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# Precipitation Network Design

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**Abstract** : *Rainfall network design for hydrological purposes has been the subject of study and investigations for a long period of time. In this paper different methods applicable to raingauge network design have been discussed and demonstrated by suitable examples for the use of each suggested method. It is hoped that this article on rainfall network design will prove to be useful to all those who are in the process of establishing a minimum raingauge network or improving the design and management of existing networks in different river catchments of this country.*

## Introduction

Precipitation is the term employed for all forms of atmospheric moisture deposited on the ground. It includes drizzle, rain, snow and hail. Precipitation in the tropics consists almost entirely in the form of rain and is vitally linked up almost in all fields of national economy. Rainfall data are used for assessment and management of water resources, design of hydraulic structures, agricultural planning, hydel power generation, flood control works and evaluation of weather modification experiments. An important use of rainfall is also as an input to various hydrologic models so as to compute the probability and the characteristics of floods in different time and space scales.

Whatever the use made of the rainfall data, a very important consideration is the design of rainfall measurement networks which provide basic data for the solution of a diversity of problems. The purpose of network is to achieve an adequate description of the spatial and temporal variation of rainfall. However, the density of raingauge stations required within a specific area and the periods for which these stations need be operated are governed by a number of factors including : the size of area and length of time interval over which rainfall must be measured, the purposes for which the data are intended to serve and the accuracy with which areal or temporal distribution of rainfall must be known to adequately satisfy each such purpose. For example, dense gauge networks are needed in the estimation of water resources with high degree of accuracy. For flood forecasting where economic considerations impose constraints in having a large number of raingauge stations then there is a need for designing a small network of stations which can provide reliable estimate of the true value of the areal average rainfall. Special purpose networks are established for specific projects, such as watershed management research or the evaluation of weather modification experiments.

The problem of network design has been dealt with in a number of scientific papers and reports produced by various organisations and agencies. Perhaps, the best known earliest studies concerned with network design were those of Horton (1923) and Drozdov (1936).

Horton studied the relation of the error in the determination of mean annual rainfall in terms of the number of gauges and showed that errors are proportional to the range and inversely proportional to the square root of the number of gauges.

Later, investigations on the network design of raingauges for hydrological purposes have been carried out by several investigators and these have guided the design of proper network in a river catchment. The WMO/IASH symposium on design of hydrological network held in Quebec in June, 1965 discussed many methods of network design and planning of precipitation gauges related to different types of catchments. Rodda (1969) summarised much of the work on network design. The WMO Guide to Hydrological practices (WMO, 1974) provides raingauge density criteria based on broad definition of the hydrological, climatological and topographical regions which are to be gauged to define an acceptable minimum network. The WMO case book on Hydrological Network Design Practice (1972) gives accounts of a number of examples of networks established by countries together with explanatory notes on the objectives and principles applied. The purpose of this paper is to review problems and methods of rain gauge network design so as to provide guidelines in improving the design and establishment of raingauge network in different river basins of the country.

## 2. Network concept and problems of rain gauge network planning

According to Langbein (1965) and Kozvel (1969), a network is defined as an organised set of stations at which observations of a specific kind are made to satisfy the demands of its principal users for scientific and practical purposes with each point of observation fulfilling one or more definite requirements in either space or time. It should basically be so planned to avoid serious deficiencies of data that hamper economic resources development. The WMO Guide to Hydrological practices (WMO, 1974) describes that the aim of a network is to provide a density and distribution of stations in a region such that, by interpolation between data sets at different stations, it will be possible to determine with sufficient accuracy for practical purposes the characteristics of the elements at any point in the region.

As regards rainfall is concerned, it is renowned for its high variability both in space and time and as such the density and distribution of rainfall stations within a network and the period for which individual gauges should be maintained depend upon the space and time variability of rainfall. In general, the spatial variability of rainfall is greater in arid and mountainous regions and over small areas, then in humid and flat regions and over large areas. This indicates that denser networks are required to obtain desired degree of accuracy in estimating areal rainfall depth for the former group of conditions. However, there is no theory which can determine the density of raingauges required in a particular region in order to measure the spatial variability of rainfall. The required station density depends on the areal variability of rainfall which, in turn can be determined only after adequate sampling has been carried out in the region of interest. Also. a network implies interpolation of data, it is essential that the type of raingauge and the method of installation and observational practices have to be necessarily identical throughout the network.

In view of the above, there are four basic scientific problems involved in the rainfall network design.

(a) the equipment used for the measurement of rainfall.

(b) the number of rainfall stations required,

(c) the location of raingauges sites and

(d) the period for which data are to be collected.

## 3. Measurement of rainfall

Rainfall and other forms of precipitation are measured in terms of depth, the values being expressed in inches or millimeters. Rain-gauges provide the simplest and most common means of measuring rainfall. Raingauges are either automatically recording or non recording. In the water resources planning, the most important measurements of rainfall are the daily measurements with non-recording gauges. The standard pattern of raingauge in use has been the Symon's pattern raingauge with a 127 mm (5 in.) diameter funnel.

The World Meteorological Organisation (WMO) stressed the desirability of having a common type of raingauge adopted to metric system of measurement. As such India Meteorological Department (IMD) has designed and fabricated a new non-recording raingauge. The specifications for the new raingauge have been brought out as an Indian Standard IS 5525-1969 in collaboration with the Indian standards institutions, New Delhi. The new non-recording raingauge is made of fibre glass reinforced polyester and provided with a deep funnel. It has two collectors with areas of 200 $cm^2$ and 100 $cm^2$ and receivers of 2,4 and 10 litre capacities. The system with 2 collectors and 3 receivers can be assembled to give 5 raingauges with capacities of 100, 200, 400, 500 and 1000 mm of rainfall.

Recording raingauges are those raingauges in which the total amount of rainfall gets recorded automatically. They range from the simple daily drum chart types to the more sophisticated digital instruments that record the information on magnetic tape. They usually work by weighing the catch or by the use of tipping buckets or empty by siphoning as in float gauges. The gauges provide a record of cumulative rain with time in the shape of a mass curve of rainfall which help in determining the duration and intensity of rainfall. Intensity duration data is primarily of value in the study of floods, urban drainage and erosion problems. Automatic telemetering raingauges that transmit rainfall information to distant collecting centres at specified intervals are also used at present. These networks are primarily designed to supplement the rainfall and river data in a flood forecasting and reservoir management scheme by providing information inputs from critical remote unmanned locations.

## 4. The number of rainfall stations required

Many hydrological studies require the estimation of the mean rainfall depth for variety of durations over areas which are either fixed (e.g. a river basin) or variable in space. Depending on the problem, networks of non-recording raingauges are required to ensure that an adequate distribution of the spatial variation of rainfall is achieved. For a basin where raingauges have not been installed, there is no simple method of determining as to how many raingauges are needed. In these circumstances the WMO Guide to Hydrological practices (WMO, 1974) have recommended certain minimum densities of raingauge based on broad definitions of the hydrological, climatic, and topographical factors of a region. The minimum raingauge density as recommended by the World Meteorological Organisation are given in Table 1 for use of such basins where raingauges are to be installed.

Table 1 : Minimum density of raingauge stations

| Region | Minimum density range $km^2$/gauge |
|---|---|
| Temperate, Mediterranean and Tropical zones | |
| 1. Flat areas | 600-900 |
| 2. Mountainous areas | 100-250 |
| 3. Small mountainous islands | 25 |
| 4. Arid and Polar zones | 1500-10,000 |

Another approach is to saturate the area with gauges and at a later stage to remove those which are not needed to estimate the mean rainfall to the desired accuracy. In the San Dimas basin in California for example, the original network consisted of 318 gauges, but was reduced to 72 gauges (Hamilton, 1954). Once observations from a network have been collected, there are a number of scientific methods of estimating its adequacy. In the following sections, four methods of areal rainfall analysis applicable to raingauge network density are presented. The methods are also demonstrated by suitable examples.

### 4.1 Coefficient of spatial variation of rainfall and its application to raingauge network

Several investigators have used the rainfall records to derive a statistic for instance, the coefficient of spatial variation or spatial variance, and have related this statistic to the number of gauges required to provide an estimate of the mean rainfall to a certain accuracy.

Rycroft (1949) used the variance in space to determine the optimum number of raingauge in the Jonkershoek catchment. The equation devoloped by Rycroft for obtaining N, the optimum number of raingauges is

$$N = \left[\frac{2V}{X}\right]^2 \qquad (1)$$

where V is value of variance in space of the rainfall on the basis of the existing number of gauges and X is the desired variance.

Ganguli et. al (1951) used coefficient of variation in space of the monthly rainfall to determine N, the optimum number of raingauges. The formula used by them is

$$N = \left[\frac{CV_m}{\alpha}\right]^2 \times n \qquad (2)$$

where $CV_m$ is the coefficient of space variation of mean monthly rainfall on the basis of the existing network and $\alpha$ is the tolerable value of the coefficient of variation and n is the number of existing stations.

Ahuja (1960) developed a technique of obtaining N, the optimum number of raingauge stations based on the coefficent of variation in space of rainfall to estimate the mean areal rainfall within a desired accuracy. The formula proposed is

$$N = \left[\frac{CV}{E}\right]^2 \qquad (3)$$

where CV is the coefficient of space variation of rainfall values of existing raingauges and E is allowable percentage error in the estimate of catchment rainfall. Ahuja method also provides means of allocating the raingauges systematically within the catchment.

Panchang and Narayanan (1962) and Stephenson (1967) showed that for monthly totals recorded in a network of n gauges, which were uniformly distributed, the coefficient of variation of the mean ($CV_m$) for each month could be employed in determining the adequacy of the network. Stephenson calculated the values of $CV_m$ by expressing the monthly rainfall amounts as a percentage of average annual rainfall. This calculation is performed for enough months (Stephenson employed 120) to enable the construction of a cumulative frequency curve of $CV_m$, from which the value of $CV_m$ ($C^1$) exceeded on 5 percent of occasion was determined. If $C^1$ is 10 or less, then the number of raingauges existing in the network is considered to be adequate. When $C^1$ is more than 10 then the number of gauges required can be calculated from the equation

$$N = \left[\frac{C^1}{10}\right]^2 \times n \qquad (4)$$

This method and the same criteria for $C^1$ was employed to assess network adequacy for 9 areas of varying size in Great Britain, using 10 years of records. The results for one of the areas are shown in Fig. 1, two frequency curves being constructed, one for the month of convective rainfall and the other for orographic months.

Ismail (1981) developed a technique based on the stability of the distribution of coefficient of space variation to obtain adequacy of raingauge network for estimation of areal rainfall within a desired accuracy. The technique was developed by considering monthly, seasonal and yearly rainfall data of 64 raingauge stations in Vidarbha sub-division of Maharashtra state for a period of 60 years. The relationship between the size of area and the adequate number of raingauges required for the estimation of areal rainfall obtained by Ismail for Vidarbha area is shown in Fig. 2 It is seen that 14,20 and 37 raingauges are adequate for areas of sizes 12000 km$^2$, 24000 km$^2$ and for 98000 km$^2$ respectively.

### 4.1.1 Application of coefficient of space variation

The estimation of optimum number of raingauges within a catchment and their allocation presented here is based on the method used by Ahuja (1960). The method is applied to a typical catchment to annual rainfall. Let the catchment has four raingauges within the catchment whose average annual rainfall is 63, 43, 35 and 32 cm (see Fig. 3). In order to obtain optimum number of raingauges, the mean annual rainfall value together with the variance and coefficient of variation have been calculated first from 4 annual values. The following results are obtained :

(i) the mean annual rainfall over the catchment = 43.3 cm

(ii) the spatial variance ($\sigma^2$) = 195 cm$^2$

(iii) the coefficient of spatial variation (CV) = 32.3%

The optimum number (N) of raingauges to estimate mean rainfall depth with a percentage error less than or equal to 10% is calculated as :

$$N = \left[\frac{CV}{E}\right]^2 = \left[\frac{32.3}{10}\right]^2 \backsimeq 11 \qquad (5)$$

The optimum number of raingauges in the catchment should be atleast 11 and as such 7 more raingauges within the catchment are required.

For allocating the additional raingauges in the catchment, isohyetal zones as shown in Fig. 3 taking into consideration the rainfall of the stations outside the catchment are first drawn. Then the areas bounded by different consecutive isohyetal zones within the catchment are measured by a planimeter. The proportionate areas of the different isohyetal zones $X_1$, $X_2$, $X_3$, $X_4$ and $X_5$ as shown in the figure are found to be 0.12, 0.38, 0.34, 0.10 and 0.06 respectively. The 11 raingauges are then allocated to the different zones in proportionate of their areas. The optimum number of raingauges in different isohyetal zones of $X_1$, $X_2$, $X_3$, $X_4$ and $X_5$ have been found to be 1, 4, 4, 1 and 1 respectively. The allocation of the additional raingauges has been made randomly and the new sites are indicated by dark circles in the figure.

### 4.2 Structure function of rainfall field and its application to network design

The relationship between the error of linear interpolation and distance between stations has been used by several workers to determine the adequacy of the raingauge networks and also to locate the sites for new gauges for improving the existing network.

The first quantitative attempt was made by Drozdov in 1936. Taking three stations in a straight line and the central stations being equidistant from the two others, Drozdov determined by analysing a mass of observational data from these stations, the relationship between the standard error of linear interpola-

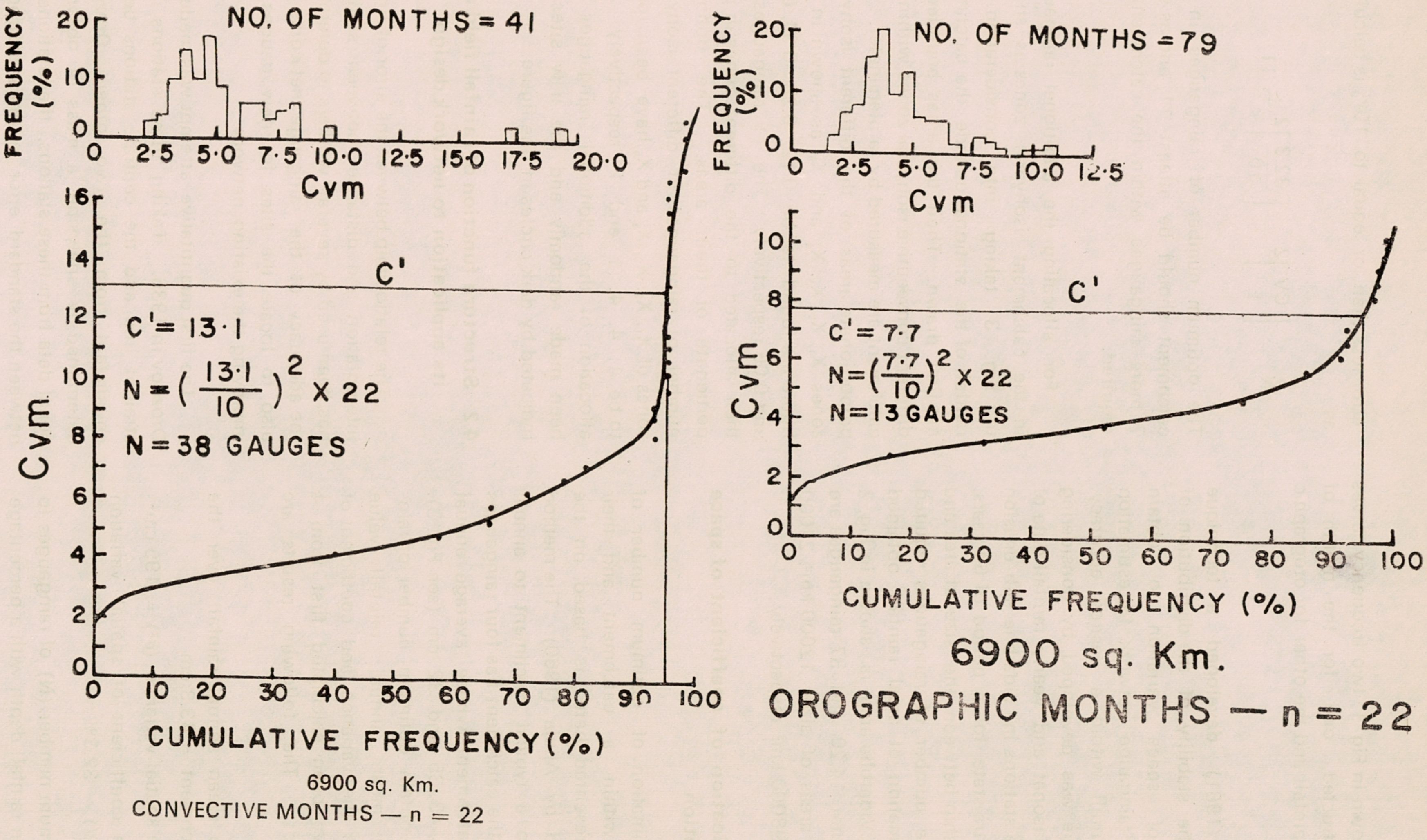
NO. OF MONTHS = 41
FREQUENCY (%)
Cvm
Cvm
C'
C' = 13·1
N = ( 13·1 / 10 )^2 X 22
N = 38 GAUGES
CUMULATIVE FREQUENCY (%)
6900 sq. Km.
CONVECTIVE MONTHS — n = 22
NO. OF MONTHS = 79
FREQUENCY (%)
Cvm
Cvm
C'
C' = 7·7
N = ( 7·7 / 10 )^2 X 22
N = 13 GAUGES
CUMULATIVE FREQUENCY (%)
6900 sq. Km.
OROGRAPHIC MONTHS — n = 22

Fig. 1

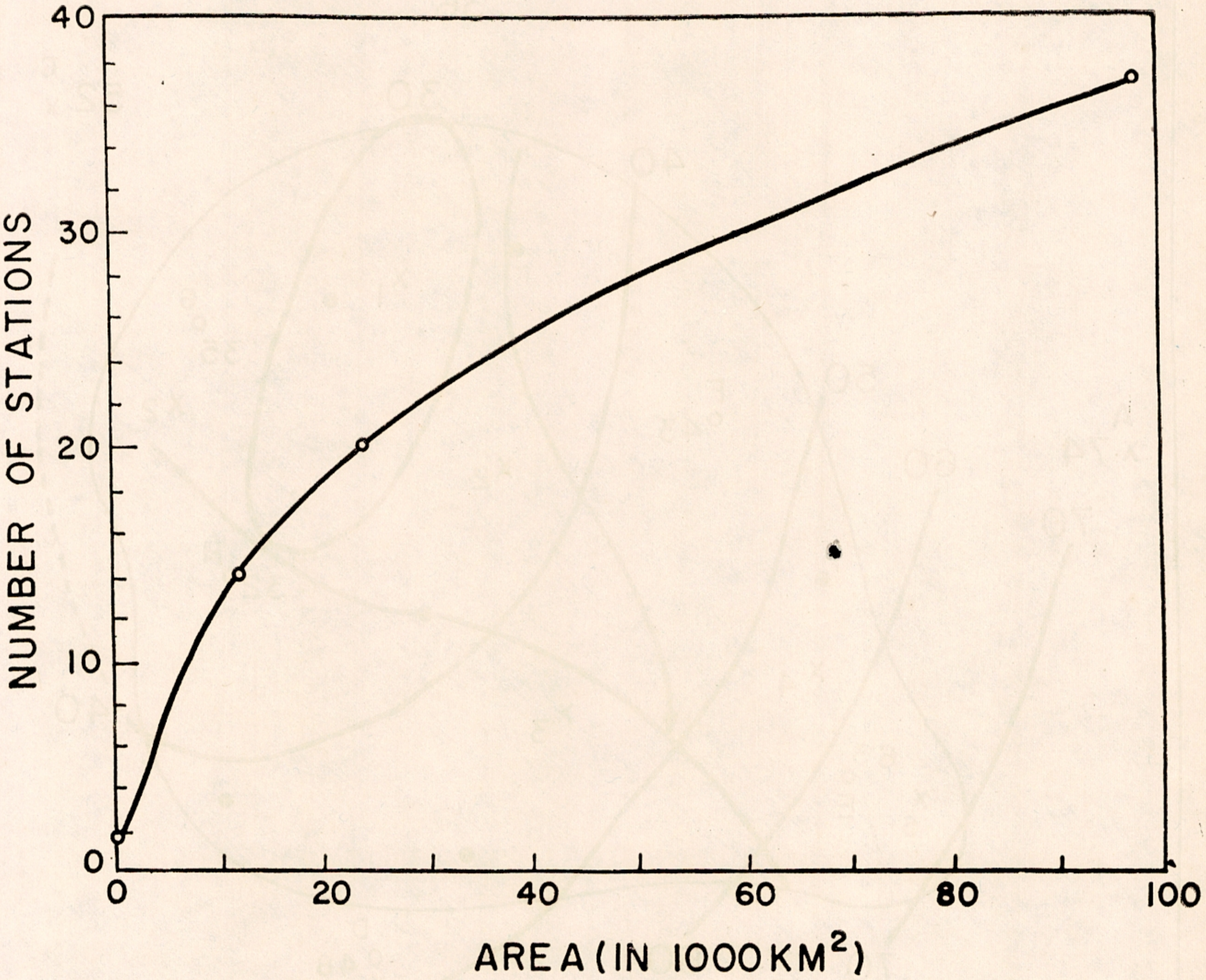


Fig. 2—Relationship Between the Area and the Number of Raingauges Required for Stabilisation of CVS Distribution

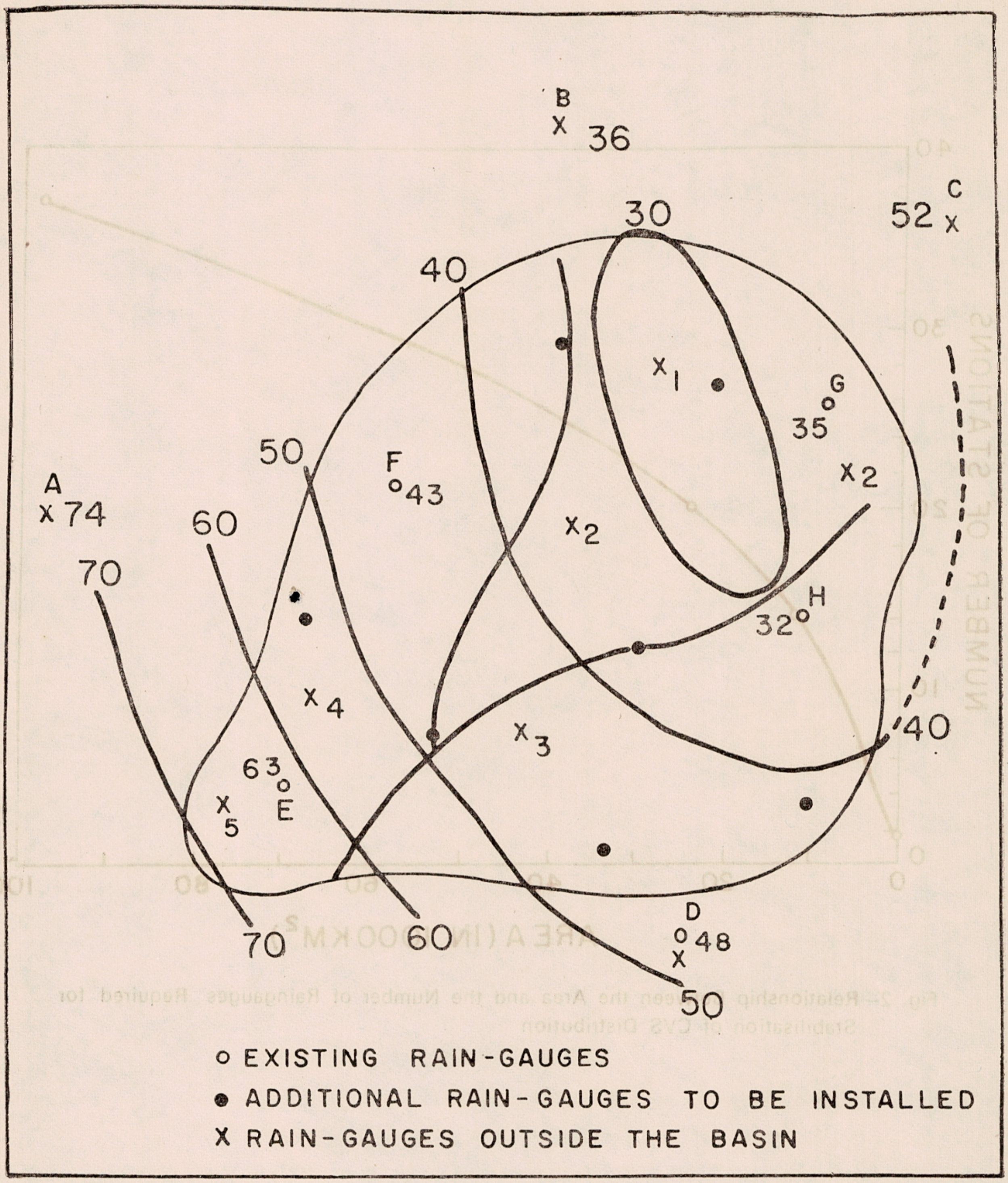


Fig. 3—Distribution of Rain-Gauges in a Typical River Basin

tion and the distance between the extreme stations. Later Drozdov and Sepelevskii (1946) showed that the error in question was uniquely related with a structure function (b), the mean square of the difference in values between two points of the meteorological elements being considered. The structure function has been widely used in USSR as a basis for network design (Gandin, 1970) and in Hungary (Czelnai, 1972). Before describing the method of network estimation, the structure function and how they are calculated is discussed.

### 4.2.1 Structure function of rainfall field

Let $R_j$ be the rainfall value for any given time interval at a station j in space and its deviations from the time mean $\overline{R_j}$ be $R'_j$. The average product of the deviations at two stations j and k is the covariance function ($C_{jk}$) and the mean square of $R'_j$ is called the variance ($C^2_j$). These are expressed as

$$C_{jk} = \overline{R_j' R_k'}, \; C_j^2 = \overline{R_j'^2} \quad (6)$$

The bar denotes the process of averaging.

The structure function of rainfall is the mean square of the difference in the values of R' at two points j and k separated by a distance d from each other. It is expressed as

$$b_{jk} = \overline{(R_j' - R_k')^2} \quad (7)$$

Expanding equation (7) and substituting from equation (6), it is seen that the structure function and the covariance functions are related by the equation.

$$b_{jk} = C_j^2 + C_k^2 - 2\,C_{jk} \quad (8)$$

Under the conditions of homogeneity and isotropy, the structure function is a function of distance and can be written as

$$b_{jk} = b\,(d), \; C_{jk} = c\,(d) \quad (9)$$

The structure function over an area, can be evaluated by calculating the values of $b_{jk}$ for every pair of stations by using equation (7). If n is the number of stations then it would be possible to compute $\frac{1}{2}n(n+1)$ structure function values. The distances between stations are grouped into different ranges of distances. The corresponding structure function values are also grouped accordingly to the classes of distance. A graph plotted with the average value of the distance and of the corresponding structure function gives the relationship between the structure function and the distance.

Kagan (1972) applied the Drozdov-Sepelevskii method of linear interpolation in a line for data at two stations. When the interpolation was made at the mid point of the line joining the two points, then the mean square error (E) of linear interpolation was obtained as

$$E = b\,(d/2) - \tfrac{1}{4}\,b\,(d) - \tfrac{1}{2}\,b\,(o) \quad (10)$$

where d = distance between the points

b = structure function defined by the formula (7)

If the structure function of the rainfall field in a region is known then the relationship between the error of linear interpolation and distance can be determined. From this relationship given the maximum admissible standard error $\sqrt{E}$, the maximum admissible distance d between stations can be evaluated. This will help to locate the site of new gauges for improving the existing network.

### 4.2.2 Application of structure function

Mooley and Ismail (1982 a) determined the structure functions of monthly (June to September), seasonal and annual rainfall field over Vidarbha, a subdivision of Maharashtra by considering the rainfall data of 64 stations having data for about 60 years. The structure functions were then used for determining the maximum spacing between the raingauge stations to meet a specified interpolation error criteria. In order to have the structure functions homogeneous and isotropic, the divided the region into four quadrants of practically equal area by east-west and north-south lines approximately through the centre. The structure functions for the months of June to September, for season and for the year for each quadrant were evaluated.

Using equation (10), the error of linear interpolation $\sqrt{E}$, at the mid-point of the segment of various lengths for 50 to 200 km were calculated for all 4 quadrants separately for the modthly, seasoeal and annual rainfall. Table 2 gives the error of linear interpolation af mid points of segments separated by distance of 50, 100 and 200 km over Vidarbha (Mooley and Ismail, 1982 a).

Mooley and Ismail (1982 a) found that for a permissible error of 25-30 percent in thc linear interpolation of rainfall for monsaon months. the maximum spacing allowed between gauges should be 50 km and for a permissible error of about 15% in the case of seasonal and annual rainfall the corresponding maximum spacing should be about 100 km.

Table 2 : The range of the error, $\sqrt{E}$ of linear interpolation of point rainfall over Vidarbha

| Period | Mean rainfall (mm) | Error of linear interpolation (%) at the mid-points of the segments 50 km | 100 km | 200 km |
|---|---|---|---|---|
| June | 169 | 27–33 | 30–38 | 35–44 |
| July | 314 | 18–27 | 22–35 | 25–38 |
| August | 249 | 17–35 | 23–38 | 25–44 |
| Sept. | 172 | 22–34 | 28–39 | 33–42 |
| Season | 950 | 11–17 | 13–19 | 14–21 |
| Year | 1037 | 11–15 | 12–17 | 13–18 |

## 4.3 Spatial correlation function and its application to network design

The technique of spatial correlation function has been used by several workers (e.g. Hershfield, 1965; Kagan, 1966; Huff and Shipp, 1969; Hendrick and Comer, 1970; Hutchinson, 1970 and Stol, 1972) in raingauge netwerk design. The spatial correlation function is the relationship between the correlation coefficient of rainfall totals at various stations in a relatively uniform area and the distance between the stations. A general theoretical review of spatial correlation methods for the planning of meteorological networks has been given by Gandin (1970). Some details of specific approach and its application to the Indian region have been described by Mooley and Ismail (1982 b). The determination of the correlation function is described below.

As described in the previous section, the correlation coefficient $r_{jk}$ for each pair of stations j and k can be calculated by the formula

$$r_{jk} = \frac{R_j' R_k'}{C_j C_k} \qquad (11)$$

If the correlation function is assumed to be homogeneous and isotropic then the correlation coefficient is a function of distance between stations and can be written as

$$r_{jk} = r\ (d) \qquad (12)$$

The correlation function r (d) over an area can be evaluated by calculating the values of

$r_{jk}$ for each pair of stations by using equation (11). If there are n stations then it would be possible to calculate $\frac{1}{2}$ n (n + 1) correlations. The correlations $r_{jk}$ are then classified into intervals on the basis of distance between stations. The average distance and average correlation for the stations falling within each interval are then calculated. The correlation function giving the relationship between the correlation coefficient and distance is obtained by plotting average value of distance against average correlation. In most cases, the correlation functions of rainfall fields can be satisfactorily described by an exponential relationship of the form

$$r(d) = r(o)\, e^{-d/d_o} \qquad (13)$$

where d is the distance, $d_o$ is the correlation radius or distance at which the correlation is r(o)/e and r(o) is the correlation corresponding to zero distance. Theoretically r(o) should be equal to one but is rarely found to do so in practice due to random errors in rainfall measurement and microclimatic irregularities for small distances over an area. The variance ($\sigma^2$) of these random errors has been given by Kagan (1966) as

$$\sigma^2 = (1 - r(o))\, \sigma_r^2 \qquad (14)$$

where $\sigma_r^2$ is the variance of rainfall time series at a fixed point.

Using the equations (13) and (14), Kagan (1972) showed that for an area A with n stations, the variance of the error in the average rainfall over A is given by

$$V = \frac{\sigma_r^2}{n}\left[1 - r(o) + \frac{0.23}{d_o}\sqrt{\frac{A}{n}}\right] \qquad (15)$$

The relative root mean square error (E) is then defined as

$$E = \frac{\sqrt{V}}{\overline{R}} = CV\left[\frac{1 - r(o) + \frac{0.23}{d_o}\sqrt{\frac{A}{n}}}{n}\right]^{\frac{1}{2}} \qquad (16)$$

where CV is the coefficient of variation in space, $\overline{R}$ is the average rainfall over an area A and n the number of stations.

The formula (16) can be used to determine the value of n required to meet a specified error criteria (E) if r (o) and $d_o$ are known or conversely given n, E can be evaluated. It has been found that if the stations over the area A are distributed at the intersection points of square grid, the distance (1) between them is $\sqrt{\frac{A}{n}}$ and at a triangular grid the distance is $1.07\sqrt{\frac{A}{n}}$

It may however, be mentioned that in applying such a approach, care must be taken to ensure that conditions necessary for the existence of a spatial correlation function such as homogeneity and isotropy are fulfilled. In mountainous regions these assumptions are unlikely to be fulfilled and as such this method is appropriate for flat areas with a relatively homogeneous underlying surface.

### 4.3.1 Application of correlation function.

Let us assume that we have to organise a raingauge network in a catchment area of 7200 km². The catchment has 4 raingauge stations and the statistical characteristics of 24 hours rainfall are as follows

$CV = 1.7$, $r(o) = 0.966$, $d_o = 186$ km

Using equation (16) we have

$$E = 1.7\left[\frac{1 - 0.966 + \frac{0.23}{182}\sqrt{\frac{7200}{n}}}{n}\right]^{\frac{1}{2}}$$

$$E = 1.7\left[\frac{0.034 + \frac{0.107}{\sqrt{n}}}{n}\right]^{\frac{1}{2}} \sim 18$$

Assuming permissible error of 10 percent, we have an estimate of n = 18. Thus the network density should be 400 km²/station. If the stations are located in a triangular network then distance between them is 21.4 km.

### 4.4 Network density based on optimum interpolation method.

Gandin (1970) applied the method of optimum interpolation to find the weights to be assigned for the raingauges to estimate the areal rainfall and suggested that the error involved in the estimation can be used to determine the adequacy of the raingauge network. Gandin (1970) showed that if the optimum interpolation is worked out at the mid point of a segment joining two points separated by a distance d, then the relative square error in interpolation is given by the following formula.

$$E_{opt} = 1 - \frac{2\, r^2\, (d/2)}{1 + r\,(d) + \eta} \qquad (17)$$

where r (d/2) and r (d) are the correlations between rain fall at distances d/2 and d, respectively. The quantity $\eta$ is estimated as 1-r (o). The formula for the relative error of optimum interpolation at the centre of an equilateral triangle is

$$E_{opt} = 1 - \frac{3r^2(d/\sqrt{3})}{1 + 2r(d) + \eta} \qquad (18)$$

and at the centre of a square is

$$E_{opt} = 1 - \frac{4\, r^2\, (d/\sqrt{2})}{1 + 2r\,(d) + r(\sqrt{2}.d) + \eta} \qquad (19)$$

The above equations can be used to determine the maximum admissible spacing between raingauges for a tolerable error in interpolation over an area.

Mooley and Ismail (1982 b) employed Gandin's techniques to determine the spacing between raingauges for Vidarbha region of Maharashtra. They first determined correlation-distance relationship for Vidarbha region by using monthly, seasonal and annual rainfal data of 64 stations. The correlation function for the month of July and year as a whole are shown in Fig. 4. Utilising the relationship between correlation function of rainfall field and the distance, the errors of optimum interpolation of rainfall at the mid points of varying length of segments have been computed by applying equation (17). The relation between the errors of interpolation and the distance is shown in Fig. 5 from which the maximum spacing allowed between raingauges for a specified tolerable error in interpolation can be obtained. Mooley and Ismail (1982) found that for a tolerable reiative error of 20 to 30 percent in the interpolation at the mid point of a straight line segment for monsoon months, the maximum spacing allowed between raingauges is about 50 km. For a tolerable error of about 15 percent in the case of seasonal and annual rainfall, the corresponding distance is about 100 km.

### 4.5 Trend surface representation of rainfall field by fitting of polynomials.

The representation of trend surfaces of rainfall data have been used by many research workers in connection with network design (Pullen et al, 1966 and Edward, 1972). Edward (1972) estimated areal rainfall by fitting surfaces to the data points by least square method. The technique of trend surface fitting to rainfall field is described below.

Let $R_j$ $(x_j, y_j)$ be the rainfall values at n stations, j = 1, 2, ........... n in a space where $(x_j, y_j)$ are the plan coordinates. Then the polynomial surface to the observed rainfall can be represented as

$$R = b_1 + b_2x + b_3y + b_4x^2 + b_5xy + b_6y^2 \quad (20)$$

This equation describes a surface of second degree and the number of coefficients is six.

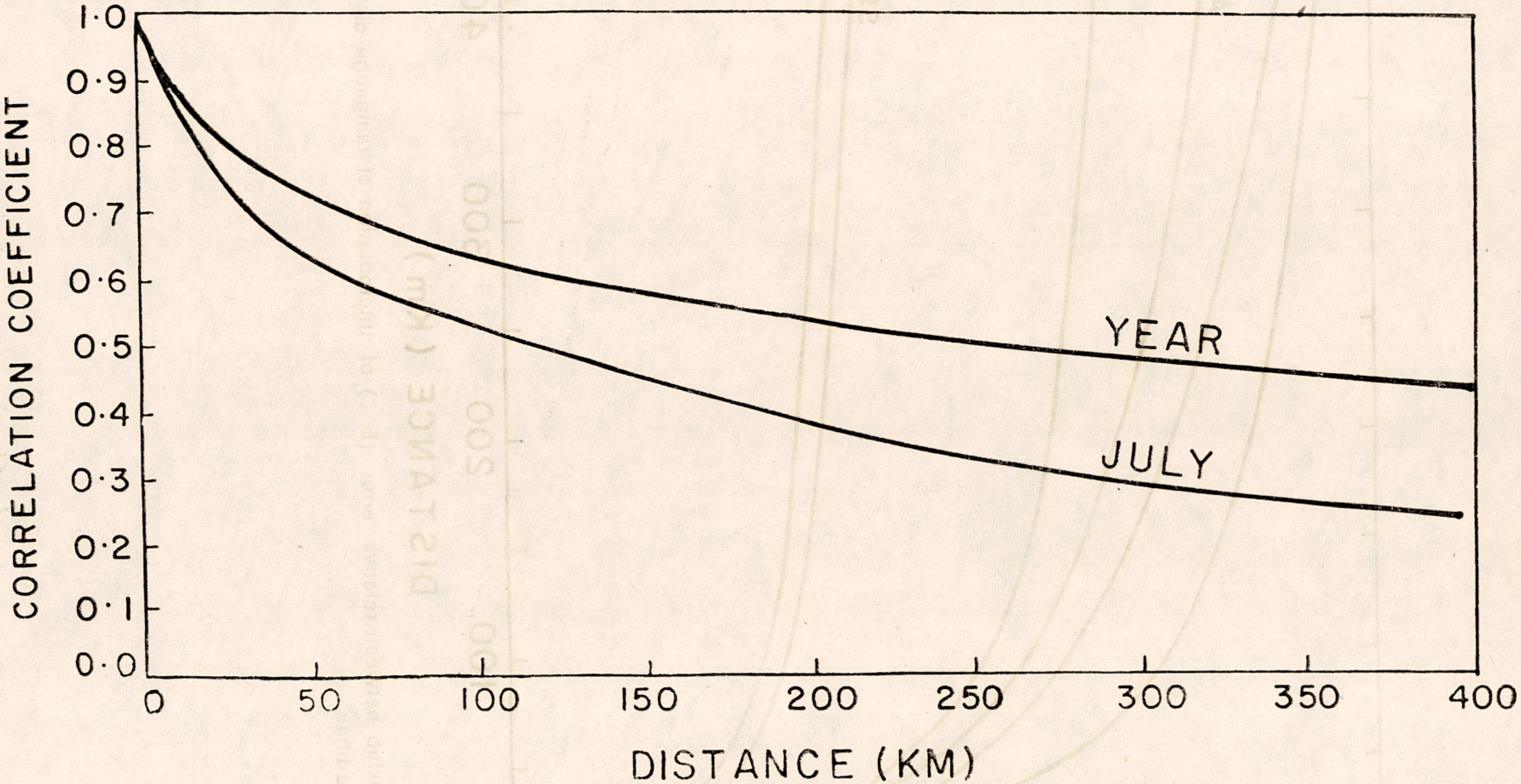


Fig. 4—Correlation function of rainfall over Vidarbha for July month and year as a whole

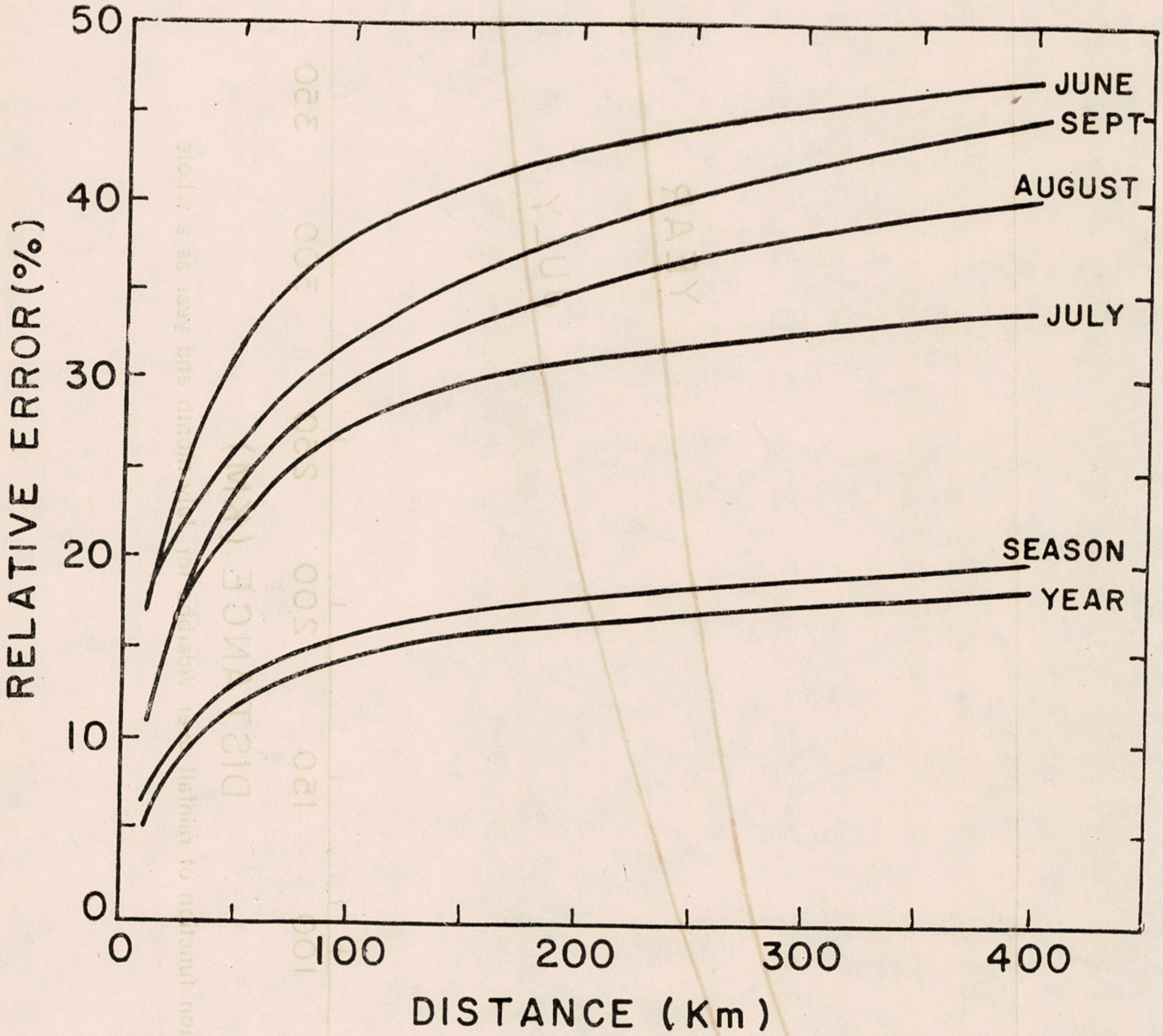


Fig. 5—Relationship between relative error ($E_{opn}$) of interpolation of raingauge distance for Vidarbha

The calculated values of rainfall ($R_j'$) on the polynomial surface is given by

$$R_j' = b_1 + b_2x_j + b_3y_j + b_4x_j^2 + b_5x_jy_j + b_6y_j^2 \quad (21)$$

The sum of the squares of the residuals differences ($R_j - R_j'$) for all n data points is minimised to obtain the values of the coefficients b. The efficiency of the fitting of polynomial surface is measured by computing the root mean square deviation (RMSD) and goodness of fit as given below

$$\text{RMSD} = \left[ \frac{\Sigma (R_j - R_j')^2}{n-m-1} \right]^{\frac{1}{2}}$$

$$\text{Goodness of fit} = \left[ 1 - \frac{\Sigma (R_j - R_j')^2}{\Sigma R_j^2 - \frac{1}{n}(\Sigma R_j)^2} \right] \times 100$$

where n is number of raingauge stations and m is the number of coefficients.

Pullen et al (1966) applied the method to the Wear catchment in South Africa for the average annual rainfall data. The degree of polynomial was increased from quadratic to find the optimal fit. The results obtained are shown in Table 3.

Table 3 Polynomial fitting by least squares (35 stations. Arithmatic mean = 93 cm)

| Degree | No. of coefficients | $(R_j - R_j')^2$ | RMSD | $\frac{\text{RMSD}}{\text{Mean}}$ % | Goodness of fit | Catchment rainfall (cm) |
|---|---|---|---|---|---|---|
| 2 | 6 | 150730 | 73 | 7.8 | 95.8 | 83 |
| 3 | 10 | 38814 | 40 | 4.3 | 98.9 | 85 |
| 4 | 15 | 18950 | 32 | 3.4 | 99.5 | 84 |
| 5 | 21 | 17713 | 37 | 4.0 | 99.5 | 84 |
| 6 | 28 | 18175 | 55 | 5.9 | 99.5 | 84 |

Table 3 shows that for annual rainfall data 4th degree polynomial is seen to be most efficient according to RMSD and Goodness of fit. The areal rainfall is obtained by integrating the volume under the surface over the catchment divided into conveniently described rectangles and dividing the summation by the total area of the catchment.

The above method of describing the rainfall surface and finding the areal rainfall can be used repetitively to determine the optimum raingauge network for particular requirements.

**5. Location of rningauge sites.**

The selection of sites of the distribution of raingauges is as important as its density. This selection is considered at two levels. Level 1 concerns, how should the gauge be spaced so as to form the network and level 2 deals where should a gauge be placed in relation to its immediate surroundings.

The spacing of raingauges can be established to a certain pattern or can be installed according to the accessibility or the availability of observers. Some networks have been constructed to an entirely random design while others are spaced uniformly except in areas where orographic or other spatially-fixed influences are likely to cause significant differences. However, the errors in estimates of areal rainfall are less for a uniformly spaced than for a randomly spaced network. Some investigators (Light, 1947; Linsley and Kohlar, 1951; Huff and Neill, 1957) have shown that for rainfall which is essentially random in space, a centrally located gauge gives, on the average the best measure of areal rainfall. Wichet

(1941) and Law (1957) have favoured the method of moving gauges at random within an experimental area or interception studies in forests. Equal divisions of space have been employed in some studies (Wilm, 1943), while in others, basins have been divided into topographic domains-areas where factors such as slope and elevation extend over a limited definable range, that make it possible to differentiate one domain from another. Gauges are sited at random with domains, but this method is unsuitable for flat areas or areas where relief is rugged. However, where hydrological information is most needed 25 to 30 km has been accepted as rational distance between rainfall stations in flat region and approximately half that in mountainous areas. For networks where records have been collected for some time, the adequacy of gauge spacing to meet a desired criterion can be ascertained by computing correlation and strcctured functions of rainfall field as described in section 4.

As regards exposure of site is concerned, the raingauge should be placed on level ground not upon a slope or terrace and never on a wall or roof. The ground, where raingauge is fixed should not slope steeply on the side of prevailing winds.

## 6. Period of data and the uniformity of observations

The period of precipitation record needed to analyse a problem within a reliable safety factor depends upon the nature of the problem and on the time variations in rainfall in the region of interest. For example, if the frequency distribution of mean annual rainfall depth at a point or over an area becomes essentially stable after a certain period, the addition of further years of observations will not add significantly to the accuracy. The length of record needed to achieve a stable frequency distribution varies between seasons and regions. For example, analysis of a 75 year record for the Sutlej catchment showed the the deviations of 35-year means from the 75-year means were within $\pm$ 10 per cent for the May-October season, and within $\pm$ 15 per cent for the November-April season (Panchang and Ganguli, 1956). On the basis of limited studies, estimates of the number of years required to obtain stable frequency distribution of rainfall amounts are therefore recommended as in Table 4.

Table 4 : Period of data required for different catchment lay out

| Catchment layout | Number of years Extra tropical region | Tropical region |
|---|---|---|
| Islands | 25 | 30 |
| Shore | 30 | 40 |
| Plains | 40 | 40 |
| Mountain | 50 | 50 |

## 7. Design of raingauge network for operational flood forecasting

Rainfall data form an important input for flood forecasting systems. The success of a forecast depends how quickly after the accurrence of a flood producing rainstorm, the real time data from point observations within the catchment are obtained, to estimate the areal average rainfall of a catchment. During a given flood situation, it is not always feasible to collect rainfall for a large number of raingauges where obviously time factor does not permit such an exercise. Hence for flood forecasting, there is a need for designing a small network of stations from the existing number of stations which will be sufficient to provide true value of areal average rainfall within permissible limits of statistical error. The objective approach to determine such a network is to select the stations which have got a high degree of correlations with the areal average rainfall of the catchment. By this procedure, it is possible to arrive at only 4 to 5 stations which are representative of catchment rainfall for an area of about 10,000 km$^2$. Such stations are called representative stations or key stations and the aggregate of these stations is known as a key station network. For operational flood forecasting this then is adequate network. A combination of raingauge stations is selected in order of their importance and entered into the multiple regression equation with average basin rainfall as the dependent variable and individual station rainfall as the independent variables.

The equations for each rainfall event takes the following form

$$R = a_1 x_1 + a_2 x_2 + a_3 x_3 + \ldots\ldots\ldots\ldots a_n x_n \quad (22)$$

where R is the estimate of areal rainfall. and $x_1, x_2, x_3, x_4 \ldots\ldots\ldots\ldots x_n$ are the point rainfall observed at the stations selected in the network

Rao and Bhalla (1972) determined representative raingauge networks for flood forecasting in Yamuna and Damodar basins and Prasad (1982) for the Sone Catchment.

## 8. Network of raingauge stations in Iudia

Rainfall measurement in India was started towards the end of the 18th century. The first recorded data were obtained at Calcutta in 1784 followed by observations at Madras from 1792, Bombay from 1823 and Simla from 1840- However, the recording of meteorological data including rainfall for more stations in various provinces was started towards the middle of 19th century. In 1875 the provincial meteorological departments were centralised and the India Meteorological Department (IMD) was established. Rainfall registration however remained with the Provincial Governments. It was realised that for a country like India where the entire prosperity rested on the monsoon rainfall, rainfall data should be collected with a common standards of instruments to ensure uniformity. As a result Government of India brought the subject of rainfall registration under the overall technical control of IMD by their rainfall resolution of August 1980. According to this resolution which is still the basis of registration of rainfall the recording, collection and publication of rainfall data became the responsibility of provincial (now states) Governments whereas technical control came under the purview of the India Meteorological Department. The rainfall resolution made it obligatory for the State Governments to supply manuscript as well as published copies of daily, monthly and annual rainfall to the IMD for compilation of the two annual publication viz the 'Daily Rainfall of India' and 'Monthly and Annual rainfall of India'.

After India became incependant in 1947, the need for increasing the basic hydrometeorological data, in planning of water resources development has been fully realized and as a result vaious river valley development projects have been taken. up. Upto the end of 1950 there were in India about 2754 raingauge (Ahuja, 1960). India Meteorological Department in consultation with Central Water and Power Commission reviewed in 1956-57 the network of ordinary raingauges for all river catchments in the country and recommended that one raingauge should be provided for every 500 km. Since then a systematic approach was made on network planning, selection and setting up raingauge stations in various river basins and as a result the number of raingeuge stations in various river basins and as a result the number of raingauge stations in India has increased rapidly. The present network of raingauge stations ih India is 5472 of which 561 are operated by India Meteorological Department. The remainder are manned by State Government Departments. This gives one raingauge in about every 600 km$^2$.

There are about 4651 other raingauge stations under different ageucies (Railways, Irrigation. Public Works Departments. Agriculture and Forest Department) spread all over India. Data from these stations, through regularly recorded are not published and therefore, are not easily available for use in the hydrologic studies. However, these data can be obtained from these agencies on request for specific purpose. The common time of observations of all raingauge stations throughout this country is 0830 hrs ISI and represents the total for the preceding 24 hours.

There are about 522 self-recording gauges throughout India of which 323 are operated by IMD. The optimum number of self recording raingauges will depend on the use to be made for such observations. However, the WMO (1974) has suggested that at least 10 percent of the total number of raingauges be equipped with self-recording raingauges. This means that there should be about 550 self-recording raingauges in India which is nearly double the existing number,

The hourly, daily and monthly rainfall data of these stations with long records are available in India Meteorelogical Department (IMD), Pune on magnetic tapes.

## 9. Conclusions

Rainfall is by far the most important input variable in many hydrologic studies. As such the rainfall network should be designed in such a way to ensure that an adequate distribution of the spatial and temporal variation of rainfall in a region of interest is achieved. The investigations hence revealed that the areal and temporal variability of rainfall which determine the density of raingauge station can best be determined only after adequate sampling has been carried out. In this paper different methods of rainfall analysis applicable to raingauge network design have been presented. It has been seen that the density of the networks of rainfall stations depends upon the size of area and on the duration over which sampling is desired. In Vidarbha region far more gauges are required to give comparable accuracies for areal rainfall on monthly basis than for seasonal or annual basis.

The density of the rainfall stations in India at present is about 600 km$^2$ to a gauge whereas WMO standards stipulates a range of between 600-900 km$^2$ for one station. This achievement was mainly due to the progressive increase in the number of stations during the past 40 years to obtain adequate and reliable data for planning and development of water resources. The present network probably satisfies the input requirements of a daily rainfall-runoff model on some river catchements. However, if an evaluation of the network is required for specific area then a more detailed analysis should be carried out.


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