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RAINGAUGE NETWORK DESIGN FOR PAGLADIYA BASIN

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PREFACE

A hydrological network is an organised system for the collection of information of specific kinds such as precipitation, run off, water quality, sedimentation and climate parameters. The accuracy in the decision making in the water project design depends on how much reliable information is available for the region concerned. Having enough relevant and accurate hydrologic information reduces the chances of underdesign or overdesign and thus minimizes the economic losses, which leads to the overall increase in the benefit/ cost ratio. The failure of the many capital intensive projects throughout the world can be attributed in part to an inadequate record length, the sparseness of the network, or inaccuracy of the hydrologic information. But for extracting the areal information from the point measurement one cannot increase the number of stations injudiciously, particularly in developing countries like India as this involves a considerable cost. Therefore, the optimum number of stations required for the measurement of point value to derive areal value with certain accuracy level must be given due attention. Network design study covers this aspect. An ideal design should be based on economic consideration although no methods are available till now. Therefore, engineering approach is the only resort to such problem now.

On the request of Brahmaputra Board, Guwahati this study of raingauge network design for Pagladiya basin has been carried out. The characteristics of the precipitation based on the existing network has been analysed. The accuracy of the existing network has been determined and discontinuation of few redundant stations has been proposed. Also the number of additional raingauge stations required to arrive at certain accuracy level and their probable location has been prescribed to estimate the areal rainfall from point measurements.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Precipitation is the most basic data required for any water resources studies. Estimation of the number and location of the rain gauge stations which will provide sufficient information regarding rainfall falling over the catchment is referred as network design. A rain gauge network is intended to serve the general as well as specific purposes such as water supply, hydro power generation, flood forecasting, irrigation and flood control etc.

In the present study, the network design for the Pagladiya basin has been carried out. Rainfall occur mostly during March to October in the basin. During March and April the rainfall is sporadic, but it is steady and heavy or very heavy during May to October. Annual rainfall in the basin is over 2300 mm. Wide spatial variation of rainfall is observed in this catchment. The rainfall data of ten existing raingauge stations in and around the study area have been analysed using various methods which take into account the location of raingauges and type of basin and its climate, precipitation characteristics from the existing raingauge stations etc. Apart from BIS recommendations, C_v method, Key station method, Spatial correlation method and Entropy method have been used. Based on the study, it has been found that additional stations are required in certain parts of the basin while in other parts some redundant stations have been identified. For adequate and economical network design discontinuation of two existing stations and installation of additional 4 stations have been proposed in the catchment with their possible locations.

1.0 INTRODUCTION:

A hydrological network is an organised system for collection of information of specific kinds such as precipitation, run off, water quality, sedimentation and other climate parameters. The accuracy in the decision making in the water project design depends on how much information are available for the region concerned. Having enough relevant and accurate hydrologic information reduces the chances of underdesign or overdesign and thus minimizes the economic losses, which leads to the overall increase in the benefit/ cost ratio. The failure of many capital intensive projects throughout the world can be attributed in part to an inadequate record length, the sparseness of the network, and/ or inaccuracy of the hydrologic information. It has not, so far, been possible to define the optimum level of hydrologic information required for planning, design and development of a specific project in a region, due to difficulties in developing a benefit cost function of hydrologic information. It is, therefore, difficult to attain an optimum balance between, on one hand the economic risk arising from inadequate information and on the other hand, the cost of a hydrologic network capable of transmitting the required information. Unless techniques to evaluate such a balance are developed, the network design methods sited in the literature can not be universally applied.

There are several ways to define the objectives of the hydrological network design, but the fundamental theme, in most cases, is the selection of an optimum number of stations and their optimum locations. Other considerations that can arise in the network design are; achieving an adequate record length prior to utilizing the data, developing a mechanism to transfer information from gauged to ungauged locations when the need arises and estimating the probable magnitude of error or regional hydrologic uncertainty arising from the network density, distribution and record length. Another difficulty in developing a network design methodology is related to the complexity in dealing with the multi variate interaction of hydrologic events in the domains of space and time. The stochastic nature of the hydrologic variables complicates the problems further.

The objective of providing a network of raingauge is to adequately sample the rainfall and explain its variability within the area of concern. The rainfall variability depends on topography, wind, direction of storm movement and type of storm. The location and spacing of gauge depends not only on the above factors but also upon the use of that data for that region. For example in the tea garden areas of the North East region, the density of precipitation gauge is found to be much higher, even in the valleys, in comparison to the hills where jhoom cultivation are practiced, since the data are used for irrigation planning of the tea gardens. Network design covers following three main aspects (WMO, 1976):

a. Number of data acquisition points required.
b. Location of data acquisition points and
c. Duration of data acqusition from a network

Measurement stations are divided into three main categories by WMO, namely

1. Primary stations: These are long term reliable stations expected to give good and reliable records.
2. Secondary or Auxiliary stations: These are placed to define the variability over an area. The data observed at these stations are correlated with the primary stations, and if and when consistent correlations are obtained secondary stations can be discontinued or removed.
3 Special stations: These are established for particular studies and do not form a part of minimum network or standard network.

In the present study, the network design for the Pagladiya basin has been carried out. The rains are of long duration and occur mostly between March and October. During March to April the rainfall is sporadic, but it is steady and heavy or very heavy during May to October. Annual rainfall in the basin is around 2300 mm. There is wide spatial variation in this catchment. Various methods have been tried which takes into account the location and type of basin and its climate, precipitation characteristics from the existing raingauge stations etc. Apart from BIS recommendations, C_v method, Key station method, spatial correlation method and entropy concept have been tried for determining the adequate number of raingauge stations and their suitable location. Based on the study certain conclusions have been made regarding the existing network accuracy, total number of additional stations to be installed in the catchment and their possible locations.

2.0 LITERATURE REVIEW:

Various studies have been conducted to determine the standard error of estimates of precipitation with different size of drainage area with different raingauge densities since long. One of the earliest work is of Linsley et. al. (1947) determining the standard error of estimates of storm rainfall over Muskingum basin. Huff and Neil (1957) carried out a study of areal variability of rainfall in a region characterized by thunderstorm activities in Illinois state, USA.

Kagan (1966) has suggested a procedure for computing the error in estimation of mean areal rainfall which could be used as a criterion for determination of the optimum network density.

Eagleson (1967) used the technique of Harmonic Analysis and the concept of Distributed linear systems to study the sensitivity of peak catchment discharge to characterise spatial variability of convective and cyclonic storm rainfall. Sampling theorem was used to generalise the relations for optimum network density for flood forecasting.

The Indian Standard Institute (now Bureau of Indian Standards, IS 4987-1968) has recommended the design of a raingauge network based on type of area and rainfall type as follows:

1. For plain areas one raingauge upto 520 sq. km. shall be sufficient. However, if the catchment lies in the path of low pressure, the system which causes precipitation in the area during its movement which can be seen from the map published by India Meteorological Department, then the network should be denser particularly in the up stream.
2. In the region of moderate elevation (upto 1000m above msl), the network density shall be one raingauge in 260-390 sq. km.
3. In predominantly hilly areas and where heavy rainfall is experienced, the density recommended is one raingauge for every 130 sq. km.

Matheron (1971) considered the variables which show variations of relation to space and/or time as regionalised variables and developed the theory of regionalised variables. In this theory he proposed a method of estimation, which is termed as kriging technique, for spatial interpolation in random fields. Later, Delhomme and Delfiner (1973) used universal kriging to interpolate rainfall on a regular grid for a large storm over an arid region of Chad. They calculated the gain in the estimation of mean rainfall during a storm resulting by setting a new fictitious gauge at a point within the basin.

Hall (1972) suggested a method for determination of key station network for flood forecasting. First correlation coefficient between the average of the storm rainfall and individual rainfall are found. The stations are arranged in the descending order of the correlation coefficient and the station with the highest correlation coefficient, called key station, are considered for inclusion in the network. Then the first key data are removed and second key station from the remaining data is found similarly. As each stations gets added to the key station network, the total amount of the variance which is accounted for by the network at that stage is determined. From this the number of gauges required to achieve an acceptable degree of error can be found.

Osborn and Handley (1972) considered the climate of the watershed for determination of the optimum network density. On correlating the rainfall and runoff in a test basin of one square mile area, they observed that the optimum network density was varying directly with the accuracy and inversely with the area of the watershed.

The Bureau of Indian Standards and India Meteorological Department (1972) have recommended a simple formula:

$$N = \left(\frac{C_v}{P} \right)^2 \tag{2.1}$$

Where,

N = optimum number of Raingauges to be installed in the basin.

C_v = coefficient of variation of rainfall for the existing raingauge network

P = permissible degree of percentage error for estimation of the average areal rainfall.

Zamadzki (1973) derived analytical expression for the error in the area averaged rainfall as estimated by a network of raingauges, the fluctuations in the estimate and actual variance of the area averaged rainfall in terms of the mean, the mean square and the space auto-correlation function of the areal distribution of the rainfall. He evaluated the error equation for an exponential auto-correlation function and obtained a linear approximate expression.

Rodriguez-Iturbe and Mejia (1974) formulated a general methodology for design of raingauge network. They expressed the rainfall process in terms of its auto-correlation structure in time and space. They developed a general framework to estimate the variance of the sample long term mean areal rainfall of a storm event. Expressing the variance as a function of correlation in space, correlation in time, length of operation of the network and the geometry of the gauging array, they developed the trade-off of time verses space.

The World Meteorological Organisation (1976) has recommended the minimum network densities for general hydrometeorological practices.

1. For plain regions of temperate mediterranean and tropical zones one station for 600-900 sq. km.
2. for mountainous region of temperate mediterranean and tropical zones one station for 100-250 sq. km.
3. For arid and polar region one station for 1,500-10,000 sq. km.

Bras and Rodriguez-Iturbe (1976) considered rainfall as multidimensional stochastic process. By using such process and multivariate estimation theory they developed a procedure for designing an optimal network to obtain mean areal rainfall of an event over a fixed area. This methodology considered three aspects of network design, namely spatial uncertainty and correlation process, error in measurement techniques and their correlation and non-homogeneous sampling costs. They found out the optimal network (density and location of the raingauge) together with the resulting costs and mean square errors of rainfall estimations.

Bras and Colon (1978) developed a procedure for the estimation of mean areal rainfall through a state of augmentation procedure and the use of multivariate linear estimation concepts, in particular, the Kalman-Bucy filter. The resulted technique could be used to analyze the existing data network, design new networks and process data for new networks.

Crowford (1979) described an experimental design model using an array of multivariate sensors, which was developed to evaluate trade-offs involved in the optimal sampling of rainfall. The model was used to examine the effects of sensors density reduction on the ability of a sampling system to detect signal variations.

Jettmar et. al. (1979) presented a methodology for assessing the value of river flow forecasting by possible changes in the existing precipitation and stream flow networks.

Jones et. al. (1979) used the optimal estimation procedure for preparation of maps of root mean square error of point interpolation for suggesting the accuracy of estimation of mean areal rainfall for any shape of area and any configuration of raingauges.

Lane et. al. (1979) suggested the use of principal component analysis in conjunction with the optimal interpolation for design of raingauge network.

Moss (1979a) advocated the use of a third dimension, the model error for modeling the rainfall process and analysis of hydrologic networks. Later he (1979b) suggested that to achieve a complete network design, the efficiency of data collection and the effectiveness of the resulting information must be integrated.

O' connel et. al. (1979) employed optimal estimation procedure in the redesign of a raingauge network in South England. Root mean square errors were calculated using the estimates of spatial auto-correlation of daily and monthly rainfall. Later Mooley et. al.(1981) used this theory by imposing climatological constraints to minimise the root mean square error estimation. The areal value can be given by,

$$P_R = \frac{1}{A} \iint P(x,y)\,dx\,dy \tag{2.2}$$

Where, P(x,y) is the rainfall at point (x,y).

This areal average can be estimated by a linear combination of point observational values as

$$\hat{P}_R = \sum_{j=1}^{n} W_j P_j \tag{2.3}$$

where n is the number of gauges. P_j is the rainfall at j th station.

The relative root mean square error is given by.

$$E = \left[\sum_{j=1}^{n} W_j P_j - \frac{1}{A} \iint_A P(x,y)\, dx\, dy \right]^2 \tag{2.4}$$

E should be minimum in an optimized network.

The optimum number of gauges required over an area for the estimation of areal rainfall can be directly determined from the relationship for a given error tolerance. The advantage of this method of optimum estimation is that it takes into account the local variation as well as inter station relationship of rainfall, spatial distribution of gauges over an area is also taken into account.

Thorpe et. al. (1979) suggested the use of double Fourier series for spatial interpolation of rainfall for a better estimation of mean areal rainfall.

Wood (1979) developed the sequential probability ratio test and applied to the network design problems. The decision whether to discontinue a station was considered to be dependent on the statistical considerations that to include the error probabilities of accepting a model when it is incorrect as well as rejecting it when it is correct.

Stole (1981) described an analytical method to determine the correlation function for a given storm, which has major uses in the spatial interpolation of rainfall and estimation of mean areal rainfall. Later he (1982) reviewed the phenomenon of occurrence of negative correlation functions between the gauge stations.

Dymond (1982) derived a simple expression for mean square error in basin rainfall as determined from a raingauge network. The expression involves the established correlation between the neighboring raingauges and the number of gauges in the network. A rational approach was proposed for network reduction. Later this method was reviewed by Bradsley and Manly (1985) and supported on the condition that, to apply this method the network should have negligibly small errors due to spatial variation of the rainfall process.

Husain (1989) applied the concept of maximum entropy for selection of optimum stations from a dense network and expansion of an existing network. He used the maximization of information transmission principle for above purposes.

Seed and Austin (1990) simulated the mean standard error using the sparse network to estimate the daily and monthly mean areal convective rainfall. They found out that a network with a regular configuration gives somewhat less variable errors than a random raingauge network.

3.0 STUDY AREA :

3.1 General:

Pagladiya river is one of the major tributary of Brahmaputra on its north bank. The river originates on southern slopes in hills of Bhutan at an altitude of 3000 m above msl. After traversing through the Bhutan territory it enters the Nalbari district of Assam near Chowki. It meets Brahmaputra near Lowpara village. The basin is lying between 26°14′ - 27°0′ N latitude and 91°18′ - 91°42′ E longitude. A dam has been proposed on the main river near village Thalkuchi. The catchment area of the basin is 1507 km^2 of which 1084 km^2 is in India and remaining 423 km^2 is in Bhutan. The hilly part of the catchment area comprises of 465 km^2 (423 km^2 in Bhutan and 42 km^2 in India). The river length is 196.8 km out of which it flows a length of 19 km in the hilly tracts of Bhutan and the rest 177.8 km in plains of Nalbari district of Assam. The major tributaries of the river are Mutunga (L- 30 km, A- 130 km^2), Dimla (L-25.5 km, A- 48.75 km^2), Nona/Mutunga (L- 63 km, A- 268 km^2) and Chowlkhowa (L- 75 km, A- 538 km^2) on its left bank. **Fig. 1** shows study area and the location of raingauges in the basin.

3.2 Existing Raingauge Network :

Rainfall in the catchment occurs mostly during June to October. There are also some pre-monsoon and post-monsoon showers. The average annual rainfall in the catchment is in the order of 2300 mm. Daily rainfall records have been maintained at fourteen different raingage stations(Brahmaputra Board, 1996) but for this study, the data could be collected for ten stations only. The details of data used in the study is given in **Table-1.** For Nagarjuli, Darrang, Giobergaon and Rangiya rainfall data are available for a period of about 22 years, from 1975 to 1996 (rainfall for few days are missing) while for Maneka, Uttarkuchi, Hajo and Masalpur data is available for about 15 years. For Gerua and Nayabasti data are available from 1991 to 1994 only. The concurrent daily rainfall is available for a limited period only (from 1991 to 1994) for 9 stations (except Masalpur). Most of the hills are in Bhutan and no raingauge station is available. in this region. It has been assumed that the data collected at Uttarkuchi, Menaka, Darang and

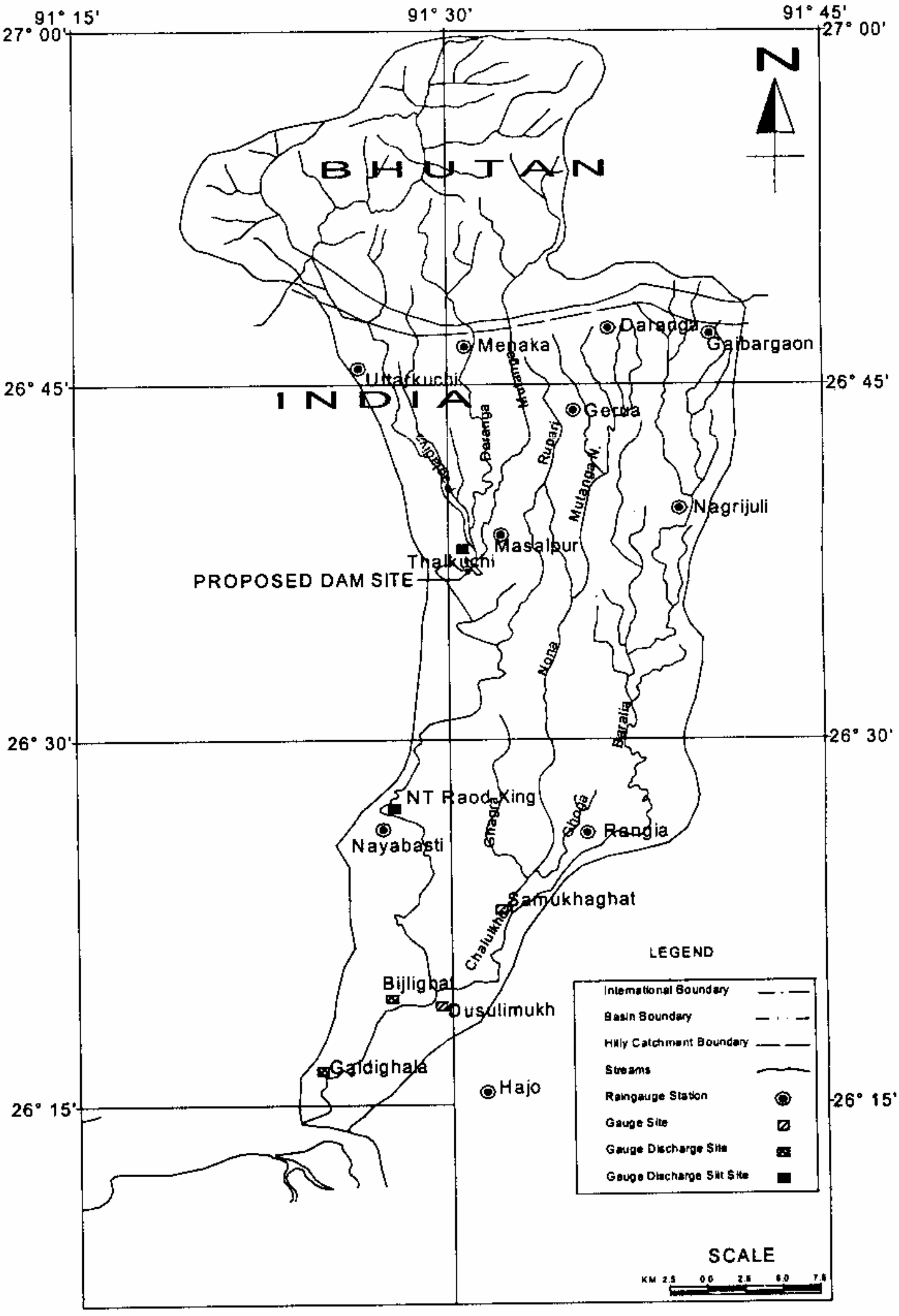


Fig. 1 Study Area

Goibergaon, all along the foothills, exhibit the rainfall characteristics of hilly portion of the basin. Average annual rainfall in the catchment is 2300 mm and its seasonal distribution is pre-monsoon 26.66%, monsoon 64.86%, post monsoon 5.5% and winter 2.97%. **Fig. 2** gives the seasonal and annual rainfall pattern for all the stations for which data has been used in the study. **Fig. 3(a)** to **(e)** shows the isohyetal map of the basin in different seasons. As all the stations are in the plain portion of the basin, SURFER has been used to draw the isohytes. Also, because there is no raingauge station available in the hills of Bhutan, the rainfall pattern could not be predicted and isohyetes is confined to the plain part of basin (Indian territory) only.

Table-1. Data Availability

Station	Year
Darrang	1975-96
Menaka TE	1976, 1983-96
Uttarkuchi	1980-96
Gaibargaon	1975-96 except 1990
Nagarjuli TE	1975-96
Gerua (Kumarikata)	1990-94
Masalpur	1975-88 except 1979
Nayabasti (Nalbari)	1991-94
Rangiya	1976-95 except 1990
Hajo	1980-95 except 1990

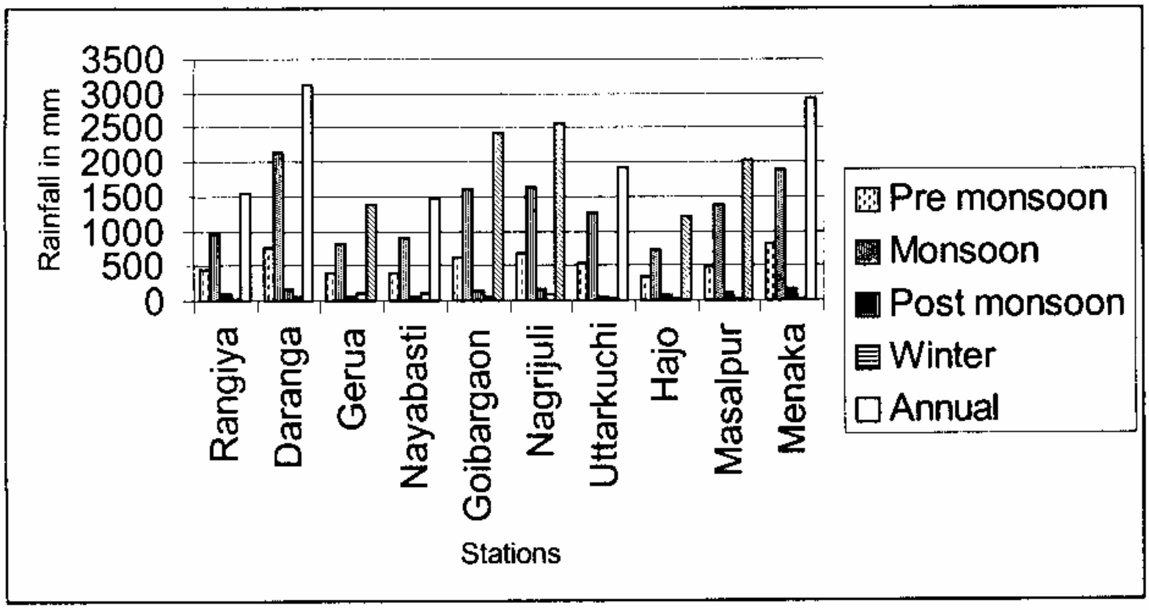
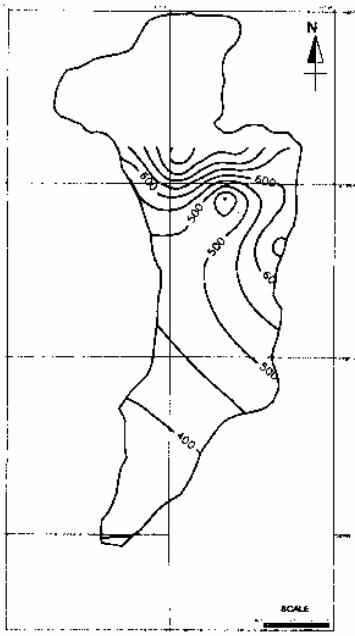
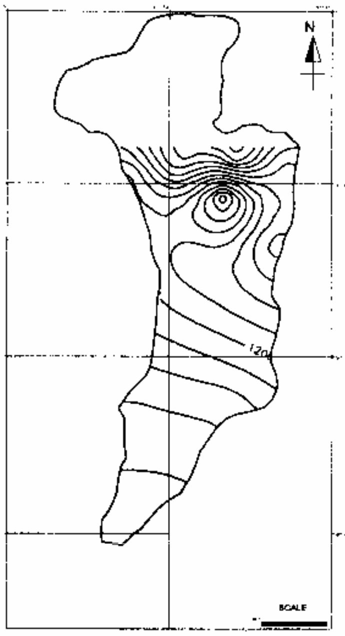


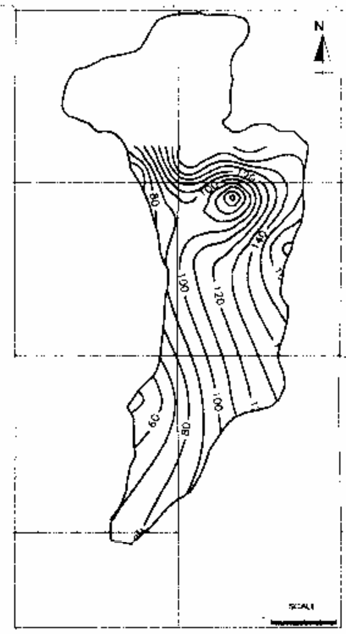
Fig. 2 Rainfall pattern in the study area



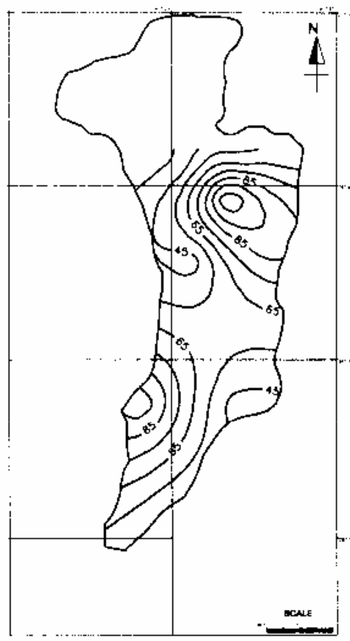
(a) Pre-monsoon



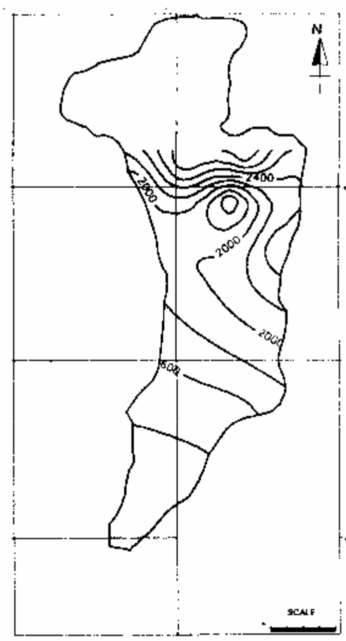
(b) Monsoon



(c) Post-monsoon



(d) Winter



(e) Annual

Fig. 3 Isohyetal map of the Pagladiya basin

4.0 STATEMENT OF THE PROBLEM:

For the management of a water resource system different sets of data and criteria are necessary for different objectives for which the system has been planned. The task of rainfall station network which is one of the important hydrological parameter of any water resource project needs due attention. To cope with the requirements of always increasing population from the limited resource the general tendency is to propose multipurpose schemes in stead of single purpose. It means while designing the network in a basin proper attention must be given on the nature of project proposed in the catchment. The studies are generally set for :

a. Hydrological studies,
b. Climatological and water balance studies,
c. Flood forecasting and computation of runoff studies and
d. Weather modification evaluation studies.

The objective of the optimum network design, in this study, is the selection of optimum number of stations and their judicious locations in the Pagladiya basin where a multipurpose dam (basically for flood protection in the districts of lower Assam) has been proposed by Brahmaputra Board. Various stages of network design to be followed are:

1. Collection of information like:
   a. Location of area,
   b. Size of catchment,
   c. Climate of the area,
   d. Precipitation characteristics,
   e. Location of existing precipitation stations and collection of data,
2. Determination of accuracy of existing network,
3. Determination of number of new stations required, if any and planning of new sites in the network.

5.0 METHODOLOGY:

The following methodologies have been used in the present study

5.1 IS 4986-1968 guidelines:

The Bureau of Indian Standard suggests that one raingauge upto 500 sq. km. might be sufficient in non-orographic regions. In regions of moderate elevation (upto 1000 m above msl), the network density might be one raingauge for 260-390 sq. km. In predominantly hilly areas and areas of heavy rainfall, the density recommended is one for 130 sq. km.

5.2 C_v Method:

The problem of ascertaining the optimum number of raingauges in various basins is of statistical nature and depends on spatial variation of rainfall. Thus, the coefficient of spatial variation of rainfall from the existing stations is utilised for determining the optimum number of raingauges. If there are already some raingauges in the catchment, the optimal number of stations that should exist to have an assigned percentage of error in the estimation of mean rainfall is obtained by statistical analysis as:

$$N = \left(\frac{C_v}{P}\right)^2 \qquad (5.1)$$

where,

N = optimal number of stations,

p = allowable degree of error in the estimate of mean rainfall and

C_v = coefficient of variation of rainfall values at the existing m stations.

If there are m stations in a catchment and $P_1, P_2, \ldots\ldots P_m$ is the recorded rainfall at a known time at 1, 2, ...m station, then the coefficient of variation C_v is calculated as:

$$C_v = \frac{100 \times \sigma_{m-1}}{\overline{P}} \tag{5.2}$$

where

$$\sigma_{m-1} = \frac{\sqrt{\sum_{i=1}^{m} P_i^2 - m \times \overline{P}^2}}{(m-1)} \tag{5.3}$$

P_i = monthly average precipitation at i th station and

P = the average rainfall of 'm' number of stations, given by,

$$\overline{P} = \frac{\sum_{i=1}^{n} P_i}{m} \tag{5.4}$$

It is usual practice to take p =10%.

σ_{m-1} is used for calculation of C_v (Eq. 5.2) when number of stations, m, in the network is less than 30 otherwise σ_m can also be used.

5.3 Key Station Network Method:

One of the most rational method for determination of key station is as suggested by Hall (1972). In this method, at first, the correlation coefficient between the average of storm rainfall and the individual station rainfall are found. The stations are then arranged in the order of their decreasing correlation coefficients and the station exhibiting highest correlation coefficient is called the first key station and its data is removed for determination of next key station. The procedure is repeated by considering the average rainfall of the remaining stations. The station showing the highest correlation coefficient after removing the data of first key station is called the second key station. Similarly third and successive key stations are determined after removing the data of already selected key stations. Now the sum of the squares of deviations of the estimated values of average rainfall from the actual rainfall in respect of 1st, 2nd, 3rd key station etc. is determined and a graph is plotted between the sum of the square of deviation and corresponding number of stations in combinations. It will be seen that a stage comes when the improvement in the sum of squares of deviation is very little with the addition of more stations. The corresponding number of stations at that stage is taken to be representative and key stations for the network in the catchment/ basin.

5.4 Spatial correlation Method:

Under the assumption that spatial variability of rainfall can be quantified through a spatial correlation function, a network of raingauges can be designed to meet a specified error criterion (Kagan, 1966 and WMO, 1972). However in applying such an approach, care must be taken to ensure that condition necessary for the existence of spatial correlation function, such as hydrological homogeneity and isotropy are fulfilled; flat areas with a relatively homogeneous surface are more appropriate for the application of the technique. A general theoretical spatial correlation method for the planning of meteorological networks has been given by Gandin (1970). Some details of the specific approach and its application have been given by Kagan (WMO, 1972). The basis of this method is the correlation function ρ(d) which is a function of the distance between the stations, and the form of which depends on the characteristics of the area under consideration and on the type of precipitation. The function ρ(d) can frequently be described by the following exponential form:

$$\rho(d) = \rho(0)e^{-d/d_0} \quad (5.5)$$

where ρ(0) is the correlation corresponding to zero distance and d_0 is the correlation radius or distance at which the correlation is ρ(0)/e.

Theoretically, ρ(0) should equal to unity but is rarely found so in the practice due to random errors in precipitation measurement and micro climatic irregularities over an area. The variance of those random errors has been given by Kagan (1966) as

$$\sigma_1^2 = \left[1 - \sigma(0)\right]\sigma_h^2 \quad (5.6)$$

where σ_h^2 is the variance of the precipitation time series at a fixed point.

The quantities $\rho(0)$ and d_0 provide the basis for assessing the accuracy provided by a network. In this context two accuracy criterion may be of interest.

Criterion 1: The accuracy with which the average rainfall over a given area may be obtained is to be evaluated. For an area 's' with the center station, and assuming $\rho(d)$ exists and described as above, the variance of the error in the average precipitation over 's' is given by Kagan (1966) as:

$$v = [1 - \rho(0)]\sigma_h^2 + 0.23\sigma_h^2 \frac{\sqrt{s}}{d_0} \tag{5.7}$$

where, the first term is attributed to random error and second term with spatial variation in the precipitation field.

For an area 'S' with 'N' stations evenly distributed so that S = N × s, the variance of the error in the average rainfall in the area 'S' is given by

$$v_n = \frac{\sigma_h^2}{n}\left[1 - \rho(0) + 0.23\frac{\sqrt{s}}{d_0} \times \sqrt{n}\right] \tag{5.8}$$

The relative root mean square error is then defined as:

$$z_1 = \frac{\sqrt{v_n}}{\bar{h}} = \frac{C_v}{n}\sqrt{1 - \rho(0) + 0.23\frac{\sqrt{s}}{d_0} \times \sqrt{n}} \tag{5.9}$$

where $C_v = \sigma_h/h$ and h is the average precipitation over the area S. From the above equation the value of 'n' to meet a specified error criterion Z_1 can be obtained if the values of $\rho(0)$ and d_0 are known or vice versa. The uniform spacing of station over the area S is such that S = N ×s can be achieved on the basis of a square grid for which the spacing between the station is: L= √S/N. However a triangular grid is usually more convenient if the area S has a complex configuration and its spacing is given L=1.07 √S/N

Criterion 2: The accuracy of spatial interpolation is to be evaluated. Kagan (WMO, 1972) has given the relative errors associated with linear interpolation between two points and interpolation at the center of square and triangle, where the maximum error of interpolation occur. For a triangular grid with a spacing one, the relative error is given by as:

$$z_2 = C_v \sqrt{\frac{[1-\rho(0)]}{3} + \frac{0.52 \times \rho(0) \times \sqrt{s}}{\sqrt{n \times d_0}}} \qquad (5.10)$$

Assuming that ρ(d) can be described by Eq. 5.5

Application: The derivation of z_1 and z_2 in a particular case requires the estimation of ρ(0) from which ρ(d) and d_0 can in turn be derived. The function ρ(d) can be evaluated by calculating the correlation ρ(i,j) as a function of distance between stations. The value of ρ(i,j) is calculated as:

$$\rho(i,j) = \frac{\sum(h_i - \bar{h}_i)(h_j - \bar{h}_j)}{\sqrt{\sum(h_i - \bar{h}_i)^2}\sqrt{\sum(h_j - \bar{h}_j)^2}} \qquad (5.11)$$

Where the summations are taken from 1 to m and m is the number of pairs of observations. For determination of ρ(0) and d_0 distance is plotted against correlation and an exponential curve is drawn through the points. The value of ρ(0) is found out by extrapolating ρ(d) to zero distance, and d_0 is calculated as the distance corresponding to a correlation of ρ(0)/e. Alternatively, ln[ρ(d)] may be plotted against d which should result in a linear plot with slope $(-1/d_0)$ and intercept is ln[ρ(0)]. The objective of fitting of a straight line to the plotted points by least square may result in values of ρ(0) greater than unity which would be nonessential. Consequently, a subjective approach such as fitting by eye is apparently only the alternative.

5.5 Entropy Method

One of the important objectives of network design is to estimate the probable magnitude of error or regional hydrological uncertainty arising from network density, distribution and record length. In entropy method, the hydrological information and regional uncertainty associated with a set of precipitation station are estimated using Shannon's entropy concept. Since time series of rainfall data can be represented by gamma distribution due to the presence of skewness, the entropy term is derived using single and bivariate gamma distribution.

Let **X** represents precipitation variables measured at a station with events $\mathbf{x_1, x_2, \ldots\ldots x_n}$ and with the probability of occurrence of $\mathbf{j^{th}}$ event denoted by $\mathbf{p(x_j)}$. Shannon and Weaver (1949) defined the average uncertainty, also known as entropy with **n** event as

$$H(X) = -\sum_{j=1}^{n} p(x_j)\log_2 p(x_j) \tag{5.12}$$

where, **H(X)** is the uncertainty or entropy of variable X.

Similarly, the joint entropy in a region with m station and precipitation variables (X_1, X_2, ...X_m) can be extended to

$$H(x_1, x_2, \ldots\ldots x_m) = -\sum_{j=1}^{n} p(x_j^1, x_j^2, \ldots x_j^m)\log_2 p(x_1, x_2, \ldots\ldots x_m) \tag{5.13}$$

where, X_1, X_2, ... X_m represents precipitation variables measured at m station and $p(x_j^1, x_j^2, \ldots x_j^m)$ is the joint probability of occurrence of j^{th} event at m^{th} station.

Computation of Entropy

A random variable X is said to be gamma distributed if its probability density function is given by,

$$f(x, \sigma, \lambda) = \frac{1}{\sigma\Gamma(\lambda)}\left(\frac{x}{\sigma}\right)^{\sigma-1} e^{-\frac{x}{\sigma}} \tag{5.14}$$

for **x, s, l > 0**

where **s** is scale parameter, **l** is shape parameter and **G(l)** is the gamma function and equals to

$$\int_0^{\lambda} x^{\lambda-1} e^{-x} dx \tag{5.15}$$

the parameters **s** and **l** can be calculated by following method:

Expected value of **X** = $\mu_1(X) = \sigma\lambda$ (5.16)

The variance of **X** = $\mu_2(X) = \sigma^2\lambda$ (5.17)

Similarly, the third and forth central moments of X are

$$\mu_3(X) = 2\sigma^3\lambda \quad (5.18)$$

$$\mu_4(X) = 3\sigma^4\lambda(\lambda + 2) \quad (5.19)$$

The entropy of gamma probability density function is calculated as

$$H(X) = -\int_0^{\infty} f_G(x,\sigma,\lambda)\ln f_G(x,\sigma,\lambda)dx \quad (5.20)$$

which is simplified to (Husain, 1987)

$$H(X) = -(\lambda - 1)\psi(\lambda) + \Gamma(\lambda + 1)/\Gamma(\lambda) + \ln(\sigma\Gamma(\lambda)) \quad (5.21)$$

where $\psi(\lambda)$ is the digamma function:

$$\psi(\lambda) = \partial/\partial\lambda(\ln\Gamma(\lambda) \quad (5.22)$$

The bivariate gamma distribution, as proposed by Moran (1969) can be transformed to normalised variates z and w as follows:

$$\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} e^{-0.5t^2}dt = \int_0^{x} f(t,\sigma_x,\lambda_x)dt \quad (5.23\text{ a})$$

$$\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} e^{-0.5t^2}dt = \int_0^{y} f(t,\sigma_y,\lambda_y)dt \quad (5.23\text{b})$$

In the above equation X and Y are variables with univariate gamma distribution and with their parameters as (s_x,l_x) and (s_y,l_y) respectively. Z and w are normalized variates of X and Y respectively, with a mean of zero and standard deviation of unity. If r_{zw} is the correlation coefficient between z and w, then the information transmitted by variable Y about X, T(X,Y) or by variable X about Y, T(Y,X) is given by Shannon and Weaver (1949):

$$T(X,Y) = T(Y,X) = -\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f_n(z,w) \ln \frac{f_n(z,w)}{f_n(z) f_n(w)} dzdw \tag{5.24}$$

where $f_n(z,w)$ is the bivariate normal probability density function of normalized variates z and w and is transformed from the bivariate gamma probability density function $f_g(x,y;s_x,l_x,s_y,l_y)$. $f_n(z)$ is the normal probability density function of normalized variate z and is transformed from the gamma probability density function $f_g(x;s_x,l_x)$. Similarly, $f_n(w)$ is the normal probability density function of the normalized variate w and is transformed from the gamma probability density function $f_g(y; s_y,l_y)$. The information transmission relationship is simplified to:

$$T(X,Y) = T(Y,X) = -\frac{1}{2}\ln(1-\rho_{zw}^2) \tag{5.25}$$

Now, considering a triangular element (**Fig. 4**) formed by joining three precipitation station (i,j,k) measuring precipitation X_i, X_j, X_k respectively. The entropy $H(X_i)$ and $H(X_j)$ for the line i-j can be written as:

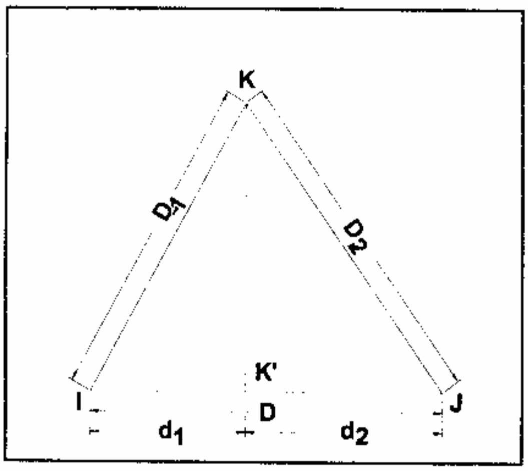


Fig. 4 Triangular element formed by joining three raingauge stations.

$$H(X_i) = T(X_i, X_j) + H(X_i, X_j) - H(X_j) \tag{5.26a}$$

$$H(X_j) = T(X_i, X_j) + H(X_i, X_j) - H(X_i) \tag{5.26b}$$

It means, the entropy $H(X_i)$ at a station, which is also the transmitted information about the variable X_i at station I can be decomposed into: (a) common information $T(X_i, X_j)$ between station pair i and j which will remain constant throughout the segment i-j and (b) the net information $H(X_i, X_j)-H(X_j)$ at i, considering station pair (i,j), which depends on the the distance between the station pair and is maximum at station location (**Fig. 5**)

Similarly for station pair (i, k) and (j, k)the following relationships can be written:

$$H(X_i) = T(X_i, X_k) + H(X_i, X_k) - H(X_k) \tag{5.26c}$$

$$H(X_k) = T(X_i, X_k) + H(X_i, X_k) - H(X_i) \tag{5.26d}$$

$$H(X_j) = T(X_j, X_k) + H(X_j, X_k) - H(X_k) \tag{5.26e}$$

$$H(X_k) = T(X_j, X_k) + H(X_j, X_k) - H(X_j) \tag{5.26f}$$

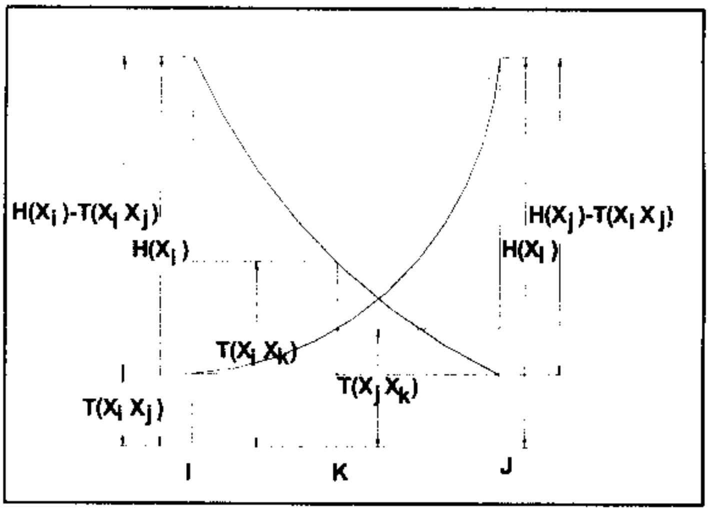


Fig. 5 Schematic diagram showing information transmission relationship

The common information between station pairs for gamma distributed variables can be computed using the relationship derived in Eq. 5.25 by transforming the gamma variates to normalized variates. The net information term in the above equations is a function of distance from the stations. The variation of the net information term with distance has been found to be exponentially related as follows:

$$Y_i = ce^{-(bd_i/(D-d_i))} \tag{5.27}$$

where, Y_i is the net information ordinate at a distance d_i from the i station, c is the net information ordinate at station location and b is the coefficient of exponential decay curve, which is determined as:

Case (a) the coefficient b (originating from i to j)

$$b = \left[(D - d_1)/d_1\right]\left[H(X_i) - T(X_i, X_j)\right] / \left[T(X_i, X_k) - T(X_i, X_j)\right] \qquad (5.28a)$$

Case (b) the coefficient b (originating from j to i)

$$b' = \left[d_1/(D - d_1)\right]\left[H(X_j) - T(X_i, X_j)\right] / \left[T(X_j, X_k) - T(X_i, X_j)\right] \qquad (5.28b)$$

Hence, the information at any point on line i-j, say at a distance d_l from i can be interpolated as:

$$H(X_l) = T(X_i, X_j) + \left[H(X_i) - T(X_i, X_j)\right] e^{-b\left[d_1/(D-d_1)\right]} + \left[H(X_j) - T(X_i, X_j)\right] e^{-b'\left[(D-d_1)/d_1\right]} \qquad (5.29)$$

5.6 Location of Precipitation Gauges:

Determination of location of raingauge station is very important in the design of precipitation guage network. Isohyetal method is commonly used to locate raingauges in the catchment. In this method the isohyetes are drawn over the catchment. This divides the whole catchment into a number of zones. Number of station should nearly be equal in every zone. The exact location should be decided keeping in view the following points:

1. The raingauge should be located near village or town.
2. The site should be accessible throughout the year.
3. The distribution should be uniform over the catchment area.
4. As far as possible number of raingauge should be proportionate to area of the sub-catchment in which it is placed.

6.0 ANALYSIS AND DISCUSSION:

Estimation of the number and location of the raingauge stations have been analysed by IS guidelines, C_v method, key stations method, correlation method and using entropy concept. The study area, Pagladiya basin having nine raingauge station inside and one station outside the catchment area of about 1507 sq. km. The major hilly portion of the catchment (about 423 sq. km) is lying on the other side of international border in Bhutan and there is no raingauge station in this part. In the hills inside Indian territory (about an extent of 42 sq. km), no station is existing and all along the foot hills, there are four stations which, obviously may not represent the rainfall characteristics of the hills. In the plain portion of the basin (area about 1042 sq. km) altogether there are ten stations and it can be assumed that data of ten stations should be sufficient to represent the rainfall in the basin. The rainfall in the catchment shows a wide variation in space and time. The location of these stations are not uniform over the catchment, therefore even if there is relatively large number of raingauge in some part of the basin, it does not give the adequate representation of the basin rainfall. Therefore, proper network design is required to sample the precipitation in the basin. The results and observations for each methods are discussed in details as follows:

IS guidelines:

The catchment lies in the region of heavy rainfall zone. It is recommended as per IS4987-1968 that there should be one raingauge for every 130 sq. km of hilly area and one for every 260 sq. km of plain area. As per this guidelines, the minimum number of raingauge in the hilly area (423 sq. km) should be equal to four and in plain (1042 sq. km) another four. Therefore, the method prescribed total number of eight stations in the basin. Out of existing ten precipitation stations all are inside the catchment except Hajo. These stations are not well distributed. The north hilly part of the catchment is totally unrepresented. Though the major portion of the hills are in Bhutan, there in no station even in the 42 sq. km hilly terrain inside India. Therefore this method suggest the relocation of raingauge stations in the basin.

C_v Method:

The coefficient of variation evaluated for the average annual rainfall for the existing raingauge network is 0.43 and with N = 10, the probable error in the observation of the rainfall is 13.3%. To keep it within 10% of probable error 19 numbers of station is required. When the same exercise was done on the rainfall values of monsoon season only C_v has been evaluated as 0.39 and probable error as 12.4% and required number of station is 16 to keep it within 10% of probable error. These values show the extent of spatial variation of rainfall in the catchment which can also be judged from **Fig. 2** which shows for some of the stations (Menaka, Darranga, Goibargaon and Nagarjuli, all are in the north-central part of the basin) average annual rainfall (aar) is around and above 2500 mm while for few others (Rangiya, Gerua, Hajo and Nayabasti) it is around 1500 mm or even less than this. Therefore, C_v method may not give the true picture when all the stations in the basins are considered in one spell. It was therefore decided to divide the basin in two parts as per the location of existing raingauge stations; one where aar is above 2000 mm and the other where it is below 2000 mm. Also as the precipitation during the monsoon period is critical for the flood protection structure, it was decided to consider the monsoon rainfall only for calculation of C_v. When first group of stations (Darranga, Goibergaon, Nagarjuli and Menaka) were considered, the required number of stations are three only and when the rest of the stations are considered, it comes to be equal to eight only. Hence, it may be concluded that for the whole basin total number of station required is 8+3= 11. The distribution of these stations will be three in north-central part and other eight to be well distributed in rest of the basin.

Key Station Network Method:

It has been tried to select the days in such a way that the rainfall data at maximum number of stations are available. Because of the unavailability of long term concurrent data at every station only nine stations (except Masalpur all is available) have been found (maximum possible) for which the data for 961 days are available. Key stations then, have been determined according to the procedure given in methodology. **Table-2** gives the details of combination of stations for determination of key stations and also their correlation. Determination of key stations helps in the reduction of network. It helps in deciding which stations are to be retained in the network to attain a certain accuracy level. The decrease in root mean squares error (RMSE) with the increase in the number of stations has been shown in **Table-3**. **Fig. 6**. shows the graphical representation of **Table-3** from which it can be seen that the RMSE decreses at faster rates till the seventh station and after the introduction of the eighth station in the combination the rate of decrease in RMSE is insignificant. It means 7 keys stations namely; Daranga, Goibargaon, Rangiya, Nagrijuli, Menaka, Hajo, Nayabasti may be considered as adequate and economical for estimation of average areal rainfall in the basin.

Thus the method suggests the exclusion of Uttarkuchi, Gerua stations from the network. This input is of vital importance when the redistribution of raingauge stations are determined. However, it is to be mentioned here that this methodology does not give any idea about the station (Masalpur) for which data is not available for the concurrent period.

Table-2. Correlation coefficient with different combination of stations

Sl No.	No. of stations in combination	Combination of stations	Key station	Correlation of key station
1	9	Daranga, Goibargaon, Rangiya, Nagrijuli, Menaka, Hajo, Nayabasti, Uttarkuchi, Gerua	Daranga	0.762385
2	8	Goibargaon, Rangiya, Nagrijuli, Menaka, Hajo, Nayabasti, Uttarkuchi, Gerua	Goibargaon	0.763693
3	7	Rangiya, Nagrijuli, Menaka, Hajo, Nayabasti, Uttarkuchi, Gerua	Rangiya	0.727482
4	6	Nagrijuli, Menaka, Hajo, Nayabasti, Uttarkuchi, Gerua	Nagrijuli	0.739477
5	5	Menaka, Hajo, Nayabasti, Uttarkuchi, Gerua	Menaka	0.776523
6	4	Hajo, Nayabasti, Uttarkuchi, Gerua	Hajo	0.82318
7	3	Nayabasti, Uttarkuchi, Gerua	Nayabasti	0.872339
8	2	Uttarkuchi, Gerua	Uttarkuchi	0.825515

Table-3. Change in the sum of the square of with increase in the number of station

No of stations	RMSE
1	21.45172
2	11.64701
3	6.956837
4	6.892627
5	5.19651
6	3.812188
7	2.047332
8	1.148477

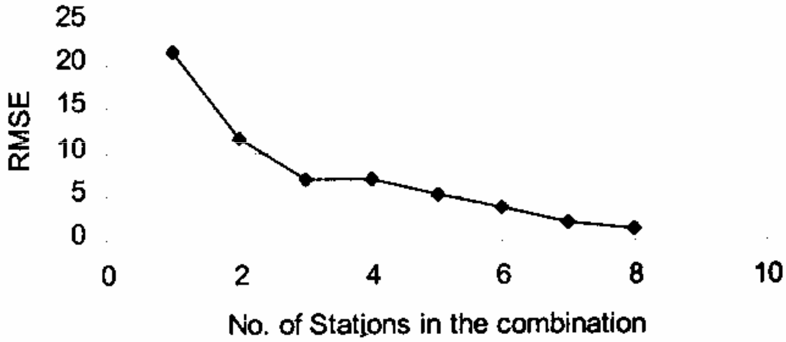


Fig. 6 Decrease in RMSE with increase in no. of stations

Spatial correlation Method

For spatial correlation method daily rainfall data has been used. As there are ten stations in the basin total 45 number of combination is possible out of which there is no concurrent data available for Gerua & Masalpur and Nayabasti & Masalpur, therefore, inter-station distance and their correlation for 43 combinations has been calculated and tabulated in **Table-4**. **Fig. 7** shows the line of best fit of the correlation and the distance (on semi log scale). The slope of this line is equal to -0.030996314 which is equal $1/d_0$ and the Y intercept is 0.009585797 which is $\log[\rho(0)]$. It means the value of d_0 is 32.2619 km and $\rho(0)$ is 0.990460. Then the relative error (root mean square error, RMSE) has been derived from the Eq. 5.9 and tabulated in **Table-5** which shows the decrease in relative error with increase in number of raingauge stations. This is also shown in **Fig. 8**. This figure shows that the gain in the accuracy of rainfall estimation is very insignificant after introduction of ninth station. It means eight stations can be recommended for the basin based on this study.

Table-4. Inter-station distance and their correlation

Station Name	Station Name	Distance	Correlation
Gerua	Daranga	6.635933	0.281523
Goibargaon	Daranga	6.720109	0.487851
Menaka	Uttarkuchi	7.234885	0.448008
Menaka	Gerua	8.698046	0.280573
Menaka	Daranga	9.633291	0.480566
Nagrijuli	Gerua	10.21089	0.17029
Goibargaon	Gerua	10.71486	0.346644
Masalpur	Nagarijuli	12.02968	0.254124
Nagrijuli	Goibargaon	13.37846	0.355068
Nayabasti	Rangiya	13.61854	0.368347
Nagrijuli	Daranga	14.43904	0.296527
Menaka	Masalpur	14.46311	0.645556
Uttarkuchi	Gerua	14.61809	0.24556
Masalpur	Uttarkuchi	15.72948	0.476863
Menaka	Goibargaon	16.2681	0.427164
Uttarkuchi	Daranga	16.85225	0.382571
Masalpur	Daranga	17.21371	0.451507
Menaka	Nagarijuli	18.79007	0.25819
Masalpur	Goibargaon	20.59654	0.468624
Hajo	Rangiya	20.63936	0.396006
Hajo	Nayabasti	20.87076	0.281303
Masalpur	Rangiya	23.24876	0.343275
Uttarkuchi	Goibargaon	23.42803	0.415388
Uttarkuchi	Nagarijuli	23.76972	0.24444
Nagrijuli	Rangiya	25.3396	0.281992
Nagrijuli	Nayabasti	31.36899	0.214145
Gerua	Rangiya	31.99795	0.299989
Nayabasti	Gerua	34.21938	0.907909
Uttarkuchi	Nayabasti	34.91605	0.257129
Menaka	Nayabasti	36.98174	0.282765
Menaka	Rangiya	37.68367	0.422015
Uttarkuchi	Rangiya	38.2408	0.369154
Daranga	Rangiya	38.24285	0.399103
Goibargaon	Rangiya	38.67579	0.39844
Nayabasti	Daranga	40.85275	0.298737
Masalpur	Hajo	42.0461	0.248119
Goibargaon	Nayabasti	43.41789	0.335313
Hajo	Nagarijuli	45.93341	0.193902
Hajo	Gerua	51.81685	0.265757
Hajo	Uttarkuchi	55.24055	0.177415
Menaka	Hajo	56.30718	0.430246
Hajo	Daranga	58.28824	0.36881
Hajo	Goibargaon	59.21265	0.335097

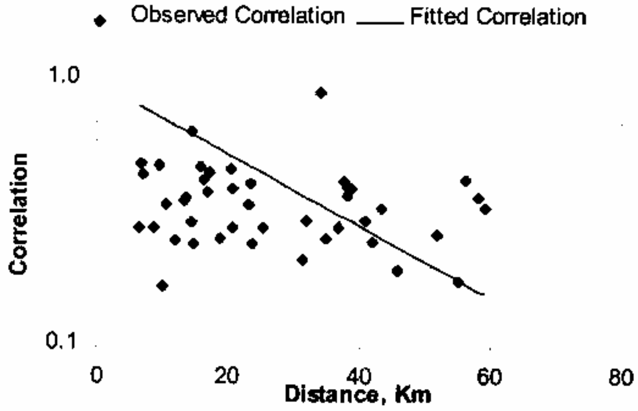


Fig. 7 Variation of correlation with inter-station distance

Table-5. Variation of relative root mean square with number of stations

Number of station	RMSE
1	0.776178
2	0.388089
3	0.258726
4	0.194045
5	0.155236
6	0.129363
7	0.110883
8	0.097022
9	0.086242
10	0.077618
11	0.070562
12	0.064682
13	0.059706
14	0.055441
15	0.051745

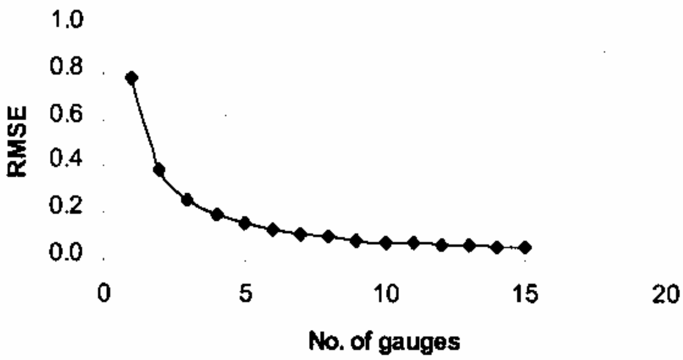


Fig. 8 Variation of relative root mean square error (RMSE) with number of stations

Entropy Method

The total annual rainfall at each station for all the available years were computed and used as basic data for this method. Since this method uses some numerical approximations for calculation of entropy, a computer programs was developed specifically for it. The detailed steps followed are presented below.

Using the basic time series data, the mean and variance for each station were estimated. Substituting these in Eqs. 5.16 and 5.17 the scale and shape parameters (σ and λ) at each point were estimated. The entropy of rainfall variable measured at each station, H(X) were computed using Eq. 5.21. This equation contains two functions viz. the digamma function ($\psi(X)$) and gamma function ($\Gamma(X)$). The values of these functions can not be estimated analytically for the entire range of X. Hence the numerical approximations (Appendix - I and II) for these functions were used to estimate their values. The estimated values of H(X) are presented in **Table- 6**.

Table-6. The estimated values of entropy, H(X) at each station location

Sl. No.	Name of Station	H(x)
1	Rangiya	6.5572
2	Daranga	7.6584
3	Gerua	7.1210
4	Nayabasti	7.2387
5	Goibargaon	6.6690
6	Nagrijuli	8.1847
7	Uttarkuchi	7.4961
8	Hajo	7.1237
9	Masalpur	6.6924
10	Menaka	6.8139

Using the mean and variance of the time series data, the rainfall at each station were transformed into normal variates and the correlation coefficient (ρ_{zw}) for each pair of station were computed from the normal variates. However, the correlation of some of the combinations, as explained in the previous section, could not be obtained because of paucity of concurrent data. Substituting ρ_{zw} values in Eq. 5.25 the information transmission, $T(Xi;X_j)$ for all the combination of stations were computed. The $T(Xi;X_j)$ matrix are presented in **Table-7**.

The entire study area was divided into seven triangles. The vertices of the triangles were decided in such a way that (a) correlation between all three stations at the vertices exist, and (b) none of triangles has any obtuse angle. The selection of triangles is shown in **Fig. 9**.

The information transformation at 10 points (equally spaced) along each side of all the triangles are then computed using Eqs. 5.27, 5.28 and 5.29. Using these information, information transmission contours are plotted as shown in **Fig. 10**.

Table-7. Information transmission matrix

Stn No. \ Stn No.	1	2	3	4	5	6	7	8	9	10
1	6.5573	0.0192	0.2154	0.0932	0.3585	0.0054	0.1767	0.0407	0.0643	0.0178
2		7.6584	0.2815	0.4118	0.2297	0.0240	0.1229	0.0501	0.0474	0.0938
3			7.1210	1.5565	0.0143	0.0819	-	0.1874	-	0.3763
4				7.2387	0.0008	0.1821	-	0.0848	-	0.6166
5					6.6690	0.0040	0.0021	0.0446	0.0004	0.2025
6						8.1847	0.0122	0.0722	0.0064	0.0374
7							7.4961	0.3331	0.0370	0.0329
8								7.1237	0.0039	0.0276
9									6.6924	1.2792
10										6.8139

- indicates non existence of correlation/ information transmission from the available data

The information contours shows the existence of very high level of information in the north-central part of the basin while few patches of sparse information zone is shown in the southern portion of the basin. But even these patches of low information zones are having information more than 50%. It means, the overall information availability in the basin is too high and when we go for locating the sites less than 55% of information zone, very few and small region appears, between Rangiya and Nayabasti. Also, the isohyetal map of the basin for monsoon season **Fig. 3(b)**, most critical period, shows the uniform variation rainfall in the southern part of the basin and comparatively higher variation in the north-central part. From these two maps it can be infer that more than adequate number of stations are already available in the high variability rainfall region and also even for the shadow zone no additional stations is required.

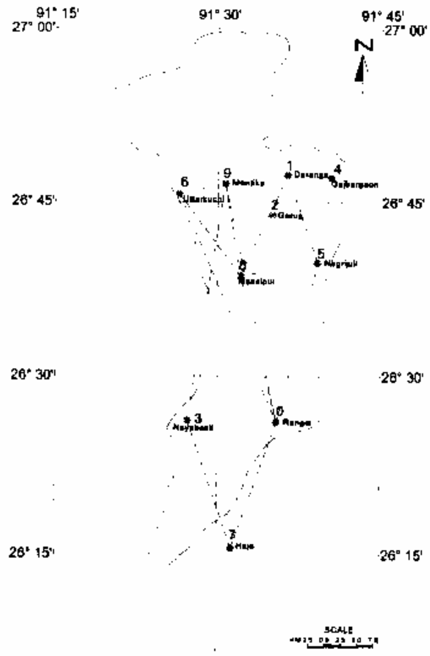


Fig. 9 Study area divided into feasible triangles by joining selected stations

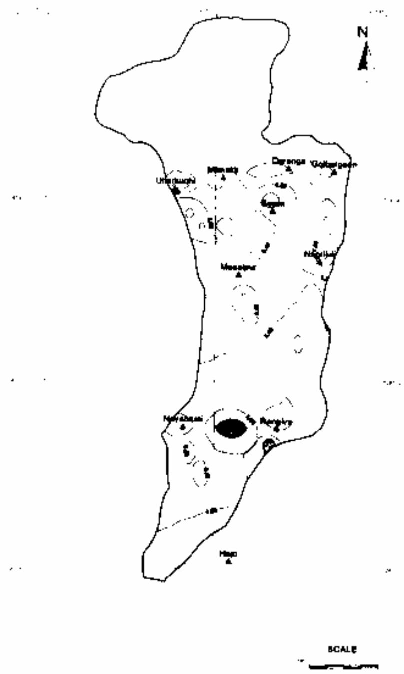


Fig. 10 Information contours

7.0 CONCLUSIONS:

The various methods suggested that the rainfall in the basin is not sampled well. Except C_v method (which suggests 11 numbers of stations), the study shows that maximum 8 number of stations are adequate to represent the rainfall in the plain area of the basin. No method other than IS method says anything about the number of stations in the hilly part of the basin which is mostly in the Bhutan territory. IS method recommends 4 number of stations in this hilly portion. Therefore, it may be inferred from this study that total number 12 stations are required in the basin, 4 in the hilly portion and another 8 in the plains. As there are already 10 number of stations available, 2 stations may be discontinued (Uttarkuchi and Gerua as suggested by Key Station Index Method). Also Entropy Method shows very high concentration of information in the north-central part of the basin, the discontinuation of these two stations will not affect the adequacy of the network.

The suitable location for the raingauge stations in the hilly portion should be well distributed. As the topo-sheet of the Bhutan area could not procured, it is not possible to suggest the exact site for raingauges, but the possible locations has been marked in **Fig. 11**

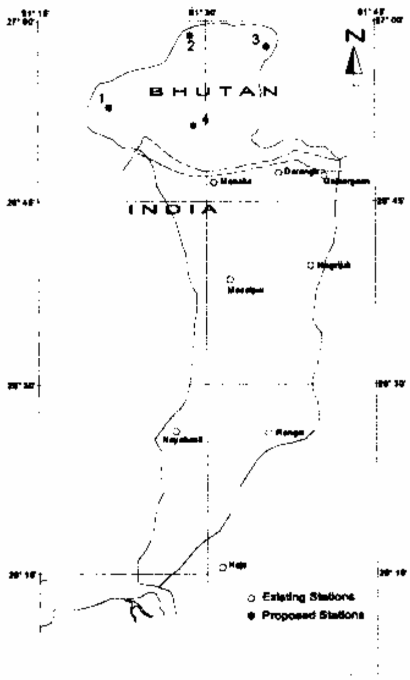


Fig. 11 Proposed raingauge locations in the basin

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APPENDIX - I

Numerical approximation of Gamma function

Gamma function is given by,

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t}\, dt$$

For integer arguments the function is simply the factorial function as,

$$\Gamma(x+1) = x!$$

However, for non integer arguments the following approximation (Lanczos, as reported by Press et al.) may be used.

$$\Gamma(x+1) = \left(x + \gamma + \tfrac{1}{2}\right)^{\left(x+\frac{1}{2}\right)} e^{-\left(x+\gamma+\frac{1}{2}\right)}$$
$$\times \sqrt{2\pi}\left[c_0 + \frac{c_1}{x+1} + \frac{c_2}{x+2} + \ldots + \frac{c_N}{x+N} + \varepsilon\right] \quad (\forall x > 0)$$

The error term is parameterised by ϵ. For γ=5 and N=6, and a certain set of constants (i.e., c_0 to c_6), the error is smaller than 2×10^{-10}. The set of constants are given by

$c_0 = 1.000000000190015$

$c_1 = 76.18009172947146$

$c_2 = -86.50532032941677$

$c_3 = 24.01409824083091$

$c_4 = -1.231739572450155$

$c_5 = 0.1208650973866179 \times 10^{-2}$

$c_6 = -0.5395239384953 \times 10^{-5}$

APPENDIX - II

Numerical approximation of Digamma function

Digamma function is given by,

$$\psi(x) = \frac{\partial \ln(\Gamma(x))}{\partial(x)}$$

Where, C is the Eular's constant given by 0.5772156650

For integer arguments the function is simply the factorial function as,

$$\psi(x) = \sum_{k=1}^{x} \frac{1}{k} - C$$

However, for non integer arguments the following approximation may be used (Schied, F, 1989)

$$\psi(x) = \sum_{i=1}^{\infty} \frac{x}{i(i+x)} - C$$

Which can be rewritten as

$$\psi(x) = \sum_{i=1}^{\infty} \left(\tfrac{1}{i} - \tfrac{1}{i+x}\right) - C$$

The value of $\psi(x)$ can be obtained taking the iterative sum of the series formed by the above equation. The iterations are stopped at the value of 'i' when the term in the parenthesis becomes less than some error criterion (e.g. 1×10^{-10}).

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