CASE STUDY

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FLUVIAL GEOMORPHOLOGICAL CHARACTERISTICS OF FOUR SUB BASINS OF UPPER NARMADA

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PREFACE

It is a well known fact that the climate and geomorphological characteristics of a basin affect its response to a considerable extent. Thus, linking of geomorphological parameters with hydrological characteristics of a basin provides a simple way to understand their hydrological behaviour. Quantitative study of geomorphological parameters is prerequisite for taking up hydrological simulation studies using these parameters. The geomorphological properties that are important to the hydrological simulation studies include the linear, areal and relief aspects of the basin. Many investigators had suggested various measures to represent the linear, areal and relief aspects of the basin.

In this report an attempt has been made to present methodology to quantify various geomorphological parameters. The geomorphological parameters evaluated for four sub basins of upper Narmada are discussed in hydrological context. Effect of map scale on parameter evaluation is also addressed by studying one of the four sub-basins as special case. Brief discussion about utility of various parameters estimated is discussed. This report is aimed to give commonly used geomorphological parameters of four sub basins of upper Narmada for further hydrological studies. This study has been carried out by Shri M. K. Jain, Scientist B, and Shri U. K. Singh, R. A. in the Mountain Hydrology Division, National Institute of Hydrology, Roorkee.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The geomorphological characteristics of a watershed represent its attributes which can be employed in synthesizing its hydrological behaviour. For hydrological studies, geomorphological characteristics can be divided in three groups; (i) linear aspects, (ii) areal aspects and (iii) relief aspects. In this study various geomotphological parameters representing linear, areal and relief aspects of four sub basins of upper Narmada are evaluated. The relations between stream order versus number of streams, mean stream length, and mean drainage area are established. Inter comparison of these basins is attempted based on various geomorphological parameters. Effect of map scale is also evaluated by treating one of the basin as special case and for that, various geomorphological parameters have been evaluated in 1:2,50,000 and 1:50,000 map scales. It was observed that most of the important geomorphological parameters such as area, length of main stream, length to C. G., basin perimeter and dimensionless parameters such as area ratio, bifurcation ratio, length ratio etc. remain fairly constant with change of scale of measurement. However, noticeable differences were observed in drainage density, constant of channel maintenance and stream segment frequency with change of scale of measurements.

The geomorphological parameters, thus estimated, may be used for developing the hydrological models to simulate hydrological response of the basin. Such models are very useful and are being widely used for simulating hydrological response of ungauged basin or basin with limited data.

1.0 INTRODUCTION

One of the most important tasks in theoretical as well as practical hydrology is to find the laws of runoff processes in river basins. The difficulty of this task increases when there is a lack of hydrological data as often happens in mountainous areas. It is a well known fact that the climate and geomorphological characteristics of a basin affect its response to a considerable extent. Thus, linking of geomorphological parameters with hydrological characteristics of a basin provides a simple way to understand their hydrological behaviour and particularly of the ungauged basins.

Quantitative study of geomorphological parameters is prerequisite for taking up hydrological simulation studies by using these parameters. The geomorphological properties that are important to the hydrological simulation studies include the linear, areal and relief aspects of the basin. Many investigators had suggested various measures to represent the linear, areal and relief aspects of the basin. In this study various geomorphological aspects such as linear, areal and relief aspects of four sub basins of upper Narmada, namely, Narmada upto Manot, Burhner upto Mohegaon, Banjar upto Hridenagar and Sher upto Belkheri are evaluated. The toposheet maps of the scale of 1:2,50,000 covering these four sub basins were used. Effect of change of map scale on various geomorphological parameters evaluated, is also studied by analysing Sher sub basin in 1:50,000 map scale. The derived geomorphological characteristics can be utilized for hydrological studies of these sub-basins as well as for the hydrological studies of the region. Some potential applications of geomorphological studies are also reviewed. Inter-relationship among various parameters is attempted to identify independent parameters which can be used together in regional studies.

2.0 APPLICATION OF GEOMORPHOLOGICAL PARAMETERS IN HYDROLOGY

A large number of studies (Brush 1961, Coulter 1961) have related indices of drainage basin composition rock and soil type, vegetation and land use to hydrological behaviour, especially measures of water and sediment yields and their frequency distributions. Of all the indices, the basin area, drainage density, main stream length and main stream slope appears to have been utilized most frequently.

Snyder (1938) employed basin area, main stream length, and main stream length to the centroid of the area to synthesize unit hydrograph lag, peak flow and peak time. Taylor and Schwartz (1952) used these as well as mean stream slope to synthesize the runoff hydrograph. A large number of studies (Laten et al. 1940; US Army Corps of Engineers, 1954; O'kelly, 1955; Gray, 1962; Morgan and Johnson, 1962; Mirajgaonkar and Chitambaran, 1963; Askew, 1963; Hopkins and Kachis, 1964; Schulz et al., 1971; Body et al.,1979) have since appeared on synthesis of unit hydrographs in ungauged areas. Recently, Rodriguez-Iturbe (1982); Rodriguez-Iturbe et al.(1982); Rodriguez-Iturbe and Valdes (1979); Gupta et al. (1980), Singh (1983), Pristochova (1990) employed bifurcation ratio, length ratio, area ratio, stream lengths and stream areas for synthesizing unit hydrograph. Rosso (1984) gave relation between Nash model parameters and Horton's order ratios. Zelazinski (1986) applied GIUH theory to evaluate parameters of two conceptual models.

White (1975) classified 112 basins in Pennsylvania and surrounding states according to drainage density, Channel slope, shape factors, and geometric factors for the purpose of evaluating their flood potential. Clang and Body (1977) used watershed and climate factors for estimation of low flows. Ebisemiju (1979) used drainage density, stream numbers, ˋam lengths, and relief for identifying morphologically and hydrologically uniform basins. A study by Patton and Baker (1976) concluded that drainage density, steam magnitude and relief ratio are practical measures of flood potential in basins smaller than 100 mile in area.

Melton (1957) found a strong correlation of drainage density with the ratio of average annual precipitation to average annual evaporation. A comprehensive account of potential application of drainage density was given by George (1977, 1979) and Gurnell (1978).

2.1 Development of Empirical Formula

The approach involving the establishment of the relationships between model parameters and physically measurable watershed characteristics is well recognised for the estimation of runoff for ungauged watersheds. Many empirical relationships have been developed for estimating the discharge characteristics from rainfall and watershed characteristics (Kinnison and Colby, 1945; Chow, 1962; Thomas and Benson, 1970; Duru, 1976; Chang and Boyer, 1977; Aron and Miller, 1978; Dingman, 1978; Crippen, 1982; Aron, Kibler and Taghati, 1981; Mosley, 1981; Adejuwan, Jeje and Ogunkoya, 1983; Mimikou, 1983; Harlin, 1984). Out of various characteristics considered, the peak discharge has been the most popular which have been frequently used in hydrograph synthesis (Snyder, 1938; Carter, 1961; Wu, 1963; Rao, Assenzo and Harp, 1966; Bell, 1967; Larson and Machmeier, 1968; Bell and Omkar, 1969; Cordery, 1971).

Even though these relationships are simple in nature but the scope of these applications is somewhat limited. Whenever relationships are used one should be very cautious in their application. They should be generally used in the regions for which they were developed. A measure drawback of these equations arises not so much from their empirical nature but more so from the lack of knowledge of exact conditions of their applicability.

2.2 Regional Unit Hydrograph Studies

The unit hydrograph technique is one of the most popular and powerful technique available for the estimation of design flood. It represents the integrated effect of various physical features on the routing of the rainfall input through the catchment system. For gauged catchments, the available rainfall-runoff records may be analysed to derive the unit hydrograph of desire duration. However, most of the small catchments are generally having either limited data or not at all gauged. Therefore, the unit hydrograph characteristics for such catchments have to be estimated by using data on climatological, physiographic, geomorphologic and other factors of these catchments. This could be achieved by relating the physical and geomorphological characteristics of the catchments, falling in a hydrometeorologically homogeneous region, with the unit hydrograph parameters. Most commonly used physical characteristics of the catchment include length of the main stream, length of a stream from a point on the stream nearest the centroid of the catchment to the outlet, catchment area and average slope of the main stream etc.

A large number of regional unit hydrograph studies have been carried out in different parts of the world. Prominent among others include studies carried out by Bernard (1935), Snyder (1938), McCarthy (1938), Commons (1942), Taylor and Schwartz (1952), Soil Conservation Service (SCS) (1955, 1971), Ardis (1972, 1973), Clark (1945), O'Kelly's (1955), Minshall (1960), Nash (1960), Gray (1961), Hall (1974, 1977), NERC (1975) and Sangvaree and Yevjevich (1977), which are worth mentioning. In India also some efforts have been made to develop the regional unit hydrograph relationships. The small catchment directorate of CWC have carried out the regional unit hydrograph study by dividing whole of India in 26 hydrometeorological sub-zones. All the major storms are analysed for each of the gauge catchments to derive reasonable representative unit hydrographs for these sub-zones. The unit hydrograph parameters are related with physical characteristics of the catchment of a sub-zone in order to develop regional unit hydrograph relationship for that sub-zone.

Singh (1984) developed the regional unit hydrograph relationships for Godavari basin sub-zone 3f relating the average parameters of Nash Model and Clark Model with the physical characteristics of the five gauged catchments.

Thus the derivation of physical and geomorphological characteristics of the catchments is necessary in order to develop better regional unit hydrograph relationships.

If the geomorphological parameters are readily available, one may try various forms of the regional relationships in India to arrive at the suitable form of the regional unit hydrograph relationships.

2.3 Regional Flood Frequency Analysis

Flood Frequency Analysis approach is used to estimate the design flood of the desired frequency by analysing the historical flood records. For a gauging station having adequate length of record, flood frequency analysis can be performed exclusively on the record of that station. But generally annual flood series available at site of interest is short, therefore it may not be able to provide the consistent and reliable flood estimates particularly for the higher return periods. In such situation the regional flood frequency approach, wherein the at site data together with the regional information are utilized, may be preferred. For the ungauged sites the regional frequency analysis may be carried out using only the regional information in the form of regional frequency curve together with an estimate of mean annual flood obtained from the appropriate relationship established between the mean annual flood and geomorphological characteristics for the hydrologically homogeneous region. Some of the important geomorphological characteristics which may influence the mean annual flood at a given site are catchment area, streamflow, land slope, stream density, stream pattern and elevation etc. In addition to these the channel storage, artificial and natural storage in lakes and ponds, orographic conditions, underlying geology, soil cover and cultivation etc. also influence the mean annual flood.

Out of various regional flood frequency analysis studies carried out in India and abroad, some have been reviewed with particular reference to the geomorphological characteristics used in respective studies.

(a) Method used by U.S. Geological Survey :

The methods and practices of Geological Survey to carry out regional flood frequency analysis have been brought out in the form of a manual under Geological

Survey Water Supply paper 1543-A by T. Dalrymple (1960). The proposed analysis provided for development of two curves. The first curve expressed the graphical relationship between the median ratios of different recurrence interval flood to the mean annual flood, with recurrence interval. The second curve relates the mean annual flood to the size of drainage area alone or some other significant basin characteristics. These two curves together form the regional frequency relationship for a homogeneous region whose homogeneity has been tested using a recommended procedure by U.S. Geological Survey Dept. at the level of 10 years recurrence interval. For estimating the flood of desired frequency for ungauged catchment the drainage area and appropriate basin characteristics are derived from the maps of the respective catchments located in the homogeneous region. Further the relationship between the mean annual flood and basin characteristics is utilized to estimate the mean annual flood knowing the appropriate basin characteristics. The frequency curve developed for the region is used to estimate the flood of desired recurrence interval for the ungauged catchment.

(b) Methods based on U.K. flood studies report :

A comprehensive report brought out by NERC (1975) in five volumes dealing with hydrological studies, meteorological studies, flood routing studies, hydrological data and maps on the basis of work carried out in different organizations of the United Kingdom. For regional applications extensive studies have been carried out for flood estimation from catchment characteristics, so that where no record is available at a site, a preliminary estimate may be made from relations between floods and geomorphological characteristics. Various catchment geomorphological characteristics, Meteorological characteristics and other important characteristics selected and utilised in the studies include Catchment area, Stream frequency, soil type, climate, Taylor-Schwartz slope and S1085 slope in (m/km). The S1085 can be easily calculated. But as it depends on the two points on the profile, it may be more affected by measurement errors. The Taylor-Schwartz slope is based on the square root of the gradients and it uses the fact that velocity for each reach of a sub-divided main-stream is related in the manning's equation to the square root of slope. The index is equivalent to the slope of a uniform channel having the same length as the longest water course and an equal time of interval.

Nash and Shaw (1966) analysed discharge records of 57 catchments of Great Britain and the parameters of the frequency distributions of annual maximum flood peaks were correlated with the catchment area, slope and mean annual rainfall of the catchments. The authors also provided method for working out the variance of the estimate of the flood of any given return period using Gumbel and log-normal distributions and the regression relationships.

Cole (1966) applied the USGS procedure of regional flood frequency analysis to the data of stations in Eastern England for 1939-60 and Western England and Wales for 1938-62. The author also established the relationships between mean annual flood and catchment area for different homogeneous groups of the catchment.

(c) Regional flood estimation procedure in Australia :

Ward (1968) presented a procedure using regional flood estimation technique for stream gauging stations with limited data. The procedure involved establishing the relationship between the mean daily discharge of 10 years recurrence interval with catchment area. Then the average ratio of instantaneous peak discharge to mean daily discharge are determined for the stream using available data. Subsequently the value of the drainage discharge for 10 years recurrence interval is multiplied by the average ratio. The peak discharges for other recurrence intervals can also be estimated by applying the same ratio.

(d) Typical Studies in India :

Goswami (1972), Thiruvengadachari et al. (1975), Seth and Goswami (1979), Jakhade et al. (1984), Seth and Goel (1985), Perumal & Seth (1985), Goel & Seth (1985), Rao and Goel (1986), Huq (1985), Venkataraman and Gupta (1986), Venkataraman et al (1986), Thirumalai and Sinha (1986), Mehta & Sharma (1986), James et al (1987) and Gupta (1987) have carried out regional flood frequency analysis for different regions in India. In most of the studies the mean annual floods were related with catchment area. Average slope, length of main stream and shape factor of the catchment were also tried in some of the regional flood frequency studies.

Perumal and Seth (1985), Singh and Seth (1985), Huq et al (1986) and Seth and Singh (1987) have carried out regional flood frequency analysis for few typical regions in India using the new approaches. However the problems related with regional homogeneity and the regional relationship between the mean annual flood and catchment characteristics are still unresolved. Even today the catchment area is being considered as one of the prominent catchment characteristics while developing the regional relationship for the mean annual flood. One of the reasons is the non availability of other prominent geomorphological properties for the catchment.

Thus there is an urgent need to quantify the various important geomorphological properties for different catchments so that a reliable relationship could be established for estimating the mean annual flood for ungauged catchments.

2.4 Geomorphological Instantaneous Unit Hydrograph (GIUH) Studies

The Rodriguez-Iturbe & Valdes (1979) has synthesized the hydrologic response of a catchment to surface runoff by linking the IUH with the geomorphological parameters of a basin. Equations of general character are derived which express the IUH as a function of Horton's numbers R_A, R_B and R_L, an internal scale parameter and a mean streamflow velocity. The IUH is time varying in character both throughout the storm and for different storms. This variability is accounted for by the variability in the mean streamflow velocity. Gupta et al. (1980) has related the approximate linear response of a river basin to its geomorphological characteristics and a representative linear response of channels of a given order.

Valdes et al (1979) have derived the instantaneous unit hydrograph from the geomorphologic characteristics of the basin and a time component, the velocity of the discharge using the concept presented by Rodriguez-Iturbe & Valdes (1979). To analyze this geomorphologic IUH in real world basins, study was carried out on several basins in Venezuela and Puerto Rico. The geomorphologic IUH for each basin was compared with the IUH's derived from the discharge hydrograph produced by a physically based rainfall-runoff model of the same basins. The effects that the nonlinearities of the rainfall runoff model have on the derivation of the IUH are analyzed, and further, controlled experiments are carried out in which the IUH is derived under constant velocity conditions. The geomorphologic IUH's and the ones obtained in the experiments are remarkably similar in all the basins analyzed.

Rodriguez et al (1982) and Wang et al (1981) have also studied the parameterization of the channel linear response functions, mainly the velocity terms appearing in the exponential distribution assumed by Rodriguez, Iturbe & Valdes (1979). From the studies it may be observed that the IUH of each channel may be derived from the applicable differential equations of motion. It is also apparent that the resulting channel responses are considerably different from those obtained by Rodriguez-Iturbe & Valdes (1979).

M. Krishen & Bras (1983) has derived the instantaneous unit hydrograph as a function of basin geomorphological and physiographic characteristics. The response of the individual channels composing the basin is inherent in the basin IUH. The response of the individual channels is derived by solving the continuity and momentum equations for the boundary conditions defined by the IUH. Both the effects of upstream and lateral inflow to the channels is taken into account in the derivation of the basin's IUH. The time to peak and peak response are used as a basis for comparison between the results produced by this model and those produced by a model where the channel's response is assumed to be an exponential distribution. The comparisons indicate that of the approach taken is indeed accurate, for example, the assumptions used do not invalidate the model, then the type of channel response used for the basin's IUH is significant, and future efforts must be directed towards parameter estimation.

Beven & Wood (1983) also examined the dynamic nature of runoff contributing areas and their relationship to the geomorphological structure of catchments. It has been shown that both runoff and flood frequency predictions are very much sensitive to assumptions about the nature of the contributing area. A methodology for predicting variable contributing areas on the basis of initial storage deficits to allow the prediction of combined surface and subsurface responses. It is felt that this improves on the earlier response model of Beven and Kirkby (1979) by allowing the feeling of initial deficit and a more explicit treatment of time delays in the unsaturated zone in predicting the contributing areas.

2.5 Application of Geomorphological Parameters in other Hydrological Studies

Black (1972) conducted a study with an objective of ascertaining the effect of selected watershed characteristics on hydrograph parameters under a rainfall simulator. Since most of the runoff contributing to the peak flow was found to emanate from the lower half of the drainage, a measure of watershed eccentricity utilizing easily measured properties in that area is derived and evaluated as a reliable predictor of peak magnitude. Studies were made into the similarities between the models and real world watersheds. Three of the several conclusions are : 1) the models exhibit hydrologic responses similar to those of a wide range of real watersheds, 2) watershed shape does not have a tremendous effect on peak magnitude, and 3) watershed eccentricity is an effective, easily measurable and useful expression of watershed shape and affects maximum peak flows and certain time parameters of the hydrograph.

The problems of geomorphic description, hydraulic similitude, equipment, model studies (Black 1970a) and size hydrograph relations (Black & Cronn 1972) have been discussed by many investigators. The studies conducted by Gravato & Eagleson (1970) and Roberts and Kungeman (1970) have adequately shown the limitations and feasibilities of using laboratory model studies for basic investigations and for successful application and relation of results to real world watersheds as interpreted from the works of Chow (1967) & Wooding (1966). Hall and Wolf (1967) asserted that the shape of the hydrograph resulting due to uniform rainfall patterns may be governed by the watershed characteristics. Further the shapes of the hydrograph are determined solely by catchment characteristics if the catchment are large enough for the effects of any local variations in rainfall intensity to be damped. At the other stream, however geomorphic influences are more pronounced on smaller watersheds where regional climatic factors that influence runoff characteristics are modify producing the well documented hydrographic area concept of descriptive hydrology (Black 1970b). Overton (1968) found that the shape variate, based on a length width ratio, was one of four component which jointly represented 85% of the total explained variance of the data used. The other three were slope, size and a drainage variate which alongwith the first component of shape used for identification of any basin characteristic.

Pilgrim (1982) discussed some problems in transferring hydrological relationships between small and large drainage basins and between regions. The study illustrates the facts that basin processes vary considerably from one region to another, and over small distances within one region. These processes include the type and characteristics of storm runoff, small scale variations in infiltration and runoff, spatial aspects of non-linear flood response, annual runoff relations and channel transmission losses. The problems in identifying similarity relationships resulting from interaction of model parameters with basin size and from random and systematic errors in available hydrologic data are also discussed with the help of few specific examples.

3.0 PROBLEM DEFINITION

Fluvial geomorphological characteristics are needed for rainfall-runoff analysis from ungauged catchments for establishing regional relations such as development of regional unit graph, regional flood frequency analysis and geomorphological unit graph etc. These parameters are also extensively used in low flow studies and water availability studies. The estimation of such parameters gains further importance in case of hilly catchments because direct measurement of hydrologic data is difficult in such areas. Quantification of these parameters is cumbersome and time taking.

In this study, various geomorphological parameters of four sub basins of upper Narmada, namely, Narmada upto Manot, Burhner upto Mohegaon, Banjar upto Hridenagar and Sher upto Belkheri are evaluated. Effect of change of map scale on various geomorphological parameters evaluated, is also studied by analysing Sher sub basin in 1:2,50,000 and 1:50,000 map scales. Inter-relationship among various parameters is attempted to identify independent parameters which can be used together in regional studies.

4.0 METHODOLOGY

Systematic description of the geometry of a drainage basin and its stream channel system requires the following measurements (i) linear aspect of drainage network, (ii) areal aspect of drainage basin, and (iii) relief aspect of channel network and contributing ground slopes. Here, the first two categories of measurement are planimetric (i.e. treat properties projected upon a horizontal datum plane) and the third category treats the vertical inequalities of the drainage basis forms.

4.1 Ordering of Streams

For all practical purposes, the quantitative study of channel networks used to begin with Horton's (1945) methods of ordering of channels. Later on, Strahler (1952) proposed a modification of Horton's ordering scheme. Strahler's method is now generally preferred due to its simplicity and greater freedom from subjective decisions. In this report, the Strahler's method will be employed. There are three steps involved in Strahler's ordering procedure.

(i) Channels that originate at a source are defined to be first order streams;

(ii) When two stream of order w joins, a stream of order (w+1) is created; and

(iii) When two streams of different order joins, the channel segment immediately downstream has the higher order of the combining streams.

4.2 Linear Aspects

In linear aspects, those parameters representing length are considered. Linear measures proposed by various investigators which are of importance in hydrological studies, are described below. The methodology used to quantify them is also stated.

4.2.1 Number of streams of given order (N_w)

The quantity N_w represent total number of all streams, counted as the stream segments, having the order, "w" present in the watershed. Since a watershed of a given order can be modelled as a collection of elements of lower orders, the number of streams of each order is an important concept in hydrologic synthesis.

4.2.2 Bifurcation Ratio (R_B)

The bifurcation ratio for a given channel network can be obtained by determining the slope of the fitted regression of the plot of the logarithm of number of stream on ordinate versus order on abscissa. The regression coefficient, b is identical with the logarithm of R_B. The R_B is a dimensionless quantity and shows only a small variation from region to region. The value of R_B varies normally between 3 to 5 and is a useful index for hydrograph shape for watersheds similar in other respect. The R_B computed using Horton's law of stream numbers which states, "The number of stream segments of each order form an inverse geometric sequence with order number" or

$$N_w = R_B^{k-w}$$

Where; k is the order of trunk segment and N_w is the number of segments of order w. Taking log we have,

$$\log N_w = a - bw$$

where;

$$a = k \cdot \log R_B$$

$$b = \log R_B$$

or;

$$R_B = \log^{-1}(b)$$

For computing R_B, linear regression based on least square approach is used.

4.2.3 Length of main channel (L_Ω)

This is the length along the longest water course from the outflow point of designated sub basin to the upper limit of the catchment boundary. Several methods are available to measure length. In this study length is measured by traversing a divider along the main stream.

4.2.4 Mean stream length ($\bar{L}_w$)

Mean stream length is the total length of all streams of order w in a given drainage basin divided by number of stream of order w. or;

$$\bar{L}_w = \frac{\sum_{i=1}^{N_w} L_i}{N_w}$$

4.2.5 Stream Length Ratio (R_L): This is the ratio of mean stream length of order w to the mean stream segment length of order (w-1):

$$R_L = \frac{\bar{L}_w}{\bar{L}_{w-1}}$$

The value of R_L ranges normally between 1.5 and 3.5 in natural networks. The R_L is calculated by using Horton's law of stream lengths and stream numbers, or;

$$L_w = \sum_{i=1}^{w} \sum_{j=1}^{N} L_{ij} = \bar{L}_1 R_b^{w-1} \frac{R_{Lb}^{w}-1}{R_{Lb}-1}$$

Here; L_w, L_1 and R_L are known. The above equation is solved for R_{Lb} by using Newton-Rapson non-linear optimization technique. The R_L is calculated by

$$R_L = R_{Lb} R_B$$

4.2.6 Length of overland flow (L_o)

The length of over land flow can be defined as the length of flow of water over the ground before it becomes concentrated in defined stream channels. It can be measured as the length of flow path, projected to horizontal, of non channel flow from a point on the drainage divide to a point on the adjacent stream channel. Horton recommended using half the reciprocal of drainage density D for the average length of over land flow L_0 for entire watershed.

$$L_o = \frac{1}{2D}$$

4.2.7 Length of channel between outlet and a point near to C.G. (L_c)

It is the length of the channel measured from the outlet of the catchment to a point on the stream nearest to the centroid of the basin.

4.2.8 Basin length (L_b)

It is defined as the distance between outlet and farthest point on the basin boundary.

4.2.9 Watershed eccentricity (τ)

Watershed eccentricity is given by

$$\tau = \frac{\sqrt{L_c^2 - W_L^2}}{W_L}$$

Where;

τ = watershed eccentricity, a dimensionless factor

L_c = length from the watershed mouth to the centre of mass of the watershed

W_L = the width of watershed at the centre of mass and perpendicular to L

It is to be noted that if L = W , τ = 0, and as either L or W increases, τ increases. Thus the lower the value of τ, the greater the compactness of the watershed concentrated near to the mouth and higher the peak flood. The τ is calculated using formula described earlier.

4.2.10 Basin perimeter (P)

Basin perimeter is defined as the length of the watershed divide which surrounds the basin. The perimeter P of the basin is obtained using the same procedure as for length.

4.2.11 Wandering ratio (R_w)

The wandering ratio can be defined (Smart and Surkan, 1967) as the deviation of the main stream path from the straight line length extending from mouth to tip of the main stream. It should be noted that for abnormally shaped basins, the straight line distance from tip to mouth may not follow valley. The resulting value of Rw may, therefore, be unusually high.

4.2.12 Fineness ratio (R_{fn})

Mèlton (1957) defined the fineness ratio as the ratio of channel length to the length of the basin perimeter.

4.3 Areal Aspects

In areal aspects those Geomorphological parameters are considered which represent area. Some of these include drainage area (A), drainage density (D), constant of channel maintenance (C), area ratio (R_A), circularity ratio (R_c), elongation ratio (R_e), watershed shape factor, unity shape factor, form factor (R_f), Channel segment frequency and are defined by Chow (1964) and Singh (1989).

4.3.1 Drainage area (A)

Drainage area represents the area enclosed within the boundary of the watershed divide. The drainage area A is probably the single most important characteristics for hydrologic design. It reflects the volume of water that can be generated from rainfall.

Catchment area is calculated using digital planimeter by calibrating it for map scale and traversing its curser along basin boundary. Now boundaries for different order streams are worked manually and their areas (A_i) are also calculated using the same procedure.

4.3.2 Drainage density (D)

Drainage density is defined as the ratio of total length of channels of all orders in the basin to the drainage area of the basin. The drainage density is calculated using formula.

$$D = \frac{\sum_{i=1}^{w}\sum_{j=1}^{N_i} L_{ij}}{A_w}$$

4.3.3 Constant of channel maintenance, (C)

Constant of channel maintenance is defined as the ratio between the area of a drainage basin and total lengths of all the channels expressed as square metre per metre. It is equal to the reciprocal of drainage density. This parameter indicates the number of square meters of watershed surface required to maintain one linear metre of channel. It is calculated as,

$$C = \frac{1}{D}$$

4.3.4 Stream frequency (F)

Stream frequency is defined as the number of streams per unit area. Melton (1956) analysed in detail the relationship between drainage density and stream frequency and gave following relation,

$$F = 0.694D^2$$

Stream frequency, F is computed as the number of streams per unit area. Or;

$$F = \frac{N}{A}$$

where,

N is the total number of segments of all orders in the catchment area and A is the drainage area of basin.

4.3.5 Circularity ratio (R_c)

Basin circularity ratio is defined as the ratio of the basin area to the area of a circle having circumference equal to the perimeter of the basin. As the basin shape approaches to a circle, the circularity ratio approaches to 1. It is computed as the ratio of basin area to the area of a circle having same perimeter as of the basin.

4.3.6 Elongation ratio (R_e):

It is defined as the ratio between the diameter of a circle with the same area as the basin and basin length. The value of R_e approaches to 1 as the shape of the basin approaches to a circle. This ratio varies from 0.6 to 1 over a wide variety of climatic and geologic regimes. Typical values are close to 1 for areas of very low relief and are between 0.6 and 0.9 for regions of strong relief and steep ground slope.

4.3.7 Form factor (R_f)

Horton defined form factor, as the ratio of basin area A, to the square of basin length, L. The R_f is a dimensionless parameter and is computed as;

$$R_f = \frac{A}{L^2}$$

4.3.8 Unity shape factor (R_u)

The unity shape factor was introduced by smart and Surkan (1967) and can be defined as the basin length (L_b) to the square root of the basin area.

$$R_u = \frac{L_b}{\sqrt{A_w}}$$

4.3.9 Watershed shape factor (W_s)

The watershed shape factor, W_s was defined by Wu et al (1964) as the ratio of main stream length, L_Ω to the diameter D_c of a circle having the same area as of watershed. Or;

$$W_s = \frac{L_\Omega}{D_c}$$

4.4 Basin Relief Aspects

In relief aspects, the parameters evaluated are discussed below:

4.4.1 Total relief (H)

The basin relief or total relief is the maximum vertical distance between the lowest (outlet) and the highest (divide) points in the watershed. It has been defined in several ways. Schumm (1956) measured it along the longest dimension of the basin parallel to the principal drainage line. On the other hand, Maxwell (1960) measured relief along the basin diameter, an objectively defined axial line, whereas Strahler (1954, 1957) obtained it by determining the mean height of the entire watershed divide above the outlet. Relief is an indicative of the potential energy of a given watershed above a specified datum available to move water and sediment down slope. In this study relief is measured as the maximum vertical distance between the outlet and the highest (divide) point in the watershed.

4.4.2 Relief ratio (R_h)

The relief ratio is a dimensionless ratio and can be defined as the ratio between the relief and the distance over which the relief is measured. It measures the overall steepness of the watershed and can be related to its hydrological characteristics.

4.4.3 Relative relief (R_p)

Melton (1957) defined relative relief as the ratio of basin relief H to the length of the perimeter, P. It is an indicator of general steepness of the basin from summit to mouth. It is computed using equation;

$$R_p = \frac{H}{P}$$

4.4.4 Ruggedness number (R_n)

Melton (1957) and Strahler (1958) defined a dimensionless number called Ruggedness number, R_n as a product of relief, H and drainage density, D in the same unit. The ruggedness number combines slope and length characteristics in one expression. The areas of low relief but high drainage density are as ruggedly textured as areas of higher relief having less dissection.

4.4.5 Main channel slope (S_m)

The main channel slope is one of the most important parameters influencing watershed hydrology. This can be determined variously. The main channel slope is determined by a method proposed by Johnston and Cross (1949) (Singh, 1989). The channel can be divided into N number of reaches each having a uniform slope S_i. Thus the equivalent slope S_m is calculated as;

$$S_m = \left[\frac{\sum_{i=1}^{N} L_i \, S_i^{0.5}}{\sum_{i=1}^{N} L_i} \right]^2$$

This is designed to estimate the slope that would result in the same total time of travel as the actual stream if length, roughness, channel cross section and any other pertinent factors other than slope were unchanged.

5.0 THE STUDY AREA

The Narmada is a major west flowing river in central India traversing through Madhya Pradesh, Gujarat and Maharastra and finally meets Arabian Sea. It rises in the Amarkantak plateau of Maikala range in the Shahdol district of Madhya Pradesh at an elevation of 1057 metres above mean sea level. Upper Narmada lies in sub zone 3(c) defined by Central Water Commission. It comprises of about twelve tributaries of river Narmada meeting to left or right banks. For the present study, four sub basins of upper Narmada are selected. They are Narmada upto Manot, Burhner upto Mohegaon, Banjar upto Hridenagar and Sher upto Belkheri. Index map of upper Narmada is shown in Figure 1.

Narmada upto Manot lies between east longitude 80° 24′ to 81° 47′ and north latitudes 22° 26′ to 23° 18′ in Mandla and Shahdol districts of Madhya Pradesh. The river rises in Maikala range near Amarkantak in the Shahdol district of Madhya Pradesh at an elevation of 1057 metres. Figure 2 shows stream network and drainage boundary of Manot sub-basin.

The river Burhner rises in the Maikala ranges, southeast of Gwara village in Mandala district of Madhya Pradesh at an elevation of about 900 metres, at north latitude 21° 42′ and east longitude 80° 50′ and flows generally in north-westerly direction for a total length of 184 kilometres to join Narmada near Manot. Its stream network alongwith drainage boundaries are is shown in figure 3.

The Banjar river rises in the Satpura range in the Durg district of Madhya Pradesh near Rampur village at an elevation of about 600 metres at north latitude 21° 42′ and east longitude 80° 50′ and flows generally in north-westerly direction for a total length of 184 kilometres to join Narmada from left bank near Mandala. Figure 4 shows this sub basin.

The Sher river rises in the Satpura ranges near Patan in Seoni district of Madhya Pradesh at an elevation of 600 metres at north latitude 22° 31′ and east longitude 79° 25′ and flows in north-westerly direction for a total length of 129 kilometres to its confluence with Narmada from left near Brahmand. This sub basin is shown in figure 5.

The Upper Narmada has a complex relief. High ranges of above 900 metre exist over a small area near the source of Narmada river. Areas varying in height between 600 and 900 metre lies along eastern and middle portions of the boundary. The Upper Narmada has a continental type of climate. It is very hot in summer and cold in winters and receives most of the rainfall from South-West monsoon from June to October. Mean annual rainfall varies approximately from 800 to 1600 mm.

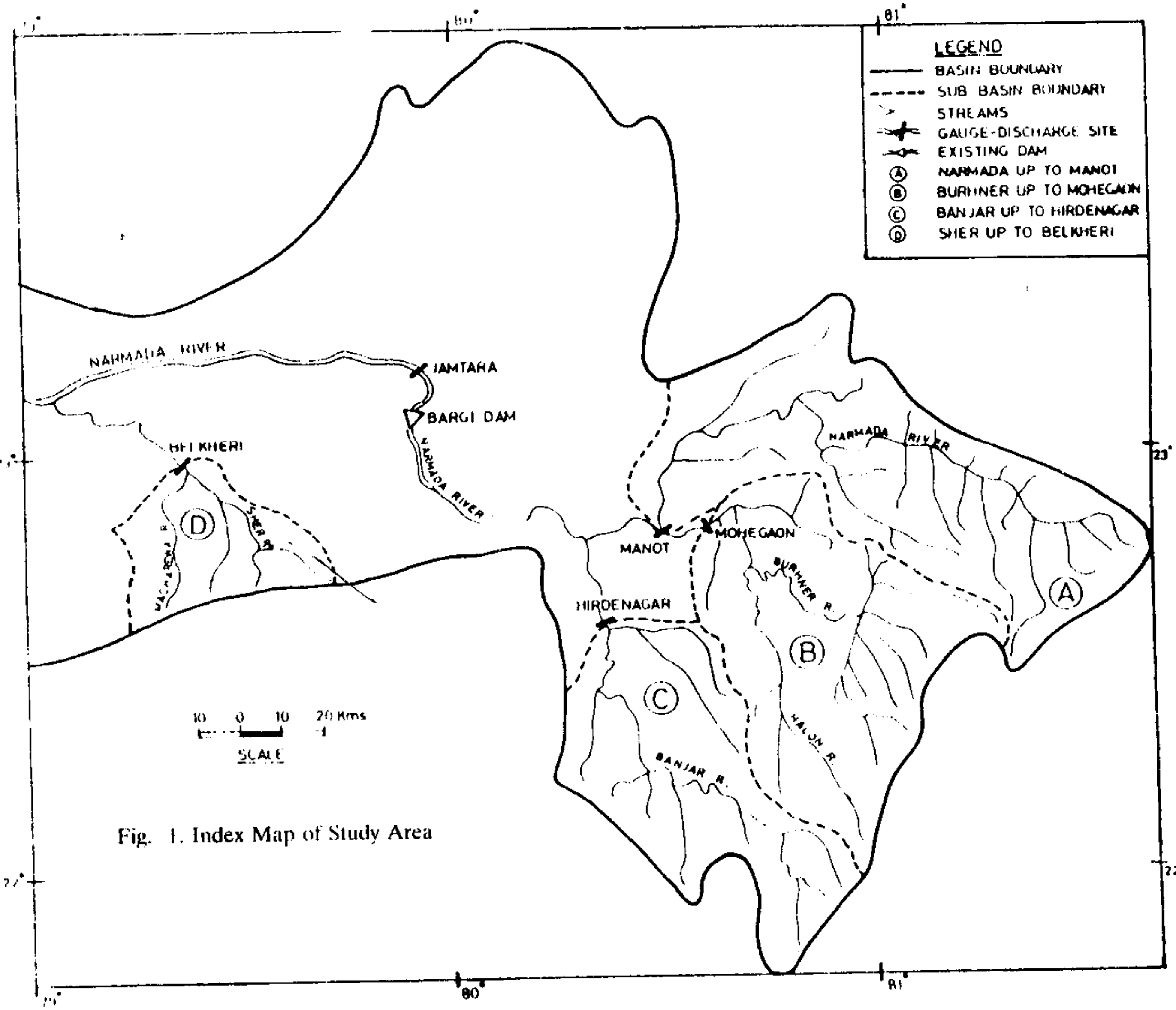

Fig. 1. Index Map of Study Area

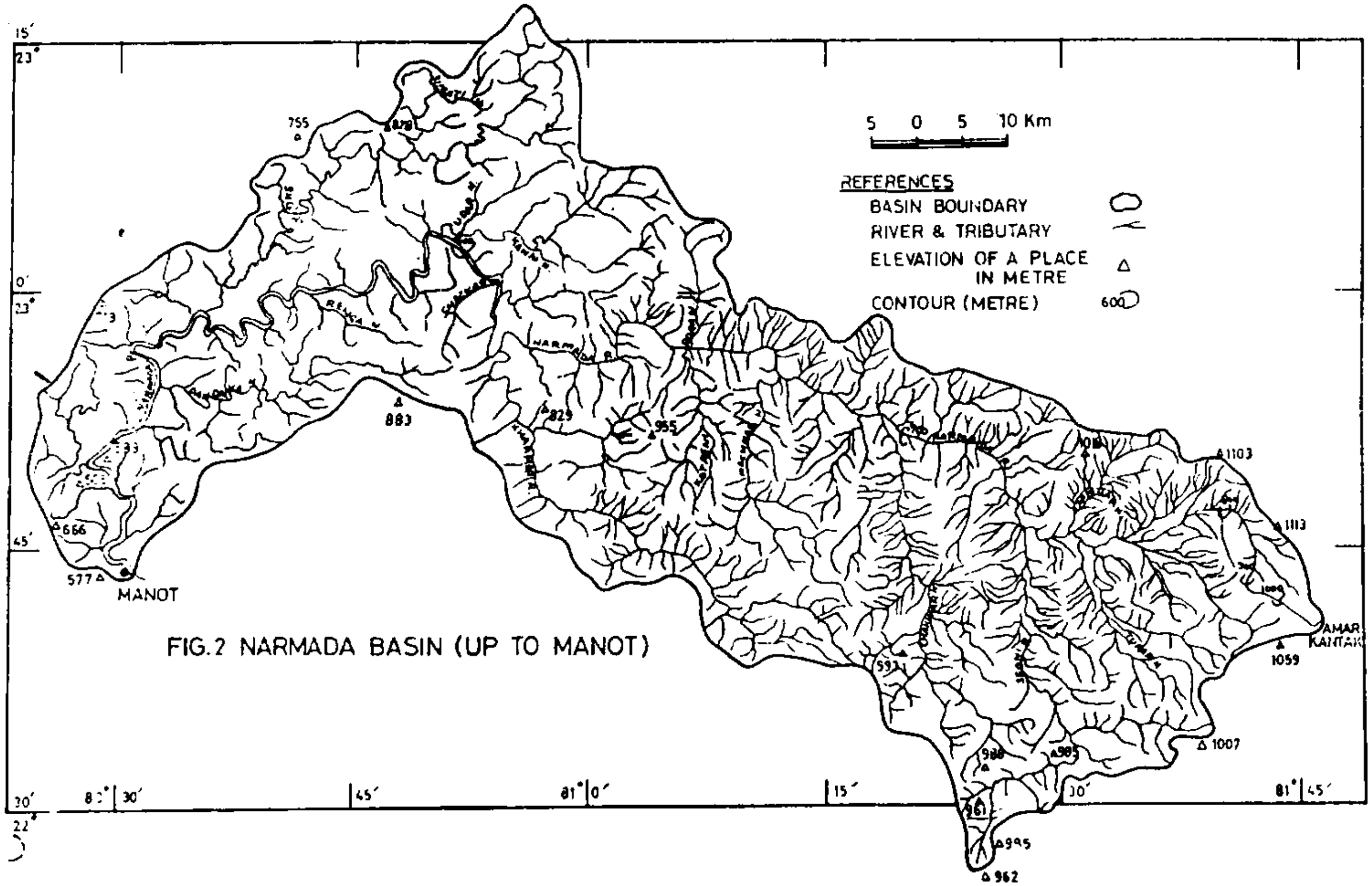

FIG.2 NARMADA BASIN (UP TO MANOT)

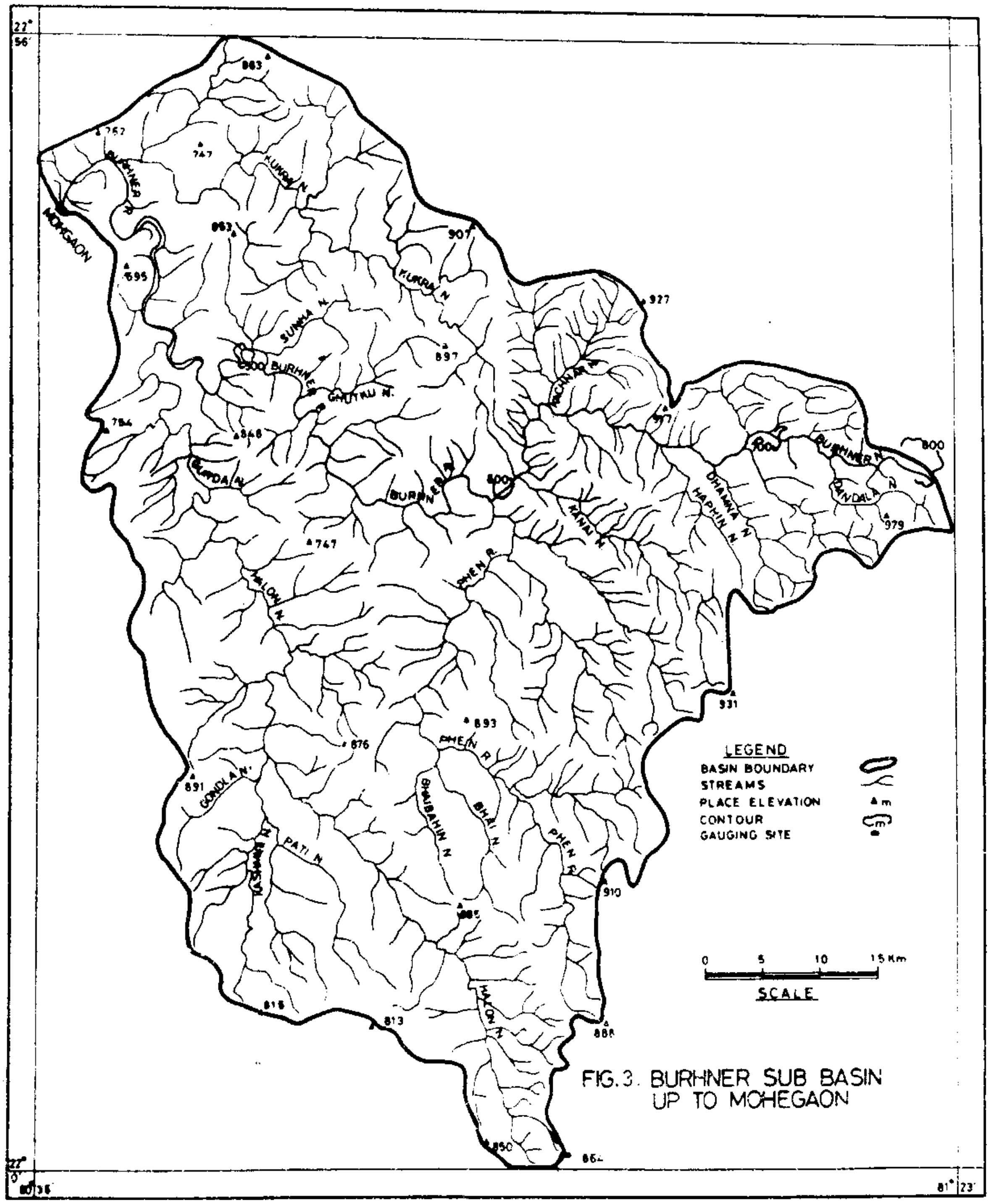

FIG.3. BURHNER SUB BASIN UP TO MOHEGAON

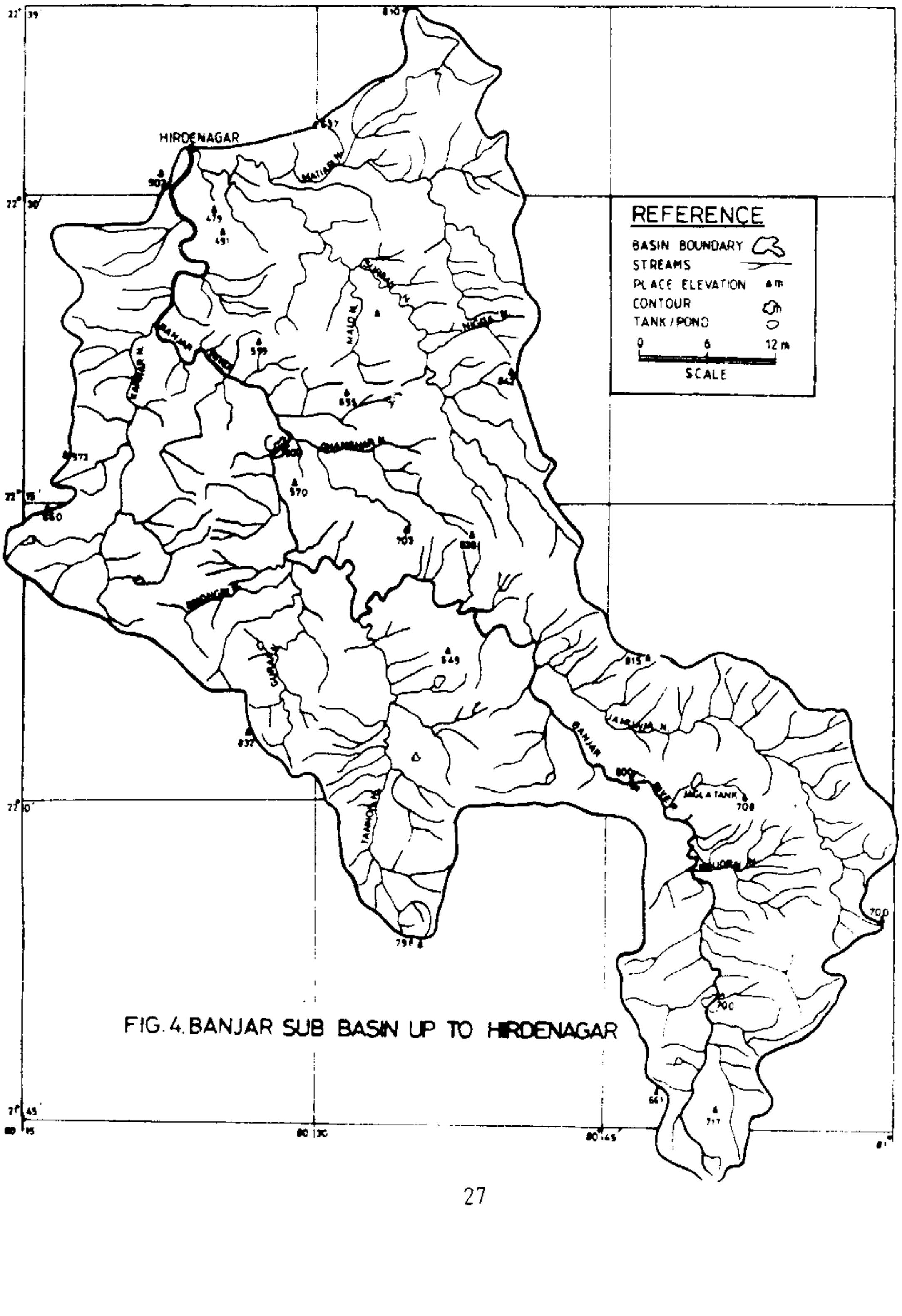

FIG. 4. BANJAR SUB BASIN UP TO HIRDENAGAR

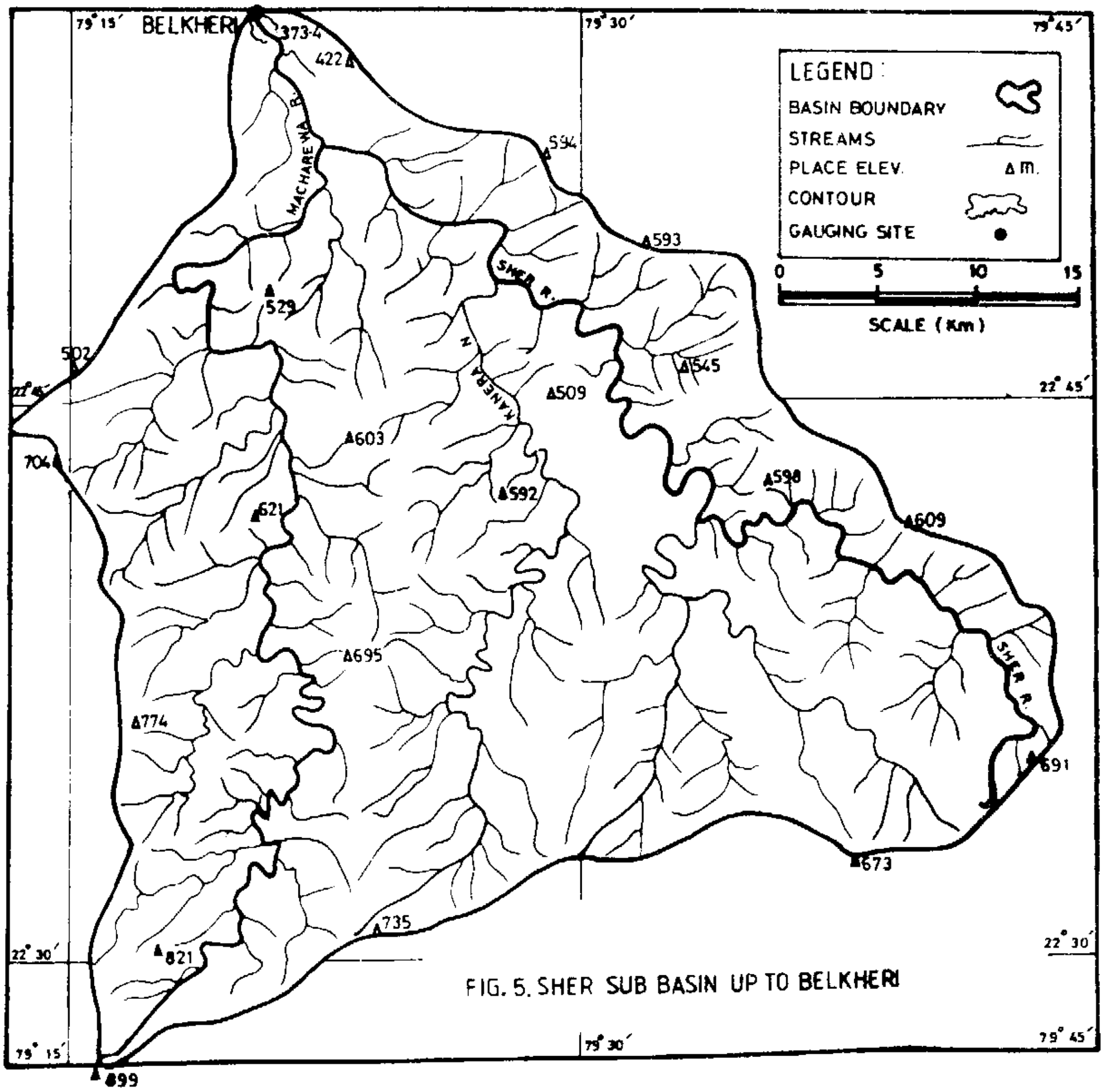

FIG. 5. SHER SUB BASIN UP TO BELKHERI

6.0 ANALYSIS AND DISCUSSION OF RESULTS

The catchment boundaries and river system were drawn from Survey of India toposheets covering upper Narmada basins. For evaluating different geomorphological parameters, the river system of the basins were ordered according to Strahler ordering scheme. It is observed that Narmada upto Manot and Burhner upto Mohegaon are sixth order basins while, Banjar upto Hridenagar and Sher upto Belkheri are fifth order basins in 1:2,50,000 map scale. However, in 1:50,000 scale, the Sher basin is of seventh order. Table 1 show the measures according to order of streams for all these basins.

Table 1

Measures according to order of streams

Parameter	Narmada upto Manot	Burhner upto Mohegaon	Banjar upto Hridenagar	Sher upto Belkheri	
Scale →	1:2,50,000	1:2,50,000	1:2,50,000	1:2,50,000	1:50,000
N_1	821	491	282	233	2975
N_2	178	102	76	46	455
N_3	37	22	14	4	120
N_4	11	6	2	2	24
N_5	3	2	1	1	4
N_6	1	1	--	--	2
N_7	--	--	--	--	1
$\bar{L}_1$	3.20	3.07	3.97	2.93	1.42
$\bar{L}_2$	3.72	4.82	4.76	5.21	2.40
$\bar{L}_3$	7.55	6.97	15.36	29.25	3.70
$\bar{L}_4$	15.93	28.08	47.37	28.75	9.00
$\bar{L}_5$	28.75	9.50	77.00	10.00	26.10
$\bar{L}_6$	170.00	90.00	--	--	15.10
$\bar{L}_7$	--	--	--	--	11.00
$\bar{A}_1$	3.80	4.36	7.22	4.24	0.35
$\bar{A}_2$	9.23	17.20	26.33	12.84	1.43
$\bar{A}_3$	41.10	57.88	160.94	274.18	8.55
$\bar{A}_4$	182.91	539.50	743.15	693.85	45.87
$\bar{A}_5$	655.17	802.05	3472.00	1456.88	314.50
$\bar{A}_6$	4980.00	4103.00	--	--	690.10
$\bar{A}_7$	--	--	--	--	1456.00
R_B	3.981	3.524	4.446	4.074	3.890

In Table 1, parameter N_1 to N_7 denotes number of streams for order 1 to 7; $\bar{L}_1$ to $\bar{L}_7$ denotes average length of streams for order 1 to 7 and $\bar{A}_1$ to $\bar{A}_7$ denotes mean drainage area for order 1 to 7 respectively. It can be seen from table 1 that number of streams for first order increases phenomenally with change of scale for Sher basin. Main reason for this is increase in resolution with change of map scale from 1:2,50,000 to 1:50,000. Since a watershed of a given order can be modelled as a collection of sub elements, the number of streams and mean stream lengths of each order is an important concept in hydrology. To check the applicability of Horton's law of stream numbers and length for these basins, plots of stream order versus number of streams and stream order versus mean length were made and are shown in figures 6 to 9 for Manot, Burhner, Banjar and Sher sub basins respectively. Figure 10 shows same plot for Sher sub basin in 1:50,000 scale. It can be seen from figures 6 to 10 that the average length of stream and number of streams of various orders follows Horton's law of stream length and number for all the basins. Negative slope of best fit line between stream order and number shows reduction in number of streams with increase in order.

Table 2 shows other linear measures evaluated for these basins. The stream length ratio and bifurcation ratio are important dimensionless parameters. These dimensionless parameters are very useful in synthesizing hydrograph characteristics. Rodriguez-Iturbe and Valdes (1979), Gupta et al. (1980), Gupta and Waymier (1983) and other investigators have used R_A, R_B, R_L, L_Ω and maximum stream flow velocity to synthesize IUH for the basin popularly known as Geomorphological Instantaneous Unit Hydrograph (GIUH). It can be seen from the Tables 1 & 2 that the dimensionless parameters R_B, and R_L remain fairly constant with change in map scale for Sher sub-basin. This property of these dimensionless parameters give added advantage for their use in hydrograph synthesis.

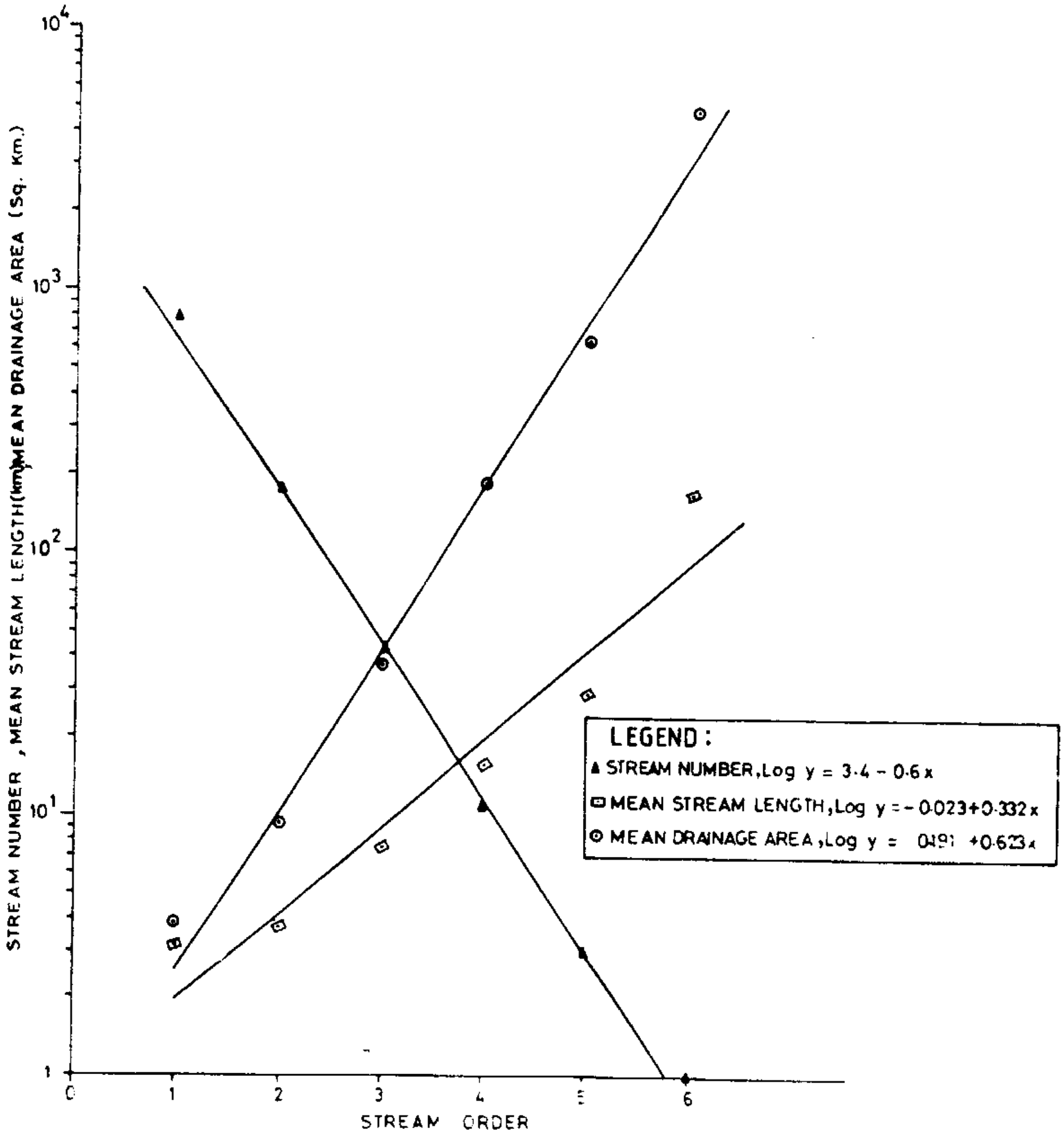

FIG. 6 SEMILOG PLOT OF STREAM NUMBERS MEAN STREAM LENGTHS AND MEAN DRAINAGE AREAS VERSUS STREAM ORDER ILLUSTRATING HORTON'S LAW FOR NARMADA BASIN UP TO MANOT

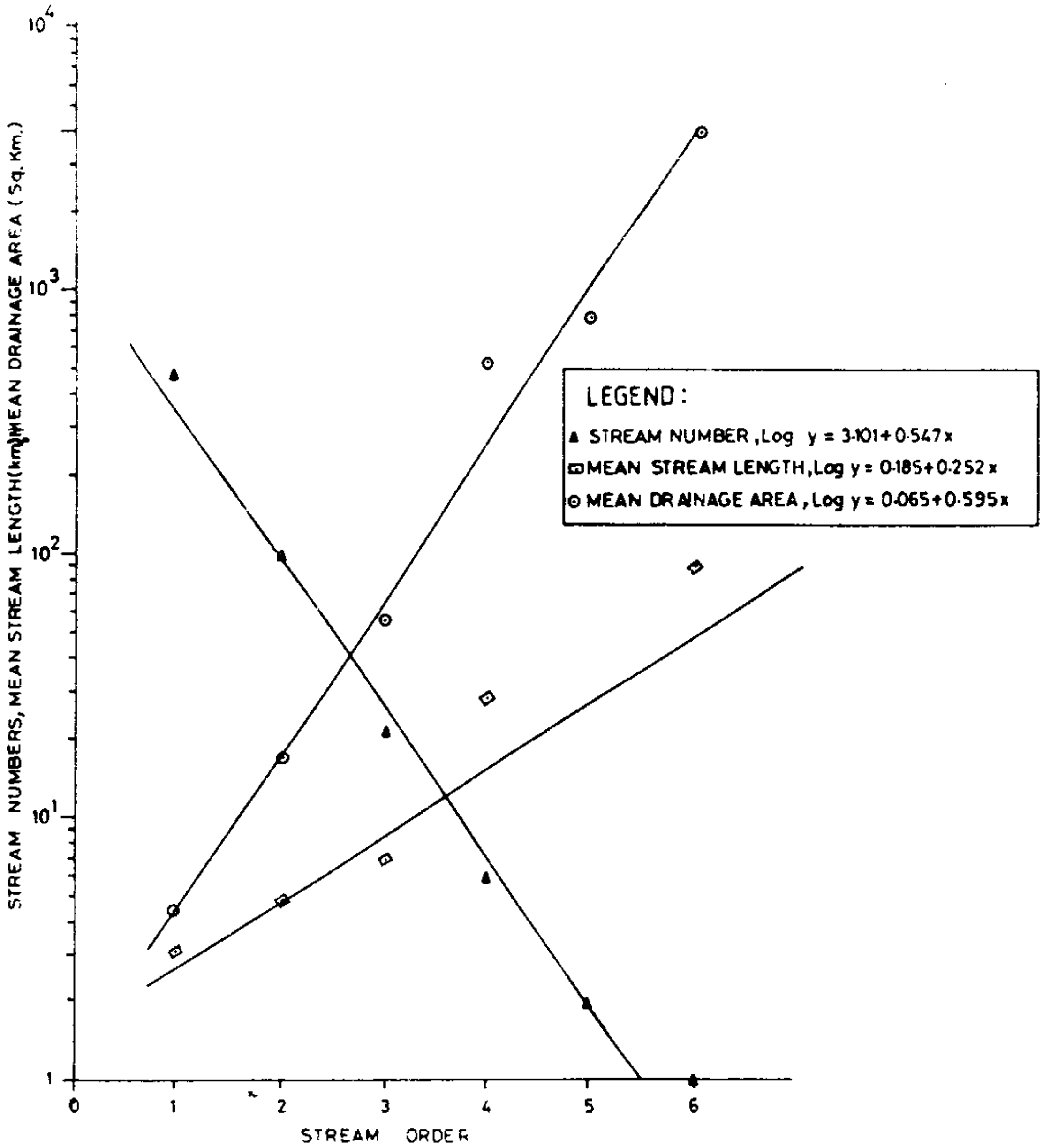

FIG. 7 SEMILOG PLOT OF STREAM NUMBERS, MEAN STREAM LENGTHS AND MEAN DRAINAGE AREAS VERSUS STREAM ORDER ILLUSTRATING HORTON'S LAW FOR BURHNER SUB BASIN UP TO MOHEGAON

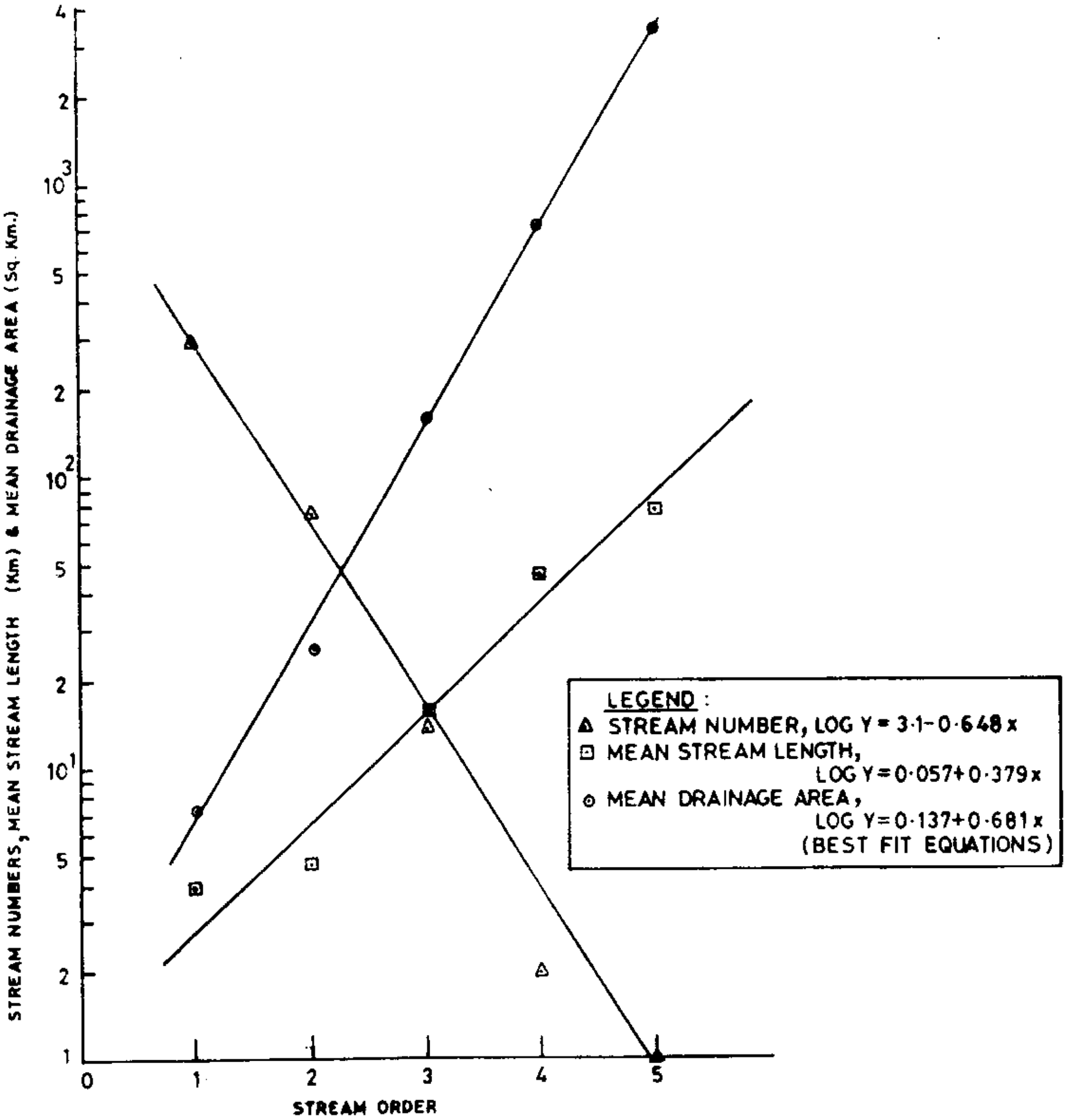

FIG. 8 SEMI LOG PLOT OF STREAM NUMBERS, MEAN STREAM LENGTHS & MEAN DRAINAGE AREA VERSUS STREAM ORDERS ILLUSTRATING HORTON'S LAW FOR BANJAR RIVER SUB-BASIN UPTO HIRDENAGAR

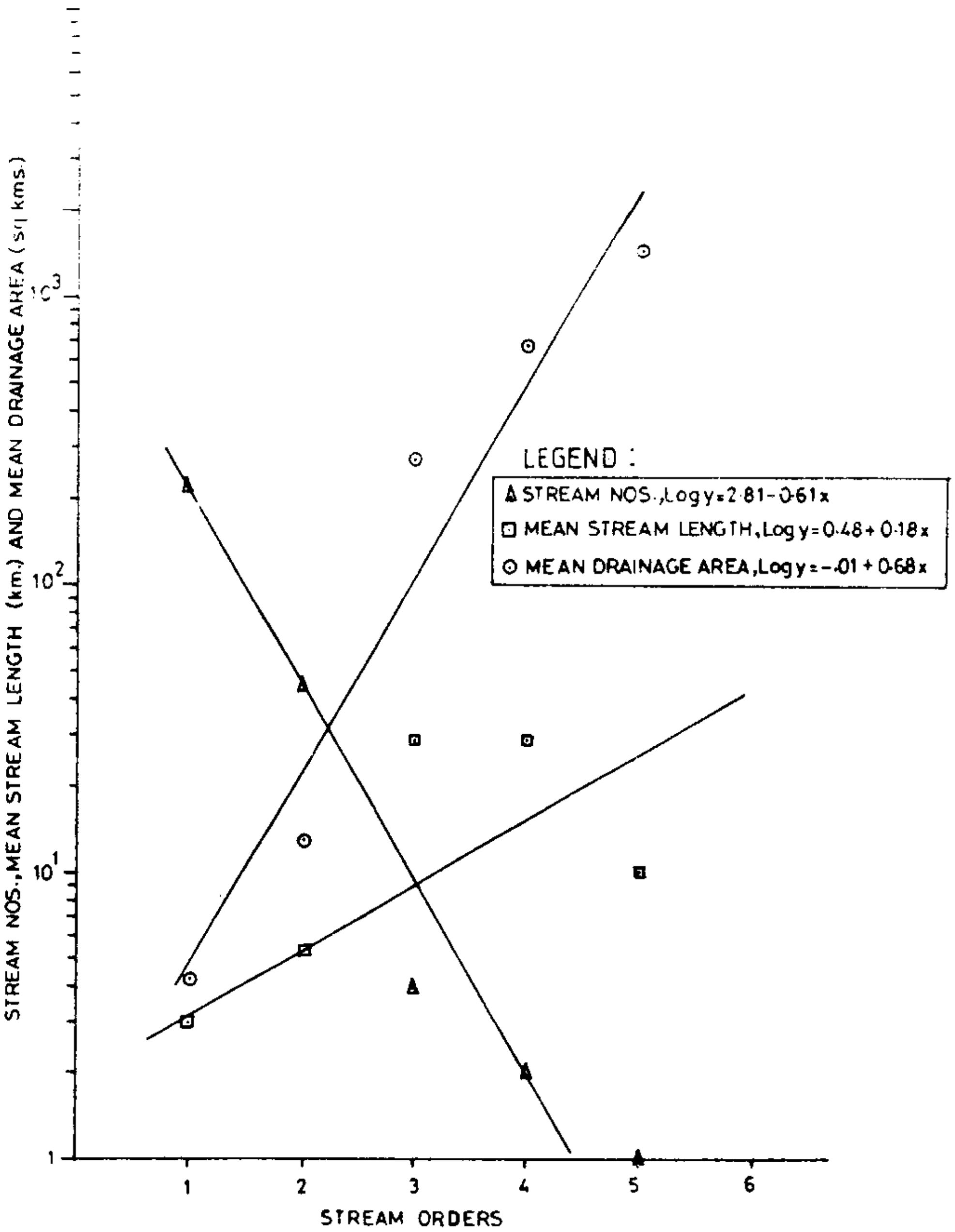

FIG 9 SEMI LOG PLOT OF STREAM NOS.,MEAN STREAM LENGTHS,AND MEAN DRAINAGE AREA VERSUS STREAM ORDERS ILLUSTRATING HORTN'S LAW FOR SHER RIVER SUB BASIN UPTO BELKHERI.
(TOPOSHEET MAP SCALE 1:250,000)

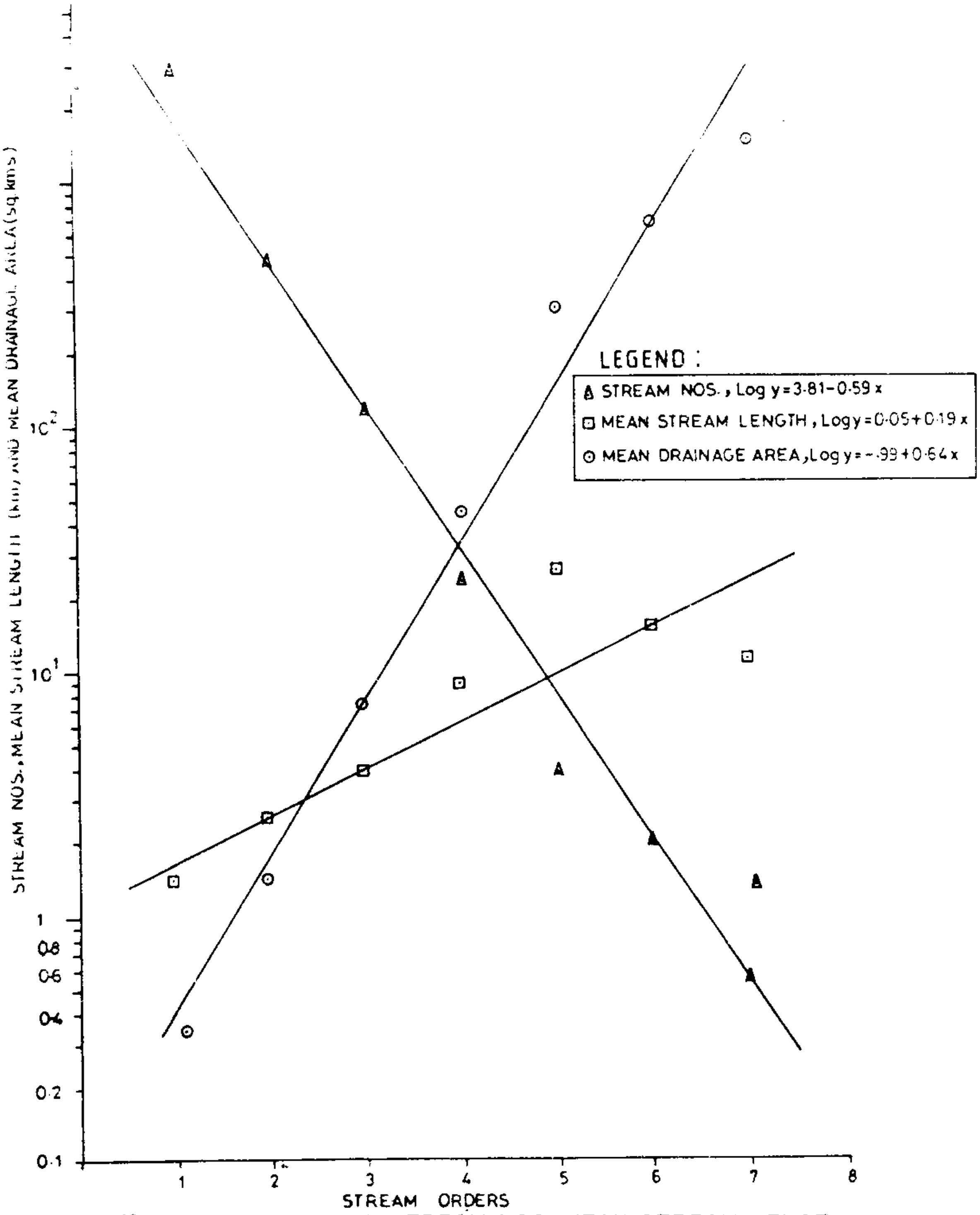

FIG.10 SEMI LOG PLOT OF STREAM NOS., MEAN STREAM LENGTH AND MEAN DRAINAGE AREA VERSUS STREAM ORDERS ILLUSTRATING HORTN'S LAW FOR SHER RIVER SUB BASIN UPTO BELKHERI (TOPOSHEET MAP SCALE 1:50,000)

Table 2

Geomorphological parameters based on linear aspects

Parameter	Narmada upto Manot	Burhner upto Mohegaon	Banjar upto Hridenagar	Sher upto Belkheri	
Scale ⇒	1:2,50,000	1:2,50,000	1:2,50,000	1:2,50,000	1:50,000
P	440.000	320.000	355.000	170.000	172.000
L_Ω	239.000	138.000	185.000	77.000	78.500
L_c	140.000	70.000	78.000	35.000	35.500
L_b	126.250	96.300	104.250	53.750	54.300
R_w	1.893	1.433	1.775	1.433	1.446
R_{fn}	0.543	0.431	0.521	0.453	0.456
R_L	2.148	1.786	2.393	1.514	1.549
τ	0.796	0.599	0.696	0.600	0.650

Length of channel between outlet and a point near to centre of gravity is an important parameter used extensively for deriving synthetic unit hydrographs for small basins. Snyder (1938) relates the time from centroid to the peak of unit hydrograph to L_Ω and L_c. Gray (1973) related lag time of the basin with L_Ω, L_c and S for some small basins in USA. These relations, however, empirical in nature are of immense use for deriving unit hydrographs for ungauged small catchments. Other linear measures which have been computed for study basin include perimeter of basin, length of main stream, watershed eccentricity etc. and are given in table 2. Length of main channel is an important parameter employed extensively for calculating time of concentration of the catchment in conjunction with average slope. Parameters L_Ω and L_c are highly correlated. To demonstrate the correlation between L_Ω and L_c a plot among them is established which is shown in Fig. 11. Watershed eccentricity τ indicates compactness of the basin. Higher the value of τ indicates less compactness of the basin which in turn indicates flat peaked hydrograph of the basin and vice versa. Out of these four basins the value of τ is highest for Manot basin which indicate flat peaked hydrographs for Manot basin compared to other three basins. It can be seen from table 2 that most of the linear measures remain fairly constant with change in map scale in case of Sher sub-basin.

Various areal measures evaluated for study basin are listed in table 1 and 3. Table 1 shows and mean drainage areas for order 1 to 7 streams. Mean drainage area of various orders in an important parameter and provide a feel of runoff potential available from a particular segment or cascade of the basin. Plots between mean drainage area and order are established and shown in figure 6 to 9 for Manot, Burhner,

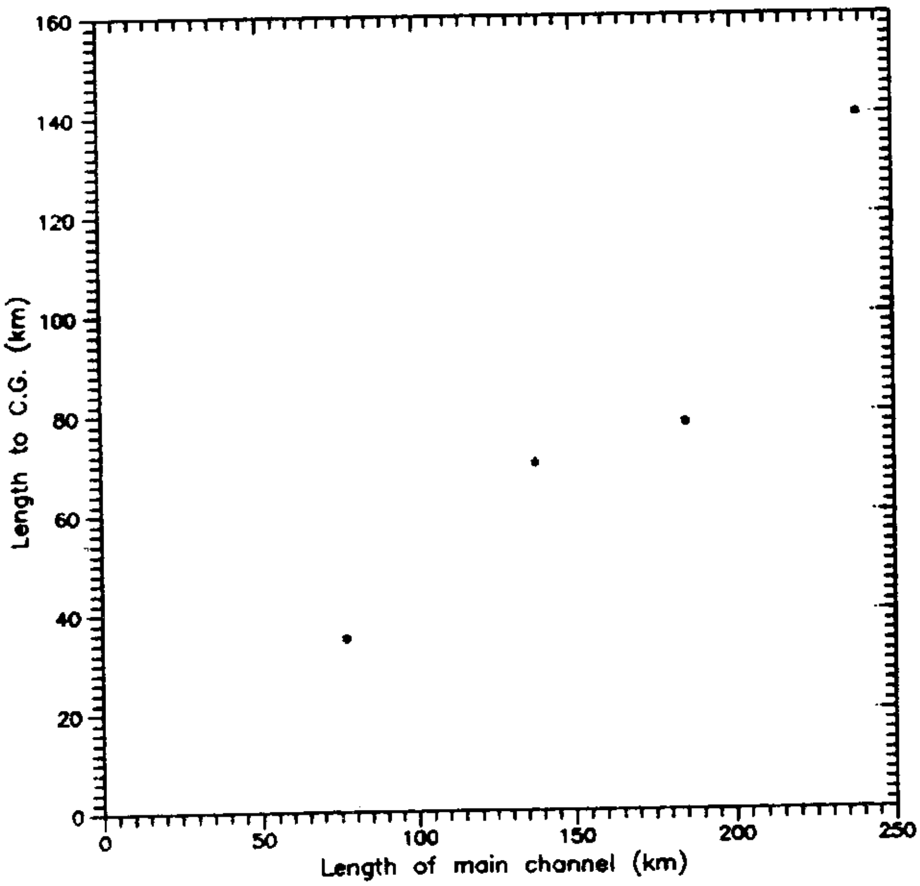

Fig. 11 Plot between L and L_c

Banjar and Sher sub basins respectively. Figure 10 shows same plot for Sher basin in 1:50,000 scale. It can be seen from these figures that mean drainage area of various orders follow Schumm's law of drainage areas for all the basins.

Table 3

Geomorphological parameters based on areal aspect

Parameter	Narmada upto Manot	Burhner upto Mohegaon	Banjar upto Hridenagar	Sher upto Belkheri	
Scale ⇒	1:2,50,000	1:2,50,000	1:2,50,000	1:2,50,000	1:50,000
A	4980.000	4103.000	3472.000	1456.880	1456.000
D	0.804	0.593	0.538	0.760	4.220
C	1.244	1.686	1.858	1.315	0.240
R_A	4.198	3.936	4.797	4.786	4.365
R_c	0.323	0.504	0.346	0.634	0.620
R_e	0.631	0.750	0.638	0.801	0.790
W_s	3.002	1.909	2.783	1.788	1.820
R_u	1.789	1.503	1.769	1.408	1.420
R_f	0.312	0.442	0.319	0.504	0.490
C_f	0.211	0.152	0.108	0.196	2.460

Total drainage area of a basin is a very important geomorphological parameter and has been used widely in various hydrological simulation studies. Other areal measures which have been computed for these basins are, elongation ratio, circularity ratio, drainage density, area ratio, form factor, constant of channel maintenance and stream frequency and are listed in table 3. Elongation ratio and circularity ratio are shape parameters and give a feel of the basin shape compared to a circle. As the value of elongation ratio and circularity ratio approaches to one, the shape of the basin approaches towards a circle.

In areal aspects most of the parameters evaluated, remain constant, with change of map scale except D, C and C_f. Main reason for this change is greater resolution in 1:50,000 map scale compared to 1:2,50,000 scale.

Some of the important relief measures evaluated for the basin are listed in table 4. These measures include slope of main stream, basin relief, relief ratio, relative relief, Ruggedness number, Main channel slope. Relief measures are indicative of the potential energy of a drainage system present by virtue of elevation above a given datum. Main channel slope is one of important relief measures and has been used widely in various hydrological studies, particularly for estimation of time of concentration of basin. Figure 12 to 15 shows the profile of the main drainage channel for Manot, Burhner, Banjar and Sher sub basins respectively. The relief parameters govern the overland and stream flow processes of a basin. Possibility of a close correlation between relief ratio and hydrologic characteristics of a basin are suggested by Schumm (1954), who found that sediment loss per unit area is closely correlated with relief ratio. Ruggedness number combines the qualities of slope steepness and length, and is formed of the product of relief and drainage density. If D is increased while H remains constant, the average horizontal distance from divides to adjacent channels is reduced, with an accompanying increase in slope steepness. If H is increased while D remains constant, the elevation difference between divides and adjacent channels will also increase, so that slope steepness increases. Relief parameters are important in hydrological studies in mountainous areas, and are often used in modelling hydrological responses of these areas.

Table 4

Geomorphological parameters based on relief aspect

Parameter	Narmada upto Manot	Burhner upto Mohegaon	Banjar upto Hridenagar	Sher upto Belkheri	
Scale →	1:2,50,000	1:2,50,000	1:2,50,000	1:2,50,000	1:50,000
H	542.000	509.000	372.000	447.600	447.600
R_h	0.004	5.4E-3	1.02E-2	9.5E-3	9.5E-3
R_p	0.001	1.6E-3	2.0E-3	2.6E-3	2.6E-3
R_n	0.436	0.301	0.200	0.340	1.89
S_m	6.9E-4	2.1E-3	1.3E-3	3.3E-3	3.2E-3

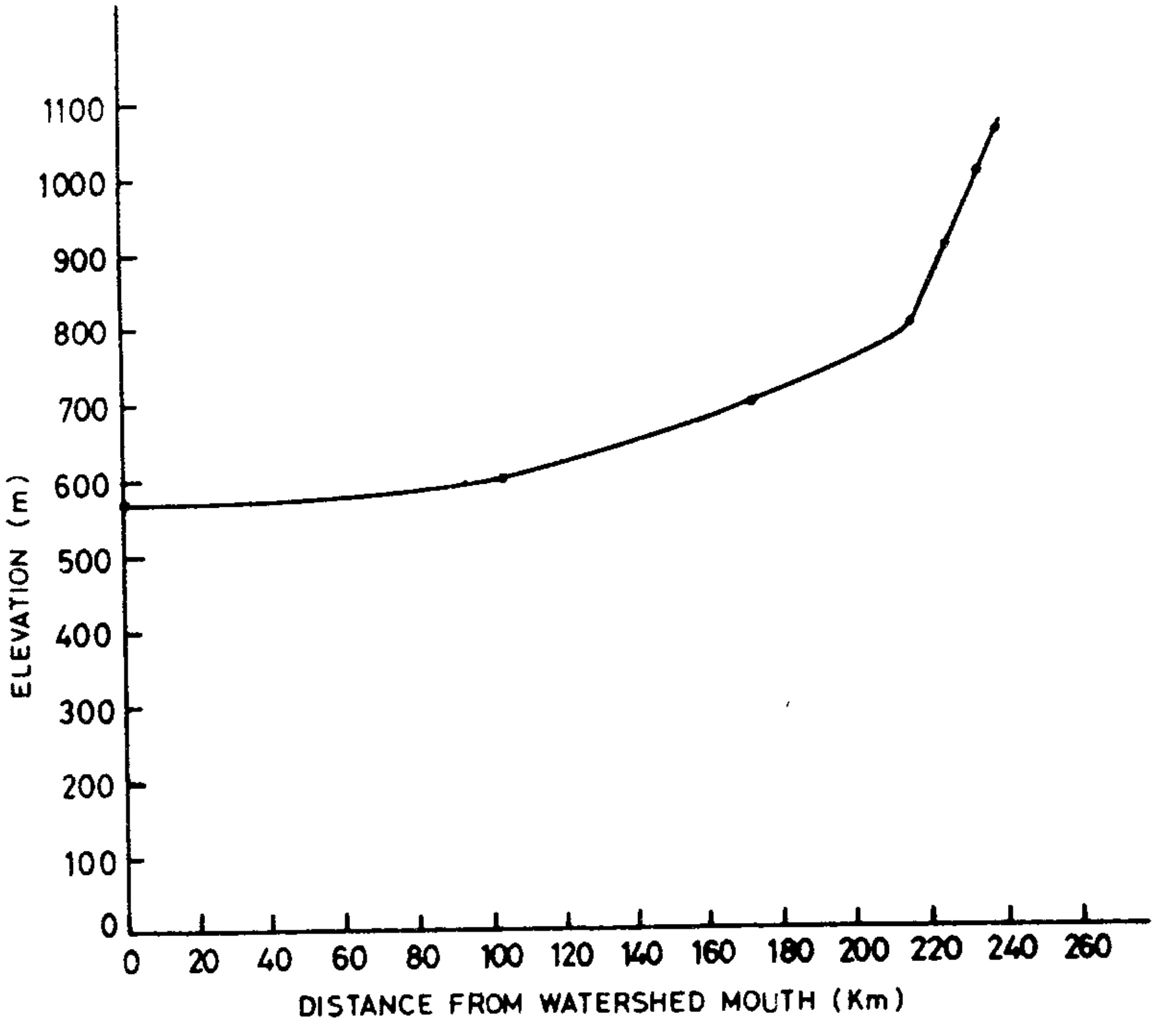

FIG.12 MAIN CHANNEL PROFILE OF NARMADA RIVER UPTO MANOT

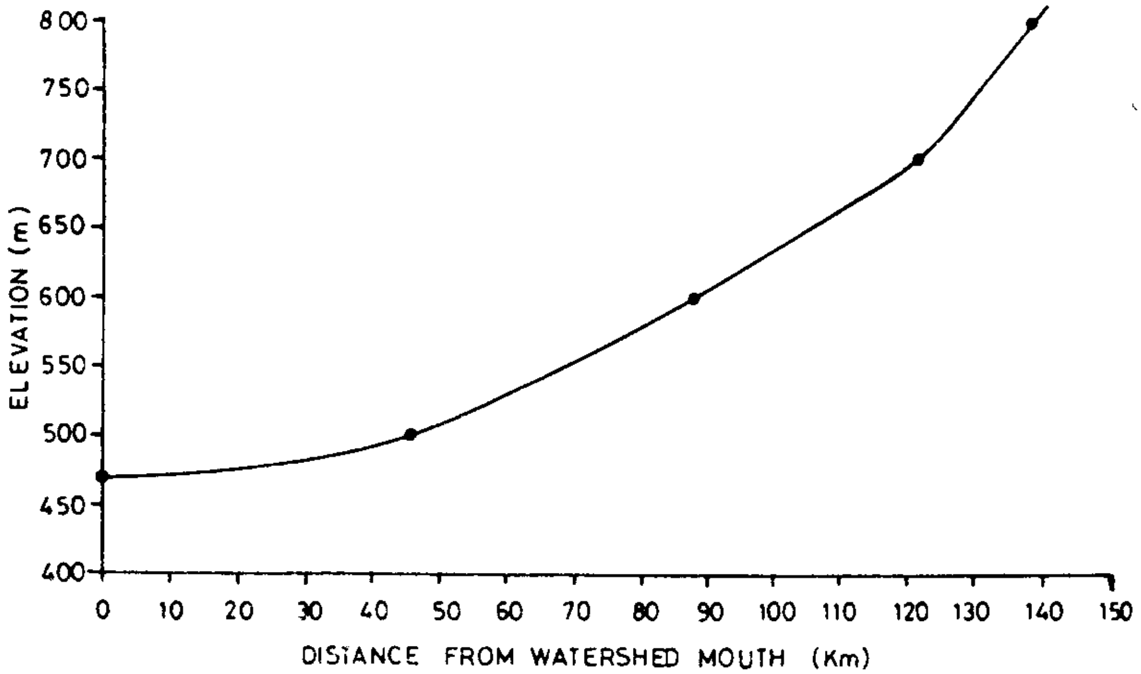

FIG. 13 MAIN CHANNEL PROFILE OF BURHNER RIVER UP TO MOHEGAON

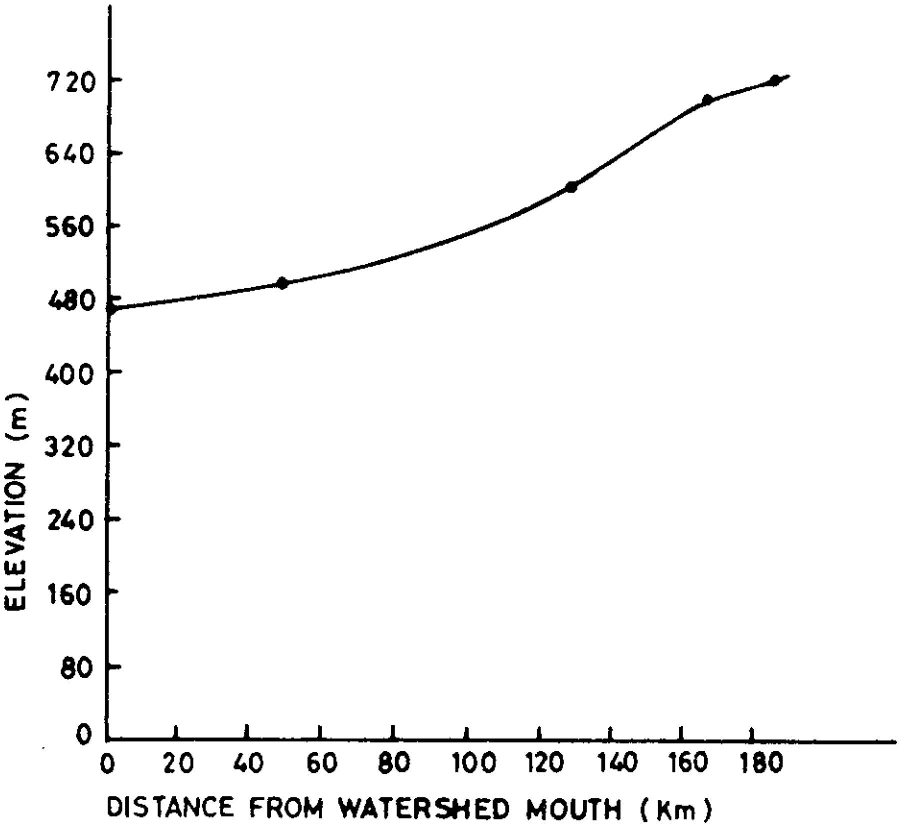

FIG.14 MAIN CHANNEL PROFILE OF BANJAR RIVER UPTO HIRDENAGAR

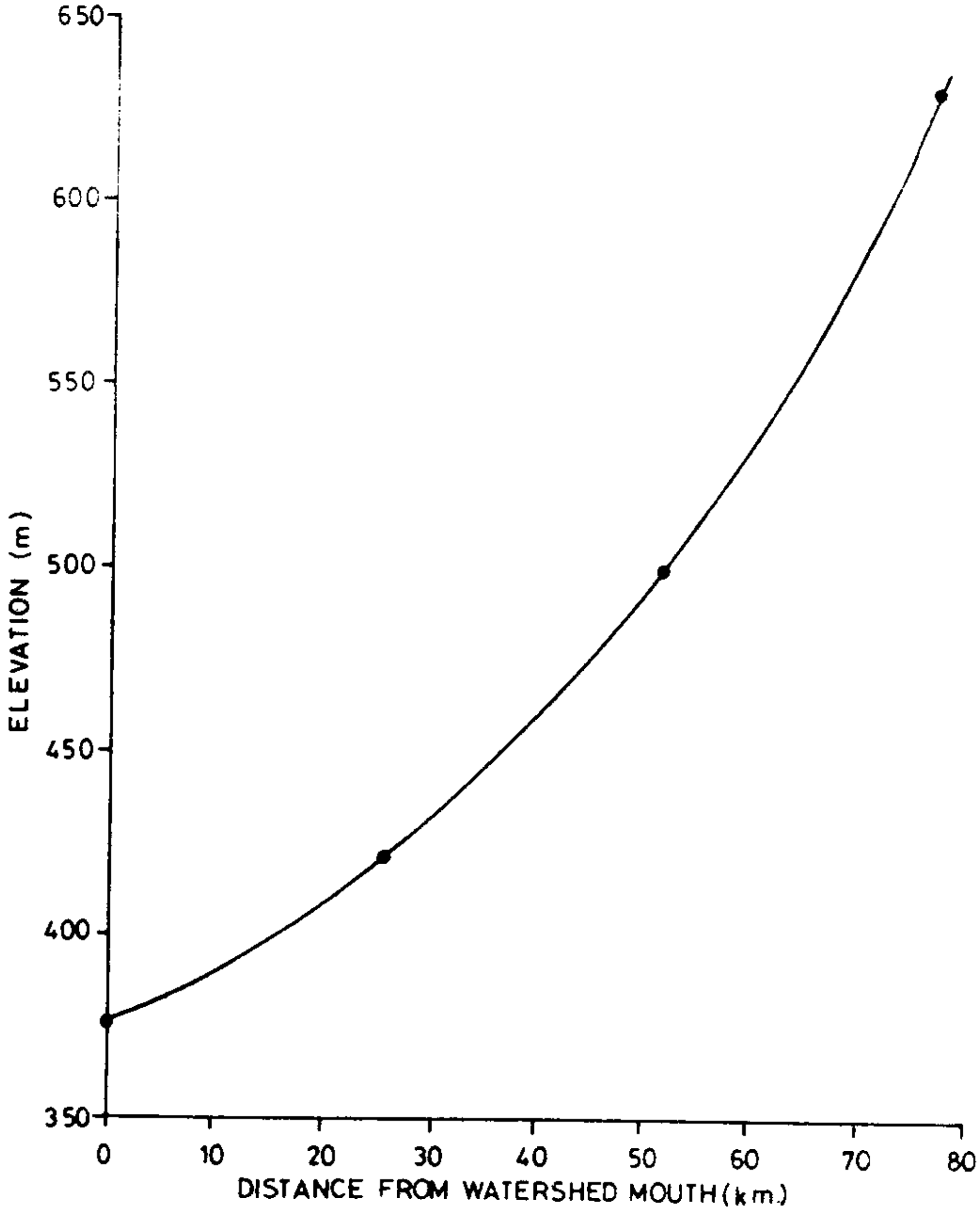

FIG. 15 MAIN CHANNEL PROFILE OF SHER RIVER UPTO BELKHERI

7.0 SUMMARY AND CONCLUDING REMARKS

In this study various geomorphological parameters covering linear, areal and relief aspects of four sub basins of upper Narmada have been evaluated. It is observed that Narmada upto Manot and Burhner upto Mohegaon are sixth order basins while, Banjar upto Hridenagar and Sher upto Belkheri are fifth order basins in 1:2,50,000 map scale. However, in 1:50,000 scale, the Sher basin is of seventh order. The relations between stream order versus stream number of streams, mean stream length, and mean drainage area are established. Inter comparison of these basins is attempted based on various geomorphological parameters. Effect of map scale is also studied by treating one of the basin as special case by evaluating various geomorphological parameters in 1:2,50,000 and 1:50,000 map scales. It was observed that most of the important geomorphological parameters such as A, L_Ω, L_c, H and dimensionless numbers R_A, R_B and R_L remain fairly constant with change of scale of measurement. However, noticeable deviations were observed in drainage density, constant of channel maintenance and stream segment frequency with change of map scale. It is, therefore, suggested that important geomorphological characteristics which are scale independent should be used for hydrological studies.

The present study is an effort in the direction of developing regional geomorphological data base for future use in regional Geomorphological Instantaneous Unit Hydrograph studies. The geomorphological parameters, thus estimated, may be used for developing the hydrological models to simulate hydrological response of the basin. Such models are very useful and are being widely used for simulating hydrological response of ungauged basin or basin with limited data.

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List of Notations:

P = Basin perimeter (km)

$\bar{L}_i$ = Mean length of channel of order i (km)

L_Ω = Length of main channel (km)

L_c = Length of centre of gravity along main channel from basin outlet (km)

L_b = Basin length (km)

R_w = Wandering ratio

R_{fn} = Fineness ratio

R_L = Stream length ratio

R_B = Bifurcation ratio

τ = Watershed eccentricity

A = Area of watershed (km^2)

$\bar{A}_i$ = Mean drainage area of order i (km^2)

D = Drainage density (km per km^2)

C = Constant of channel maintenance

R_A = Area ratio

R_c = Circularity ratio

R_e = Elongation ratio

W_s = Watershed shape factor

R_u = Unity shape factor

R_f = Form factor

C_f = Channel segment frequency (per km^2)

H = Basin relief (metre)

R_h = Relief ratio

R_p = Relative relief

R_n = Ruggedness number

S_m = Main channel slope.

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