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GEOMORPHOLOGY OF KOLAR SUB-BASIN FOR HYDROLOGICAL STUDIES

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PREFACE

The geomorphological properties represent the attributes of a watershed, which can be employed in synthesizing and understanding its hydrological behaviour. The geomorphological properties of channel network are generally referred to the basin composition which represents the topographical and geometric properties of the basin. The linear, areal and relief aspects of the watershed are some of the important characteristics which are considered generally in science of geomorphology and particularly in hydrological studies.

In this report an attempt has been made to present a comprehensive review of various geomorphological characteristics, emphasizing their needs in various hydrological studies. A computer software has been developed for quantifying some of the important geomorphological parameters. The application of the developed computer programme has been illustrated by estimating the some of the important geomorphological parameters for Kolar sub-basin of Narmada basin. It provides an effective way for the derivation of the most important geomorphological parameters of a watershed, which are frequently used in hydrological studies, particularly for simulating the hydrologic response of ungauged watersheds. This study has been carried out by Shri R.D. Singh, Scientist 'E' and Mrs. Vibha Jain, Senior Research Assistant, National Institute of Hydrology, Roorkee.

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ABSTRACT

The hydrologic response of a watershed usually depends upon the climatological and watershed characteristics. The geomorphological characteristics of a watershed represent the attributes of the watershed that can be employed in synthesizing, and perhaps understanding its hydrologic behaviour. For the purpose of hydrological studies,geomorphological characteristics can generally be classified in three groups;(i) the characteristics representing the linear aspects of the watershed, (ii) the characteristics which represent the areal aspects of the watershed, and (iii) the characteristics representing the relief aspects of the watershed.

In this report a comprehensive review of the geomorphological properties, covering the linear, areal and relief aspects of the watershed are presented. Methodology for the estimation of some of the important geomorphological parameters are also described. Based on the given methodology a computer software has been developed in FORTRAN-77 language.It requires the digitized data of the drainage network as input. The developed computer software has been implemented and tested on VAX 11/780 computer system available at NIH. The different geomorphological characteristics of Kolar subbasin of Narmada basin are derived using the developed software. Further a review of the application of geomorphological properties in various hydrological studies such as Empirical Formulae, Regional Flood Frequency Analysis, Regional Unit Hydrograph and Geomorphological Unit Hydrograph etc., are also presented in the report. It is observed from the review of various hydrological studies that the different geomorphological parameters derived for Kolar subbasin can be utilized for modelling its hydrologic response. Such applications are generally found to be more useful specifically for the ungauged catchments or catchments having the limited data in simulating their hydrologic response.

1.0 INTRODUCTION

Streamflow synthesis from ungauged basins has long been recognised as a subject of scientific investigations. The simple and most popular approach, in this regard, comprises the empirical relations for determining the parameters of conceptual models or some key characteristics of streamflow hydrographs, such as lag time, peak discharge, time to peak, or hydrograph duration. These relationships are developed by standard curve fitting methods based on data from gauged basins and are then applied to ungauged basins hoping for desired results. Although such relations can be useful in particular cases, they do not seem to be scientifically sound. On the other hand, geomorphologic techniques have recently been advanced for hydrograph synthesis. These techniques have added a new dimension to application of geomorphology to the hydrologic simulations particularly to tne effective rainfall-direct runoff relationship. However, they remain to be tested on wide variety of gauged basins and have yet to be applied to ungauged basins.

Geomorphology is a science which deals with the basin composition with respect to the topographical and geometric configurations of the basin. It is well known fact that the climatic as well as geomorphologic characteristics affect the basin response to a considerable extent. Thus the liking of the geomorphological parameters with the hydrological characteristics of the basin provides a simple way to understand the hydrologic behaviour of the different basins particularly of the ungauged basins. Before taking up the studies related with hydrologic simulations using the geomorphologic characteristics, the important geomorphological properties have to be quantified from the available topographical map of the basin. The geomorphological properties which are important from the hydrological studies point of view include the linear, areal and relief aspects of the watersheds. Various measures have been suggested by many investigators to represent the linear, areal and relief aspects of the watersheds. The quantification of those measures is quite cumbersome and time consuming, if it is carried out manually. With the help of digital computers, considerable computational time can be saved once the topographical maps are accurately digitized using electronic digitizer connected with the computer. The digitized data points are automatically stored in a file opened by the user on the computer at the time of digitizing the maps.

In this report various geomorphologic characteristics representing the linear, areal and relief aspects of the watershed are reviewed. A computer software in FORTRAN-77 language is developed to quantify some of the important geomorphological properties of the basin. The toposheet maps to the scale of 1:2,50,000 covering the Kolar sub-basin of Narmada basin upto Satrana gauging site have been digitized using the electronic digitizer available at the Institute. Different geomorphologic parameters for Kolar sub-basin upto Satrana are derived using the developed computer software. The derived geomorphological characteristics can be utilised for the hydrological studies of the sub-basin as well as for the hydrological studies of the region. Furthermore some potential applications of geomorphological characteristics in the hydrological studies are also reviewed.

2.0 REVIEW

Drainage basins are the fundamental units of the fluvial landscape and, accordingly, a great amount of research has focused on their geometric characteristics including the topology of the stream networks, and the quantitative description of drainage texture, pattern, shape and relief(Abrahams, 1984).

Horton, who made the first modern quantitative studies of drainage basins (Horton, 1932, 1945), provided the theoretical base for the hydrogeomorphic approach by suggesting that there were certain unvarying or intransient drainage basin characteristics that correlate to the hydrologic response of a basin. Horton's important contribution was his description of the laws of drainage network composition (Horton, 1945).

The quantitative analysis of drainage networks is a subject of interest to both geomorphologists and hydrologists. Although the two groups naturally have somewhat different objectives, both find it convenient to choose as a basic unit for study the set of all channels above a given point in a network, i.e. all channels that contribute to the discharge at that point. If the channels are idealized as single lines, the resulting diagram is known in the geomorphological literature as a channel network. Horton (1945) introduced the term composition of the drainage network (or basin) as: 'Composition implies the numbers and lengths of streams and tributaries of different sizes and orders, regardless of their pattern'.

The intent of this quote can be expressed by saying that the basin composition refers to the geomorphologic(topographic and geometric) properties of channel networks.

Under the impetus supplied by Horton, the description of drainage basins and channel networks was transformed from a purely qualitative and deductive study to a rigorous quantitative science capable of providing hydrologists with numerical data of practical value. Horton's work was supplemented by Longbein (1947), then developed in detail by Strahler and his Columbia University Associates.Subsequently, a significant amount of research works have been done by many investigators in the area of geomorphology.

Under this section of the report a comprehensive review of various geomorphological characteristics including their use in different hydrologic studies have been presented.

2.1 Geomorphological Characteristics

Every hydrologic design is different because the factors that affect the design vary with location. Thus it is necessary to make measurements at the design site of factors that affect the design. The factors to be measured characterize the processes of the hydrologic cycle that are important to the design problem. Given the importance of such factors as input to a hydrologic design, the accuracy with which the measurements of these factors are made will determine, in part, the accuracy of a design.

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

The geomorphologic characteristics of a watershed can be classified into two groups: (1) those relating to the channel system, and (2) those relating to the drainage basin as shown in table 1. This classification is extracted from Coffman et al (1971). Discussions on many of these characteristics are given by Horton (1945); Strahler (1964); Markovic (1966), Eagleson (1970); Bunik and Turner (1972); Smart (1972a); Abrahams (1984); Edgar and Melhorn (1974), Warntz (1975); James and Padmini (1983). The topograpahic attributes of drainage basins covering linear, areal and relief aspects are given in table 2. Table 3 provides some of the non-dimensional measures of the drainage basin shape derived by the different investigators referred in the table. Some of the parameters given in table 2 & 3 have been reviewed and their evaluations have been discussed in this section of the report.

2.1.1 Ordering of the Streams

For all practical purposes, the quantitative study of channel networks began with Horton's (1945) method of classifying channels by order. Later on, Strahler (1952) proposed a modification of Horton's ordering scheme. Strahler's method is now generally preferred because of its simplicity and greater freedom from subjective decisions. The original Horton ordering system was, however, much used in the earlier literature. Fig.1 illustrates different methods of stream orderings.

Table 1 :Classification of geomorphologic characteristics (adapted from Coffman et.al.1971)

Channel System		Drainage Basin	
Geometry	Topology	Form	Fabric
A.Length	A. Stream segments	A. Size	A.Texture
(1) Cumulative	(1) Channel order	(1)Area	(1) Drainage density
(2) Total	(2) Basin order	(2)Basin length	(2)Constant of channel maintenance
(3) Segment	(3)Number of Segments	(3)Main stream length	(3) Fineness
(4)Link		(4)Perimeter	(4) Texture ratio
			(5) Link texture ratio
			(6) Channel frequency
B. Fall	B.Stream links	B.Shape	B.Hypsometry
(1)Cumulative	(1)Channel magnitude	(1)Circularity ratio	(1) Hypsometric curve
(2) Segment	(2)Consistent order	(2)Elongation ratio	(2) Hypsometric integral
(3) Slopes	(3)Number of links	(3)Unity shape factor	(3) Valley slopes
		(4)Watershed slop factor	(4) Amount of upland
			(5)Avalable relief
			(6) Elevation-relief ratio
C.Oscillatory	C. Branching relationships	C.Relief	C.Energy factors
(1) Sinuosity	(1) Bifurcation ratio	(1) Total	(1) Potential Energy
(2) Wandering ratio	(2) Division ratio	(2) Relief Ratio	(2) Relation to hypsometric integral
	(3) Junction angles	(3) Relative relief	(3) Topographic roughness
			(4) Hydraulic roughness
		D.Orientation	
		(1) Basin azimuth	
		(2) Mainstream azimuth	

Table 2 :Topographic attributes of drainage basins

Scale	Basin	Network	Channel reach	Channel cross-section
Dimension				
Area	Drainage Basin area Area of storage,e.g.lakes	Area tributary to strain channels	Area of channel	Cross-sectional area of channel
Length	Basin length Basin perimeter	Drainage density Stream length	Channel length Sinuosity	Width
Shape	Basin shape	Drainage pattern Network shape	Channel shape	Shape
Relief	Basin relief Basin slope	Network relief Network slope	Channel relief Channel slope	Depth

Table 3 :Some methods of expression drainage basin shape

Method	Derived by	Source
From Factor (F)	$F = \frac{A}{L^2}$ where A=drainage area L = basin length	Horton (1932)
Basin circularity(C)	$R_c = \frac{\text{Area of basin}}{\text{Area of circle with same perimeter}}$ $= \frac{4\pi A}{p^2}$ where p=basin perimeter	Miller(1953)
Basin elongation	$E = \frac{\text{Diameter of circle with same area as basin}}{\text{basin length}}$ $= \frac{2\sqrt{A/\pi}}{L}$	Schumm(1956)
Lemiscate(K)	Based upon comparison of basin with lemiscate curve $K = \frac{L^2}{4A}$	Chorley, Malm and Pogorzelski (1957)

The Horton and Strahler ordering procedures begin in the same ways:(1)Channels that originate at a source are defined to be first order streams.(2)When two streams of order u join, a stream of order u+1 is created.(3)When two streams of different order join, the channel segment immediately downstream has the higher of the orders of the two combining streams. These three steps constitute the Strahler ordering procedure.

For Horton ordering, some streams are reclassified:(4)At each point where two streams of the same order join, the stream that enters the junction more nearly parallel to the segment immediately downstream is given the order of that segment; if both enter at about the same angle, the longer stream is given the order of the downstream segment; finally, in the words of Horton (1945) "Exceptions may occur where geological controls have affected the stream courses".

The order of a channel network or drainage basin is that of its highest order stream. Shreve (1957) proposing a method of ordering called segment ordering in which each outer link or first order segment is designated magnitude and each subsequent link designated as a magnitude equal to the sum of all the first order segments which are tributary to it.

Certain objections to the Strahler and Horton ordering methods have been raised by Scheidegger (1965) and others:(1) both basin order and the order of individual streams depend on the scale of map used, (2) the order in a stream network changes only when two streams of equal order join,but the physical properties change at any kind of junction and (3) the rule for combining streams is not associative. These objections are surely well founded and various other ordering schemes have been designed to avoid them. These alternative methods have their own inherent difficulties, however, and most geomorphologists and hydrologists have continued to use the Strahler method.

They propose a small change in the stream ordering system currently employed.In the preceding sections the convenient and operationally significant system employed by Horton (1945) as modified by Strahler (1964) was used. Basically they suggested that what are now regarded as first order streams and basins must be considered as of zero order and that present second order be called first and so on. They also gives the justification for and the convenience attending such a change as below.

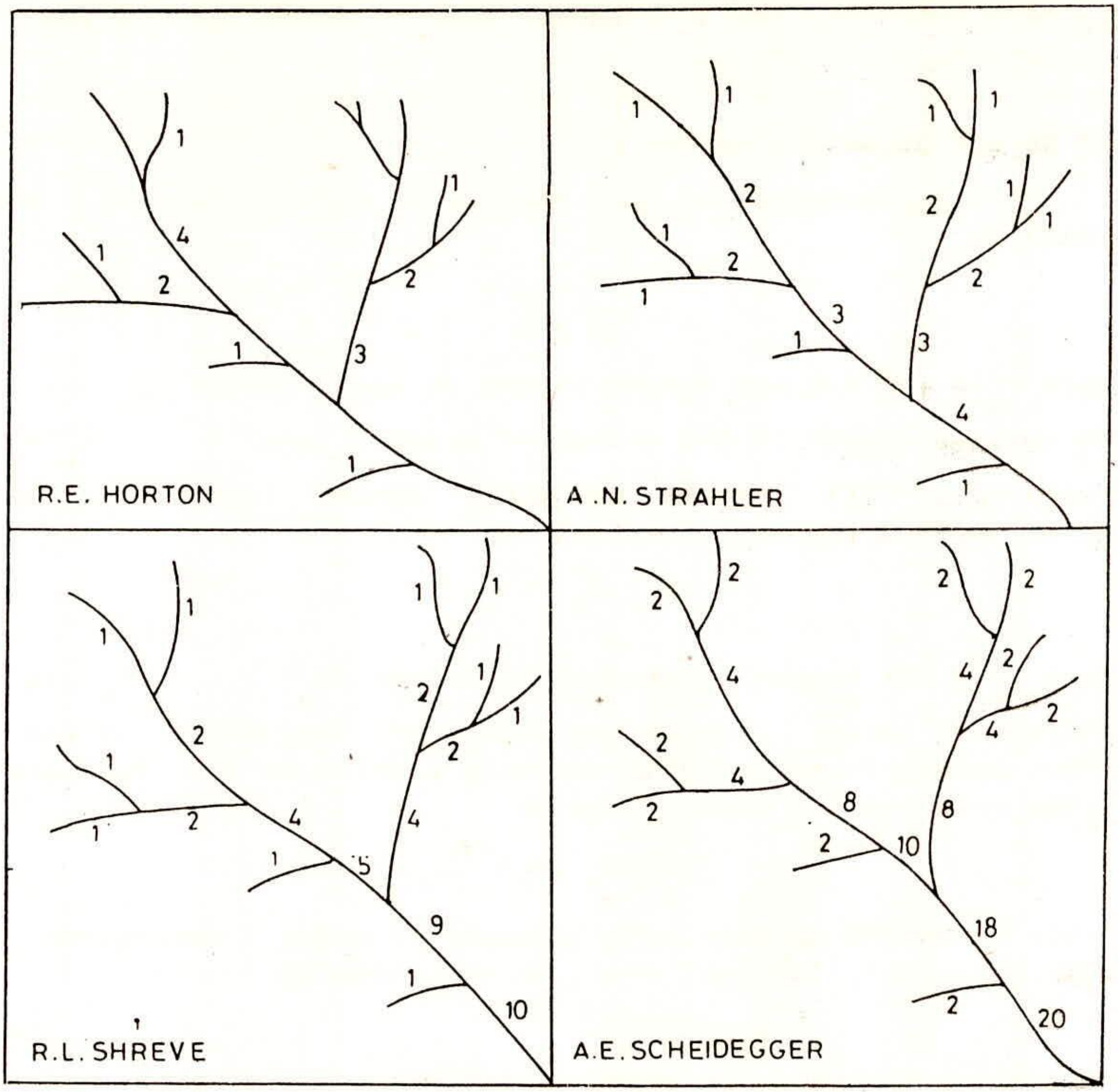


FIG. 1 METHODS OF STREAM AND SEGMENT ORDERINGS

Several laws of fluvial morphology suggested by Horton may be classified in two ways, direct geometric series, and inverse geometric series.

(i) Direct geometric series :

In mathematical form the law of stream lengths, Horton (1945) is

$$\bar{L}_u = \bar{L}_1 R_L^{u-1} \tag{1}$$

where $\bar{L}_u$ is the average length of the stream of order u, $\bar{L}_1$ is the average length of the stream of order 1, and R_L is the length ratio **(ii) Inverse geometric series :** Horton's law of stream numbers (Horton, 1945) is

$$N_u = R_b^{k-u} \tag{2}$$

Where N_u is the number of streams of order u R_b is the bifurcation ratio k is the order of the trunk stream. For direct geometric series, the variable y which is the function of stream order may be generalized as

$$\bar{y}_u = y_1 \ (R_y)^{u-1} \tag{3}$$

If the threshold streams were actually of order zerorather than order one, this statement could be rewritten as

$$\bar{y}_u = y_0 \ (R_y)^{u} \tag{4}$$

similarly inverse geometric series would be written as

$$y_u = R_b^{k-u} \tag{5}$$

and would be unchanged by the change in the order for threshold streams. Hence identifying the threshold streams, as order zero simplifies direct geometric series, and has no effect on inverse geometric series.

2.1.2 Linear aspects

In the literature of geomorphology various linear measures have been proposed by many investigators which include:

(a) Number of streams of a given order

Horton(1945) gives an inverse geometric sequence with order number which can be used to compute the total number of streams of all order. Shreve (1966) hypothesized that the law of stream numbers is indeed largely a consequence of random development of the topology of channel networks according to laws of chance. Werner (1970,1972) has indeed derived this law by employing these laws.

(b) Bifurcation Ratio (R_b)

Bifurcation ratio (R_b)for a given channel network can be made by determining the slope of the fitted regression of logarithm of numbers (ordinate) on order (abscissa). The regression coefficient b is identical with the logarithm of R_b.This is a dimensionless quantity and shows only a small variation from one region to another. The bifurcation ratio is normally between 3 and 5 and can be used as an index of hydrograph shape for watersheds similar in other respects. Recent studies on application of geomorphology to watershed runoff modelling have explicitly employed bifurcation ratio (Gupta et al., 1980; Rodriguez-Iturbe and Valdes, 1979; Rodriguez-Iturbe et al., 1979; Valdes et al;1979; Rodriguez-Iturbe, 1982; Singh, 1983).

(c) Division Ratio (R_d)

Scheidegger (1966a, 1966b) showed that R_b is constant in a Horton network only if the streams of order u received tributaries of order u-1 only. Thus, if the lost segments are removed and the ratio of N_{u-1} and N_u is computed according to the Horton, then this ratio is the division ratio. Evidently, R_d is analogous to R_b, except for exclusion of lost segments. Coffman and Melhorn (1970) examined the consistency of both R_b & R_d within and between six fourth-order basins located on glacial hill within a single drainage system in India. They reported a wide and erratic variation in R_b for the test watersheds, but R_d was almost equal to 3 with one exception. The concept of R_d may be very useful in estimating parameters of rainfall runoff models.

(d) Stream-Junction Angles:

Horton (1945) was the first to discuss the stream-entrance angle.He showed that this angle was related to the slopes of the joining stream segments as

$$\cos \theta = \frac{\tan \theta_1}{\tan \theta_2} \tag{6}$$

where

θ is the junction angle

θ_1 is the slope of the higher order channel

θ_2 is the slope of the lower order stream or tributary

Schumm (1954a, 1954b, 1956) has shown that the angle of junction decreases with age, as do the gradients.

(e) Length of main channel (L)

This is the length along the longest water course from the outflow point of designated subbasin to the upper limit to the catchment boundary. Schulz (1976) described the following five methods which may be used for length measurement from topographic maps:

(i) Pair of dividers
(ii) Thread length
(iii) Edge of paper strip
(iv) Opisometer
(v) Analog to digital converter

(f) Stream lengths(L_u)

Stream length L_u is the total length of all streams of order u in a given drainage basin,

$$L_u = \sum_{i=1}^{N_u} L_i \tag{7}$$

Stream lengths are employed in development of simplified geometric configurations required in hydraulic modelling of watershed response. Horton's law of stream lengths predicts that the mean length of streams $\bar{L}_u$ of order u increases as a geometric series with ratio R_L. In other words, the individual stream length ratios

$$\lambda_u = \bar{L}_u / \bar{L}_{u-1} \sim R_L \tag{8}$$

Smart (1968, 1972a) developed an alternative stream length model based on two assumptions that are subsumed by the two postulates underlying the random model. These assumptions are (i) that channel networks are topologically random and (ii) that the lengths of interior links in a given network are independent random variables drawn from a single population.

Smart's stream length model is superior to Horton's law of stream lengths in that it permits the individual stream length ratios to vary within a single network, whereas Horton's law assumes that they are constant. The values of λ_u predicted by Smart's model conform fairly closely to the observed values, whereas Horton's law predicts that λ_u is in all cases,2.36 (Smart, 1972a, 1974).

(g) Stream length ratio (R_L)

This is the ratio of the mean stream segment of order u to the mean segment of order (u-1),

$$R_L = \frac{\bar{L}_u}{\bar{L}_{u-1}} \tag{9}$$

Value of R_L is normally between 1.5 and 3.5 in natural networks. As shown by Eagleson (1970), it equals to 2 for basin-stream similarity to hold. Since this is a dimensionless parameter, it is useful in synthesizing hydrograph characteristics.

(h) Law of Stream length

Horton's law of stream lengths, which states that the mean lengths of stream segments of successive orders of a given watershed tend to approximate a direct geometric series in which the first term is the meanlength of segments of the first order:

$$\bar{L}_u = \bar{L}_1 R_L^{u-1} \qquad (10)$$

Although this law has been confirmed by data from many watersheds (Leopold and J.P.Miller, 1956; Schumm, 1954a, 1956; Broscoe, 1959; Morrisawa,1959), Melton (1957) as well as Maxwell (1960) found that the stream segments formed a geometric series only by chance. In a subsequent study, Broscoe (1959) obtained a geometric series using cumulative mean length L_u^c instead of mean length:

$$L_u^c = L_1^c R_L^{u-1} \qquad (11)$$

This result was further substantiated by Bowden and Wallis (1964) as well as Edgar and Melhorn (1974).

(i) Length of Overland Flow (L_o)

The length of overland flow can be defined as the length of flow of water over the ground before it becomes concentrated in definite stream channels. Horton (1945) defined length of overland flow as the length of flow path , projected to the horizontal, of non channel flow from a point on the drainage divide to a point on the adjacent stream channel. He noted that 'Length of overland flow is one of the most important independent variables affecting both the hydrologic and physiographic development of drainage basins'. Horton recommended using half the reciprocal of drainage density D for the average length of overland flow $\bar{L}_o$ for the entire watershed,

$$\bar{L}_o = \frac{1}{2D} \qquad (12)$$

Where drainage density, D, is defined in section 2.1.3.

(j) 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 the mouth to the tip of the main stream. It should also be noted that unusually shaped basins the straight line distance from tip to mouth may not actually follow the valley and the resulting value of the wandering ratio will appear abnormally high.

(k) Sinuosity Ratio (S_r)

The sinuosity ratio of a stream is defined as the ratio of the length along the center line of the stream to the length along the valley.

(l) Fineness ratio

Melton (1957) suggested that the ratio of channel lengths to the length of the basin perimeter is fineness ratio which is a measure of topographic fineness .

(m) Watershed eccentricity

The watershed eccentricity is given by the expression:

$$\tau = \frac{\sqrt{\left|(L_c^2 - W_L^2)\right|}}{W_L} \tag{13}$$

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 the watershed at the centre of mass and perpendicular to L_c.

It is to be noted that if $L_c = W_L$, $\tau = 0$, and as either L_c or W_L get large, τ increases. Thus the lower the value of τ, the greater the compactness of the watershed concentrated near the mouth and higher the flood peak.

(n) Basin perimeter

Basin parameter is defined as the length of the watershed divide which surrounds the basin.

2.1.3 Areal Aspects

Various areal aspects of the geomorphological characteristics which have been reviewed here include:

(a) Drainage area (A)

Drainage area represent the area enclosed within the boundary of the watershed divide.The drainage area (A) is probably the single most important watershed characteristic for hydrologic design. It reflects the volume of water that can be generated from rainfall. Drainage area is required as input to models ranging from simple linear prediction equations to complex computer models. Schulz (1976) described the following methods for the determination of the area of a drainage basin from the available toposheets of the basin.

(i) Estimation
(ii) Polar planimeter
(iii) Dot grid
(iv) Strip sub division
(v) Geometric sub division
(vi) Analog to digital converter.

(b) Drainage density (Horton 1932, 1945)(D)

Drainage density is defined as the ratio of the total length of channels of all orders in a basin to the area of the basin. Drainage density measurements have been made over a wide range of geologic and climatic types of the United States. The lowest values, between 3.0 and 4.0 miles/sq.mi, are observed in resistant sandstone strata of the Appalachian Plateau Province (Smith 1950, Morisawa 1959). Values in the range 8 to 16 are typical of large areas of the humid central and eastern United States on rocks of moderate resistance under a deciduous forest cover (Strahler 1952, Coates 1958). Comparable values are found in parts of the Rocky Mountain region (Melton 1957), but in the drier areas of that region values range from 50 to 100.

(c) Constant of channel maintenance (Schumm 1956)

Constant of channel maintenance is defined as the ratio between the area of a drainage basin and the total length of all the channels expressed in square metre per metre. It is equal to the reciprocal of the drainage density.

(d) Stream frequency (F) (Horton 1932, 1945)

Stream frequency is defined as the number of streams per unit area in a drainage basin. Melton (1958) analysed in detail the relationship between drainage density and stream frequency as

$$F = 0.694\ D^2 \qquad (14)$$

Both F & D measure the texture of the drainage net, but each of which treats a distinct aspect.

(e) Circularity ratio (Miller 1953) (R_c)

Basin circularity ratio is defined as the ratio of the basin area to the area of a circle having a circumference equal to the perimeter of the basin. The value of this ratio approaches 1 as the shape of the basin approaches a circle. Miller believed that this parameter would remain constant in homogeneous geologic materials and would serve as an expression of a universal equilibrium form.

(f) Elongation ratio (Schumm 1956) (R_e)

Elongation ratio of a basin is defined as the ratio between the diameter of a circle with the same area as the basin and the basin length. The value of this ratio also approaches 1 as the shape of a drainage basin approaches a circle. This ratio varies from .6 to 1.0 over a wide variety of climatic and geologic regimes. Typical values are close to 1.0 for regions of very low relief and are between .6 and .9 for regions of strong relief and steep ground slopes.

(g) Form Factor (Horton 1932) (R_f)

Horton (1932) defined a dimensionless parameter, called the form factor, R_f, as the ratio of basin area (A) to the square of the basin length (L)

$$R_f = \frac{A}{L^2} \qquad (15)$$

The inverse of this factor has been used by the U.S.Army Corps of Engineers (1954) in unit hydrograph studies.

(h) Lemniscate Ratio, (R_m) (Chorley et al., 1957)

This ratio measures the closeness of basin form to the lemniscate form and is defined as the ratio of the perimeter of the lemniscate to the actual perimeter of the basin.

(i) Watershed shape factor (R_s) (Wu et al., 1964)

Watershed shape factor is defined as the ratio of the mainstream length to the diameter of a circle having the same area as the watershed.

(j) Unity Shape factor (R_u)(Smart & Surkan 1967)

Unit shape factor is defined as the ratio of the basin length to the square root of the basin area.

(k) Law of stream areas

Horton (1945) inferred that mean drainage basin areas of progressively higher orders should increase in a geometric sequence, as do stream lengths. Schumm (1956) expressed this relationship in a law of stream areas:

$$\bar{A}_u = \bar{A}_1 R_a^{u-1} \qquad (16)$$

Hack (1957) examined the relationships between area and length in terms of Horton's law of drainage network composition.

2.1.4 Relief Aspect

The parameters covering the relief aspect of the basins and channel networks are as follows:

(a) Basin relief (H)

Relief of a basin is the maximum vertical distance from the stream mouth to the highest point on the divide. Basin relief 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 about the outlet. Relief is an indicative of the potential energy of a given watershed about a specified datum available to move water and sediment downslope. A study by Hadley and Schumm (1961) indicates that normally high points on a divide should not be used for determining the basin relief.

(b) Relief Ratio (R_h)

Relief ratio is defined as the ratio between the basin relief and the basin length. In normally shaped basins the relief ratio is a dimensionless heigh t - length ratio equal to the tangent of the angle formed by the intersection at the basin mouth of a horizontal plane passing through the highest point on the divide. This parameter permits comparison of the relief of the two basins without regard to the scale of the toposheet. It measures the overall steepness of a watershed and can be related to its hydrologic characteristics (Schumm, 1954a; Maner, 1958).

(c) Law of Basin Relief

Maxwell (1960) postulated a law of basin relief, which states that the mean relief of basins tends to closely approximate a geometric series.Thus the mean relief $\bar{H}_u$ of a watershed of order u is equal to the product of the mean relief of the first order basins, $\bar{H}_1$, and the basin relief ratio raised to the power u-1

$$\bar{H}_u = \bar{H}_1 R_n^{u-1} \tag{17}$$

where R_n is the relief ratio.

(d) Relative Relief (R_p)

Relative relief is defined as the ratio of the basin relief, to the length of the perimeter. Relative relief is an indicator of the general steepness of a basin from summit to mouth. It has an advantage over the relief ratio in that it is not dependent on the basin length which is a questionable parameter in oddly shaped basins.

Melton (1957) define relative relief. Maxwell (1960) used basin diameter and the horizontal distance to compute relative relief.

(e) Ruggedness number (R_n)

Melton (1957) and Strahler (1958) defined a measure called the ruggedness number, R_n, as a product of relief H and drainage density D where both terms are in the same units:

$$R_n = HD \qquad (18)$$

This is a dimensionless measure and combines slope and length characteristics into one expression.

(f) Taylor and Scharwtz slope

Taylor and Schwartz (1938) described the slope of the main channel in parts per 10,000.

Studies of hydraulic geometry of stream channel cross sections in addition to employing measurements of channel slope at a particular station and these parameters together have been employed in at-a-station analysis (Leopold, Wolman and Miller, 1964).

The elevation difference between two points in a watershed or along a stream is a very significant variable in the hydraulics of the flow of water from the watershed. The slope is related to rate at which the potential energy of the water at high elevation in the head waters of the catchment is converted to kinetic energy. Losses in various form occur in the process. Water is held in storage and the travel time in the hydrologic system is in general inversely related to the slope.

2.2 Hydrological studies using geomorphological characteristics

In many hydrological studies such as design flood estimation, water availability studies and runoff estimation, geomorphological characteristics have been frequently used, particularly in the regional studies, in order to make the required estimates for ungauged catchments. In this section some of the hydrological studies, wherein the different aspects of the geomorphological characteristics are utilized, have been reviewed.

2.2.1 Development of Empirical formula using geomorphological parameters :

Whenever neither sufficient rainfall data, enough discharge data is available the regional empirical formula have to be used for flood flow computation. Since no flood formulas can be considered to be of universal application, one has to develop a regional empirical formulae application to different regions in India. Some of the empirical formulae developed for specific regions in India and widely used for flood flow computation, are given in table 4.

The empirical form of relationships were developed not only in India but also in other parts of the world. The formulae developed in various countries are also given in table 4. The results indicate the need for better knowledge of actual hydrological process and watershed characteristics at basin scale to enable the transfer of hydrological relationships between different size basins and different regions in more systematic manner. This may require more information on the spatial variation of many hydrological processes over a wide range of regions including the pertinent geomorphologic and watershed characteristics affecting them together with the stream flow and rainfall data currently being collected.

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 A.C.Miller, 1978; Chang and Boyer, 1977, Aron and A.C.Miller, 1978; Chang and Boyer, 1977, Aron and A.C.Miller, 1978; Dingman, 1978; Crippen, 1982; Aron, Kibler and Taghati, 1981; Mosley, 1981; Adejuwon, 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.

2.2.2 Use of geomorphological and physical characteristics of watershed in regional unit hydrograph studies :

The unit hydrograph technique is one of the most popular and the 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

Table 4
Empirical Formulae

No.	Author	Formula	Limitations
		A. INDIAN FORMULAE	
1.	Dicken Professional Paper on Indian Engg. Vol.II.1865	$Q=CA^{3/4}$ Q in cumec, A in sq.kms. C=11.42 for areas with annual rainfall 600-1250 mm; max value of C=35	Generally applicable for moderate size basins in North and Central India.
2.	Ryves	$Q = CA^{2/3}$ C=6.8 within 80 km.of coast; 8.3 for areas betweem 80 and 2400 kms. from the coast, 10.0 for limited area near the hills. Actual observed values are upto 40.	Derived from a study of river basins in south India.
3.	Craig. Proc. of Inst. C.E.Vol.LXXX 1884-85pp.201	$Q = 7.75\ NB\ \ln(4.97\frac{L^2}{B})$ N = 0.12 to 0.18 B=average width of strip in km. L=length of strip in km. or $Q=10CVi\ \ln(\frac{4.97L^2}{B})$ where C=coefficient of discharge V=velocity in m/sec. i = rainfall in cms.	Area should be divided into a number of triangular strips before application; gives too low values in practice.
4.	Lillie Proc. of Inst. C.E.Vol.CCXVII 1923-24 pp. 295	$Q=0.058VR\ \lambda\Sigma(\theta L)$ $\lambda=(1.1+\log.0.621L)$ $R = 2 + \frac{P}{38.1}$	The catchment area has to be divided into a number of sectors of circles.

	P=annual rainfall in cm. = angle substanded by a strip at site. L = length of arm in km. V = velocity of flow in m/sec.	Formula gives too high values.
5. Inglis Tech. Paper No.30 Bombay P.W.D.1940	$Q = \frac{124A}{\sqrt{A+10.4}}$	Derived on the basis of rivers of Maharashtra
6. Ali Nawaz Jung Author's original note	$Q=C(0.386x\ A^{(0.925-1/14 \log 0.386A)}$ C=49 to 60;max value=86	Lower values for south India and upper values for North India
7. Rhind Proc.Inst. of CE Vol.CLIV,1902-3 pp.292	$Q=0.095\frac{CSRa}{L}x\ (0.386A)^{P}$ S=average slope in m/km for 5 km.above the site. Ra= greatest average rainfall in cms. P = index. L=greatest length of the catchment in km. C= a coefficient which varies as $\frac{Ra}{L}$	Derived on the basis of data of some Indian rivers. Formula is not of much practical utility.
8. Dredge and Burge U.S.G.S.water supply Paper No.771	$Q=19.5W.L^{1/3}$ or $=19.5\frac{A}{L^{2/3}}$ W=average width of basin in km. L = length of basin in km.	Based on Indian records but not useful.
9. Hyderabad formula for Tunghbhadra.	$Q=49.6(0.386x\ A^{(0.92-1/14 \log 0.386A)}$	Local Application

10.	Madras formula for Tunghbhadra.	$Q=56.7(0.386x\ A^{(0.89-1/15 \log 0.386A)}$	Local Applicability
11.	Willian Branyby	$Q = 80\ A^{0.52}$	For Western Indian catchments.
12.	Bourges	$Q=19.6A/L^{2/3}$	

B. FOREIGN FORMULA

1.	Fanning Treatise on Hydraulics and Water Supply.pp.65	$Q=2.64A^{4/5}$	Based on data of New England Appalachian basins in America
2.	Chamier-Proc. Inst.CE.Vol. CXXW Part IV 1897-98 pp.313	$Q=3.5\ CRA^{3/4}$ R = in cms/hour $C=0.875$ to 2.28	Applicable to small catchments.
3.	Murphy-U.S.G.C. Water Supply Paper162,1906	$Q=[1325/(A+831)+0.164]A$	Mainly applicable to North-eastern U.S.A. and areas under 26,000 sq.km.
4.	Metcalf and Eddy Drainage and Flood Control Engg. by Pickels pp.75	$Q=6.22A^{0.73}$	Local application to water sheds over 500 sq.km. in area for American conditions.
5.	Burkli Ziegler-Trans.ASCE Vol. 77, 1914 pp.616	$Q=4.12\ A^{3/4}$	Local application for American conditions.
6.	Possenti-Trans. A.S.C.E.Vol.77, 1914 pp.616	$Q=48.4\sqrt{A}$	Local application; derived in U.S.A.
7.	Bremner-Drainage and Flood Control Engineering by Pickels pp.75	$Q=26.4A/(2.42+\sqrt{A})$	For design of water way openings in C.B. & Q.R.R.in U.S.A. Applicable to small basins.

8. Ganguillet-Trans A.S.C.E.Vol.77, 1914 pp.615	$Q=25A/(5+\sqrt{A})$	Applicable to Swiss streams.
9 Italian Formulae- Trans.A.S.C.E.Vol.77 1914, pp.615.	$Q=\frac{32A}{0.5+\sqrt{A}}$	For Streams in Italy
	$=\frac{45.7A}{0.5+\sqrt{A}}$	For small brooks in Italy.
10. O'Cornell-Trans. A.S.C.E.Vol.77, 1914pp.615	$Q=9.53(A+0.0182)^{1/2}$	American original Local application.
11.Cramer-Trans. A.S.C.E.Vol.77, 1914 pp.616	$Q=\frac{0.884A}{1+0.0985A^{1/3}}$	For Mohawak river U.S.A.
12. Lanter Burg-Trans. A.S.C.E.Vol.77, 1914, pp.616.	$Q=(\frac{6710}{6000+A}+0.085)A$	American origin-local applicability.
13. Coutagne (Newzealand)	$Q = 352 (\sqrt{A})$	For Newzealand rivers, which are usually small.
14. Kuichling U.S.G.S.Water Supply Paper-771.	$q=(\frac{1245}{A+440}+0.022)$ for occasional floods	
	$q=\frac{3,590}{A+960}+0.081$ for rare floods q = cumec/sq.km.	Areas up 13,000 to sq.km;mainly derived for Mohawak river in U.S.A.
15. Cooley Drainage and Flood Control Engg. by Pickels pp.75.	$Q=0.015(145A+A^{2/3})$ for return period 6 to 10 years.	For Mississippi Valley-local applicability

16. Fuller Trans.A.S.C.E. Vol.77, 1914,pp. 564.	$Q_{av}=0.0132CA^{0.8}=C_1A^{0.8}$ $Q=Q_{av}(1+0.8\log T)$ $Q_{max}=Q(1+2.5A^{-0.3})$ Q_{av} =yearly average flood Q = max.24 hr.flood for frequency once in T years. Q_{max} =maximum instantaneous flood discharge. C = various from 0.026 to 2.27	Constants derived on records of U.S.A. basins.If at least 10 years data is available it is applicable with sufficient reliability.
17. Grunsky Trans.A.S.C.E. Vol.85, 1922 pp. 66-136.	$Q=\frac{13.6a.R.A.}{t^{1/2}}$ t = critical time in minutes. R =rainfall in cms. $a=\frac{60}{60+C_1\sqrt[3]{t}}$ C_1=0.5 to 250.	Derived in California, not widely used.
18. Myers(Modified) Trans.A.S.C.E. Vol.89, 1926 pp. 985.	$Q=176p\sqrt{A}$ p= depends on drainage factors and frequency of floods usually unity.	Based on long data of U.S.A.rivers. Wider applicability for first approximation.
19.Horton Trans.A.S.C.E. Vol.77, 1914 pp.665.	$q=114\ T^{0.25}/A$ q = flood discharge in cumec/sq.km.equalled or exceeded in an average interval of T years.	Constants variable & determinable basis of actual data. Hence not readily applicable.

20 Lane Trans.A.S.C.E. Vol.89, 1926 pp. 1048.	$Q=k(\log T+B)A$ T=return period in years B= a constant for the region.	K and B determinable on basis of actual data.
21. Pettis "A new theory of river flood flow" 1927 & The Engg. News.Record June 21, 1934.	$Q=C(PW)^{1.25}$ C=varies from 0.195 for desert areas to 1.51 for humid areas. p=precipitation(100 year maximum)1 day rainfall in cms. W = average width of the basin in km.	Catchment between 2,600 to 26,000 sq.km.
22 Switzar and Miller Floods Cornell Univ.Eng.Exp. Stn.Bulletin 13, Dec.15, 1929.	$Q = P.C.W.^{1.5}$ P = rainfall in cms. C = 0.436 usually	For Miami Conservancy district.
23.Boston Society Journal of the Boston Society of Civil Engineers September-1930. Report of the Committee on floods.	$Q = 5.54P/T.A$ T = Base period of hydrograph in hours. p = rainfall in cms.	Wide applicability if some actual hydrograph and rainfall data are available.
24.J.M.Baird & J.F.Macillwraith -IV I:C.O.L.D. world peak.	$Q = 3010A/(277+A)^{0.78}$	Maximum recorded flood flows throughout the world.
25.Australia	$Q = \dfrac{5720A}{(480+A)^{0.9}}$	Maximum recorded flood flows throughout the world and worst cloud bursts in Australia.

26.Coutagne France	$Q = (10 \text{ to } 70)A^{0.5}$	Mild rain, A between 3,000 and 160,000 sq.km.
	$Q_a = 150 A^{0.5}$	Violent rain A between 400 and 3,000 sq.km.
	$Q_m = 200 A^{0.4}$	A between 30 and 1,0000 sq.km.
	$Q_a = 54.6 A^{0.4}$	River Garonne;A between 300 and 55,000 sq.km.
	$Q_m = 10.76 A^{0.737}$	For dams of Massic Central France
27.Fridrich (Germany)	$Q = 24.12 A^{0.516}$	
	Mean flow A from 15 to 200,000 km^2	
28. Whistler(Italy)	$Q_m=\{1538/(A+259)+0.054\}A$	A between 1,000 to 12,000 km^2
Pagliaro(Italy)	$Q_m = \{(2900/(A+90)\}A$	A≤ 1,000 sq.
Scimemi	$Q_m = \{(600/(A+90)+1\}A$	do
Baratta	$Q_m = \{(280/A)+2\}A$	For mountain basins

Giandotti	$Q_m = \{532.5/(A+16.2)+5\}A$	do
Forti	$Q_m = \{1625/(A+125)+1\}A$	$A \leq 1000$ sq.km max.rainfall 400 mm in 24 hrs
Forti	$Q_m = \{1175/(A+125)+0.5\}A$	Max.rainfall 200mm in 24 hrs.
29.Creager	$Q_m = C_1(0.386A)^{0.894(0.386A)^{-0.048}}$	
30.Hunter & Wilmot U.K.	$Q_m = 38.5\ A^{0.72}$	$A \leq 25$ sq.km
	$Q_m = 80\ A^{0.52}$	$A > 25$ sq.km.
31. Hazan.Lazarevic (Morocco)		
Central Rif.	$Q=15.55\ A^{0.776}$	Rainfall 100-130cm
Western Rif.	$Q = 9.78\ A^{0.793}$	80-100
Eastern Rif.	$Q=7.58\ A^{0.808}$	60- 80
H.Atlas Sahara	$Q=9.38A^{0.742}$	20- 40
Middle Atlas	$A = 14.94\ A^{0.626}$	70 -90
"	$Q = 13.51\ A^{0.613}$	50 -70
" (Karst)	$Q = 13.41\ A^{0.587}$	40 -70
32. Besson	Qm =(Pm/Pr) Q2	Very rational Applicable to all places where data is available

Q_m = max.expected flood.

Q_r = observed max.flood

P_m = Expected max. rainfall

P_r = Rainfall that caused Q_r

catchment system. For gauged catchments, the available runoff rainfall 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 each 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 Schwarz (1952), Soil Conservation Service (SCS) (1955, 1971), Ardis (1972, 1973), Clark (1945), O'Kelly's (1955), Minshal (1960), Nash (1960), Gray (1961), Hall (1974, 1977), NERC (1975) and Sangvaree 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 hydrometeorologically subzones. All the major storms are analysed for each of the gauge catchments to derive reasonable representative unit hydrographs. The unit hydrographs parameters are related with physical characteristics of the catchment of a subzone in order to develop regional unit hydrograph relationship for that subzone.

Singh (1984) developed the regional unit hydrograph relationships for Godavari basin subzone 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 the 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.

2.2.3 Use of Geomorphological Characteristics in Regional Flood Frequency Analysis

Flood Frequency Analysis approach is used to estimate the design flood of the desired frequency 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 consistant 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.

In this section various regional flood frequency analysis studies carried out in India as well as abroad have been reviewed with particular reference to the geomorphological characteristics used in the 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 homogenity has been tested using a recommended procedure by U.S.Geological Survey Deptt. 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:

1. Catchment area (km^2) :(AREA)
2. Taylor-Schwarz (TAYSLO) and 10-85% (as S1085) slope in (m/km) The S1085 can be is easily calculated. But as it depends on the two points on the profile, it may be more affected by measurement errors. The Taylor-Schwarz 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 travel.

3. Drainage network: The stream frequency, (STMFRQ) used as an index, which is defined as the number of junctions per square km of catchment.

4. Climate: On the basis of available information two rainfall indices were considered. The first was average rainfall for a standard period 1916-50, (SAAR), which was easily available from published maps. The other index was (RSMD) based upon daily rainfall and soil moisture deficit. The soil moisture deficit is calculated from a water balance between daily rainfall and the

Penman estimate of actual transpiration.

5. Soil: The proportion of catchment covered by each class of soil was determined from the soil map and a composite runoff index was developed.

6. Land Use: The proportion of the catchment in an urban area (URBAN) was used as a parameter.

7. Lakes: The proportion of the catchment draining through a lake was used as the index, (LAKE) for including the effect of lakes.

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 establish 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, the length of main stream and shape factor of the catchment were also tried in some of the regional flood frequency studies.

With the advancement in the area of flood frequency analysis some new approaches involving the fitting of general extreme value distribution, Wakeby distribution, probability Weighted Moment based EV1 distribution and Two Component Extreme value distribution have been widely introduced to carry out the regional flood frequency analysis.

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 a 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.

2.2.4 Application of geomorphological parameters for developing Geomorphological Instantaneous Unit Hydrograph (GIUH)

The Rodriguez-Iturbe & Valdes (1979) has synthesized the hydrologic response of a catchment to surface runoff by linking the instantaneous U.H. 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 velocity of streamflow.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. The underlying unit in the nature of the geomorphologic structure is thus carried over to the great variety of hydrologic responses that occur in nature. An approach is initiated to the problem of hydrologic similarity. A dimensionless ratio which is a characteristics variable constant for a basin is derived for each basin. This ratio is independent of the storm characteristics and linked to the geomorphology of the watershed and to its hydrologic response structure.

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. The main concepts used are:

(i) The basin obeys Horton's geomorphologic laws.

(ii) The instantaneous unit hydrograph of the basin is interpreted as the probability density function (P.d.f.) of the travel time for a drop of water landing anywhere in the basin.

(iii) Channels of given order have non-linear response functions (IUH's).

(iv) The effective rainfall input is known; no infiltration is considered anywhere in the basin.

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.

2.2.5 Application of geomorphological parameters and physiographic characteristics in other hydrological studies

With the advent of high speed digital computers mathematical modelling of hydrological process is becoming more and more popular in planning design and operation of water resources project. A general hydrologic model represents the runoff phase of hydrologic cycle by a series of moisture accounting equations containing various parameters. For a gauged catchment those parameters are estimated either by trial and error method or by optimization technique to match the simulated flows with the recorded flows. But for ungauged catchments, the recorded flows are not available, therefore, the above procedure can not be applicable for calibrating the parameters of a hydrological model. In such a situation the parameter estimates obtained for gauged catchments may be correlated with the geomorphological and physical characteristics of those catchments. Such relationships, which are also known as regional relationship may be utilized to estimate the parameters of the specific hydrological model applicable for an ungauged catchment.

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. In the process of isolating watershed,shape, slope, size, drainage pattern, and soil depth were isolated and, along with rainfall intensity, direction of storm movement, and antecedent moisture conditions, evaluated for the models. 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, of itself, does not have a tremendous effect on peak magnitude, and 3) watershed eccentricity is an effective, easily measured, meaningful, and useful expression of watershed shape in so far as that characteristic 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 DESCRIPTION OF THE STUDY AREA

The Kolar subbasin is situated in two districts of Madhya Pradesh, Sehore and Raisen in the latitude range of 22°40' to 23°08' and longitude 77°01' to 77°29'. The Kolar river originates in the Vindhyachal mountain range at an elevation of 550 m above mean sea level (msl) in the district Sehore of Madhya Pradesh State. The river length from its origin to the point where it joins the river Narmada near a place Neelkanth is 100 km. During its 100 km course river first flows towards east and then towards south. The index map of the subbasin is given as fig. 2. Hydrology of the Kolar basin and other details about the basin are given in case study (NIH 1989-90).

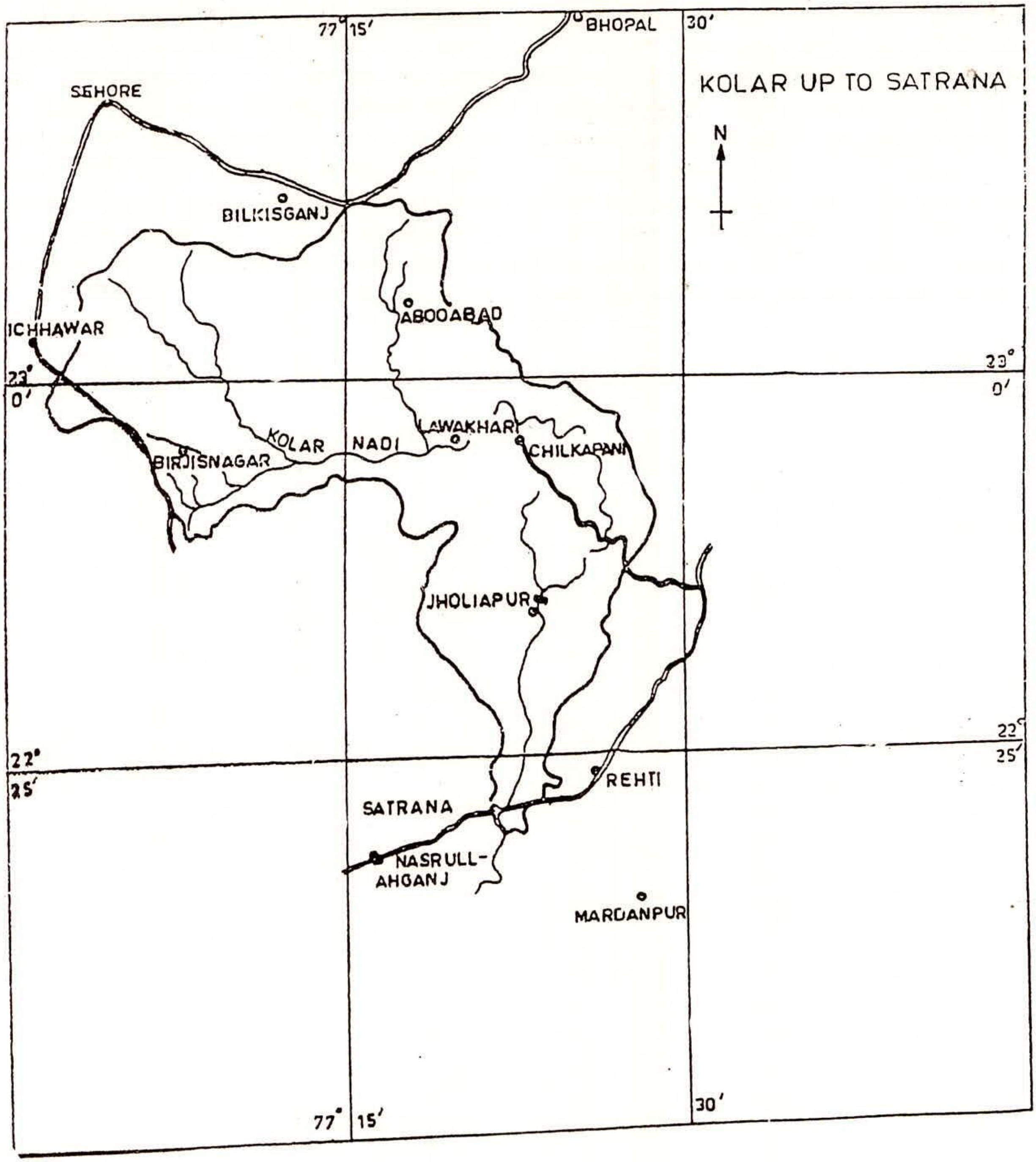


Fig. 2 : The Kolar basin upto Satrana gauging site. Also shown are the locations of hydrometeorological sites and important towns.

4.0 METHODOLOGY

This section describes the methodology used for the quantification of some of the important geomorphological characteristics.

(a) Stream Length (L)

For the preparation of data files to the programme topographic map of desired basin was prepared. The basic data for computing the length (L) of the main channel obtained by tracing along the main channel with the cursor of the analog to digital converter. Analog to digital converter is used to record x and y coordinates of closely spaced points. Coordinates of the main channel points are stored in a file R.dat and by using this data file length of a small segment between first two points is obtained by

$$\text{Distance} = [(\Delta x)^2+(\Delta y)^2]^{1/2} \qquad (19)$$

For the length of the channel, distances of all small segments of the channel are to be added. For this purpose a subroutine, LENGTH is developed. Length of all streams of each order (L_i) have also been computed using the same procedure.

(b) Catchment Area(A)

The data for computing the area (A) of the catchment are obtained by tracing around the catchment boundary with the cursor of the analog to digital converter. The coordinates of closely spaced boundary points are stored in a data file. After digitizing the boundry, a centre point in the catchment is digitized whose x and y co-ordinates are stored in the same file as the last point. Center point should be such that the lines joining each boundry point to it lie within the catchment. Some times the catchment shape is such that a single centre point within the catchment does not fulfill this condition. In such cases the catchment should be divided into two or more parts according to the shape. Then each part of the catchment should be digitized and separate data files should be prepared. While running the main program GEO.FOR, the user will be prompted for (i) for how many parts do you want to divide the catchment ? and (ii) the filename corresponding to each part of the catchment having digitized data.A subroutine AREA is developed for computing the area using the digitized data of the catchment boundary or for a part of the catchment.For computing the area of the catchment, each digitized points along the boundary are joined with the centre point dividing the whole catchment into smaller triangles. Area of each triangle was computed using formula :

$$A = \sqrt{s(s-a)(s-b)(s-c)} \tag{20}$$

where

a,b & c are the lengths of sides of triangle
and $S = (a + b + c)/2$

The areas of all triangles lying within each part of the catchment are added in order to have the areas for different parts of the catchment. Subsequently, the areas of each part of the catchment are added to obtain the total catchment area. Now boundaries for different order streams are drawn manually and their areas(A_i) are also obtained using the subroutine AREA.

(c) Perimeter of the Catchment(P)

Perimeter (P) of the catchment is obtained using the same procedure as for length. The sum of the lengths of different segments along the catchment boundary including the length between first and last digitized point provides the estimate for perimeter of the catchment.For this the data file is prepared by digitizing the boundary of the catchment. A subroutine PARAM is developed for computing the perimeter.

(d) Length of the Channel between the outlet and a point nearest 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 the centroid of the basin. Thus, the first step involved in the computation is to locate the centre of gravity of the basin.

For computing the center of gravity (x_g, y_g) of the basin, it is divided into small triangles as discussed in section 4.0 part (b). x and y co-ordinates for the centres of small triangles (x_c, y_c) are calculated using:

$$x_c = (x_1 + x_2 + x_3)/3 \tag{21}$$

$$y_c = (y_1 + y_2 + y_3)/3 \tag{22}$$

where (x_1, y_1),(x_2, y_2) and (x_3, y_3) are the coordinates of the three nodes of any triangle. If the catchment is divided into n parts, as discussed in section 4.0 part (b), for computing the catchment area, the x coordinate for the centre of gravity of each part(x_{ai}) is obtained by dividing the sum of the multiples of x_c and area of all respective triangles by the sum of area of all triangles. Similarly, the y-coordinates of the centre of the gravity (y_{ai}) are also obtained for each parts of the catchment. The x and y coordinates for centre of gravity of the whole catchment is computed by:

$$x_a = \frac{\sum_{i=1}^{n} x_{ai} \text{ Area}_i}{\sum_{i=1}^{n} \text{Area}_i} \qquad (23)$$

$$y_a = \frac{\sum_{i=1}^{n} y_{ai} \text{ Area}_i}{\sum_{=1}^{n} \text{Area}_i} \qquad (24)$$

where Area_i represents the area of the i^{th} part of the catchment.

Now a point nearest to the centre of gravity can be located on a channel segment taking the minimum of the perpendicular distances from the centre of gravity to the different channel segments. Subsequently the length of the channel from the outlet to the nearest located point from C.G., is computed using the Subroutine LENGTH. The computer software is developed based on the above stated procedure in order to compute the length of the channel between the outlet and a point nearest to C.G. (L_c).

(e) Elongation ratio (R_e)

It is computed as the ratio of diameter of a circle of the same area as the basin to the maximum basin length.

(f) Circularity ratio (R_c)

It is computed as the ratio of basin area to the area of a circle having the same perimeter as the basin.

(g) Bifurcation ratio (R_b)

It is computed using the Horton's law of stream numbers which states that the numbers of stream segments of each order form an inverse geometric sequence with order number or

$$N_u = R_b^{k-u} \qquad (25)$$

where k is the order of the trunk segment
and N_u is the number of segments of order u.

$$\log N_u = (k-u) \log R_b \qquad (26)$$

$$\text{or } \log N_u = a - bu \qquad (27)$$

where

$a = k \log R_b$ and

$b = \log R_b$

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

For computing $\log R_b$, subroutine for linear regression REG based on least square approach is used. This value of R_b is used to compute the total number of streams of all order (N) in a given network :

$$N = \sum_{u=1}^{k} N_u = \frac{R_b^k - 1}{R_b - 1} \qquad (28)$$

(h) Mean length of the channels

To obtain the mean length of channel $\bar{L}_u$ of order u, the total length is divided by the number of segments N_u of that order,

$$\bar{L}_u = \frac{\sum_{u=1}^{N} L_u}{N_u} \qquad (29)$$

Total length of channels of all orders for a catchment is computed as the sum of the lengths of all order streams.

(i) Length Ratio (R_L)

For computing the length ratio (R_L), R_{Lb} is computed using the formula

$$\sum_{u=1}^{k} \sum_{u=1}^{N} L_u = \bar{L}_1 R_b^{k-1} \frac{R_{Lb}^{k} - 1}{R_{Lb} - 1} \tag{30}$$

here L_u, $\bar{L}_1$ & R_b are known.

Since the form of the above equation is a non-linear, therefore, a separate subroutine, NEWTON is developed based on the Newton-Raphson nonlinear optimisation technique in order to provide the solution for R_{Lb}. The R_{Lb} is defined as:

$$R_{Lb} = \frac{R_L}{R_b} \tag{31}$$

Substituting the values of R_{Lb} and R_b in eq.(31) the value of R_L is computed.

(j) Watershed Eccentricity(τ)

The watershed eccentricity is evaluated using eq.(13)

(k) Form Factor

Form factor (R_f) is dimensionless ratio of basin area A to the square of basin length L, thus it is computed as

$$R_f = A/L^2 \tag{32}$$

(l) Drainage Density

Drainage density (D) is computed as the ratio of total channel segment lengths cumulated for all orders within a basin to the basin area, i.e.

$$D = \frac{\sum_{i=1}^{k} \sum_{i=1}^{N} L_u}{A} \tag{33}$$

(m) Constant of channel maintenance

Constant of channel maintenance (C) is computed as the inverse of drainage density.

(n) Stream Frequency (F)

Stream frequency (F) is computed as the number of stream segments per unit area, or

$$F = \frac{N}{A} \tag{34}$$

where N is the total no. of segments of all order within the given basin.

(o) Slope

Slope (S_i) is simply the gradient, or vertical distance between two points, whose elevations are known, divided by the horizontal distance between them.

(p) Basin relief

Basin relief (H) of a basin has been computed as the maximum vertical distance from the stream mouth to the highest point on the divide.

(q) Relief Ratio

Relief ratio(R_h) was obtained as the ratio between the basin relief and the basin length. In normally shaped basins the relief ratio is a dimensionless height-length ratio.

(r) Relative Relief

Relative relief (R_p) is computed as the ratio of the basin relief to the length of the perimeter.

(s) Ruggedness number

Ruggedness number (R_n) is computed by the product of drainage density and relief, both in the same unit.

(t) Taylor and Scharwtz slope of the channel

To obtain the average slope of the river, it is divided into several parts through the points where the elevation of the river change. The slopes for each part is obtained using the definition of slope given in section 4.0 part (o).

Now the channel is treated as series of lengths(l) of approximately uniform slope (s), whose times of flow are considered to be proportional to $(1/\sqrt{s})$. The average slope of the channel is, therefore, computed by

$$L/\sqrt{T_s} = \sum (1/\sqrt{s}) \tag{35}$$

where T_s is the Taylor and Scharwtz slope of the channel of the same length and time of flow as the actual length.

5.0 ANALYSIS AND DISCUSSION OF RESULTS:

The topographic map of the Kolar subbasin of river Narmada was prepared using the Survey of India toposheets No.55E & 55F of scale 1:250,000. Fig. 3 and Fig. 4 illustrate the river network and contour for the Kolar subbasin respectively. The river network has been ordered using Strahler's ordering scheme. It is observed that the Kolar river is a fifth order stream. The rivers of various orders have been digitized using electronic digitizer.

The digitized data were stored on VAX-11/780 computer system. The points over the subbasin boundary were also digitized along with the boundry of the areas covered by the different order streams. The computer program GEO.FOR has been run taking the digitized data as input. The length of different order streams for Kolar sub-basin computed using eq.(30) are given in table 5 along with the number of streams of different orders and other linear measures. It is observed from the table that the mean lengths, which have been computed as the ratio of the total length of specific order streams and the total number of streams of that order, are 3.97, 6.52, 11.6, 14.05 and 21.89 km for order one, two, three, four and five respectively. The number of streams for different orders are 76, 24, 7 ,3 and 1 respectively. It indicates the increasing trend in the mean length with the higher order of streams and number of streams of different order shows decreasing trend from lower to higher order streams. The bifurcation ratio and the length ratio for Kolar subbasin are 2.92733 and 1.51959 respectively. These non dimensional parameters reflects the hydrological characteristics particularly effecting the time of peak characteristics of the Kolar subbasin and may be considered for the purpose of hydrological modelling. The length of C.G. of the catchment along the main stream upto the outlet of the catchment is 18.27 km. This characteristic has been frequently used in hydrological modelling using regional unit hydrograph based approaches together with other measures. The other linear measures which have been computed for Kolar subbasin are perimeter of the subbasin, length of the main stream and watershed eccentricity and their values are given in table 5. Fig.5 shows the variation of No. of streams of different orders with their order no. on semi-log plot. The slope of the straight line is negative showing the reduction in number of streams with increase in order. It follows the law of stream numbers. Fig.6 shows the variation in average stream length with different orders of the stream. The plot shows increasing trend in average length of different orders and it follows the Horton's law of stream length.

SCALE-1:250,000

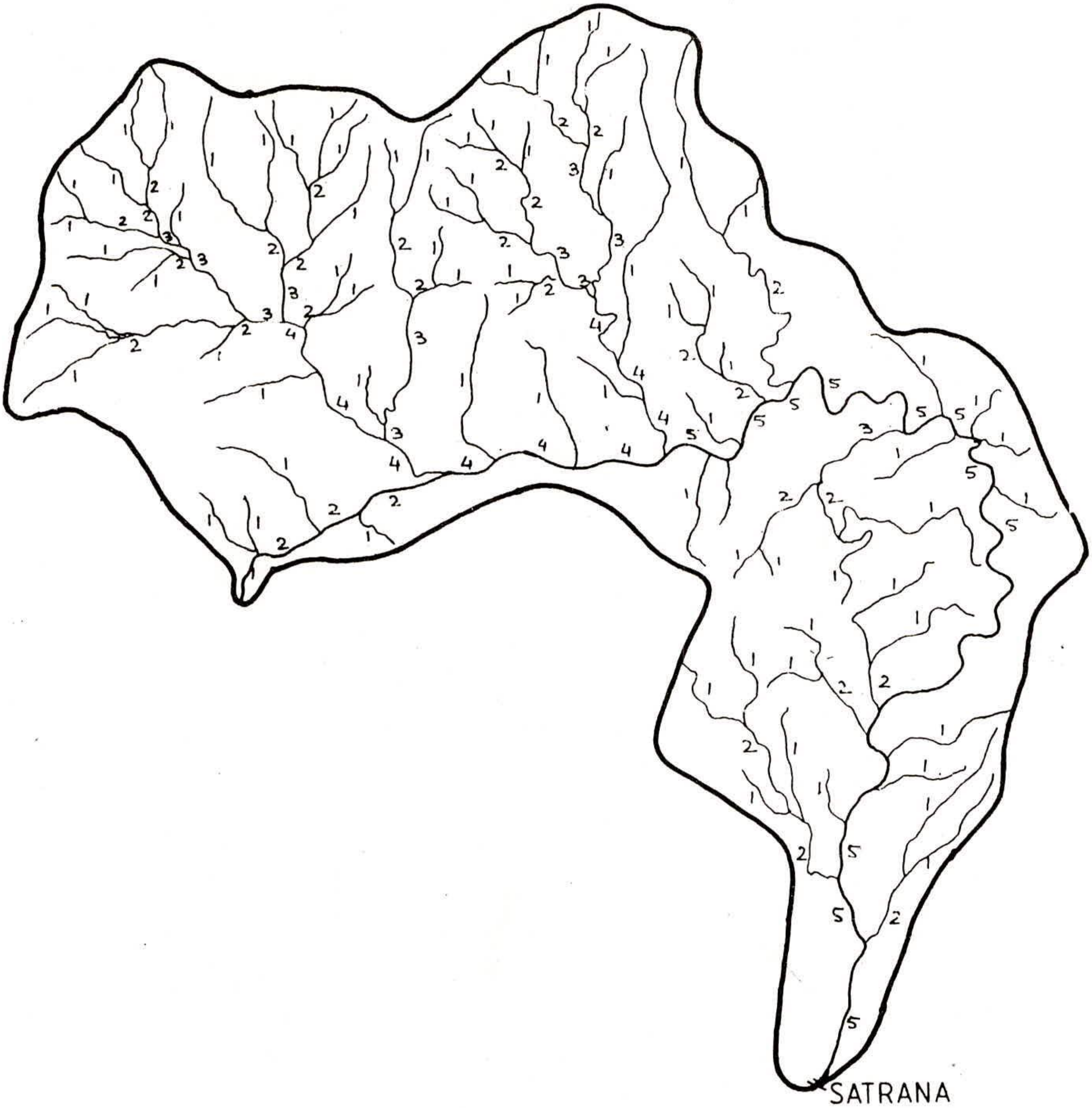
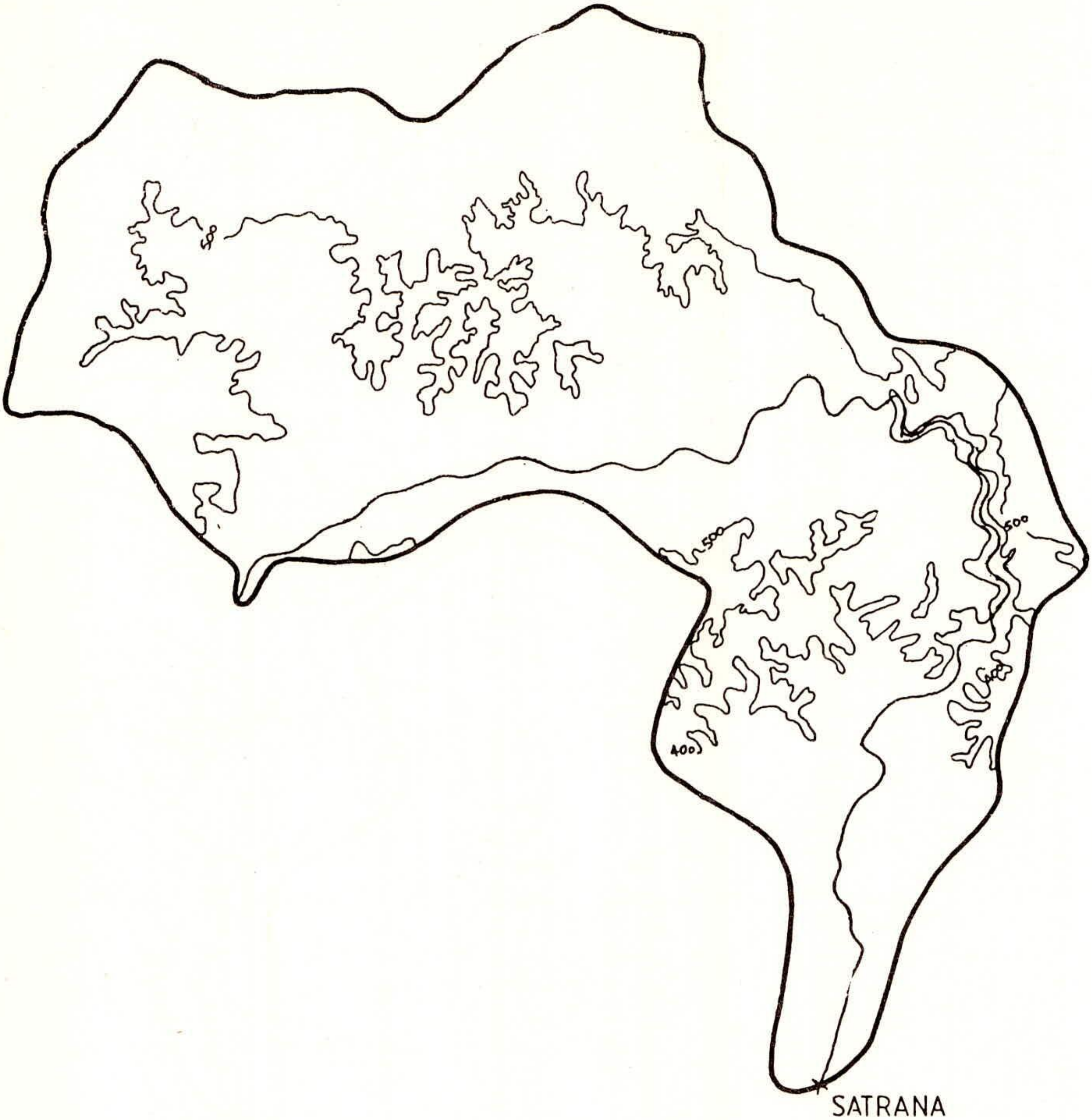


FIG. 3-RIVER CHANNEL NETWORK OF KOLAR SUB-BASIN UP TO SATRANA GAUGING SITE



SCALE - 1 : 250,000

FIG. 4 - CONTOUR PLOTS FOR KOLAR SUB-BASIN UP TO SATRANA GAUGING SITE

The various areal measures described in section 4.0 are given in table 6 for Kolar subbasin. In this table the total area covered by different order streams have been reported along with the mean areas. The table 6 indicate the mean areas as 11.28, 29.07, 87.85, 117.96 and 881.36 respectively for different order streams. It shows that there is an increasing trend in the mean areas of different order streams with the increase in the stream order. Computed subbasin area is 903.88 Sq.km. The subbasin area is considered to be one of the important geomorphological characteristic and has been used frequently in various hydrological studies. The other areal measures which also include the nondimensional measures are elongation ratio, circularity ratio, Area ratio, drainage density, constant of channel maintenance, form factor and stream frequency, and their values are given in table 6. These areal measures govern the peak and shape of the sub-basin response hydrograph. Such areal measures may be used in the modelling of hydrological response using geomorphological features without considering the runoff records. The variation of average area for different order streams with their order no. is shown in Fig.7. It can be seen from the plot that the drainage network follows the Horton's law of stream areas.

The third important measures which represent the geomorphological characteristics of the subbasin are relief measures. In literature various relief measures have been described and used in many hydrological studies. However in this study some of the important relief measures have been evaluated using the procedure described in section 4.0. The various relief measures computed for Kolar subbasin are given in table 7. These measures include slope of the main stream, Basin relief, Relief ratio, Relative relief, Ruggedness number and Taylor & Scharwtz slope. Out of the various relief measures presented here. most of them are non-dimensional measures except the basin relief. The relief measures have significant importance specially in the modelling of mountainous catchment where velocity of flow are considerably high. The relief parameters govern the overland flow and stream flow processes of a subbasin. Therefore these measures may be used to model the flow processes of the subbasin.

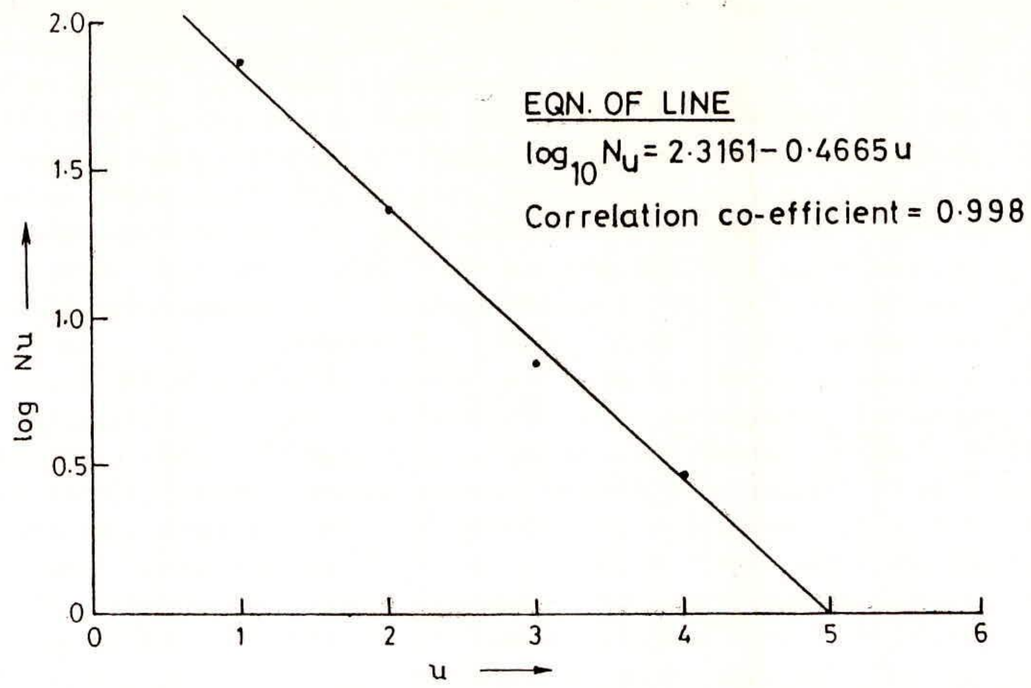


FIG. 5-VARIATION OF NO. OF STREAMS WITH THEIR ORDER NO.

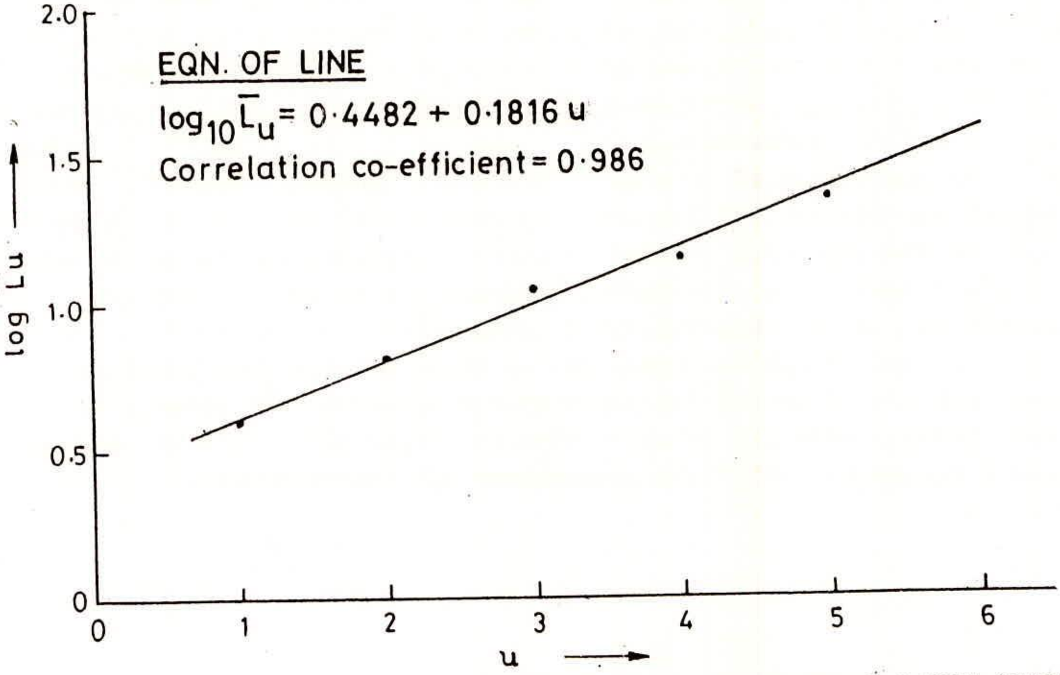


FIG. 6- VARIATION OF AVERAGE STREAM LENGTHS WITH THEIR ORDER NO.

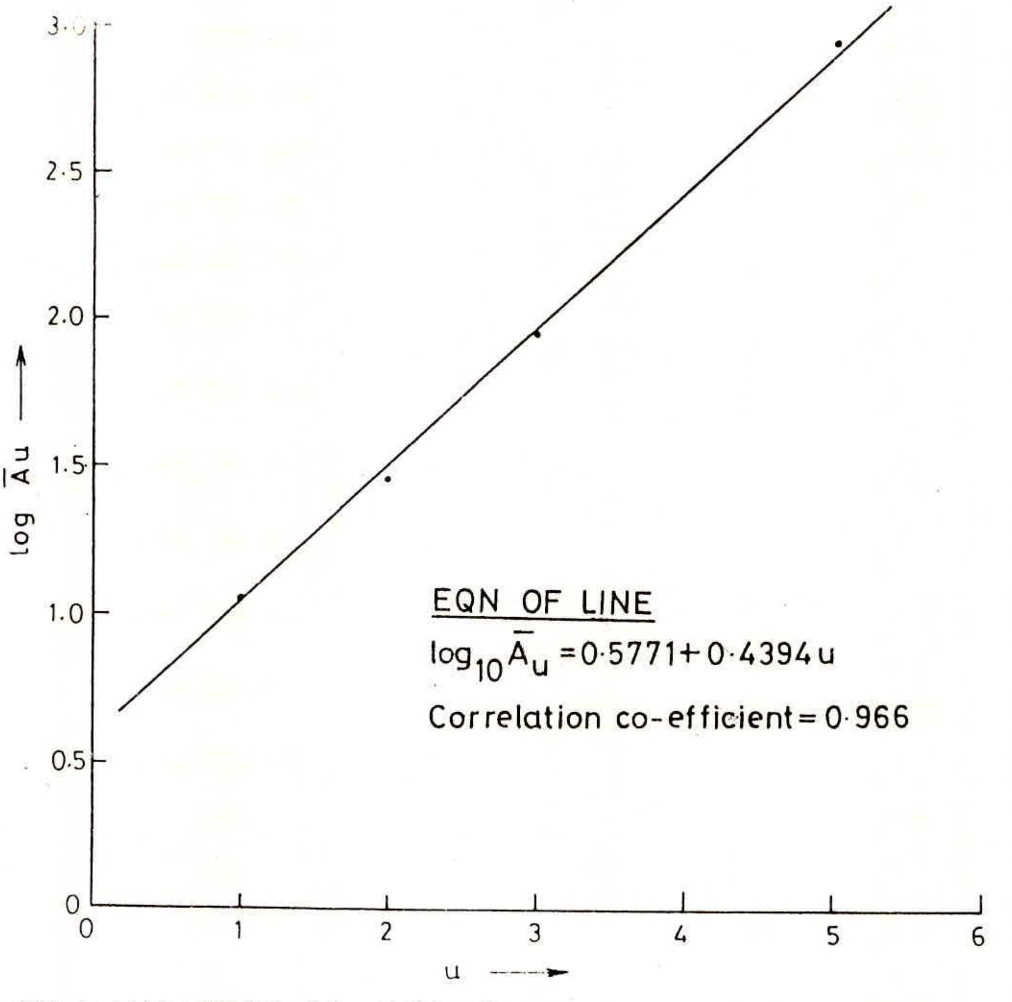


FIG. 7 - VARIATION OF AVERAGE AREA WITH THEIR ORDER NO.

Table 5 : Linear Measures

P	160.46 km.
L	75.34 km.
X_a	32.26 km.
Y_a	40.50 km.
L_c	18.27 km.
R_b	2.92733
R_L	1.51959
L_1	301.43 km.
L_2	156.47 km.
L_3	81.23 km.
L_4	42.16 km.
L_5	21.89 km.
L_u	603.18 km.
$\bar{L}_1$	3.97 km.
$\bar{L}_2$	6.52 km.
$\bar{L}_3$	11.60 km.
$\bar{L}_4$	14.05 km.
$\bar{L}_5$	21.89 km.
N_1	76
N_2	24
N_3	7
N_4	3
N_5	1
N_u	111
τ	0.4166

Table 6 : Areal Measures

A	903.88 sq.km.
R_e	0.4502
R_c	0.4414
R_a	2.7506
A_1	445.40 sq.km.
A_2	609.31 sq.km.
A_3	668.29 sq.km.
A_4	750.93 sq.km.
A_5	901.47 sq.km.
$\bar{A}_1$	11.28 sq.km.
$\bar{A}_2$	29.07 sq.km.
$\bar{A}_3$	87.85 sq.km.
$\bar{A}_4$	117.96 sq.km.
$\bar{A}_5$	881.36 sq.km.
D	0.6673 km/sq.km
C	1.4985 km.
R_f	0.1592
F	0.1228 1/sq.km.

Table 7 : Relief Measures

H	0.3000 km.
R_h	0.0040
R_p	0.0019
R_n	0.2002
T_s	0.0026

6.0 CONCLUSION

As discussed earlier, the geomorphologic properties of a basin represent its hydrologic behaviour and can be employed in synthesizing the runoff response of the basin particularly for the ungauged basins.In this report various parameters representing the geomorphologic characteristics of a basin covering the linear, areal and relief aspects have been discussed together with the mechanics of their determination. The estimation of geomorphological parameters from the toposheets is a tedious and time consuming job. Some times it leads to the erroneous estimates for the geomorphological parameters. In order to provide an ease in the computations the softwares for computing the various parameters have been developed in FORTRAN-77 language and the same have been implemented and tested on VAX-11/780 computer system. These programs have been used for estimating the geomorphological parameters for Kolar subbasin of River Narmada.

As mentioned earlier, the limited number of geomorphological parameters covering the linear, areal and relief aspects of the subbasin have been estimated for Kolar subbasin using the developed softwares. However, the software may be suitably modified for the estimation of the other parameters which have not been included in the present study. The geomorphological parameters, thus estimated, may be utilized for developing the hydrological models to simulate the hydrologic response of the basin. Such type of models are very much useful and being widely used particularly for simulating the response of ungauged basins or basins having inadequate records.

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