PAPER 10A

ADVANCED GEOMORPHOLOGY (PRACTICAL) 50 marks

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1. Analysis of drainage basin morphometry and channel aspects from topographical maps 14 marks

1.1 : Computation of stream order (Strahler's method), bifurcation ratio, drainage density and constant of channel maintenance

1.2 : Computation of braiding index, sinuosity index, meander wavelength and radius of curvature

1.3 : Computation of river profiles

2. Geomorphic mapping 14 marks

2.1 : Preparation of geomorphic maps from field data using standard symbols and colours.

2.2 : Preparation of overlays from topographical maps showing geomorphic features

2.3 : Extraction of geomorphic features from satellite FCCs

3. Velocity, discharge and sediment load analysis 14 marks

3.1 : Measurement of wetted perimeter, velocity (by current meter or floats) and discharge.

3.2 : Preparation and interpretation of hydrographs, unit hydrographs and rating curves

3.3 : Collection and analysis of coastal or riverine sediments using (J)-graded sieves and chemical / electronic balance

3.4 : Analysis of fluvial or coastal pebbles for shape and constituents.

4. Laboratory Notebook and Viva-voce 8 marks

Unit-1 ❑ ANALYSIS OF DRAINAGE BASIN MORPHOMETRY AND CHANNEL ASPECTS FROM TOPOGRAPHICAL MAPS

Structure

- **1.1 Computation of stream order (Strahler's method), bifurcation ratio, drainage density and constant of channel maintenance**
- **1.2 Computation of braiding index, sinuosity index, meander wavelength and radius of curvature**
- **1.3 Computation of river profiles**

1.1 ❑ Computation of stream order (Strahler's method) bifurcation ratio, drainage density and constant of channel maintenance

Modern approaches to drainage patterns or network stem, as do so many aspects of changing ideas on hydrology, from the work of Norton in the 1930s and 1940s, and they use mathematical methods to describe and analyse drainage networks in order to try to develop laws for the manner in which they function. Some of these mathematical attempts to quantity networks are seen below, but to understand them some basic terminology must be mastered.

The drainage basin is the area of catchment of the river and its boundary is marked by the watershed boundary. The latter can be difficult to identify in areas of indistinct relief but is generally taken to be a line joining the highest points between different drainage basins, or, failing that in level interfluve areas, the point equidistant between stream sources. Within the drainage basin streams exist in different orders. There is some confusion over the numbering of different stream orders but the system most commonly in use is the Horton-Strahler method. Each order stream has its own drainage basin, catchment area, and so on, and it has been found possible to identify a number of laws which seem to operate within the drainage basins of different orders and these are shown below.

Drainage density is a simple expression of the length of stream channels per unit area in the drainage basin, and is derived simply by dividing the total length of all stream channels (ΣL) by the area of the drainage basins (A) thus

Drainage density $D = \frac{\Sigma L}{A}$

D becomes of major hydrological significance because it reflects land use, and affects infiltration, the basin response time between precipitation and discharge, as well as being of geomorphological interest particularly for the development of slopes.

The constant of channel maintenance is the inverse of drainage density and is a measure of the area needed to support a given length of stream channel and so will indicate the influence of geology, for example, on the drainage pattern.

Constant of channel maintenance

$C = \frac{1}{D}$ where D = drainage density

A more sophisticated measure of drainage patterns is the bifurcation ratio, a measure of the amount of branching of a stream network. It is derived by dividing the number of streams of one order by the number of streams of the next highest order. The values gained are then usually expressed as a mean bifurcation ratio which indicates the complexity of the drainage network being examined. A value for mean bifurcation ratio is derived as follows:

Mean bifurcation ratio rb =

Stream order	Number of streams	Rb
1st	16	
		3.2
2nd	5	
		2.5
3rd	2	
		2
4th	1	

Mean bifurcation ratio $\overline{rb}$ $\Sigma rb = 7.7$

$\Sigma rb/_3 = 2.56$

Values for $\overline{rb}$ are between 3.0 and 5.0 in areas which are not unduly affected by structural control.

Similar to the mean bifurcation ratio is the stream length ratio derived by dividing the total stream lengths of one order by the total stream lengths of the next highest order. This ratio is also worked out for the simple drainage network

Stream order	Number of streams	Rb
1st	14.25	
		1.9
2nd	7.5	
		3.3
3rd	2.3	
		2.3
4th	1.0	

$\Sigma rb = 7.5$

Mean bifurcation ratio $\overline{Ir}$ = $\Sigma rb/_{3} = 2.5$

The opportunities which are afforded by gathering this sort of data are endless at first glance. Do drainage networks originating on the same geological strata have similar drainage density ? Is there a significant relationship between mean bifurcation ratio and a variety of climatic data ? Questions such as these were, indeed, intended by Norton to be answered by quantifying stream networks in the manner shown above, then relating them to different environments. In practice there has been some fruitful work done on the topic but the majority of attention has been concentrated on individual stream networks. Perhaps the lack of success in network/environment correlation has been due to two things. First, without strong geological control on drainage networks the number of factors that can influence the eventual network characteristics is so great that the network pattern becomes a randon one from one area to another. Second, it can be argued that the end product of the quantification process represents so much generalizing and taking of mean values that the results at the scale at which they are obtained, are too coarse to help understand the detail which really influences network form.

DRAINAGE NETWORK RELATIONSHIP OR LAWS OF DRAINAGE COMPOSITION:

From the previous analysis it is apparent that stream order number is directly proportional to shape, size and discharge system of the rivers in the system. R.E.Horton (1945) did bivariate analysis from observed relationships of stream orders with these linear and organizational properties of stream basins and thus formulated (which was later adapted by Strahler) into a group of similar laws of drainage network relating number of streams, stream lengths, basin areas and stream slopes to order number by geometric series. The geometric ratios of these series are already described in the earlier Statistical Indices Method as the Bifurcation Ratio, Stream Length Ratio, Basin-Area Ratio and Basin-Slope Ratio, respectively. These geometric ratios in this network analysis here are described as Law of Stream Nos., Law of Stream Lengths, Law of Basin Areas and Law of Stream Slopes. These relationships take the form of empirical equations. As indicated by the approximate equal signs in the equations given, these laws are not intended to be exact but rather to give the central tendency.

Schumm (1956) formulated a new law of drainage network [i.e. in pattern with Law of Allometric Growth in biological sciences (Strahler, 1969) which states that relative rate of growth of an organ is a constant function of the relative rate of growth of the individual] which related basin areas and channel lengths as a linear function whose slope is designated as the Constant of Channel Maintenance.

Because these laws are postulated as geometric series, graphs of the relationships on semi-logarithmic coordinates appear as set of points lying on straight lines with slopes which are the geometric ratios.

LAW OF STREAM NUMBERS:

The relationship between different orders of segments and numbers in a basin termed as Law of Stream numbers relate the numbers of different orders in the basin to approximate an inverse geometric series in which the first term is unity and the ratio is Bifurcation Ratio. Stated mathematically, Law of Stream Numbers in a basin of final order K is $N_U \approx R_B^{(K-U)}$ where $1 \leq U \leq K$. Total number of streams in the basin is expressed as $\Sigma^K_{U=1} N_U \approx R_B{}^K\text{-}1 / R_B\text{ -}1$; N_U represents the number of streams in order U and Rn is the mean bifurcation ratio for the basin. The number of streams NU, plotted on a logarithmic scale against the stream order U on a horizontal arithmetic scale gives a mathematical model of negative exponential function i.e. number of streams bears an inverse geometric relationship to stream order.

LAW OF STREAM LENGTHS:

- The law is defined as the cumulative mean lengths of stream segments of successive orders which tend to form a geometric series beginning with the mean length of first order streams and increasing according to a constant length ratio. Expressed mathematically the law is $L_U \approx R_L.^{(U-1)} L_1$ where R_1 is the stream-length ratio and L_1 is the mean length of the first order streams. The law of stream lengths when plotted, can be expressed as a positive exponential regression equation.

LAW OF BASIN AREAS:

Basin area is automatically cumulative in summing all nested basins of lower order within it. The above law of stream lengths can be paraphrased into a Law of Basin Areas, when stated as follows—the mean basin areas of successive stream orders tend to form a geometric series beginning with mean area of first order basins and increasing according to a constant area ratio. Stated mathematically, the law is $A_U \approx A\ R_A\ (U-l)$, where R_A is the area ratio. Mean area of basins of each order plotted against order produces a straight line regression of positive exponential form.

LAW OF BASIN RELIEF:

This law is stated as 'the mean basin relief of successive stream orders and tend to form a geometric series beginning with mean relief of first order basins and increasing according to a constant ratio'. The law is $H_U \approx H_1\ R_R$, where R_R is the basin relief ratio.

LAW OF STREAM SLOPES:

The law is defined as 'the mean slope of stream segments of successively higher orders in a given basin tend to form an inverse geometric series, decreasing, according to a constant slope ratio'. Stated mathematically, the law is $S_U \approx S_1\ R_S\ (U-l)$ where R_S is the gradient or slope ratio. This law when plotted can be expressed as a straight line regression of negative exponential form.

LAW OF CONSTANT OF CHANNEL MAINTENANCE:

Constant of Channel Maintenance is the area required to maintain unit length of drainage channel. Stated in another way, the relationship between mean drainage basin areas of each order and mean channel lengths of each order of any basin is a linear function whose regression coefficient plotted (Mean Basin Areas and Mean Stream Length) on logarithmic (or constant-ratio) scale is equivalent to the area necessary on the average for the maintenance of unit length of drainage channel. Mathematically , the law (=C) is $A_U \approx C\ \Sigma_{U=1}\ L_U\ ^B$ where $\Sigma\ L_U$ is the cumulative stream length and b is an exponent.: It is an important morphometric parameter because this relationship gives an idea of the pattern of runoff with the area which helps in calculating average discharge at any point in the drainage basin by measuring the catchment area lying above that point. Again the parallelism of the straight line regression curve of this law plotted for several basins illustrates the dimensional similarity.

QUANTITATIVE ANALYSIS OF EROSIONAL LAND FORMS:

Quantitative methods of study can be applied to any group of sequential landforms, produced by any process of erosion or deposition. But here it is limited to considering a landscape dominated by process of erosion and transportation by running water. We shall use the term fluvial morphometry to denote the measurement of geometrical properties of the land surface of a fluvial erosion system. The basic form elements of a fluvial erosion landscape in which first and simplest are the linear properties of the stream channel system. Linear properties are limited to the numbers, lengths, and arrangements of sets of line segments.

The second class of form elements of a fluvial erosion system deals with areal properties of drainage basins. Areal properties include the surface areas of drainage basins, as well as descriptions of the shapes (outlines) of those basins.

Third of the classes of form elements are the relief properties of the fluvial system. Relief refers to the relative heights of points on surfaces and lines with respect to the horizontal base of reference. Relief properties can be thought of as relating to the third dimension, perpendicular to the horizontal base on which the planimetric measurements are made.

Morphometry becomes of further scientific value when form is related to hydrologic process. For example, we shall inquire into the relationship between area of drainage basin and the trunk stream discharge.

STREAM ORDERS:

Commencing with the linear properties of a stream-system, the first consideration is to analyze the composition of the branching systems of channels, treating them as lines on a plane.

Given a map of a complete stream channel network, we can subdivide the network into individual lengths of channel, or channel segments, according to a hierarchy of orders of magnitude, assigning a sequence of numbers to the orders. Each finger-tip channel is designated as a segment of the first order. At the junction of any two first-order segments, a channel of the second order is produced and extends down to the point where it joins another second-order channel, whereupon a segment of third order results, and so forth. If large numbers of channel networks in a given region are divided into segments, each assigned an order according to the above rules, it will be possible to make some generalizations about the form and dimensions of the drainage network characteristic of that region. The order of a stream segment is designated by the symbol, u; the number of segments of a given order by the symbol N_u. Consider the ratio between the number of stream segments of any given order to the number of segments of the next higher order, a proportion designated as the bifurcation ratio (symbol R_b). The bifurcation ratio between successive orders then defined as

$$R_b = \frac{N_u}{N_{u+1}}$$

Studies of many stream networks confirm the principle that in a region of uniform climate, rock type, and stage of development, the bifurcation ratio tends to remain constant from one order to the next. Values of bifurcation ratio between 3 and 5 are characteristic of natural stream systems.

A noted hydraulic engineer, Robert E Horton, is credited with formulating a law of stream numbers, which can be stated as follows. The numbers of stream segments of successively lower orders in a given basin tend to form a geometric series, beginning with a single segment of the highest order and increasing according to a constant bifurcation ratio. For example, if the bifurcation ratio is 3, and the trunk segment is of the sixth order, the numbers of segments will be 1,3,9,27,81 and 243.

The relationship between orders and numbers that follow a geometric progression conforms to a mathematical model known as a negative exponential function. The formulized statement of Norton's law of stream numbers is then as follows:

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

Where, u is the number of stream order

N_u is the number of stream segments

R_b is the Bifurcation Ratio

K is the order of the main trunk stream; it designates the segment of highest order.

A simple test of the exponential equation can be made as follows. Assume an ideal stream net with a bifurcation ratio of exactly 3. Let the highest order, k, be 5.

ORDER	**NUMBER OF SEGMENTS, N_h**	**BIFURCATION RATIO, R_b**
1	81	3.0
2	27	3.0
3	9	3.0
4	3	3.0
K=5	$1/N_U$=I21	

Suppose that we wish to determine the number of segments of the second order (N_2), knowing only that the bifurcation ratio is 3 and that k=5. Substituting the equation

$N2 = 3^{(5-2)}$

$N_2 = 3^{(3)}$

$N_2 = 27$

Horton further observed that the total number of stream segments of the entire drainage basin can be expressed as follows;

$$\Sigma N_u = R_b^{k-1}/R_b^{-1}$$

The symbol ΣN_u means "the sum of segments within each order ". Testing the equation against the ideal set of numbers in which R_b equals 3, we obtain

$\Sigma N_u = 3^5\text{-}1/3\text{-}1$

$\Sigma N_u = 243\text{-}1/2{=}242/2$

$\Sigma N_u = 121$

STREAM LENGTHS:

It is apparent that the first order channel segments have, on the average, the shortest length, and that segments become longer as order increases.

The mean length of stream segments, in miles, increases by a ratio of roughly three times with each increase in stream order. This proportion of length increase is known as the Length ratio (symbol, R_L), tends to be approximately constant for a given drainage system. Chance variations to be expected in the configuration of any drainage system will produce inequalities of observed length ratio from one order to the next.

Definition of length ratio resembles that of bifurcation ratio and is as follows:

$$R_L = \frac{L_u}{L_{u-1}}$$

The symbol L_u represents the mean length of all stream segments of order u. In the practice of morphometry, a distance-measuring instrument (map-measure) is run over all segments of a given order on the map and their total distance read off. The number of segments of the order, yielding the mean length, then divides this total length. Staled in rigorous fashion,

$$L_u = \frac{\Sigma L_u}{N_u}$$

Where ΣL_u means "the sum of lengths of all stream segments of order u".

Study of many drainage systems led Horton to formulate a law of stream lengths, which with necessary modifications may be stated as follows: the cumulative mean lengths of stream segments of successive orders tend to form a geometric series beginning with the mean length of the first order segments and increasing according to a constant length ratio. The word 'cumulative' in this law indicates that the mean lengths are progressively added (cumulated) starting with the second order.

As with the law of stream orders, the law of stream lengths can be given mathematical expression by an exponential regression equation. There is a graph in which cumulative mean stream lengths are plotted on a constant-ratio (logarithmic) scale on the vertical axis; stream order is plotted on an arithmetic scale on the horizontal axis. If the plotted points fall on a nearly straight line, the validity Norton's law of stream lengths can be regarded as strongly supported. The straight-line relationship of points is excellent here in the graph. Notice that mean lengths differ greatly for the same orders between one basin and the other. This fact leads to the conclusion that the segments of a stream system cover a wide range of dimensions. Observed that the lines of points slope upward from left to right, whereas those on the number-order plot slope downward from left to right.

Horton's Law of stream lengths is stated mathematically by the following equation,

$$L_u = L_1 \; R_L^{(u-1)}$$

Where L is the mean length of the first order segments, the other symbols having been previously defined.

Stream Order u	Number of Segments N_u	Bifurcation Ratio R_b	Mean Length of Segments Miles L_u	Cumulative Mean Length Miles L_u	Length Ratio R_L	Average Watershed Area Square Miles A_u
1	5966	3.9	0.09	0.09	3.3	0.05
2	1529	4.0	0.3	0.4	2.7	0.15
3	378	5.7	0.8	1.2	3.1	0.86
4	68	5.3	2.5	3.9	7.8	6.1
5	13	4.3	7	11	2.9	34
6	3	3.0	20	31		242
7	1		8 +(not Complete)			550 (not Complete)

Data by M . E . Morisawa , 1959

BASIN AREAS :

Turning next to the areas of drainage basins, we can study the relationship between mean area of basin of a given order (symbol, A_u) and the order itself. In most respects, this relationship is of the same form as that between mean stream lengths and orders. First, it is necessary to examine the way in which surface areas contribute to basins of each order.

The area of a basin, of order u is defined as the total area of surface contributing to all first-order channels plus all included interbasin areas. In practice, it is only required that a single perimeter be located for a basin of a given order, and that this area be measured with an instrument known as a planimeter. Basin area is therefore automatically cumulative in summing all nested basins of lower orders within it.

Horton's Law of stream length has been paraphrased into a law of basin areas, stated as follows: the mean basin areas of successive stream orders tend to form a geometric series beginning with mean area of the first-order basins and increasing according to a constant area ratio. The definition of area ratio, R_a, is

$$R_a = \frac{\bar{A}_u}{\bar{A}_{u-1}}$$

Where $\bar{A}_u$ is mean area of basins of order u. By analogy with the law of stream lengths, the law of basin areas is as follows:

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

The symbol $\bar{A}_1$ denotes as mean area of the first order basins.

STREAM FLOW AND BASIN AREA :

One of the purposes of fluvial morphometry is to derive information in quantitative form about the geometry of the alluvial system that can be correlated with hydrologic information.

One example is the relationship of stream discharge, $\bar{Q}$, to area of watershed. Common sense tells us that the discharge of a stream increases with increasing drainage basin area. It remains to be determined what mathematical model applies to such an increase.

The figure shows the observed relationship of average discharge, $\bar{Q}$, to drainage area, A, for the Potomac River basin.

Stated mathematically, the relationship between average (mean) discharge and drainage area

$$\bar{Q} = {}_aA^b$$

Where a is a numerical constant and b is an exponent. This regression equation represents a power function. One practical use of the mathematical equation relating stream discharge to basin area is that it enables the hydrologist to estimate mean discharge at any point in the system by measuring the watershed area lying above that point. Such knowledge would be essential in designing hydraulic structures, such as dams, bridges, and irrigation diversions.

DRAINAGE DENSITY AND TEXTURE OF TOPOGRAPHY:

If, for the drainage network map, we should measure the total length in miles of all channels, and divided this figure by the total area in square miles of the entire map or watershed, the drainage density is found :

$$\text{Drainage density} = \frac{\text{Total length of streams (miles)}}{\text{Area (square miles)}}$$

Stated in symbols,

$$D = \frac{\Sigma L_k}{A_k}$$

Where D represents drainage density in miles per square mile, ΣL_k represents the total length of all channels of all orders and A_k is the total basin area.

Suppose that a drainage density value of 12 is obtained; this number is interpreted as meaning that there are 12 miles of channel for every square mile of land surface.

Range of drainage density —

Averaging 3 to 4 — Low drainage density — coarse texture

Averaging 12 to 16 — Medium drainage density — medium texture

Averaging 30 to 40 — High drainage density — fine texture

Averaging 200 to 500 — Extremely high D. — ultrafine texture

What factors control drainage density? One highly important control is rock type. Hard, resistant rocks, such as intrusive granite rock, gneiss, sandstone, and quartzite, tend to give low drainage density (coarse texture). This is because stream erosion is difficult and only a relatively large channel can maintain itself.

Therefore, the first order basins are large and provide large amounts of runoff to the channels. In weak rocks, such as shales and clays, even a small watershed can supply enough runoff for channel erosion.

A second factor is the relative ease of infiltration of precipitation into the ground surface and down ward to the water table. Highly permeable materials, such as sand or gravel, tend to give low drainage density because infiltration is great and little water is available as surface runoff to maintain channels. Clays and shales, on the other hand, have a high proportion of surface runoff and this combines with their weakness to give high drainage density.

A third major factor is the presence or absence of vegetative cover. A weak rock will have much lower drainage density in a humid climate, where a strong, dense cover of forest or grass protects the underlying materials, than in an arid region where no protective cover exists. For this reason, badlands are characteristic of arid climates, and the drainage density there tends to be markedly higher on all rock types.

STREAM SLOPES:

The typical profile of a graded river is upwardly concave and shows a progressive flattening of slop (gradient) in the downstream direction. This observation leads to a consideration of the relationship of channel slope to stream order. For this purpose, an average slope value is obtained for all stream segments of a given order within the drainage basin.

Channel slope is defined here as the ratio of vertical drop to horizontal distance, measured from the upper end to the lower end of a single stream segment of given order. Slope is given the symbol S. Slope is stated as a ratio, or proportion, and is without dimension. Thus, a slope of 0.01 is a ratio of 1:100, for example, a drop of 1 ft vertically in 100 ft horizontally.

If the slopes of all channel segments of the first order are measured and averaged, a mean slope is obtained for that order, and is denoted by the symbol S,.The same operation is carried out for slopes of orders 2,3,4,and so on (S_2,S_3,S_4 etc).The figure shows diagrammatically what has been done. Each of the triangles on the graph represents an order. The vertical leg of a triangle is the average vertical drop (H_u) of that order; the horizontal leg is the average horizontal distance of that order and is identical with mean stream length, L_u. The hypotenuse of the triangle shows the average slope, S_u. Values of S_u are given for each order.

Now plot the mean slope of each order, S_u, against order, u, using the constant ratio (logarithmic) scale for slope, as in previous graphs of stream numbers, stream lengths, and basin areas.

Homecruk, Ohio

ORDER *u*	*MEAN CHANNEL SLOPE, Su*	*SLOPE RATIO* R_s
1	0.181	0.48
2	0.087	0.32
3	0.028	0.32
4	0.009	0.56
5	0.005	

Data from ME. Morisawa, 1959

Perth Amboy Badlands, New Jersy

ORDER *u*	*MEAN CHANNEL SLOPE, Su*	*SLOPE RATIO* R_s
1	0.60	0.68
2	0.41	0.83
3	0.34	0.53
4	0.18	0.61
5	0.11	

Data from S.A.Schumm , 1956

Figure shows the plotted data of the tables. The points show minor departures from the fitted straight lines, but the agreement is generally good. On the basis of data, Horton formulated a law of stream slopes stated as follows : the mean slopes of stream segments of successively higher orders in a given basin tend to form an inverse geometric series decreasing according to a constant slope ratio. Stated as an equation, the law of stream slopes is as follows:

$$\overline{S}_u = \overline{S}_1 \, R_s^{(u-1)}$$

The symbol R_S represents the slope ratio, and is defined as $R_s = [\ \overline{S}_u / S_{(u-1)}\ ]$. Slope ratios must be less than 1. Values from 0.3 to 0.6 are typical. Individual slope ratios differ from order to order, as the tables show, due to variations in the resistance of the rock beneath the stream channel. In Motion's Law of stream slopes a single, constant value of slope ratio is assumed. Although the data of stream slopes show a rather high degree of variability within large drainage basins, the law appears to be generally valid.

The mathematical Laws of Horton, governing stream numbers, lengths, areas, and slopes, taken together, form a modern extension of Playfair's Law of streams. Playfair's law, a purely qualitative expression, states that the branches of a stream run in valleys proportioned to their sizes and that they have "a nice adjustment of their declivities (slopes)".

VALLEY SIDE SLOPES:

Complementing the slopes of stream channels are the slopes of the valley sides that enclose each channel. Together, channel slops and valley side slopes provide the gradient for water flow and debris transport within the fluvial system.

The characteristic slope of valley sides differs from one region to another. In a rugged mountains region—valley side slopes are very steep, so steep in fact that they are difficult to ascend or descend on foot. Loose debris rolls and slides freely down such slopes in dry weather. In contrast, valley side slopes found in the piedmont region are comparatively gentle. Steep valley side slopes are typical of the youthful and early-mature stages of the cycle of denudation; gentle slopes of late-mature and old stages.

The symbol S_g is used to denote valley-side slope, in distinction to the symbol S_c for channel slope, where both are in ratio units previously explained. However, we may also measure these slopes in degrees of arc, as is customary in the geologist's measurement of dip of strata. The Greek letter **theta** is used for slope angles in degrees. Hence $\varnothing_C$ and $\varnothing_g$ are symbols for mean channel slope and mean ground slope respectively.

Channel slope and ground slope cannot be wholly independent of one another. Steep valley sides shed water and coarse debris at high rates a steep channel gradient is necessary to transport this flow and prevent the debris from choking the valley. Gentle valley sides contribute little debris and it is of a fine size grade; hence streams can function on low gradients.

Observations of mean valley-side slopes and mean stream gradients from a wide range of localities can be plotted on a single graph to study these relationships. Each point represents a locality. The points are well represented by a straight line sloping upward to the right, although moderate deviations from the line exist. The relationship is considered as meaningful and conforms generally to the expected relationship based on a consideration of the activities of a fluvial system.

The mathematical equation that represents the straight line is of the power form,

$$\varnothing_g = {}_a\varnothing_c^{\,b}$$

where a, a numerical constant, has a value of 0.6. The exponent, b, is approximately

0.8. The equation is strictly empirical, meaning that it is based upon the observed data and not upon physical theory when data of other localities are introduced, the values of a and b in this power equation will change.

As relief diminishes with time, the point on the graph representing a given region will migrate down the sloping line, toward the lower left. Both valley side slopes and stream channel slopes will decrease in constant ratio as time passes and stage moves into late maturity. Old age, a time of low slopes, is represented by a point at the lower-left end of the sloping line. As constant ratio scales have no zero point, there is no provision in this model for reduction of the land surface to a condition of zero slope, that is perfect horizontally at base level. Instead, the peneplain is represented, its gentle slopes declining only with extreme slowness.

CONCLUSION:

Here we have observed that landforms of fluvial erosion systems, despite their complexity and infinite variety, can be systematically analyzed in terms of their linear, areal and relief properties. We have seen that the relationships of stream numbers, stream lengths, basin areas, and channel slopes to orders follow a group of related laws of similar form. These laws of Horton are expressed by exponential equations. We have seen that purely qualitative and descriptive laws and concepts, such as Playfair's laws and the Davis model of the denudation cycle, can be restated in modern quantitative forms at increased levels of understanding.

1.2 ❑ Computation of braiding index, sinuosity index, meander wavelength and radius of curvature

The channel pattern or map view of a river is usually considered as straight, meandering or braided. However, there is a plan form between straight and meandering which may be called sinuous. The term anastomosing was also proposed for braided patterns where islands dividing the channels are stable (Schumm, 1968). These various patterns are summarized in Table.

The sinuosity index (SI) has been defined in a number of ways :

$$SI = \frac{\text{Talweg length}}{\text{valley length}} \qquad \text{Leopold and Wolman, 1957)}$$

$$SI = \frac{\text{length of channel}}{\text{Length of meander belt axis}} \qquad \text{(Brice, 1964)}$$

Brice (1964) used the sinuosity index to separate straight from sinuous and meandering channels. If the SI < 1.05 the channel is straight, an SI between 1.05-1.5 is sinuous; if SI > 1.5 the pattern is meandering.

Schumm (1963) found that for streams on the Great Plains, as sinuosity increased there was a higher percentage of silt and clay in the channel perimeter, and the channel became narrower and deeper according to the equations

$$SI = 3.5 F^{0.27}$$

$$SI = 0.94 M^{0.23}$$

where F is width/depth ratio and M is the percent silt/clay in the channel perimeter. The SI was measured as the ratio of stream length to valley length. These equations indicate a continuum of channel shape to plan form from straight to sinuous to meandering.

		-sity		*depth ratio*	*behavior*	*behavior*
Straight	Single channel with pools and riffles, meandering talweg	< 1.05	Suspension mixed or bedload	< 40	Minor channel widening and incision	Skew shoals
Sinuous	Single channel, pools and riffles meandering talweg	> 1.05 < 1.05	Mixed	< 40	Increased channel widening and incision	Skew shoals
Meandering	Single channels (may be inner point bar channels)	> 1.5	Suspension or mixed load	< 40	Channel incision, meander widening	Point bar formation
Braided	Two or more channels with bars and small islands	> 1.3	Bedload	> 40	Channel widening	Channel aggradation, mid-channel bar formation
Anastomosing	Two or more channels with large, stable islands	> 2.0	Suspension load	< 10	Slow meander widening	Slow back accretion

The five-stage model points out that riffles and pools are intimately connected with the meandering habit of rivers. Both meander bends and pool/riffle sequences are repetitive, meander wave length and amplitude, as well as pool/riffle spacing, is related to channel width; and pools are associated with meander bends while crossovers are riffles. Bends are asymmetrical in cross-section and width increases more rapidly than depth with increasing discharge. Riffles are more symmetrical in cross-section, with high values of roughness. The centerline of flow moves toward the outer (concave) bank, swinging downstream from the outside of a bend to the outside of the next. There is, thus, a tendency toward lateral and down valley migration. The overall aspect of the meander bend tends to be symmetrical and related to size of the river.

The cause of meandering has puzzled many fluvial geomorphologists and given rise to many hypotheses. These may be classified into three basic types : (1) Meandering results from the hydraulics of flow; (2) Meandering results from the requirements of capacity and competence to carry the load supplied from upstream; and (3) Meandering can be looked at statistically as a result of minimum variance or least work principle.

Pools, riffles and asymmetrical cross-sections at bends are characteristic of meandering rivers. Bends are shaped to conform to other morphologic and hydrologic properties. Meander wave length has been related to average channel width, radius of curvature and dominant discharge. Dominant discharge has been equated with mean annual flow, bank full stage, and mean monthly flow (Carlston, 1965). Bank full flow is the discharge generally taken as the channel and pattern forming flow.

In fact, Hickin (1977) reduced these equations to :

Geometric relation (Wave length)	Source
$= 6.6^{0.99}$	Inglis (1949)
$\lambda = 10.9W^{1.01}$	Leopold and Woman (1957)
$\lambda = kW^{1.06}$	Knighton (1972)
$\lambda = 4.7r^{0.98}$	Leopold and Wokan (1957)
$\lambda = 7.5Qm^{0.62}$	Leopold and Wokan (1957)
$\lambda = 8.3Qb^{0.62}$	Leopold and Wokan (1957)
$\lambda = 36.1Qb0.47$	Dury(1965)
$\lambda = 10.6.\ IQb^{0.46}$	Cariston (1965)
$\lambda = 8.2Qb^{0.62}$	Cariston (1965)
$\lambda = 80Qmm^{0.46}$	Cariston (1965)
Amplitude	
$A = 18.6^{0.99}$	Inglis (1949)
$A = 10.9W^{1.04}$	Inglis (1949)
$A = 2.7W^{1.1}$	Leopold and Wolman (1957)
$A = kW^{0.98}$	Knighton (1972)

Wetted perimeter	
$P = 2.67^{0.5}$	Lacey (1930)
$P = 1.71Q^{0.51}$ (coarse material)	Dury (1965)
$P = 3.35Q^{0.51}$ (for sand)	Dury (1965)

$$\lambda/W = 10$$
$$\lambda/r_m = 4$$

Dury (1965) used these relationships to calculate former discharges of under fit streams. For the hydraulic geometry of meandering reaches. The hydraulic geometry of the channel is a result of the adjustment of the stream to provide the velocity distribution and shear stress in order to move the load.

Langbein and Leopold (1966) described meander loops as sine-generated curves, reasoning that statistically such a curve is the most probable one since it has the smallest variation in change of direction and thus represents least work. For meanders the sine-generated curve has the equation

$$\phi = \omega \sin {}^{s}/_{p}\, 2\pi$$

where ϕ is the angle of deviation of the tangent at the end of a segment s, ω is the maximum angle of deviation of the path from the downstream direction, P is the path distance through one meander wave length.

Recent research has introduced spectral analysis of meanders (Speight, 1965; Ferguson, 1977). This type of analysis measures variance accounted for by wave length length components by looking at the contributions to the spectrum from different frequencies. Well-defined meanders have a single dominant peak in the wave length spectrum, straight or irregular sections are multipeaked.

Meander patterns change over time and bends migrate. Hughes (1977) found that erosion rates on bends changed most during floods with a greater than 1.5 yr recurrence interval. However, substantial erosion occurred even during moderate floods of less than 1.5 yr frequency.

Lewin (1977) classified meander pattern changes as autogenic or allogenic. Autogenic changes are those inherent in river regimen. They include changes made by channel migration, crevassing, neck cutoffs etc. Allogenic changes are those taking place in response to some outside influence such as climatic fluctuations or human activities.

Daniel (1971) described the processes of channel migration in terms of rotation, expansion, and translation of loop axes. Expansion is defined as increase in path length, rotation as change in direction of the reference axis. Translation is movement of the bend downstream, maintaining a constant path length with no change in direction of the reference axis. Daniel related measured changes in meander configuration to reference axes which translate and rotate with time.

Hickin (1974) considered the process of meander development migration as discontinuous and dependent on the radius of curvature. He proposed a value of rm/W of approximately 2 to be an equilibrium value. Each migration phase had a slow initiation of migration from a slightly curved bend. Lateral movement occurred by the deposition of a point bar on the inner (convex) side of the bend and erosion on the outer (concave) bank. The rate of migration increased with curvature until the curve tightened to a radius of curvature that was twice the width. At this point there was a disequilibrium in flow with sedimentation occurring on the convex bank and erosion at the concave. This resulted in rapid widening of the channel at the bend causing a small radius of curvature at the concave bank. The resulting separation of flow there initiated active sedimentation at the concave bank and migration stopped. The critical curvature ratio of 2 represents a threshold condition in bend migration.

The braided pattern :

Schumm (1963) distinguished between braided and anastomosing patterns on the basis of stability. A braided pattern is one where the many divided channel ways are always shifting. An anastomosing pattern is one where there are many channels but they are stable and retain their identities with changing discharge and time. Both types are characterized by many channel ways separated by bars or islands. Environments of typically braided rivers include alluvial fan and deltaic regions and glacial outwash. Many streams which meander at high flow may be braided at low stages, hence braids are as common as meanders in all climatic regions. These include arctic, arid, alpine and monsoonal as well as humid.

Brice (1964) devised a braiding index (BI) :

$$BI = \frac{2(\text{sum of the length of islands or bars})}{\text{Length of the reach}}$$

However, this is a rather indefinite type of index since the length of bars or islands depends upon the stage at which they are measured.

Braiding has been attributed to many causes including erodible banks, steep river gradient, an abundant and coarse bedload, and a lack of river competence. These various causes have been advanced because each of these has been noted as characteristic of braided rivers.

1.3 ☐ Computation of river profiles

So far we have been discussing river morphology in the two-dimensional cross-section. If we think in terms of three dimensions, there is a fourth hydraulic geometry equation

$$S=tQ^z$$

Concerned with the river gradient. As with the cross-section morphology, the longitudinal profile represents a balance of capacity and competence to the amount and caliber of load that has to be transported with a given discharge. The slope adjustment is made along with the mutual interaction of other channel characteristics.

Events such as headward erosion, deltaic growth, stream capture or meandering may effect changes of river profile. However, adjustment is usually made by the stream in terms of scour or fill in the channel bed to lower or raise its gradient. To increase its competency the river will deposit material at the reach where the load cannot be moved. This increases the slope in the downstream direction and, hence, energy and competency is increased. If the river does not need all its energy to transport its load it will scour the bed. This reduces the slope in a downstream direction and, thus, the energy. This analysis, of course, is simplified, not taking into account possible adjustments in width, depth, velocity, roughness or channel pattern.

Most rivers show a concave profile, such that slope decreases in a downstream direction. Gilbert (1877) attributed this to increased competency from increased discharge. Sternberg (1875) related river gradient to caliber of the bedload which decreases downstream Rubey (1952) believed that slope decreased with increasing discharge or decreased load so that

$$SF=k(L^x D^y/Q^z)$$

where S is slope, F is depth / width, L is amount of load, D is caliber, and Q is discharge. He recognized that both slope and channel shape were adjusted to conditions imposed from upstream.

Carlston (1969a) ascribed the change in gradient on the Missouri River to the entrance of tributaries carrying heavy, coarse bedloads. This occurred below the junctions of the Grand, Niobrara and Platte Rivers with the Missouri. The entrance of the Kansas and Osage Rivers had no effect on the main stream gradient since their loads were no different from that of the Missouri itself. In a detailed analysis, Leopold and Maddock (1953) explained the concavity of the longitudinal profile in terms of the downstream decrease of sediment load in relation to discharge. As this ratio decreases capacity can be lowered. And even if capacity needs to be maintained or increased it can be done by increased efficiency of the downstream cross-section which is smoother and larger. They also point out that some rivers have convex profiles if there is a loss of discharge, or if the ratio of load to discharge increases.

Numerous attempts have been made to quantify the longitudinal profile. Green (1934) derived an equation of the type

$$x = e^{-y}$$

where x is distance from the mouth and y is elevation. Shulits (1941) using the same variables derived an equation

$$y = e^{-x}$$

where a is an abrasion co-efficient. The difference in these two equations.

Hack (1957) formulated the equation

$$H = k \, loge \, L = c$$

where H is fall, L is length to that point and c and k are constants. He found that the steepness of the slope was proportional to the size of bed material and was indicative of the stream competence needed to move the bedload. Slope varied with distance downstream on various types of bedrock so that

On sandstone	$S = 0.046 \, L^{-0.67}$
On shale	$S = 0.034 \, L^{-0.81}$
On limestone/dolomite	$S = 0.19 \, L^{-0.71}$

where S is stream gradient and L is length of stream to the point where gradient is taken. He found that near heads gradients were steep on all rock types but farther downstream gradients on sandstone were steeper that those on limestone which, in turn, were steeper than those on shale, i.e. for a given length, slopes on sandstone were steeper than those on shale or limestone. However, the rate of change of slope downstream was greater on shale than limestone or sandstone. These data were obtained on small drainage areas and Hack pointed out that the inferences may not apply to larger catchments. He also showed that width/depth ratio increased downstream and streams in softer rocks (shales) had deeper cross-sections than those in more resistant sediments (sandstone). Morisawa (1962), on the other hand, indicated that rivers of the Appalachian Plateau, flowing on sandstone had lower gradients than those flowing on shale. However, where streams cut through sandstone, gradients tended to be steeper than those on shale. Hack's rivers were in the Folded Appalachians where the streams cut through titled sediment layers.

Further, Hack (1973) demonstrated that the constant k in was not only related to slope and length but could be calculated by dividing the difference in altitude of two points at each end of a given reach ($H_1 - H_2$) by the difference in the logs of the lengths from the stream head to the same two points :

$$K = \frac{H_1 - H_2}{\text{Log } L_1 - \log L_2}$$

or $\quad K = SL$

where L is the distance from head to the midpoint of the reach and S is the slope of the reach. Hack (1974) calls the value k the gradient index and states that it should be adjusted to resistance of rocks over which the stream is flowing. He showed that along the New River, the SL ratio changed according to size of bed material and bedrock type. SL values increased when bedrock was resistant and fell on non-resistant limestones and shales. On other watersheds of the Blue Ridge, he found steep gradients and higher SL values where rivers flowed through quartzitic or gneissic rocks and lower slopes and SL values on reaches through carbonate sediments or shales. He concluded that anomalously high values may occur on a reach of high energy which could correspond to : (1) A belt of resistant rock; (2) A zone of uplift; or (3) An erosional disequilibrium where increased competence is needed to move coarser material. Leopold and Langbein (1964) in considering the most probable gradient for a river in terms of stream power and rate of work done arrived at the conclusion that the longitudinal profile was such that z in the relation of slope to discharge, S a Qz usually lies between -0.5 and -1.0.

Thus, although overall the longitudinal profile is smoothly concave, being adjusted to the required competency to carry the load, there are slope irregularities which have been attributed to change in type of rock in the bed, entrance of a tributary with a coarse bedload, discontinuities in diminution of grain size in transport, or tectonic activity.

Moreover, if one looks at the longitudinal profile in detail it is broken into a series of irregular steps of alternating steep and gentle reaches known as riffles and pools respectively. A pool is characterized by a water surface profile less than the mean stream gradient and by finer bed material, whereas a riffle has a water surface slope steeper than the mean stream gradient and is composed of coarser bed material. As discharge increases the difference in water surface slope over riffles and pools becomes less pronounced. Variations of width, depth and velocity along a channel occur because of pool/riffle sequences.

In meandering channels pools occur at bends on the concave bank and riffles occur at crossovers. Pools produce an asymmetrical cross-section while riffles have a more symmetrical one. Even though the bed material composing the riffles may move, the spacing and location of the riffles and pools remain the same. In fact, spacing of pools and riffles has been shown to be regular in both meandering and straight reaches, with the distance from pool to pool (or riffle to riffle) approximating 5-7 times the mean width:

$$Sp = 5.42W^{1.01}$$

The presence of pools and riffles in both straight and winding channels suggests that such irregularities are some kind of self-adjusting mechanism to balance energy expenditure along a stream. Cherkauer (1973) found that power expenditure was not uniform but highly irregular, being less at pools and greater at riffles. This relation of pools and riffles to energy expenditure will be discussed further in relation to river meanders.

Unit-2 ❑ GEOMORPHIC MAPPING

Structure

- **2.1 Preparation of geomorphic maps from field data using standard symbols and colours.**
- **2.2 Preparation of overlays from topographical maps showing geomorphic features**
- **2.3 Extraction of geomorphic features from satellite FCCs**

2.1 ❑ Preparation of geomorphic maps from field data using standard symbols and colours

Morphological maps : Morphological mapping, introduced by Waters (1958) and elaborated by Savigear (1965), aims to isolate morphologically indivisible elements of slopes and to define their characteristics and those of the junctions between them. Subtle changes in the land surface are mapped at large scales over small areas, using a base map at 1 : 10,000 scale or large, a field notebook and a simple instrument for slope measurement (Abney level or clinometer). A plot of key locational features such as field boundaries and buildings, obtained by ground survey or air photograph analysis, may replace the base map.

The method assumes that plane and curved elements of the ground surface adjoin in discontinuities either as slope breaks or as more gentle inflections. Initially, land elements or morphological units of uniform gradient are identified in the field, their angles being measured instrumentally, and the nature of the boundary between each element (concave or convex, break or inflection) is noted. Then, the nature of the change of slope is shown on the map by standard symbols, and the elements themselves may be classified by their surface gradient using slope categories as required. Originally, a threefold classification was proposed : into flats (<5°), slopes (5-40°) and cliffs (>40^0)

The commonly occurring operator variation can only be reduced to an acceptable level by practice and skilled supervision in the field. Particular problems arise over defining and locating slope changes which are inflections rather than breaks, although the symbols are usually large enough to cover the area of doubt on the map thereby solving the problem of locating an inflection accurately. In cases where flats and slopes are too small to be plotted on the map, a field note is made and the forms are mapped as micro-elements. Savigear (1965) discuses, and tabulates, the ground equivalents of plotting errors on various map scales; for example, a symbol 3 mm wide 'obscures' 7.5 m of ground equivalent at a scale of 1 : 2500.

Basic geomorphological skills of field observation, mapping, measurement and classification are demanded by this technique, which also provides a basis for the study of slope evolution either by measurement of extant slope processes and/or by examination of slope deposits (Savigear 1965, Pitty 1969). At a more practical level, it may be used with soil site surveys to aid interpretation of changes in pedological and drainage characteristics (Curties *eta/.* 1965, Bridges & Doornkamp 1963).

Geomorphological mapping : At their most advanced, as developed by European geomorphologists (Klimaszewski 1963, 1968, Tricart 1965, 1971, Verstappen & van Zuidam 1968), geomorphological maps provided information about landform genesis, age, lithology, structure and morphology. Detailed study of a map and its legend therefore gives the trained eye an indication of both the general geomorphology and specific landforms of an area. The map and legend are a result of and a tool for, geomorphological analysis.

The mapping process depends on the purpose of the map and size of area, which dictate scale of compilation and publication. Mapping at scales smaller than 1 : 100000 has been undertaken in Western Europe for inclusion in national atlases and is primarily a desk exercise with compilation from existing larger-scale maps, as in the case of the British Geomorphological Research Group's *Geomorphological map of Great Britain* (Brown & Crofts 1973). Such maps depict landforms or landform group's representative either of origin and form or of processes of different age. In previously unmapped territory, production of a geomorphological map is by reconnaissance survey. Initial identification of major landform components requires air photograph examination and selective field checks are made to assess the validity of the classification.

Detailed geomorphological mapping at larger scales than 1 : 100 000 demands identification and classification of individual landforms. An extensive legend devised by the IGU Subcommission on Geomorphological Mapping (Demek 1972) covers structural, lithological, chronological, genetic, morphographic and morphometric components. Individual landforms are depicted by particular symbols reflecting their shape and area extend (e.g. kames). Structural and lithological characteristics are shown by shading, genesis is implicit in the symbol and its definition in the legend, and chronology is represented by colour washes for different ages, making colour printing essential. Compilation of a large-scale map requires laborious field survey with careful observation, including examination of exposures and frequent soil pits. Initial formulation of a rough map of key landforms identified from true-colour or high quality-monochrome air photographs is recommended. The time required depends on the area to be mapped, the scale, and field logistics : an experienced geomorphologist might take a day to map a 200 ha sandy beach complex at 1 : 5000 or six months to map 700 km2 of upland hills and valleys at 1 : 10 000. Some experienced assistance is necessary before genetic interpretation of landforms achieves a satisfactory level of confidence.

Operator variability in genetic interpretation remains the greatest difficulty, although geomorphological maps may also be criticized for their undue emphasis on discrete landforms (glacial features, for example) compared with forms of fluvial and slope processes. However, the range of information shown makes the maps useful for further research and for applied purposes. Detailed maps showing slope features related to mass wasting and drainage details have proved invaluable in highway design (Brunsden *et al.* 1975), and such information is included in recommendations for engineering geology maps and plants (Geological Society 1972). Information relevant to land resource survey—sources of aggregates, physical constraints on development such as instability or flood liability—can be extracted and further evaluated (Crofts 1974). Alternatively, by combining with other information on soil capability, vegetation, landuse and engineering characteristics, maps of land potential for various economic activities can be produced.

2.2 ❑ Preparation of Overlays from Topographical Maps Showing Geomorphic Features

As we noted, some general-purpose maps depict the shape and elevation of the terrain. These are called **topographic maps.** They portray the surface features of relatively small areas, often with great accuracy. They not only show the elevations of landforms, streams, and other water bodies, but may also display features that people have added to the natural landscape. These might include transportation routes, buildings, and such land uses as orchards, vineyards, and cemeteries. Boundaries of all kinds, from state boundaries to field or airport limits, may also be depicted on topographic maps.

The U.S.Geological Survey (USGS), the chief federal agency for topographic mapping in this country, produces several map series, each on a standard scale. Complete topographic coverage of the United States is available at scales of 1:250,000 and 1:100,000. Maps are also available at various other scales. A single map in one of these series is called a *quadrangle.* Topographic quadrangles at the scale of 1:24,000 exist for the entire area of the 48 contiguous states, Hawaii, and territories, a feat that requires about 57,000 maps. Each map covers a rectangular area that is 7.5 minutes of latitude by 7.5 minutes of longitude. These 7.5 minutes quadrangle maps provide detailed information about the natural and cultural features of an area.

Because of Alaska's large size and sparse population, the primary scale for mapping that state is 1:63,360 (1 inch represents 1 mile). The Alaska quadrangle series consists of more than 2900 maps.

In Canada, the responsibility for national mapping lies with Survey and Mapping and Remote Sensing, Natural Resources (NRCAN). Maps at a scale of 1:250,000 are available for the entire country ; the more heavily populated southern part of Canada is covered by 1:50,000- scale maps. Provincial mapping agencies produce detailed maps at even larger scales.

The USGS produces a sheet listing the symbols it employs on topographic maps and some older maps provide legends on the reverse side. Note that in the case of running water, separate symbols are used in the legend and on the map to depict perennial (permanent) streams, intermittent streams, and springs; the location and size of rapids and falls are indicated. There are three different symbols for dams and two more for types of bridges. On maps of cities, where it would be impossible to locate every building separately, the built-up area is indicated by special tints, and only streets and public buildings are shown.

Cartographers use a number of techniques to represent the three-dimensional surface of the earth on a two-dimensional map. The easiest way to show relief is to use numbers called *spot heights* to indicate the elevation of selected points. A *benchmark* is a particular type of spot height. The principal device used to show elevation on topographic maps, however, is the **contour line,** along which all points are of equal elevation above a datum plane, usually mean sea level. Contours are imaginary lines, perhaps best thought of as the outlines that would occur if a series of parallel, equally spaced horizontal slices were made through a vertical feature.

The *contour interval* is the vertical spacing between contour lines, and it is normally stated on the map. The more irregular the surface, usually, the greater is the number of contour lines that will need to be drawn; the steeper the slope, the closer are the contour lines rendering that slope. Contour intervals of 10 and 20 feet are often used, though in relatively flat areas the interval may be only 5 feet. In mountainous areas, the spacing between contours is greater: 50 feet, 100 feet, or more. Normally, contour intervals are constant on any single map, although small-scale maps like those of continents often have a variable contour interval-—showing, perhaps, contour lines at 500, 1000, 2000, 3000, 5000, 7000, and 10,000 feet. If the intervals were not variable, rugged areas would be clogged by too many contour lines.

Contour lines are the most accurate method of representing terrain, giving the map-readers information about the elevation of any place on the map and the size, shape, and slope of all relief features. They are not truly pictorial, however. Most map-readers find it difficult to visualize the landscape from contour lines. To heighten the graphic effect of a topographic map, contours are sometimes supplemented by the use of shaded relief. An imaginary light source, usually in the northwest, can be thought of as illuminating a model of the area, simulating the appearance of sunlight and shadows and creating the illusion of three-dimensional topography. Portions that are in the shadow are darkened on the map.

The tremendous amount of information on topographic maps makes them useful to engineers, regional planners, land use analysts, and developers, as well as to hikers and casual users. Given such a wealth of information, the experienced map-reader can make deductions about both the physical character of the area and the economic and cultural use of the land.

2.3 ❑ Extraction of Geomorphic Features From Satellite FCCS

When topographic maps were first developed, it was necessary to obtain the data for them through fieldwork, a slow and tedious process, which involved relating a given point on the earth's surface to other points by measuring its distance, direction, and altitude. The technological developments that have taken place in aerial photography since the 1930s have made it possible to speed up production and greatly increase the land area represented on topographic maps. Aerial photography is only one of a number of remote sensing techniques now employed.

Remote sensing is a relatively new term, but the process it describes—detecting the nature of an object from a distance—has been taking place for well over a century. Soon after the development of the camera, photographs were made from balloons and kites. Even carrier pigeons wearing miniature cameras that took exposures automatically at set intervals were used to take aerial photographs of Paris. The airplane, first used for mapping in the 1930s, provided a platform for the camera and the photographer so that it was possible to take photographs from planned positions.

Aerial Photography

Although there is now a variety of sensing devices, aerial photography employing cameras with returned film remains a widely used remote sensing technique. Mapping from the air has certain obvious advantages over surveying from the ground, the most evident being the bird's-eye view that the cartographer obtains. Using stereoscopic devices, the cartographer can determine the exact slope and size of features, such as mountains, rivers, and coastlines. Areas that are otherwise hard to survey, such as mountains and deserts, can be mapped easily from the air. Furthermore, millions of square miles can be surveyed in a very short time. Aerial photographs must, of course, be interpreted by using such clues as the size, shape, tone, and color of the recorded objects before maps can be made from them. Maps based on aerial photographs can be made quickly and revised easily so that they are kept up-to-date. With aerial photography, the earth can be mapped more accurately, more completely, and more rapidly than ever before.

In 1975, the U.S.Department of the Interior instituted the National Mapping Program to improve the collection and analysis of cartographic data and to prepare maps that would assist decision makers who deal with resource and environmental problems. One of the first goals of the program was to achieve complete coverage of the country with orthophotographic imagery for all areas not already mapped at the scale of 1:24,000.

An **orthophotomap** is a multicolored, distortion-free aerial photographic image to which certain supplementary information (such as place names, a locational grid, boundaries, contour lines, and other symbols) has been added. The prefix *ortho* (from the Greek word *orthos, meaning* "correct") is used here because the aerial photographs have been rectified, or corrected, to remove the displacement caused by differences in terrain elevation and camera tilt. An orthophotomap combines the image characteristics of a photograph with the geometrical characteristics of a map. In contrast to the conventional topographic map, the photograph is the chief means of representing information. Orthophotomaps have a variety of uses, which include forest management, soil erosion assessment, flood hazard and pollution studies, and city planning.

Standard photographic film detects reflected energy within the visible portion of the electromagnetic spectrum. Although they are invisible, *near-infrared* wave -lengths can be recorded on special sensitized infrared film. Discerning and recording objects that are not visible to the human eye, infrared film has proved particularly useful for the classification of vegetation and hydrographic features. Color-infrared photography yields what are called **false-color images,** "false" because the film does not produce an image that appears natural. For example, leaves of healthy vegetation have a high infrared reflectance and are recorded as red on color-infrared film, whereas unhealthy or dormant vegetation appears as blue, green, or gray. Clear water appears as black, but sediment-laden water is light blue.

No photographic Imagery :

For wavelengths longer than 1.2 micrometers (a micrometer is 1 one-millionth of a meter) on the electromagnetic spectrum, sensing devices other than photographic film must be used. **Thermal scanners,** which sense the energy emitted by objects on earth, are used to produce images of thermal radiation. That is, they record the longwave radiation (which is proportional to surface temperature) emitted by water bodies, clouds, and vegetation as well as by buildings and other structures. Unlike conventional photography, thermal sensing can be employed during nighttime as well as daytime, giving it military applications. It is widely used for studying various aspects of water resources, such as ocean currents, water pollution, surface energy budgets, and irrigation scheduling.

Operating in a different band of the electromagnetic spectrum, **radar** (short for ra(dio) d(etecting) a(nd) r(anging) systems can also be used during the day or night. They transmit pulses of energy toward objects and sense the energy reflected back. The data are used to create images such as that which was produced by radar equipment mounted on an airplane. Because radar can penetrate clouds and vegetation as well as darkness, it is particularly useful for monitoring the locations of airplanes, ships, and storm systems and for mapping parts of the world that are perpetually hazy or cloud-covered, such as the Amazon Basin.

Satellite Imagery:

For more than 30 years, both manned and unmanned spacecraft have supplemented the airplane as the vehicle for imaging the terrain. Concurrently, many steps have been taken to automate mapping, including the use of electronic mapping techniques, automatic plotting devices, and automatic data processing. Many images are now taken either from continuously orbiting satellites, such as those in the U.S.Landsat series and the French SPOT series, or from manned spacecraft flights, such as those of the *Apollo* and *Gemini* missions. Among the advantages of satellites are the speed of coverage and the fact that views of large regions can be obtained.

In addition, because they are equipped to record and report back to the earth information from parts of the electromagnetic spectrum that are outside the range of human eyesight, these satellites enable us to map the invisible. A number of agencies in the United States, Japan, and Russia have launched satellites specifically to monitor the weather. Data obtained by satellites have greatly improved weather forecasting and the tracking of major storm systems and, in the process, saved countless lives. The satellites are one of the sources of the weather maps shown daily on television and in newspapers.

The Landsat satellites, first launched in 1972, take about 1 hour and 40 minutes to orbit the earth and can provide repetitive coverage of almost the entire globe every 18 days. Rather than recording data photographically, the Landsat satellite relays electronic signals to receiving stations, where computers convert them into photolike images that can be adjusted to fit special map projections. Composite images can be made by combining information from different wavelengths of light energy.

Landsat carries scanning instruments that pick up sunlight reflected by foliage, water, rocks, and other objects. One sensor, the multispectral scanner (MSS), covers the visible and near-infrared range, from 0.4 to 1.1 micrometers. The other sensor, the higher resolution thematic mapper (TM), has 7 wavebands, several in the thermal ranges up to 11.7 micrometers.

Landsat's cameras are capable of resolving objects larger than 30 meters (100 ft). Even sharper images are yielded by the French SPOT (Satellite Probatoire d'Observation de la Terre) *satellite* launched in 1986. Its sensors can show objects that are larger than 10 meters (33 ft) and can also produce three-dimensional pictures. Like Landsat, the SPOT satellite is in a polar orbit, which means that as it flies from south to north, the earth turns below it so that each orbit covers a strip of surface adjacent to the previous one. SPOT images the earth at the same local time on consecutive passes and repeats its pattern of successive ground tracks at 26-day interval.

Analyses of Landsat images have practical applications in agriculture and forest inventory, land use classification, identification of geologic structures and associated mineral deposits, and monitoring of natural disasters.

Mapping is only one of the applications of remote sensing, which has also proven to be an effective method of conducting resource surveys and monitoring the natural environment. Geologists have found remote sensing to be particularly useful in conducting resource surveys in desert and remote areas. For example, informations about vegetation or folding patterns of rocks can be used to help identify likely sites for mineral or oil prospecting. Remote sensing imagery has been used to monitor a variety of environmental phenomena, including water pollution, the effects of acid rain, and rain forest destruction. As noted earlier, weather satellites can monitor frontal systems and are a valuable contribution to worldwide weather forecasting. Because remotely sensed images can be used to calculate such factors as biomass production and rates of transpiration and photosynthesis, they are invaluable for modeling relationships between the atmosphere and the earth's surface.

Military applications of remotely sensed images include better aircraft navigation, improved weapons targeting, and enhanced battlefield management and tactical planning, which raises the question of who should have access to the information.

Unit-3 ❑ VELOCITY, DISCHARGE AND SEDIMENT LOAD ANALYSIS

Structure

3.1 Measurement of wetted perimeter, velocity (by current meter or floats) and discharge.

3.2 Preparation and interpretation of hydrographs, unit hydrographs and rating curves

3.3 Collection and analysis of coastal or riverine sediments using (J)-graded sieves and chemical / electronic balance

3.4 Analysis of fluvial or coastal pebbles for shape and constituents.

3.1 ❑ Measurement of wetted perimeter, velocity (by current meter or floats) and discharge

Gauging and analysis of stream flow : Measures of water flow may be required for various purposes. These include point measures of velocity in relation to sediment particle entrapment, the establishment of flow structures within a series of river channel bends, and the estimation of mean channel velocity and river discharge.

Velocity determination : Commonly used methods are summarized in Table. Surface velocities may be estimated from the travel time of floats over a known distance. This velocity is greater than that of mean velocity in the vertical, and surface floats may get blown by the wind, but a variety of submerged float designs or ones which have submerged rods or chains have been produced with conversion factors of around 0.80 to 0.95 to estimate mean velocity from observed surface velocity. If an accurate means of calibrating such devices is available, they may be a cheap and useful reconnaissance means of velocity determination, but in general such methods tend to be of limited usefulness.

Table : **Velocity determination methods and instruments**

Floats	Surface
	Submerged
Current meters	Pendulum
	Cup
	Propeller
	Electromagnetic

Tracers
Slope-hydraulic
Radius relationships Manning
Chezy

Velocities at any point within a flowing stream may better be gauged by current meter. Available models vary in design (including pendulum, cup and propeller types), and they may be rod or cable-mounted; it is important to be aware of the limitations of the particular instrument used. These concerns :

a) The practicability of using the instrument in the desired place and under the desired flow conditions. Models may prove insufficiently robust or controllable to be used at times of high flow and high sediment transport rates, or their design may not allow velocities to be gauged sufficiently close to bed or banks, or in shallow enough water. Designs vary in their efficiency in dealing with water movement oblique to the average line of flow.

b) Instruments will required calibration and perhaps (annual) servicing to give accurate results.

c) Designs vary in their sensitivity, and the length of time selected for observations may be important. For example, current meter observations are normally taken for 30's or more, and mean velocity is calculated as an average. Electromagnetic flow sensors (Kanwisher & Lawson 1975) may be especially useful in that they can give an instantaneous reading of down-channel and cross-channel flow components and they may respond to short-term velocity pulses, and these may be significant for sediment movement.

It is finally important to operate the equipment correctly; this includes standing so as not to interfere with the flow when using a wading rod, and using an appropriate correction factor for true depth with cable-suspended meters. Note that it is extremely hazardous to wade in deep, fast-flowing water on an uneven stream bed. Any stream that looks fast-flowing that is over 50 cm deep needs to be treated with caution.

Average velocity in cross section may be gauged using electromagnetic or ultrasonic devices. These rely on the fact that water, a conductor, flowing through a magnetic field generates an electrical current proportional to its speed of flow, and on the Doppler effect on ultrasonic waves passing through water which again may be related to water velocity. The practical application of these principles for river velocity gauging is well reviewed by Herschy (1976).

Average velocity for a stream reach may alternatively be estimated using salt tracing techniques (Calkins & Dunne 1970, Church 1975). If a quantity of salt is injected into a stream and allowed sufficient length to mix thoroughly with stream water, its time of travel may be obtained from stopwatch and conductivity readings, because the inserted salt increases the electrical conductance of the stream water.

Finally, mean stream velocity may be calculated from the manning formula

$$\bar{U} = \frac{KR^{2/3} \quad B^{1/2}}{n}$$

where U is the mean velocity, R is hydraulic radius, p is the sine of the angle of the stream (water surface) slope, and n is a lumped roughness coefficient determinated empirically, and ranging from about 0.02 for straight smooth-walled channels to 0.06 and more for densely vegetated streams containing boulders. Typical n values are given in many texts, including Graf (1971) and Gregory and Walling (1973), and these are illustrated with stream photographs in Barnes (1967).

Flow structure : It is known that water movement in rivers involves shearing flows at a variety of scales; these involve small-scale turbulence, jets, mesoscale flow separation (where the major zone of water movement occupies part only of the channel with low-velocity movement and back-eddies in the rest), and organized secondary motion such as helical flow cells. Field investigation requires instrumentation which sensitively records velocity fluctuations and for recording flow direction, so that only fairly recently have field studies become practicable (Hickin 1978). It is necessary to record a large number of velocity / orientation readings (Hickin too about 90 for each of 29 cross sections) which may be precisely located in cross section, and from these both directions of water movement and incident shear stresses may be calculated.

Discharge estimation in natural channels : Methods are listed in Table. Discharges (in $m^3 \, s^{-1}$) may be estimated by velocity area methods (in which mean stream velocity, assessed using current meter, electromagnetic, ultrasonic or other methods, is multiplied by the surveyed cross section of the stream), and by dilution gauging. For very small streams or pipe flows, an easier method may be to catch the entire flow (in a bucket) for a measured length of time; again mean velocity estimated from the Manning equation may be used in combination with measurement of channel cross section to give a discharge estimate. This may be helpful for approximate estimation of the magnitude of historical extreme floods whose timing may be obtained in various ways including radiocarbon dating of relict organic material (Costa 1978).

Table : **Methods for discharge estimation**

Volumetric		
Velocity-area	Using methods velocity determinations; also moving boat, electromagnetic and ultrasonic gauging.	
Dilution	Constant-rate Gulp	
Control structures	Weirs	Sharp-crested (V-notch, rectangular, compound, etc.) broad-crested (flat-V, Crump, compound etc.)
	Flumes	(H-type, trapezoidal, HRS* steep gradient etc.)

* Hydraulics Research Station

The velocity-area method using current meter observations is probably the commonest field procedure in the absence of gauging structures. The stream is notionally divided into a series of subsections; the mean velocity of each of these is then estimated, multiplied by the area of the cross section, and the results for each cross section are summed to give total stream discharge. This method requires that three decisions be made : first, on the number of subsections or vertical soundings (it is commonly recommended that each should not represent more than 10% of total stream discharge so that perhaps 15 may be needed); secondly, the number of velocity readings in the vertical (one at 0.6 x depth, but more generally two in the vertical at 0.2 x and 0.8 x depth as the minimum number whose average will give mean velocity in the vertical); and thirdly, the time over which velocity is measured (generally 30-60's). The accuracy of this method may be low in streams which have irregular beds or high weed growth, which are very shallow (< 30 cm), slow-flowing (< 15 cm s^{-1}) or which involve strong cross-channel flows.

In these circumstances, and particularly on small streams, dilution gauging may be preferable. Here an aqueous solution of known strength is injected in the stream and its concentration is sampled and measured at a point downstream after thorough mixing with and dilution by natural waters has taken place. The degree of dilution is related to natural stream discharge. This method works well with very turbulent streams in which there are reaches without significant tributary seepage and inflow or water loss. Two techniques can be used : the 'constant-rate' method in which tracer is injected at a uniform rate for a long enough time to achieve a steady concentration in samples taken over time at a downstream point, or the 'gulp' method in which a known volume of tracer is injected and the whole mass of it is accounted for by sampling the pulse of higher tracer concentration as it passes the downstream sampling point. These methods are fully discussed in a Water Research Association

Technical Paper (1970) complete with 'how to do it' instructions. Special equipment is needed for constant-rate injection (e.g. a Mariotte bottle or Andre vessel) or for rapid, regular sampling in the gulp method. There may be problems in selecting a suitable reach, and in allowing for background tracer-substance levels and tracer loss (e.g. by adsorption). Rather similar problems may occur in using dyes for water tracing; these are thoroughly reviewed by Smart and Laidlaw (1977).

Weirs and flumes : There are may designs for quasi-permanent gauging structures for which there is a design relationship between water level (usually gauged upstream of a bed constriction or overflow lip) and stream discharge. These include rectangular or V-notch sharp-crested weirs, broad-crested and compound weirs, and a number of alternative flume designs. The advantage of these structures lies generally in gauging accuracy, particularly with low flows, the major disadvantage is cost. A simple sharp-crested weir can be made relatively cheaply from marine ply and angle iron or from steel decking, and this may provide good discharge data provided that the weir is installed well (without leakage around the plate, at right angles to flow and kept clear of debris and sediment). Installation of a V-notch weir suitable for flows up to about 240 1 s^{-1}, larger discharges may be gauged using prefabricated flumes in glass fibre or wood (Barsby 1963, Smith & Lavis 1969) which have the advantage that they are at least partly self-cleaning in that sediment may pass through them. Specifications for gauging structures are given in British Standards Institution (1964), with some useful illustrations in Gregory and Walling (1973).

A particular point to stress is that all structures will be grossly affected by sediment accumulation and debris clogging, and by failure of the structure (either through faulty construction or by distortion during use) to comply with the original design. Normally, the design calibration should be checked by gauging (current metering or preferably dilution techniques). Where possible on larger rivers, it is probably best to profit from the use, by kind permission, of structures already installed at some expense by statutory gauging authorities. These may additionally provide a much longer run of discharge records that could be directly obtained during research. However, again some caution should be exercised over gauge accuracy, particularly during the high flow conditions of especial geomorphological interest. Preliminary estimate of flood magnitude likely to be encountered will help in the selection of structure; this may be obtained by methods in the *Flood Studies Report* (Natural Environment Research Council 1975).

3.2 ❑ Preparation and interpretation of hydrographs, unit hydrographs and rating curves

Measurement of Flow

Discharge measurements of a river are very important for developing economically beneficial projects, whether it be for irrigation, power production or flood control, In particular, we should know the maximum, avid minimum discharges, the total annual flows and their variation.

Catchment areas themselves cannot give an idea of the magnitude of flows. Though the catchment area of the Nile is nearly ten times the catchment area of the Godavari, the discharge in both the rivers is about the same. Similarly, the Colorado and the Columbia have almost the same catchment, but the flow in the former is only one-ninth of the flow in the latter.

In the seventeenth century Galileo had observed: 'I had less difficulty in the discovery of the motion of heavenly bodies in spite of their astonishing distances, than in the investigations of the movement of flowing water before our very eyes.' Difficulties still persist in the accurate assessment of river discharges.

The Nile is the only river in the world on which accurate measurements have beers carried out for several centuries. The records of levels extend almost continuously to as far back as AD. 660. Niliometers to measure the height of annual floods existed in many parts. The most important being the Roda Neliometer near Cairo. Irrigation was practised in ancient times through inundation due to floods. The agricultural taxes were collected according to the height was not reached in any year.

The best method of finding the discharges is by actual measurement of the volume of the flowing water. It was again the Nile river for which actual measurements of water were first made. The entire river was passing through 180 sluices in the Old Aswan Dam. There was no other spillway. For experiments water was allowed to flow through a set of selected sluices, downstream of which ciasterns were constructed. The time needed to fill them was noted. This served to obtain calibrator of discharges through sluices at different heads enabling accurate estimation of river flow.

Maximum Discharge

The intensity, the duration of rainfall and distribution over catchment, direction of storm movement area of catchment, its slope, orientation and nature of catchment are the other factors which have a bearing on the maximum discharge. There are a number of empirical formulae, which are used to estimate the peak flow after making judicious selection of co-efficients. Some of these are indicated below:

(1) Ryves Formula : $Q = CA^{2/3}$

Where 'C' is chosen as : 3,000 to 16,000

A = area in sq. km.

Q = cu. m. per second

(2) Inglis $Q = \frac{765A}{\sqrt{0.30\,A + 4}}$ If A is large then Inglis $Q = 123\sqrt{A}$

(3) Storm area method — Isohyetal lines are drawn and average rainfalls over the catchment area is calculated. These are plotted against the corresponding run-offs and used for any other storm.

(4) The Rational Method : $Q = CIA$

Q = Flood flow in cubic metres per sec.

I = Intensity of rainfall in mm per hour.

C = Run-off co-efficient. It varies from 35 in flat to 280 in hilly areas.

A = Discharge area in ha.

The rainfall is reduced to a hypothetical storm covering the whole catchment and of duration equal to the time of concentration, that is, the travel time of water from the remotest point of the watershed to the gauging point. Rainfall intensity is the average intensity of such a storm.

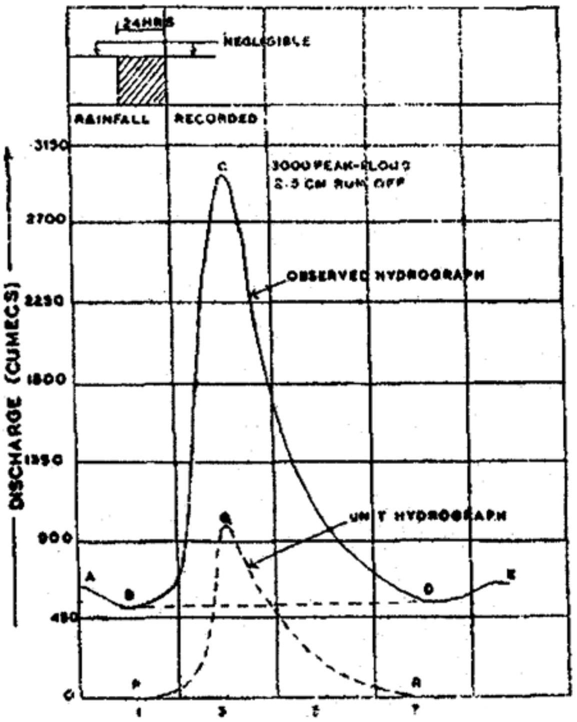
(5) The Unit Hydrograph Method: This is a very useful tool for estimating the flood hydrograph of any river. This method is based on the hypothesis that identical rainfalls with the same antecedent conditions, produce identical hydrographs on a river and also that all the combined physical characteristics of the drainage basin are reflected in the observed hydrograph. Further, the vertical ordinates of the hydrograph representing the rate of flow at that time are proportional to the volume of run-off on the same catchment.

A unit hydrograph is a derived hydrograph of the basin due to a flood of unit surface run-off in a given time. The selected duration of time should be chosen according to the size of the catchment either as one day or preferably a smaller unit; it should necessarily be less than the concentration time.

The unit hydrograph is derived from observed hydrographs of isolated storms in the following way:

Suppose ABCDE is the hydrograph of a river obtained due to rainfall occurring in 24 hours on the second day (fig. 4.1) then:

(i) Separate the ground water flow by drawing line BDE. Then the resulting hydrograph BCD is that due to surface run-off only.



(ii) Measure the area of BCD which gives the volume of surface run-off and divide the total flow by the catchment area upto the section, where hydrograph is observed. The quotient is the run-off of the storm expressed in centimetre (or smaller units).

(iii) Divide the ordinates of the hydrographs of the BCD by the run-off and plot the resulting hydrograph as PQR. Then PQR is the unit hydrograph of the basin.

As the rain producing flood run-off is of one day duration. PQR is called a one-day unit hydrograph.

From the unit hydrograph of the basin, the hydrograph for any combination of rainfall occurring in successive days can be obtained by the method of superimposition,

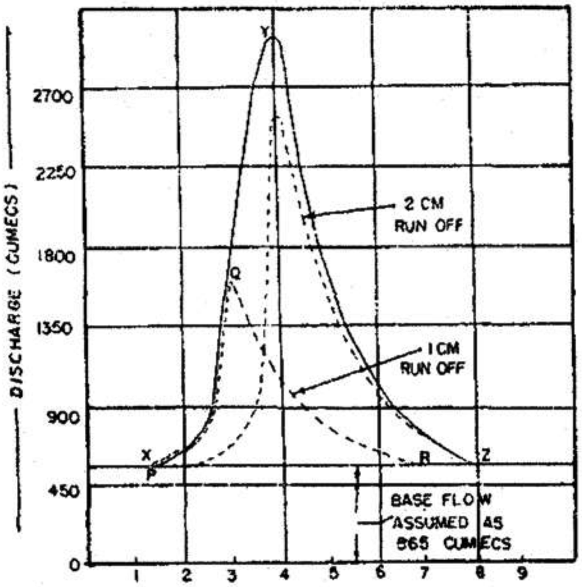
For example, if the rainfall in two successive days was found to produce run-offs of the value of one cm and 2 cm, the hydrograph for two cm run-off is plotted by the side of PQR with one day lag and with ordinates double that of PQR as shown in fig. 4.1.

A combined hydrograph is obtained by adding the ordinates of the two hydrographs as XYZ shown in fig. *4.2* adding then, the base flow, would give the complete hydrograph due to the storm.

Unit hydrograph method is used in estimating the maximum discharge for flood control projects. The maximum possible storm conditions are obtained by analysing all the past severe storms. Knowing the worst combination of storm and rainfall, a compound hydrograph for those conditions is then computed from the unit hydrograph method as described above. That hydrograph is taken as the design flood hydrograph of the river at that site.

Annual Run-off

To determine the annual run-off, discharge measurements have to be taken throughout the year; where the facility of direct measurement is not available, gauges are established at selected sites and are read daily. The flow is measured at different gauge levels on a few days. The flows for the other days are interpolated from the observed readings. Selection of sites for making observations is very important and the criteria adopted for this are given below.



Criteria for Site Selection

(1) The site should have a stable bank without the river overflowing it. The river should preferably flow in one channel, in case this is not possible, two straight channels are preferable to one defective channel.

(2) The site should be in a straight reach of as much length as possible, but not necessarily longer than two kilometres. The length of the run should be 300 to 800 metres depending upon the size of the stream. The stretch to be chosen should be stable and not subject to degradation or aggradation. The bed should drop gradually throughout this reach.

(3) Cross section within the reach should be reasonably uniform at all times of the year.

(4) The direction of the river current should be as divergent as possible from the prevailing wind directions.

(5) The site should be reasonably away from bridges, fails or other structures to avoid their resultant effects on water flow, unless the bridge itself happens to be the discharge observation site.

(6) When near a confluence, it should be sufficiently upstream if located on a tributary, and sufficiently downstream if located on the main stream so as to be free from the effects of confluence.

(7) The flow in the reach should be normal to the cross section of the stream,

(8) Where there is a tendency to form a vortex or where there is a backwater flow, the site should be avoided.

(9) The site should be easily accessible at all times of the year and, as far as possible, it should be near a village.

(10) The site should be located in the reach where flow is normal, *i.e.,* it should neither be retarded by the formation of silt or shingle bars nor accelerated being just below the shingle or silt bars. There should not be any eddies or cross current formations in the flow.

(11) A normal section should be located in the middle of the selected reach. Subsidiary sections, for fixing slope gauges, should be at the upstream and downstream ends of the straight reach which should be twice the width of the river. When this length is not available, it should be at least half the high supply river width in order to obtain correct measurements of slope.

(12) The site, as far as possible, should be free from trees and obstructions which may interfere with water flow and clear vision during observations.

Number of Sites

The minimum number of sites, at which observations are to be made as recommended by the World Meteorological Organization are given in Table 4.1.

It has also been prescribed that stations should be uniformly distributed on large rivers as well as on small streams.

As long as the minimum number of sites based on the W.M.O. norms have not been set up, a number of subsidiary stations can be put up along with the permanent base or key stations. The subsidiary stations are maintained only for a limited period. Once a good co-relation between subsidiary stations and one or more nearby permanent stations based on long term observations has been established, the observations at the subsidiary stations can be dispensed with as the co-relation can be used for extending the data of the subsidiary station based on the long term data of the permanent key station.

Gauge and Discharge Observations in India

Prior to Independence, there were very few gauge and discharge sites in India. Measurement of the flows was instituted in 1921 at all important points on the Indus and its tributaries. Daily values were regularly calculated and the resulting data formed a valuable record for the purpose of water distribution.

TABLE 4.1 *Norms as per W. M. O.*

S. No,	*Type of region*	*Range of norms for minimum network area in sq. km for 1 station*	*Range of provisional norms tolerated in difficult conditions — area in sq. km for 1 station*
1	*2*	*3*	*4*
I	Flat regions of temperate mediterranean and tropical zones.	1,000-2,500	3,000-10,000
II	Mountainous regions of temperate, mediterranean and tropical zones.[1]	300-1,000	1,000-5,000[4]
III	Small mountainous islands with very irregular precipitations, very dense stream network.	140-300	
IV	Arid and polar zones[2]	5,000-20,000[3]	

1. Last figure of the range should be tolerated only for exceptionally difficult conditions.
2. Great deserts are not included.
3. Depending on feasibility.
4. Under very difficult conditions, this may be extended to 10,000 sq. km.

The other river where regular measurements were being made was on the Cauvery to regulate the flow in the Cauvery according to an agreement between Karnataka and Tamil Nadu.

It was only in the second half of the century that observation sites were set up on a large scale. In the Indus basin gauge discharge observations are being made at 136 sites most of which are now being observed by the various State Governments concerned.

Now a number of stations have been set up in other river basins. For immediate implementation, the norms given by the W.M.O. have been modified thus:

(a) Flat areas—one station for $\frac{3{,}000 + 10{,}000}{2}$ or 6,500 sq. km instead of 2,500 sq. km

(b) Hilly areas—one station for $\frac{1{,}000 + 5{,}000}{2}$ or 3,000 sq. km instead of 1,000 sq. km

(c) Arid zones—one station for 30,000 sq. km instead of 20,000 sq. km

Even these sites amount to 500 for major basins and 100 for medium, minor and desert basins. Against this, the number of stations set up so far is only 423. As per the W.M.O.'s norms, a total of 1,700 stations will have to be set up for the river systems in India.

In addition to the observations being made by the Central agencies, the States are also observing data at 1,653 stations. The observations by the States are confined mainly to gauge readings in their own regions. It is necessary that some important hydrological observations should be made by a central organization as all major rivers pass through more than one State.

Methods Adopted for Measurement of Flow

Measurement by current meter is the only reliable one. Other methods are to be employed when current meters cannot be used and where a project has to be constructed soon and cannot await collection of data. Measurements of flow by the current-meter method have to be done for at least 30 to 40 years before reliable figures for flow in a river can be arrived at.

4.5.1. Current Meter Measurement

This method involves the determination of area and velocity. The area of the cross section is arrived at by measuring the width of the waterway and the depths from the surface of water to the bed of the channel across the "normal cross-section. For this purpose, the width of the waterway is divided into a number of segments, and the depths measured at the segment points (verticals) either by sounding rods, or by echo sounders etc.

The velocities are measured by the current meter in different ways as below:

(1) One measurement at 0.5 of depth and this value is taken as the average velocity.

(2) Two measurements at 0.2 and 0.8 of the depth and mean of the two as average velocity.

(3) Measurements taken at 0.1, 0.2 etc. depths and the mean velocity adopted as the average. This is useful where the river is clogged due to weeds and ice.

(4) The meter is lowered and raised through the entire depth at each vertical depth at a uniform rate and the average velocity calculated based on the average number of revolutions per second and the meter calibration coefficient.

(5) Surface velocity observations when the river is in high floods. The average value is obtained by a reduction factor, which is obtained when the river flows at low levels.

3.3 ❑ Collection and analysis of coastal or riverine sediments using phi graded sieves and electronic balance

Soils and sediments become an integral part of landform study, not simply because they may afford useful aids but mainly because any advantage to be gained depends on *a* full awareness of their complexities or of limitations on interpretations which might expose over-optimistic approaches or superficial generalizations.

Particle sizes

Since the publication in 1914 of J. A. Udden's attempt to relate particle-size modes to different kinds of particle movement, the significance of particle size has

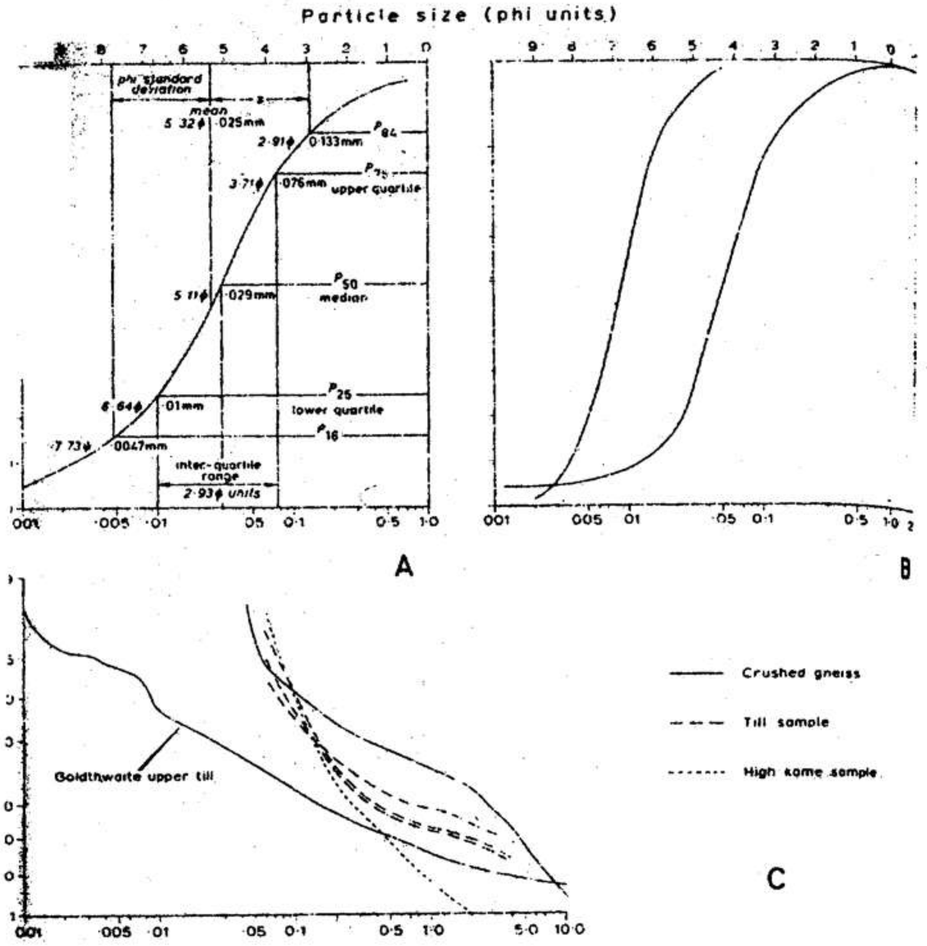


Figure : Cumulative frequency curves showing particle size distributions of sediments.

A Percentage points used in the calculation of indices to describe particle size distribution.

B Illustrations of the distinctive sorting achieved in wind-transported sediments: the fine silt is Saharan dust, wind-blown to Britain (A. F. Pitty, 1968, Nature, Vol. 220) and the coarse silt, from the Derbyshire limestone plateau is attributed to wind- transport during former periglacial conditions by C. D. Pigott (Pitty, 1966).

C Particle-size distributions drawn on Rosin's Law of crushing paper (from J. T. Andrews, 1963, Geog: Bull. No. 20). an alternative to the popular semi-logarithmic paper, illustrating the similarity between crushed gneiss and tills from cross valley moraines.

been much studied. Sizes determined by sieving and settling velocities indicate approximately the diameter of a sphere of equal volume to that of the particles. Particles smaller than 2 mm, usually taken as the upper limit for sand-sized particles, are often described in microns. A micron is one thousandth of a millimetre, often symbolized by the Greek letter *mu*, μ. References to particle sizes may appear in three contexts. First, there are boundaries between particle-size classes which are arbitrary but necessary in establishing convenient subdivisions. There are several schemes of subdivision, but most use a reversed log scale with each equal subdivision spanning a progressively narrower size range, so that a small number of large particles does not dominate the distribution. Secondly, there are specific diameters to describe a cumulative frequency distribution of a sediment sample, of which the usefulness of the P_{50}, the median indicating the central-size value of the transformed distribution (fig. III.4), is most readily apparent. This value may indicate the average velocity conditions of the depositing agent. Thirdly, there are critical sizes that appear to have some functional significance. For instance, frost-shattering appears to be incapable of splitting grains finer than 10 microns; the higher fraction of particles smaller than the 60 microns range in river sands compared with beach sands appears to be the main distinction between these two sediments. However, in general it is inadvisable to make direct and simple inferences from diameter measurements alone because so many variables are involved. Equally diagnostic are sorting indices which describe the range of sizes involved in the rearrangement or adjustment of particles to specific dynamic parameters, like current velocity. For the purposes of sedimentary petrology, the Greek letter phi is often used to describe the logarithmic transformation in terms of units of equal arithmetic width.

$$\phi = -\log, d \text{ or } d = \frac{1}{2}$$

where d is the particle size expressed in millimetres, as suggested by W. C. Krumbein in 1934. However, partly because tables of negative logarithms to the base 1 are not readily available, a certain amount of difficulty in the use of the phi transformation has arisen. Fig. III.5 is an attempt to provide sufficient detail on the micron and phi scales to permit interpolations of accuracy adequate for general purposes. For single expressions of central tendency, a description in millimetres or microns is probably more explicit. For sorting indices values of phi are obtained from cumulative curves for certain cumulative percentages (fig. III.4). The most commonly used sorting index is Krumbein's (1938) phi deviation, $\frac{\phi_{75} - \phi_{25}}{2}$ whereas A. Cailleux subtracted ϕ_{50} from ϕ_{75} and ϕ_{25} from ϕ_{50}, and used the smaller value, representing the steeper part of the curve as an index, *Hé*. In more recent work more efficient indices

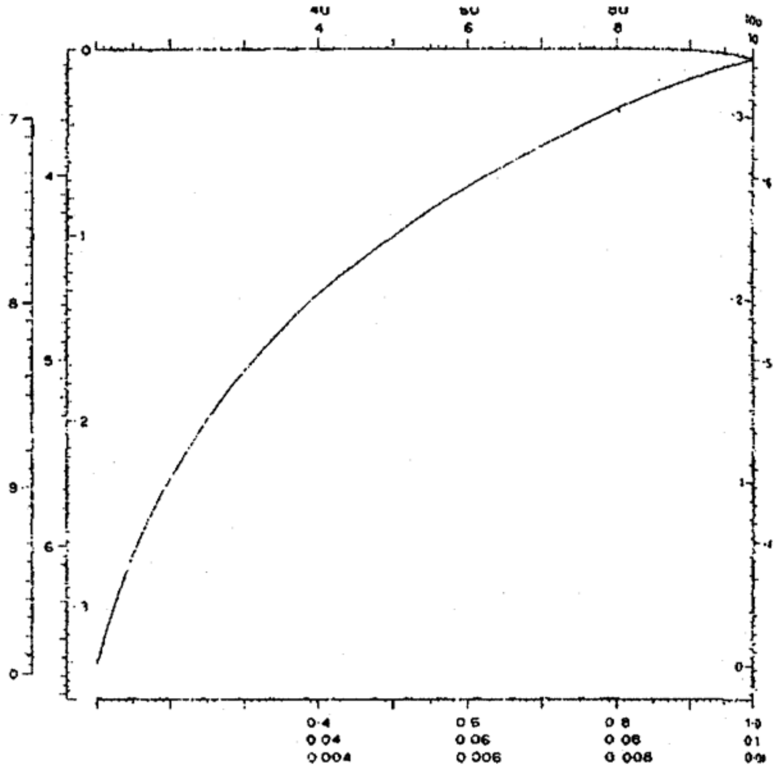


Figure A metric-phi unit conversion chart. The rows are metric units, preceded by the phi range (in brackets) to which they correspond; the latter are read off the appropriate column on the ordinates.

are based on a wider spread of percentiles, R. L. Folk and W. C. Ward suggesting a modification to Inman's (1952) statistic—

$$s = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_{5}}{6.6}$$

Fig. illustrates the steepness of curves reflecting the efficiency of wind transportation as a sorting process. A further measure is skewness, an expression of whether matetial is predominantly in either the coarser or the finer side of the median diameter or symmetrically distributed on either side. In fig. III.4 the median is coarser than the mean and the particle size distribution is therefore positively skewed. This skewness index can have some value where we finer tail of' a distribution might be removed, like the fraction smaller than 62 microns winnowed from beach sands or gravel lags which, due to truncation of sizes, tend to have negative or near zero skewness values. However, negatively skewed beach sands become positively skewed \when either the coarse tail of a symmetrical log-normal curve has been removed a fine tail added by finer material filling up a porous frame of coarse material In contrast to beach materials, transport by unidirectional flow tends to produce positive values of skewness as is often the case with river and dune deposits. Folk and Ward suggest a phi skewness index

$$\mathrm{Sk} = \frac{1}{2}\left(\frac{\phi_{84} + \phi_{16} - 2\phi_{50}}{\phi_{84} - \phi_{16}} + \frac{\phi_{95} + \phi_{5} - 2\phi_{50}}{\phi_{95} - \phi_{5}}\right)$$

In addition to a reversed log scale sediment size distributions are occasionally plotted on Rosin's 'law of crushing' paper, as both mechanical and chemical disintegration of rocks has a distribution following this 'law' for artificially crushed material which apparently results from random breakages of material.

Great care and caution are necessary in interpreting textural parameters. In addition to reflecting environmental conditions they are influenced by the liability of materials of a given size. In some environments several processes may operate simultaneously or occur within a short interval. Moreover even at one point more than one population may be present. It may include grains deposited from the bedload, material settling later from the suspended load and contributions from an underlying veneer deposited under different conditions. There is also the possibility of post-depositional resorting by frost or by organisms. These problems are magnified by the difficulty of recognizing polygenetic soils and sediments in the field. In consequence there is no guarantee that textural parameters will necessarily establish clear differences between dune and beach, glacial and proglacial, blockfields and boulder clay, or between alluvial and colluvial deposits.

2. Particle shape

There have been many attempts to use particle shape in reconstructions of erosional and depositional environments. Indices are basically of two types. First, in coarser materials, indices are based on measurements of the three axes length, breadth, and depth, which might be abbreviated to L, B, and D respectively. A. Cailleux introduced a flatness index $\frac{L+B}{2D}$ which has some discriminatory power, as fig. III.6 shows. E. D. Sneed and R. F. Folk (1958) suggest a detailed classification of a sample into several shape categories. The second type of index concerns the smoothness of particle outline. Powers approach depends on the use of a set of reference images with which each particle is compared and classified. For larger particles part of the circumference of pebbles is measured. Where corners are rounded the radius, r, of an inscribed circle is estimated by superimposing the corner on a set of concentric circles. A. Cailleux and J. Tricart have made extensive measurements of an index of wear, $\frac{2r}{L}$.

Although criteria distinguishing the effects of distinctive environments on shaping pebbles are necessarily somewhat tenuous, one or two tendencies have been observed, or significant distinctions established (fig. HI. 7). It seems that most well-rounded boulders of glacial transport may retain traces of original concave surfaces to a far greater extent than is generally observed on stream or beach cobbles. The most important factor governing pebble shape is usually, like the initial triangular form of some glacial boulders, lithoogical composition.

3.4 ☐ Analysis of fluvial or coastal pebbles for shape and constituents

Sediment particles display a great variety of geometric forms. This variation is due to a combination of the internal structure, and the origin and history of the particle. Some particles are simple and symmetric, whereas others are extremely complex.

The roundness of a particle refers to the sharpness or smoothness of the edges and corners. Both physical abrasion and chemical reactions contribute to this characteristic, although abrasion is generally the most important of the two. Roundness can be measured by dividing the average radius of the corners and edges by the radius of the maximum inscribed circle (Wentworth, 1919). This is typically accomplished by measuring cross sections or projected images of particles. A standard for comparison has been provided by Powers (1953), who developed a six-stage hierarchy comprised of descriptive names ranging from "very angular" to "well rounded". Folk (1955) proposed a logarithmic conversion called the rho (p) cale, which ranges from 0 to 6 and has units corresponding to Powers' descriptive categories.

The term sphericity refers to the degree to which a particle approaches a sphere. Although many ways of determining sphericity are available, it is most common to compare the lengths of three mutually perpendicular axes. As this ratio approaches unity, the particle becomes more spherical. Sphericity can be measured by determining the volume of the particle and that of a sphere of equal volume and then comparing the result to the volume of a circumscribing sphere (Wadell, 1932). Another sphericity determination is made by comparing the long, intermediate, and short diameters - in essence, by making a comparison of the minimum to the maximum cross-sectional area (Folk and Ward, 1957).

Sphericity is more strongly influenced by the origin of the particle than is roundness. Some grains are inherently elongate because of their crystallographic or biogenic makeup. Examples are such minerals as rutile and mica, which are rarely spherical and many types of shells, such as bivalves and branching corals. In addition, bedding or cleavage may create planes of weakness that yield on impact and prevent attainment of a spherical shape during transport.

It should be observed that roundness and sphericity may not be related in a given particle. That is some perfectly rounded objects may show low sphericity (e.g., a hot dog), and some rather spherical objects may be very angular (e.g., a cube). Of course, many things may be both well rounded and spherical (e.g., a ping-pong ball and a quartz grain).

Classification of shapes :

Although roundness and sphericity are quite important and valuable in characterizing particle shape, they do not completely describe a particle. A simple but useful classification suggested by Zingg (1935) utilizes the ratios of the three mutually perpendicular diameters. The result is four primary shape classes : oblate (disk), equant, bladed, and prolate (roller). The classification is achieved by comparing the ratio of the intermediate and the long diameters on one axis against the short versus the intermediate diameters on the other axis.

By superimposing Wadell's sphericity values on the Zingg diagram, it can be seen that different shapes may yield the same sphericity values. The importance of the Zingg classification is in its application to sediment transport. Although a disk and a roller can possess the same sphericity, their shapes are different and this is reflected in their rate and mode of transport. Shape can also be a factor in the orientation of a particle when it comes to rest.

Surface Texture :

The surface texture of sand and gravel size particles may be affected by physical and chemical phenomena, both during transport and in situ after accumulation and continuing through the postcementation history of the rock. The major cause of surface markings on particles is the impact of one particle with another. Considerable recent research has been undertaken to try to establish characteristic surficial markings as indicators of particular environments of deposition. If their effort is successful, such criteria will be quite valuable as a tool for stratigraphers and sedimentologists working with ancient terrigenous sedimentary deposits.

Pebbles, cobbles and boulders commonly exhibit relatively large surficial markings that can generally be related to sediment transport phenomena. Linear scratches, grooves, and striations are especially common on gravel particles from glacial drift. These features result from the particle moving over bedrock or in relation to an adjacent particle. Crescent-shaped cracks, sometimes called chatter marks or percussion marks are also found on large sediment particles. They result from sudden, intense impacts between particles such as might occur in a rapidly flowing stream or in the surf zone.

The surface textural elements described above are visible to the unaided eye. There is a wide variety of surficial features present on sand-size particles that must be studied with a light microscope or with a scanning electron microscope (SEN). The relatively recent application of the SEN to such studies has revealed surface textures heretofore unknown (Krinsley and Doornkamp, 1973). The frosted surface that can be seen with a hand lens or light microscope becomes a delicate pattern of surface markings when viewed with a SEN. Many of these patterns and markings have been related to depositional environments, although there is no widespread agreement as to the significance of particular types of markings.

When viewing sediment particles from the rock record, another factor must be considered regarding surface textures : diagenetic phenomena, which can create surface markings by both physical and chemical means. Great pressures may cause grains to display crescentic or concoidal fracture patterns. Chemical reaction between percolating groundwater or other fluids is the most importar diagenetic phenomenon in producing surface textures.

As a result of the movement of sediment particles from one depositional environment to another coupled with the markings produced diagenetically, it is very difficult or even impossible to ascertain an environment of depositional by examination of individual particles from the rock record.