereafter, area enclosed between each isohyetal zone might increase or decrease which, in turn, can alter the distributional pattern of optimum number of rain-gauge. Therefore, adequacy of rain-gauge network needs to be referred to the time-period.

TEMPORAL VARIATIONS

Frequency analysis of long-term data is done for monsoon rainfall only because most of the planning efforts are affected by the amount and fluctuation of monsoons, which have pre-dominant regional share in the annual rainfall. Further, 80-year record is analysed for one station only located at mean centre because temporal pattern of the spatial distribution is assumed to follow more or less the same trend in its annual variation.

As the mean centre is located at the point (24°32′ N., 79°02′ E.) where no rain-gauging station exists, therefore nearest stations lying around the same latitudes viz. Mahroni (24°35′ N., 78°43′ E.) and Bijawar (24°37′ N., 79°30′ E.) are considered. Moreover, the mean centre for the Betwa basin (24°28′ N., 78°34′ E.) and the Ken basin (24°36′ N., 79°42′ E.) also lie in close vicinity to these stations. Of the two selected rain-gauging stations at

Mahroni and Bijawar, the rainfall record is not complete for some of the years at the former station. Hence, Bijawar is selected as mean sample point to analyse the temporal variation in monsoon rainfall.

The annual fluctuations in the monsoon rainfall are marked by intermittent peaks and lows (Fig. 5). Higher extremes generally occur after a gap of four or five years. In this situation, only a probability about the occurrence of a particular value of rainfall can be known.

In order to get probability values, first of all, rainfall data is arranged in descending order of magnitude and the computations are shown in Table 4 (Col. 1 to 6).

Table 4

Computations of Recurrence Interval of Monsoon Rainfall (1901-81) at Bijawar.

Year	Monsoon rainfall (mm)	Rainfall arranged in ascending order	Rank (m)	Exceedence probability (%) p=(m/81) x 100	Return period (Years) (T_p)
(1)	(2)	(3)	(4)	(5)	(6)
1901-02	922.8	350.5	80	98.77	1.01
1902-03	834.0	370.1	79	97.53	1.03
1903-04	769.1	440.9	78	96.30	1.04
1904-05	1334.8	465.6	77	95.06	1.05
1905-06	350.5	489.5	76	93.83	1.07
1906-07	1348.9	510.6	75	92.59	1.08
1907-08	743.5	606.3	74	91.36	1.09
1908-09	1301.3	637.8	73	90.12	1.11
1909-10	780.0	654.3	72	88.89	1.13
1910-11	899.2	690.9	71	87.65	1.14
1911-12	1030.2	715.6	70	86.42	1.15
1912-13	1162.3	727.8	69	85.19	1.17
1913-14	510.6	743.5	68	83.95	1.19
1914-15	963.9	752.7	67	82.72	1.21
1915-16	1089.3	760.0	66	81.48	1.23
1916-17	1407.4	769.1	65	80.25	1.25
1917-18	1241.8	780.0	64	79.01	1.27
1918-19	440.9	822.1	63	77.78	1.29
1919-20	1548.0	834.0	62	76.54	1.31
1920-21	637.8	839.7	61	75.31	1.33
1921-22	956.8	846.1	60	74.07	1.35
1922-23	1060.2	857.2	59	72.84	1.37
1923-24	1032.5	869.6	58	71.60	1.40
1924-25	1145.0	873.2	57	70.37	1.42
1925-26	998.0	899.2	56	69.14	1.45
1926-27	1532.1	922.8	55	67.90	1.47
1927-28	1070.6	954.3	54	66.67	1.50
1928-29	715.6	956.8	53	65.43	1.53
1929-30	1030.6	958.6	52	64.20	1.56
1930-31	1061.2	960.1	51	62.96	1.59

1931-32	1170.3	963.0	50	61.73	1.62
1932-33	973.3	963.9	49	60.49	1.65
1933-34	960.1	970.1	48	59.26	1.69
1934-35	1430.0	971.3	47	58.02	1.72
1935-36	1174.7	973.3	46	56.79	1.76
1936-37	1731.1	997.1	45	55.56	1.80
1937-38	1460.6	998.0	44	54.32	1.84
1938-39	1335.8	1008.4	43	53.09	1.88
1939-40	1504.5	1009.7	42	51.85	1.93
1940-41	1258.8	1011.3	41	50.62	1.98
1941-42	690.9	1030.2	40	49.38	2.03
1942-43	1659.6	1030.6	39	48.15	2.08
1943-44	839.7	1032.5	38	46.91	2.13
1944-45	896.6	1038.2	37	45.68	2.19
1945-46	760.0	1046.0	36	44.44	2.25
1946-47	1088.0	1060.2	35	43.21	2.31
1947-48	1314.5	1061.2	34	41.98	2.38
1948-49	1271.6	1070.6	33	40.74	2.45
1949-50	822.1	1088.0	32	39.51	2.53
1950-51	873.2	1089.3	31	38.27	2.61
1951-52	1189.7	1107.2	30	37.04	2.70
1952-53	1359.9	1145.0	29	35.80	2.79
1953-54	489.5	1162.3	28	34.57	2.89
1954-55	857.2	1171.0	27	33.33	3.00
1955-56	1218.8	1173.0	26	32.10	3.12
1956-57	1008.4	1174.7	25	30.86	3.24
1957-58	654.3	1176.8	24	29.63	3.38
1958-59	1009.7	1189.7	23	28.40	3.52
1959-60	997.1	1217.6	22	27.16	3.68
1960-61	1011.3	1218.8	21	25.93	3.86
1961-62	1176.8	1218.8	20	24.69	4.05
1962-63	954.3	1241.8	19	23.46	4.26
1963-64	958.6	1258.8	18	22.22	4.50
1964-65	846.1	1301.3	17	20.99	4.76
1965-66	370.1	1314.5	16	19.75	5.06
1966-67	606.3	1334.8	15	18.52	5.40
1967-68	1460.4	1335.8	14	17.28	5.79
1968-69	752.7	1348.9	13	16.05	6.23
1969-70	1046.0	1359.9	12	14.81	6.75
1970-71	970.1	1407.4	11	13.58	7.36
1971-72	1218.8	1430.0	10	12.35	8.10
1972-73	1171.0	1460.4	9	11.11	9.00
1973-74	963.0	1460.6	8	9.88	10.13
1974-75	727.8	1504.5	7	8.64	11.57
1975-76	1038.2	1532.1	6	7.41	13.50
1976-77	1107.2	1548.0	5	6.17	16.20
1977-78	971.3	1564.0	4	4.94	20.25
1978-79	1564.0	1659.6	3	3.70	27.00
1979-80	465.6	1731.1	2	2.47	40.50
1980-81	1931.7	1931.7	1	1.23	81.00

Source : Computed from National Water Development Agency (1983) *Final Water Balance Study of Lower Betwa Sub-Basin* Technical Study No. 70.

Then, the normal distribution is fitted to the entire range of data grouped at the fixed intervals (Table 5):

Table 5
Goodness of Fit Test Between Normal and Observed Grouped Frequencies of Monsoon Rainfall at Bijawar

Rainfall range (mm)	Observed frequency (years)	Observed frequency (%) (f_0)	Normal frequency (%) (f_e)	$\chi 2$
301-500	5	6.25	3.36	2.486
501-700	5	6.25	9.74	1.251
701-900	15	18.75	18.99	0.003
901-1100	25	31.25	24.53	1.841
1101-1300	13	16.25	22.14	1.567
1301-1500	10	12.50	13.25	0.042
1501-1700	5	6.25	5.29	0.174
1701-1900	1	1.25	1.48	0.036
1901-2100	1	1.25	0.26	3.770
Total	**80**	**100.00**	**99.04**	**11.170**

Source : Table 4 op cit.

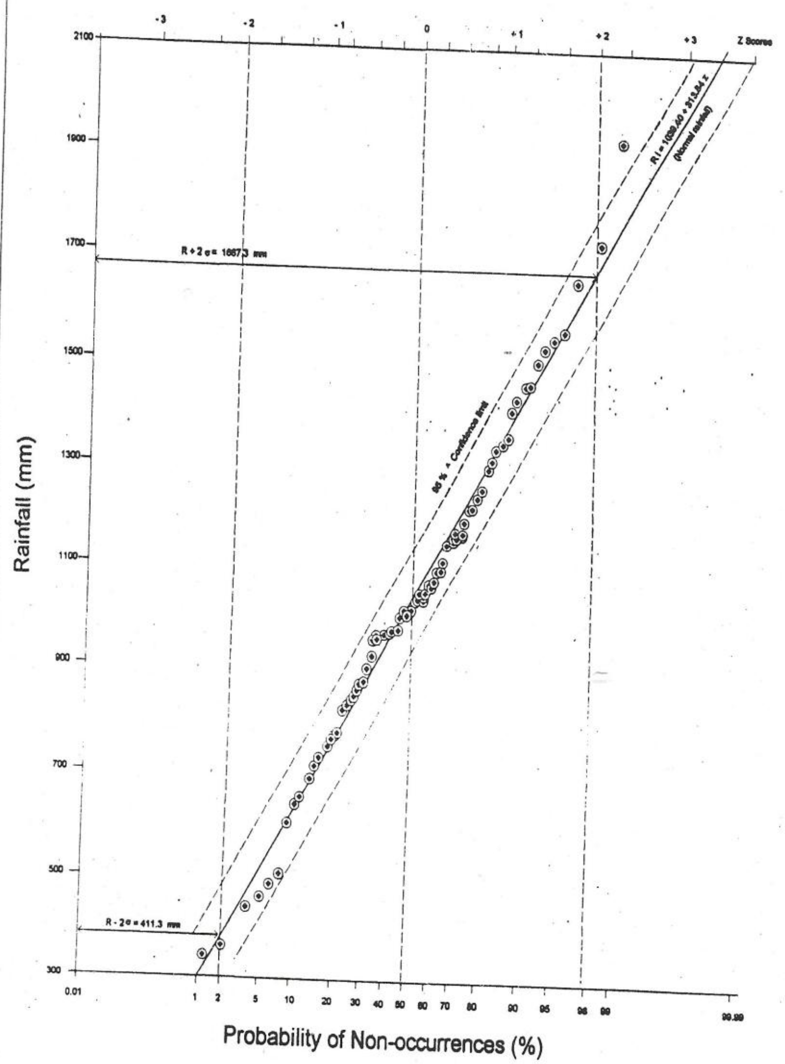
As the computed $\chi 2$ value of 11.17 is less than its critical value, therefore the difference between observed and expected frequencies of rainfall is not significant at 5% level of significance. However, at other levels (1%), the significance of error becomes important. Therefore, no sound statistical validity about the fitting of normal distribution can be achieved unless the entire set of long-term record is analysed.

The above analysis for the grouped frequencies is extended further to individual values included in raw data by computing z-scores for each point. A graphical representation of the accumulated frequencies of any distribution, therefore, indicates by its deviation from a straight line, the departure from the normal distribution.

It may be observed from the foregoing frequency analysis that even 80-year record is not sufficient to get a closer approximation about normal monsoon rainfall specially due to marked deviation of values in the upper ranges. However, the utility of probability analysis still remains in finding the probable range of maximum monsoon rainfall falling within specified confidence limits. The 95% confidence limits are derived from the equation :

Fig: 6

Relative Frequency vs. Monsoon Rainfall at Bijawar (1901 - 80)

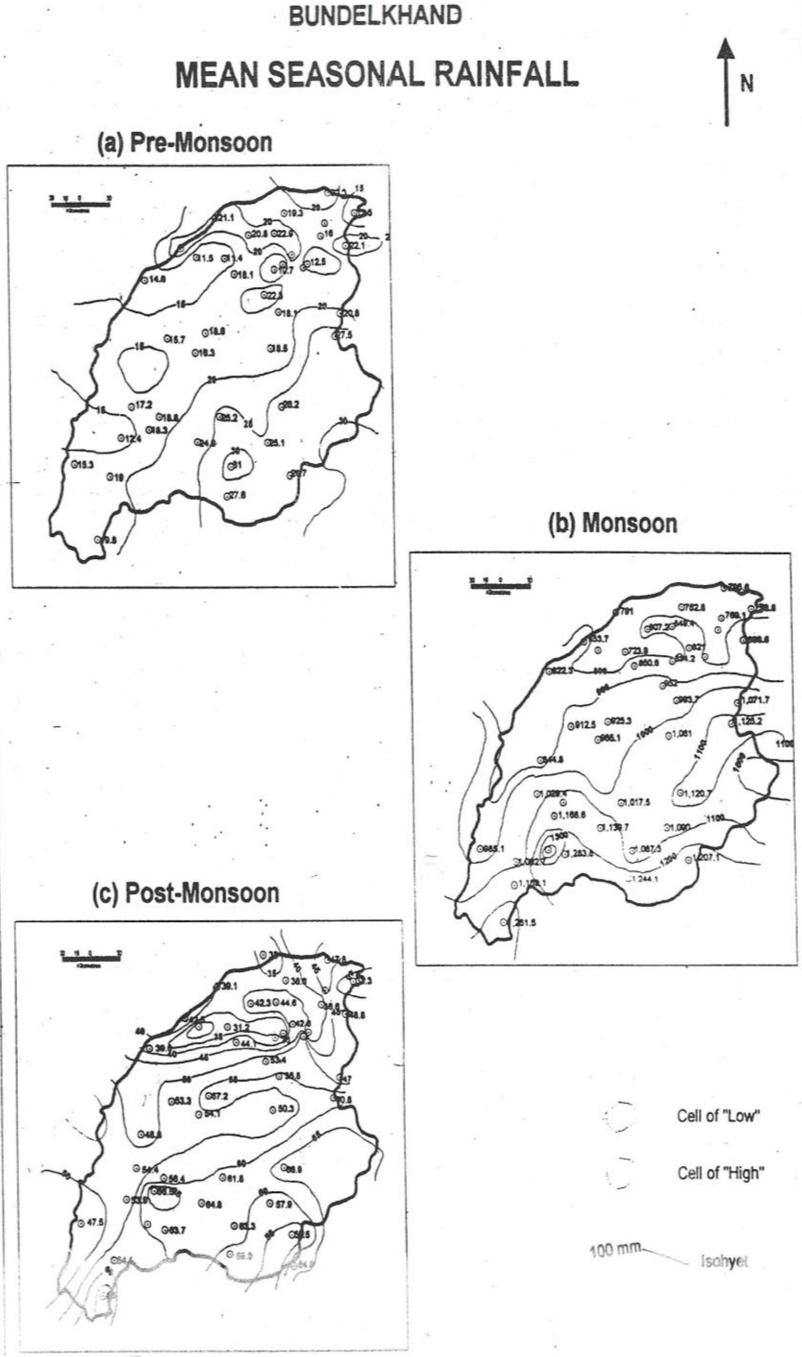


Scale on abscissa for the arithmetic probability paper,
48% probability from the centre = 4 cms (i.e. z = 2.0538)

Fig: 7

BUNDELKHAND

MEAN SEASONAL RAINFALL



Source : Based on data from Government of India, Indian Meteorological Department (1981) Climate of Madhya Pradesh; (1989) Uttar Pradesh; and Rainfall Atlas of India

$\hat{X} = \bar{X} \pm 1.96\ \sigma s$ ... Eq. (9)

$$\sigma_s = \frac{\sigma}{\sqrt{N}} = \frac{313.836}{\sqrt{80}} = 35.09 \text{ mm}$$

where, (standard error of estimate)

Substituting for σs, the above equation reduces to

$X = \bar{X} \pm 68.78$

where, $\hat{X}$ refers to estimated values of normal monsoon rainfall.

These confidence bands form linear belt around straight line normal curve (Fig. 6). Values for the corresponding bands at selected levels of probability are provide in Table 6.

Table 6
Computations to Draw 90% and 95% Confidence Band Around Normal Frequency Curve

S. No.	Probability of exceedence	Return	Estimated	Upper band	Lower band
1	99	1.01	309.10	377.88	240.32
2	90	1.11	637.06	705.84	568.28
3	50	2	1,039.40	1,108.18	970.62
4	10	10	1,441.74	1,510.52	1,372.96
5	1	100	1,769.70	1,838.48	1,700.92
6	0.1	1000	2,006.01	2,074.79	1,937.23

Source : Table 4, op cit.

Thus, 95% confidence bands include all the extremes confined within $x \pm 3\sigma$ limits. The largest upper band of normal frequency, now, can be used as reliable measure of maximum monsoon rainfall at Bijawar. Therefore, any storage reservoir in this region should have the capacity to contain, at least, 2074.79 mm of rainfall during monsoon season. The contribution of other months can be determined by examining their monthly proportions of rainfall in each season.

SEASONAL BEHAVIOUR OF RAINFALL

The effect of seasonality becomes evident from the spatial distribution of seasonal isohyetal maps representing the pre-monsoon, monsoon and post-monsoon period. A comparison of these maps with the annual rainfall map reveals slight variation in the location of 'lows' and 'highs' (Fig. 7).

The general pattern of isohyets for all the seasons indicates that rainfall in the Bundelkhand region increases southwards with the rise in relief. Offshoots of Vindhyachal range experience highest rainfall to the east of upper Betwa Valley where a prominent 'high' is formed at Mohammadgarh during monsoon season. The intermittent valleys especially of the Betwa and Dhasan rivers when encountered with plateaus and hills create bends in isohyets. Another high occurs in the Panna-Ajaigarh range and also towards Damoh plateau. This latter 'high' becomes important in the pre-monsoon season because of early arrival of monsoon on the eastern side of the region. In the post-monsoon season also, winter currents meet the steeper gradient of this range rather than the south-facing Vindhyachal range on the southwest. In the northern Bundelkhand plains, the effect of local relief results in small 'lows' and 'highs' towards low-lying valley depressions and isolated mounds respectively. Thus, the criss-cross pattern of isohyets towards northeast, especially in the pre and post-monsoon period, can be taken as climatic divide resulting into two zones of isohyets with gentle gradient.

Seasonal variation in the amount of rainfall reveals that the average contribution of monsoon rainfall to the annual rainfall is highest, i.e 93% (961.3mm) followed by only 5% (180.3 mm) during post-monsoon period. Moreover, the spatial variation in monsoon rainfall is more akin to annual rainfall pattern. The coefficient of variation for both the pre- and post-monsoon season (25% and 22% respectively) deviates largely from the coefficient of variation for the annual and monsoon period (Table 7).

Table 7
Variability of Mean Rainfall during Different Seasons

Season	Parameter	Pre-monsoon	Monsoon	Post- monsoon	Annual
Betwa Basin		17.8	952.00	48.10	1017.81
	s	3.99	189.15	11.33	200.60
	Cv	22.42	19.87	23.57	19.710
Ken Basin	R	21.70	977.10	51.10	1049.9
	s	5.32	168.54	9.98	181.15
	Cv	24.55	17.25	19.53	17.25
Total	R	19.20	961.30	49.20	1,029.67
	s	4.86	180.31	10.84	192.23
	Cv	25.24	18.76	22.03	18.66

Source : Table 2, op cit.

Monthly Variations. As the topography of the region exerts its influence on the seasonal behaviour of rainfall, therefore the monthly march of precipitation may be expected to have different patterns at different locations in the study area. Pre-dominance of southwest monsoon results in primary peak in the month of July or August. A secondary lower peak can be observed in the winter season from the retreating northeast monsoon in January or February. Minimum contribution to annual rainfall comes in April before the onset of monsoon and a secondary minima occurs in November or December after the retreat of monsoon. These monthly variations in the time of occurrence of minima and maxima have been grouped into two different types which are further divided into two sub-types based on their combinations as presented in Table 8.

Table 8
Distribution of Monthly Maxima and Minima

Type	Maxima / Minima	I_a April Dec.	I_b April Nov.	II_a May Dec.	II_b May, Dec.	Total rain-guage
I	Ia July, Jan	30	-	2	2	34
	Ia July, Feb	3	-	1	-	4
II	IIa Aug, Jan.	4	1	-	-	5
	IIb Aug, Feb.	1	1	1	-	3
		38	2	4	2	46

Source : Table 2, op cit.

It becomes clear from Table 8 that the most important grouping is that of type Ia having a primary maxima in July and a smaller secondary one in January with two minim in April and December. The spatial distribution of these types reveals that areas receiving low annual rainfall in the northern Bundelkhand plains observe their primary peak in August because southwest monsoon reaches later here. The minima also gets delayed by about one month i.e. May in plains. It may be explained that in the pre-monsoon season, duststorms accompanied by occasional hailstorm and thunderstorm may bring some amount of rain produced by convective activity in these temperature zones. Elsewhere, local relief and wind pattern cause only slight variations in the monthly pattern of rainfall.

Thus, a climatologist or hydrometeorologist has to consider the distribution of precipitation within the year besides its spatial variations. For any prediction about seasonal character of rainfall, it is essential to describe its characteristics objectively.

HARMONIC ANALYSIS

Firstly, an average precipitation curve is drawn by giving weightage to monthly means so that they are equivalent to periods of 30.43 days, i.e. one twelfth of an average year with 365.25 days. These monthly values are, then, multiplied by the sine and cosine terms with frequencies varying from one to six (Table 9).

It can be observed from the above table that even Fourier coefficients follow a cyclic trend and the net effect of these can be seen by comparing amplitudes of each harmonic as defined previously. Convergence of the resulting series can also be seen by comparing ratios of amplitudes of successive harmonic terms to the amplitude of first terms (Table 10 and Fig.9).

Table 9

Computations of Fourier Coefficients of Six Harmonic (P1, q1 ..., p6, q6) of Periodic Series of Mean

Month	t	m1	p1	q1	p2	q2	p3	q3	p4	q4	p5	q6	p6
Jan	0	16.22	16.22	0	16.22	0	16.22	0	16.22	0	16.22	0	16.22
Feb	1	1.16	9.67	5.58	5.58	9.67	0	11.16	-5.58	9.67	-9.67	5.58	-11.16
March	2	7.76	- 3.88	6.72	-3.88	6.72	-7.76	0	-3.88	-6.72	3.88	-6.72	7.76
April	3	4.12	0	4.12	-4.12	0-	0	-4.12	4.12	0	0	4.12	-4.12
May	4	7.72	-3.86	6.69	-3.86	-6.69	7.72	-	-3.86	6.69	-3.86	6.69	7.72
June	5	98.69	-85.47	49.35	49.35	-85.47	0	98.69	-49.35	-85.47	85.47	49.35	-98.69
July	6	354.44	-354.44	0	354.44	0	-354.44	0	354.44	0	354.44	0	34.44
Aug.	7	327.62	-28.72	-163.81	163.81	283.72	0	-327.62	-163.81	283.72	283.72	-163.81	-327.62
Sept.	8	168.65	-84.33	0-146.05	-84.33	146.05	168.65	0	-84.33	-146.05	-84.33	146.05	168.65
Oct.	9	26.96	0	-26.96	-26.96	0	0	26.96	26.96	0	0	-26.96	-2696
Nov.	10	14.09	7.05	-12.20	-7.05	-12.20	0-14.09	0	-7.05	12.20	7.05	12.20	14.09
Dec.	11	7.50	6.50	-3.75	3.75	-6.50	0	-7.5	-3.75	-6.50	-6.50	-3.75	-7.50
		1044.93	-8768.51	-280.32	462.96	335.31	-183.7	-202.43	80.15	67.54	-62.46	9.37	92.83

Source: Table 2, *op cit*

Fig. 8 : Phase Angle and Amplitude of Different Harmonic Terms

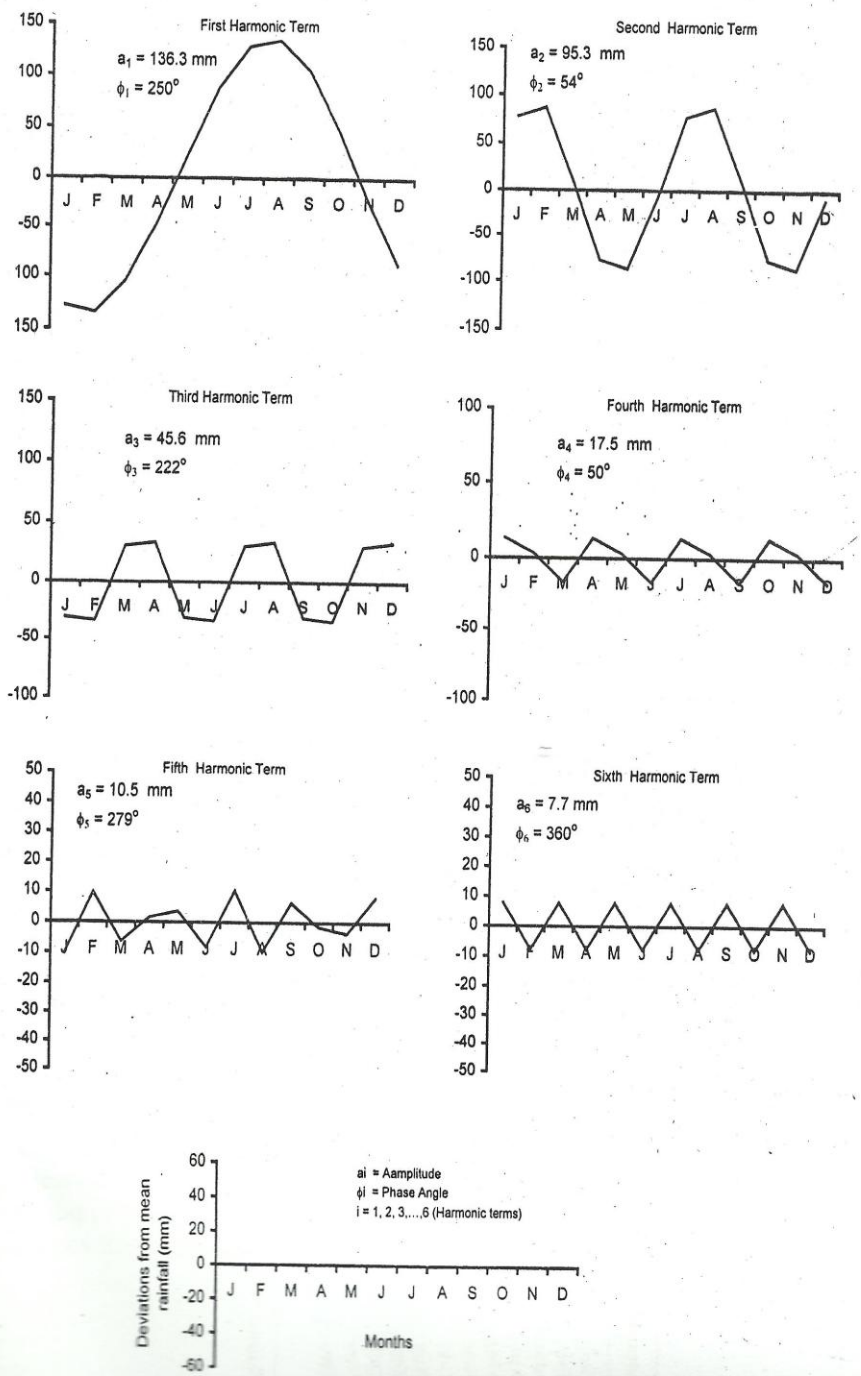


Table 10

Amplitude, Phase Angle and Explained Variance of Different Harmonics of Mean

Harmonic	Fourier coefficients		Amplitude	Phase angle	Variation	Cumulative variation	Ratio
	p_k (mm)	q_k (mm)	q_k (°)	ϕk (%)	CV_k (%)		(a_{k-1}/a_k)
1.	-128.084	-46.720	136.339	249.96°	56.28	56.28	1.00
2.	77.159	55.844	95.271	54.085°	27.48	83.76	0.70
3	-30.617	-33.738	45.559	222.223°	6.28	90.04	0.33
4.	13.358	11.257	17.468	49.878°	0.924	90.96	0.13]
5.	-10.409	1.562	10.526	278.534°	0.335	91.30	0.08
6.	7.736		7.736	360°			0.06

Source: Computed from Table 9, *op cit.*

Both, the amplitude ratio as well as cumulative percentage contribution of successive higher harmonic terms show that for practical purposes, the series in the present problem can be cut off after the third term. The fact that six harmonics exist does not mean that the observed precipitation curve has more than two or three maxim but only that the curve cannot be completely described by the first two harmonics alone. Therefore, the complete description of observed precipitation curve requires the solution of complex equation thus obtained from the above analysis:

$$Y = 87.1 + 136.3 \sin(30° \tau + 250°) + 95.3 \sin(60°\tau + 54°)$$
$$+ 45.6 \sin(90°\tau + 222°) + 17.5 \sin(12° \tau + 50°)$$
$$+ 10.5 \sin(150°\tau + 279°) + 7.7 \sin(180°\tau + 360°)$$

$$\text{or } Y = 87.1 - 128.084 \cos 30°\tau - 46.720 \sin 30°\tau + 77.159 \cos 60°\tau + 55.884 \sin$$
$$- 30.617 \cos 90°\tau - 33.738 \sin 90°\tau + 13.358 \cos 120°\tau - 11.257 \sin 120°\tau$$
$$- 10.409 \cos 150°\tau + 1.562 \sin 150°\tau + 7.736 \cos 180°\tau$$

... Eq. (10)

Solution of equation (10), again, requires the use of same trigonometric functions (sin kx and cos kx) for synthesis as for analysis. Thus, 12 equidistant values of each periodic term are calculated by multiplying the Fourier constants pk and qk with these functions. By adding together in each line the products thus obtained, the periodic term is evaluated directly for each harmonic. When annual mean (ao = 87.1 mm) is added to the total sum of all six harmonics, the observed precipitation curve was reproduced to a high degree of accuracy (Table. 11).

Table 11
Comparison of Estimated and Observed Mean Monthly Rainfall

Months	τ	Estimated rainfall (mm) m_τ	Observed average rainfall m_t (mm)
Jan	0	16.243	16.22
Feb	1	11.190	11.16
March	2	7.965	7.76
April	3	4.143	4.12
May	4	7.563	7.72
Jun	5	98.706	98.69
Jul	6	354.463	354.44
Aug	7	327.638	327.62
Sept.	8	168.491	168.65
Oct.	9	26.983	26.96
Nov.	10	14.289	14.09
Dec.	11	7.586	7.50
Total		1044.822	1044.93

Source: Table 9, ~~Appendix and Table 3.14 op cit~~.

The greatest deviation noted between the observed curve and the reconstructed monthly means was found to be 0.2 mm and this small deviation is probably due to rounding off errors.

To show the periodicity of phenomenon, the time of maximum for the first harmonic as given by the equation (8) works out to be as follows:

$$30^\circ t_m + 250^\circ = 450^\circ$$

$$\Rightarrow t_m = (450^\circ - 250^0) / 30^\circ = 20^0/30^\circ$$

$$= 6.67^\circ$$

$$= 6 \text{ months} + (0.67 \times 30.44) \text{ days}$$

$$t_m = 6 \text{ months and } 21 \text{ days } (6^M 21^d)$$

This means the time of first maxima occurs 6 months and 21 days later than the time of maxima represented by 0 vector on the harmonic dial. The date is, then, obtained by adding 16 days to the time of maxima because the monthly mean of the elements refers to the midpoint of the month. Therefore, the maximum point in the first annual harmonic series occurs on 7th August as pointed out by vector (Fig. 10).

Similarly, the time of first maxima of the second harmonic series/term is calculated by taking 90° on right hand side of the equation (8) because $\phi 2$ is less than 90°, i.e.

$$2(30^\circ t_m) + 54^\circ = 90^\circ$$

$$\Rightarrow tm = (90^\circ - 54^\circ)/60^\circ = 0.6 \text{ month}$$

$$= (18 + 16) \text{ days} = 1^M 3^d$$

Thus, first maxima in the semi-annual series occurs on 3rd February and second maxima occurs after 6 months later, on 3rd August. Due to this symmetry of half-yearly wave, the time of first maxima only is represented on harmonic dial (Fig. 11).

It is interesting to note here that the time of second maxima in the second harmonic term precedes the time of maxima in the first term. It may be due to the fact that during southwest monsoon season rain does not occur continuously, rather than in breaks of different intensity and magnitude. Thus, during monsoon season amplitude of second harmonic being lower than the first one may result either in a slightly lower peak before the actual one or in a higher peak due to superimposition of the two waves.

SPATIAL VARIATION IN PERIODICITY

To show spatial variation in the time of maximum rainfall occurrence, amplitudes and phase angles are computed for all the 45 rain-gauging stations individually. For this purpose, calculations are done up to three harmonic terms only because they explain more than 90% of the total variation. Moreover, the relative importance of amplitude as reflected in its ratio also declines to less than 1/3rd of the amplitude of first term. The spatial range of variation till the three harmonic terms is presented in Table 12.

Table 12

Minimum and Maximum Values of the Various Parameters of Harmonic Analysis

Harmonics	Amplitudes a_k (mm)	Phase Angles ϕk (°)	Time of Maxima t_m (months)	Date of t_{mm}
First	199.4-101.7	253°-247°	6.6-6.8	2nd Aug. 8th Aug.
Second	135.6-71.5	60°-46°	0.5-0.7	30th Jan 7th Feb
			6.5-6.7	30th July 7th Aug
Third	64.6-32.1	233°-207°	2.4-2.7	27th Mar 6th April
				27th July 6th Aug
				27th Nov 6 Dec.

Source: Computed from Table 7, Appendix

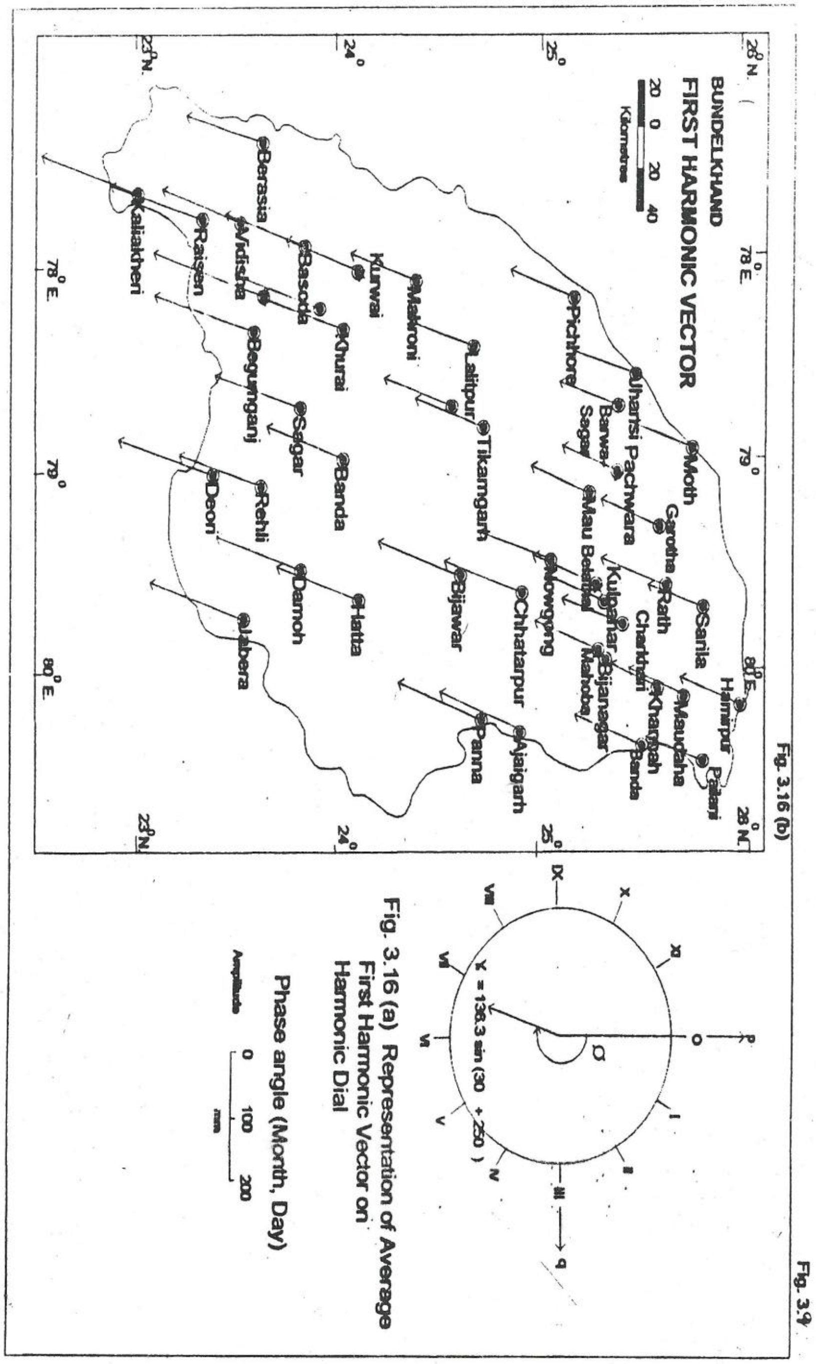


Fig. 3.16 (a) Representation of Average First Harmonic Vector on Harmonic Dial

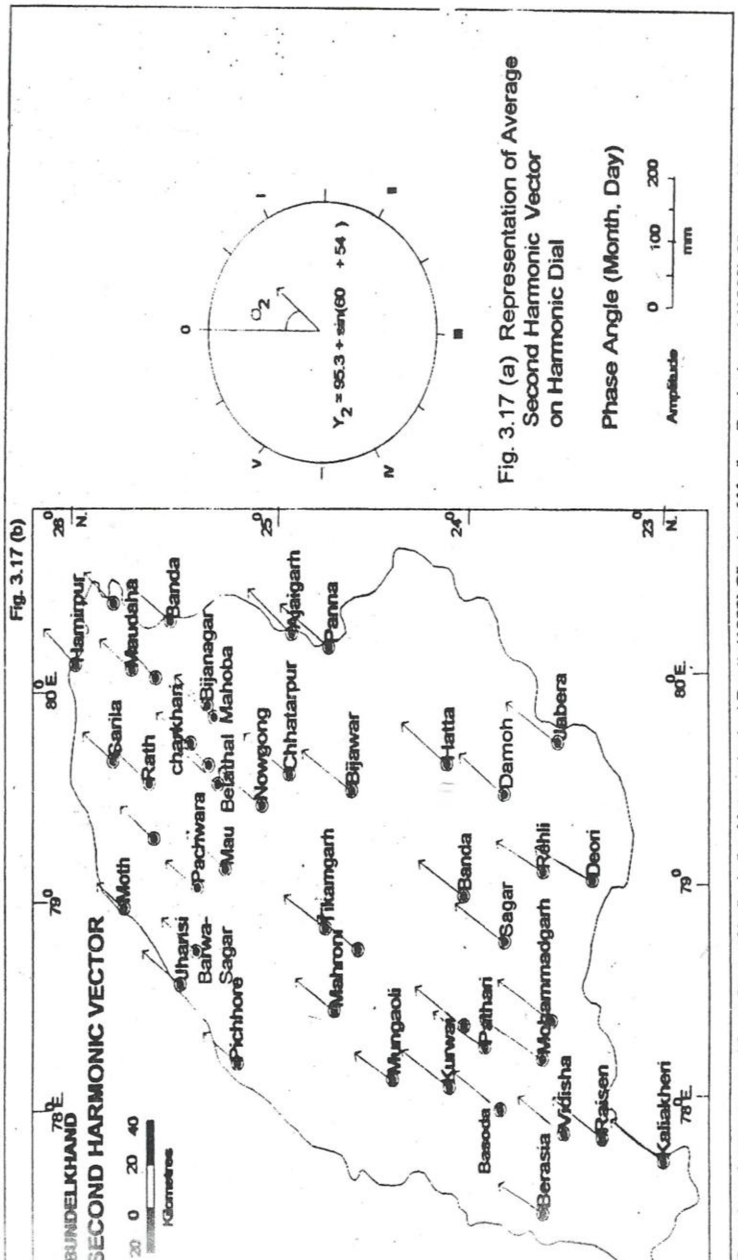


Fig. 3.17 (a) Representation of Average Second Harmonic Vector on Harmonic Dial

Source: Based on data computed from Govt. of India, Indian Meteorological Deptt. (1983) Climate of Madhya Pradesh and (1989) Climate of Uttar Pradesh.

It is clear from the above table and Fig. 10 and 11 that spatial range of variation of the time of maximum rainfall occurrence is less for both the harmonic terms. The sine curve of the first harmonic has one maxima and one minima, which describe the tendency towards an annual variation in the observed precipitation curve. As the phase angle of first harmonic varies from 247° to 253° only, it shows that normal sine curve with its maxima at 90° has been shifted at these points to the left so that the annual maxima occurs in early August (from 2nd - 8th). However, amplitude of first harmonic shows greater spatial variation as reflected by increasing length of vectors towards the plateau region. It varies from 101.7 mm in the semi-arid northwestern Bundelkhand plains to 199.4 mm towards southeastern boundary.

The second harmonic, which consists of sine curve with two maxim and two minim, describes the semi-annual tendency of the observed curve. If the observed curve had two maxim of rainfall being six months apart, the second harmonic would have fitted the curve well. But, in the present case, the amplitude of second observed maxim being much smaller than the first one, the second harmonic term explains only 24% of the total variation on an average. The phase angle, which varies from 46o to 60o, indicates that there exists a very weak semi-annual tendency in the normal rainfall pattern. The bi-annual maxim occurs in January and February (30th January - 7th February) and in the diametrically opposite months of July and August (30th July - 7th August). The fact that a second harmonic exists does not mean that the observed curve has two maxim, but the curve cannot be completely described by the first harmonic alone. Similarly, the third harmonic, which consists of sine curve with three maxim and three minim, shows three-fold variation as shown in the last row of the table.

CONCLUSION

An assessment of the existing rain-gauging stations shows that only 45 stations, out of total 75, had comparable rainfall data record exceeding 30-year period. According to WMO standards, there should be, at least, 127 rain-gauging stations having an uniform density of 575 km2. But, if variability of rainfall is considered, 160 rain-gauging stations are found to be optimum at 5% level of error in coefficient of variation. Here, areal measurement of rainfall, employing Theissen polygons and isohyets, results in mean basin rainfall of 1078.91 mm and 1069.78 mm, respectively. The spatial distribution of 114 additional rain-gauging stations placed in various isohyetal zones on the basis of area enclosed revealed that maximum rain-gauging stations are required in the central Bundelkhand region.

Temporal variations in monsoon rainfall analysed at Bijawar (located near the mean centre of the region) a zig-zag pattern, which, however, follows a normal trend. The 95% confidence limit of normal rainfall having a return period of 100 year lies between 2074.8 mm to 1937.2 mm. The probability analysis, thus, can be applied to the data of other stations from which storage capacity of future reservoirs can be estimated optimally.

Seasonal variation in mean monthly rainfall represented by isohyetal maps follows variation in relief and wind system. But, the spatial distribution of rainfall in each season is characterised by lower value of coefficient of variation. The entire precipitation curve was found to be in close approximation with the expected curve obtained by adding six harmonic terms. First, two harmonic terms come out to be more significant as they together explain more than 80% of total mean variation. The spatial distribution of these two terms shows little variation in their amplitudes and phase angles. The optimum time of annual maxima, represented on harmonic dial, ranges from 2nd to 8th August. The semi - annual variation included in second term results in the first maxima from 30th January to 7th February and second maxima 6 months later from 30th July to 7th August.

Thus, the optimality of data network can be analysed with respect to other parameters recorded at climatological and hydrological stations. It can objectively enhance the planning efforts directed towards precision estimates.

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