FLUVIAL GEOMORPHOLOGY

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Preface

This book stems from a course of lectures given to undergraduate and postgraduates in the Department of Civil Engineering, Rajshahi University of Engineering & Technology. The following work provides a brief discussion of certain of the more important aspects of fluvial geomorphology. It is designed as an introduction and a guide to a difficult and scattered literature with which students of Civil Engineering, Geography and Geology are concerned.

We live in a land of rivers. These rivers and their numerous tributaries and distributaries play in our cultural as well as economic life. Over the ages, we have accepted with gratitude the benefit in the form of easily productive, fertile riverine silt. But the destructive fury of these rivers has been a constant headache. Our inability to rein these natural forces has probably arisen from the lack of the basic physical characteristics of the rivers.

Much recent attention has focused on 'natural stream channel design' or Fluvial Geomorphology. While this scientific discipline was relatively unknown as an applied science until recent years, recent application of the science to restoration designs shows a great deal of promise for effective stream channel management. Many years of extensive research in stream function and the factors that influence stream channel stability provide the backbone for application of this science. While some aspects of the discipline are unique, it is truly a multidisciplinary field, which requires knowledge of engineering, geology, biology, hydrology, soil science, and other scientific disciplines. Fluvial Geomorphology, taken literally, means the study of river related landforms. This book explores the central principles of Fluvial Geomorphology and details the application of the science to stream channel restoration.

Although the science of fluvial geomorphology is decades old, its widespread application in watershed studies is relatively recent. River managers are rapidly recognizing the role fluvial geomorphology can play in assessing channel condition, identifying long-term solutions for channel instability, and evaluating the effectiveness of restoration efforts. A geomorphological approach to river management reduces flood damages while improving salmon and trout habitat.

As environmental awareness, regulations, and the necessity to protect water resources gain momentum in our society; innovative, science-based methods of managing stream channels are necessary. Applied Fluvial Geomorphology is a tool that provides an understanding of stream channel function and allows designs to work with the stream rather than work to control the stream.

Fluvial geomorphology is a science devoted to understanding how the natural setting and human land use in a watershed determine the shape of the river channel. A fluvial geomorphologist seeks to predict what physical changes will occur to a stream channel in response to alterations in watershed conditions; and, in turn, how these changes will impact human infrastructures.

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The book has been written to cater to the needs of university classes. An effort has been made to go in depth so that the students get a feel of the various hypotheses that have been propounded to explain various phenomena. If the students are inspired to take greater interest in the study of fluvial geomorphology and feel confident of themselves I shall consider that my labour has been amply rewarded.

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CHAPTER - 1

INTRODUCTION

1.1 GEOMORPHOLOGY

Geomorphology is the science of landforms. If we follow the Greek root of the word (*geo*→ earth, *morphe*→ form, *logos*→ discourse), we accept it as a study of landforms. Geomorphology, however, is more than a description of the features on land such as, mountains, rivers, glaciers or dunes, It also includes careful measurements of such features, understanding of the process that have shaped them, the history of their formation, and examination of their constituent material. Geomorphologists from time to time also study submarine features. The knowledge of local geomorphology is being used more and more for avoiding environmental degradation, for mitigating natural hazards such as floods and landslides, and for planning cities and roads of the future. Geomorphology, therefore, attracts students from different disciplines including geography, geology, engineering and planning. It, however, remains firmly in the domains of geology and geography, and basic version of it is often used as an introduction to both disciplines. The subject takes one to spectacular sceneries as well as ordinary features such as the channel of a stream flowing through ones hometown, a channel that has been lined with concrete by engineers for faster drainage.

1.2 TYPES AND TOOLS OF GEOMORPHOLOGY

The type of geomorphology in which processes such as running water or wind are studied in detail is known as ***process geomorphology.*** Different branches of process geomorphology are known as ***fluvial geomorphology, glacial geomorphology,*** etc. depending on the type of dominant process that shapes the landforms. Processes such as running water, glacier, wind and coastal water are associated with ***fluvial, glacial, aeolian and coastal geomorphology*** respectively.

On the other hand, if a geomorphologist is working on the effect of tectonic movements on landforms, he or she is studying ***tectonic geomorphology.*** Study of the effect of geological structure on landforms is called ***structural geomorphology,*** and the study of the dominant influence of climate on landforms is dealt in ***climatic geomorphology.*** Use of the knowledge of geomorphology for flood prevention, environmental impact mitigation etc., is ***applied geomorphology.*** An account of the

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landforms and processes found over a large area is ***regional geomorphology.*** Geomorphologists who try to build theories that explain how the processes work and how landforms are formed, carry out ***theoretical geomorphology.*** Davis was an earlier theoretician. These days theoretical work often evolves in model building. The models could be physical models or they could be simulation models done on a computer. These models not only are useful in explaining how changes happen to landforms and sediment as processes operate, but also may have the power to predict possible changes if some aspect of the controlling environment such as rainfall pattern, vegetation cover, or stability of land is disturbed. Such model building, however, is advanced research and not included in this book. In spite of geomorphology being an interdisciplinary broad-based subject, specialization is common within geomorphology.

1.3 RIVER MORPHOLOGY

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Land surface of the earth, is marked by irregularities. As a result when rainfall occurs or glaciers melt or spring water spouts, then the water flows outward and downward and there is a tendency of the water to take the shortest route. During this period the water flows like little ③ gutters. Further downward, by converging these gutters .streamlets or rivulets are formed. Still downward such streamlets unite with many others and form streams. Again, many other streams join with the main one gradually downward. In this way a complete drainage system with many, outgoing and incoming tributaries are formed. Such a concentrated flow of water, formed by the union of several streams, is known as *River.* Geomorphologists and geologists have come to define the word `river' broadly as a stream of water bearing waste of land from higher to lower ground, and as a rule to the sea ; or as the trunk stream and all its branches in a river system.

Among the most conspicuous features of the landscape, river courses are most important, as they are responsible for much of the denudation of the land surface over large parts of the earth.

In 1802 John Play fair laid the simple law that *"Every river appears to consist of a main trunk, fed from a variety of branches, each running in a valley proportionate to its size and all of them together forming a system of valleys, communicating with one another, and have such a nice adjustment of their declivities, that none of them join the principal valley, either on too high or too low a level, a circumstance which would be infinitely improbable, if each of these valleys were not the work of the stream that flows in it"* (Fig. 1).

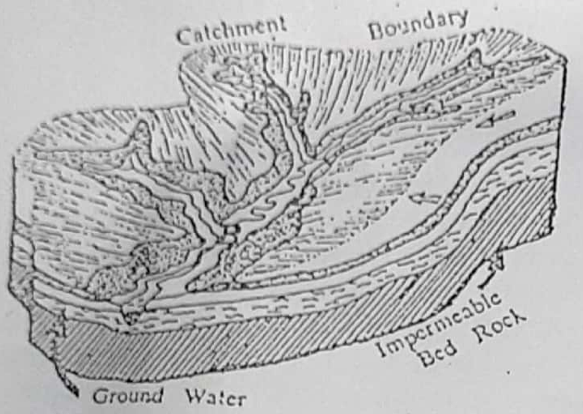

Fig. 1.1 River running in a valley

The quantity of water in a river varies almost from moment to moment. The flow of a river depends upon the duration, the amount of the precipitation and the local hydrological conditions. The rivers which carry water, only during and immediately after a rain are known as *ephemeral*. The rivers which flow during a part of the year, *e.g.* during the wet season of the humid tropics, are called *intermittent or non-perennial*; when they flow all the year round they are known as *perennial*. An extreme case of the flow is wadis, in the hot desert region a channel remains dry for months or even years but after a sudden thunderstorm the rivers start to flow. The peculiarity is that the flow may only endure for an hour or two. Streams with interior flow i.e. mix with the water surface within the country, are known as *endoreic*, and the stream with exterior flow i.e. mix to the sea are called exoreic.

1.4 IMPORTANCE OF RIVER MORPHOLOGY

Drainage basin is considered as a fundamental geomorphic unit (Chorley, 1965), as most of the landscapes of the earth's surface are sculptured by the action of the river itself or by conjunction with other land cape forming processes. Fluvial erosion develops some distinctive features such as undercut, river-cliffs, water-falls etc., during the transport of the materials potholes are produced in the river bed, again deposition can give rise to a flood plain where river-transported material is, accumulated. At the margin of the glacier, due to the thawing action, rivers are developed and glacial origni materials are transported and deposited down valley by the river-this is known as fluvioglacial deposits. In the arid region after a torrential rain some rivulets are developed which also indirectly influence and control the course of the slope development in accord with the aeolian processes by removing the

materials. In the coastal zone the river can operate in conjunction with marine processes and develop different features. Although river may not be the sole factor or agent of the development of valley form in all cases but still it is responsible for modifying the landform produced by other processes. Therefore, the analysis of, river's processes are most important than any other processes of the geomorphology.

River is, also important for its significance to human use. Not only for drinking but river can also be used for irrigation, navigation, fishing, power generation, floatation of timber, recreation etc. For this reason mainly the early civilizations were settled along the sides of the rivers, attractions are still present despite the liability of the rivers to floods and cause damage. River is important in geographical study mainly for three reasons. Firstly, it is directly responsible in the development of the major landforms of the earth surface, secondly, it is indirectly related to many other geomorphological processes in fluvially dominated landscapes and thirdly, it is very useful to human being. Therefore the study of river is significant in the physical geography.

1.5 A CHRONOLOGY OF THE STUDY OF RIVER MORPHOLOGY

Major hydraulic researches were started in the 17th century. In 1697, Guglielmini established some of the basic concepts of open channel flow and he was probably the first important writer on fluvial geomorphology. It was until 1889 only the flow of the river was recorded and the flow recorder Powell laid the foundation for linking form and processes. Actually in late 18th century scientific enquiry on river basin was started. Development in the calculation of velocity, discharge and sediment transport by Bernoulli, Chezy, Manning and Brahms provided the foundation for studies of fluvial processes. It was nearly 100 years later, in 1841, the erosional and depositional processes were recognized by James Hutton and the laws of erosion were formulated by Surrell. Subsequently on the basis of the study in Henry Mountain Gilbert established the theory of dynamic equilibrium in relationships between the processes of channel erosion and bed resistance. In 1914 based upon the observations he isolated many fundamental features of fluvial processes.

Another model of landscape development was introduced by Hutton, popularized by Playfair in 1802 and later adapted by Charles Lyell (1797-1875), that is the term uniformitarianism which implies that the 'Present is the key to the past.' This theory based on the assumption of 'Unlimited time for landscape evolution' (Petts and Foster 1985). Darwin (1809-1882) established the time-scale of earth's evolution, it estimated the age of the earth at some 4.6 billion years. After that a new era has brought in the scientific world.

In twentieth century, development in fluvial studies was delayed until Davis has established the theory that the formation of the landscape largely depend upon the processes and the stages of the river systems. In 1945 Horton introduced a quantitative approach into fluvial geomorphology which established relationship between form and processes, later elucidated by Leopold and Maddock (1953). Chorley (1962) first viewed the river within a system framework, characterised by equilibria between forms and processes which are superimposed upon a complex long term evolutionary trend, reflecting climatic change as well as progressive drainage basin denudation.

1.6 SCOPE OF STUDY

As the major Landforms of the earth's surface are formed by the action of the river; therefore in the study of river morphology not only the erosional and depositional features but also the processes of their development are discussed. Along with the discussion of the stages of the drainage basin development by joining rills and gullies form of the drainage basin is also included. Analysis of the drainage form indicate the hydrological characteristics of the river i.e. river flow pattern, nature of topography, flood character etc. Channel flow characteristics, both quality and quantity, i.e. nature of flow, causes of changing amount and nature of load etc. are important aspects of river geography. Drainage and channel patterns denote the lithological characteristics and the geological history of an area, therefore various types of drainage pattern and the causes of their development are taken into consideration. Along with the discussion of the changing drainage pattern changing river courses through geological ages is included.

To find out the drainage basin characteristics different hydrological and topographical attributes of a basin are analysed through different morphometric methods. To depict the evolution of a riverine area the physical and chemical analysis of river bed sediments can be done. In the scope of river morphology along with the study on the physical analysis the economic use of the river in different aspects of life is, also discussed.

CHAPTER - 2

DRAINAGE SYSTEM
AND
PATTERNS

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2.1 DRAINAGE BASIN

The fundamental unit of study for fluvial processes is the ***drainage basin or watershed***. A drainage basin is a portion of the Earth's surface that contains a main stream and its tributaries and is bounded by a drainage divide. The entire area that collects the rainwater and contributes it to a particular channel is called the ***drainage basin or catchment area*** (Fig. 2.1). The main or trunk stream and its tributary streams that drain the basin area collectively form the ***drainage network.***

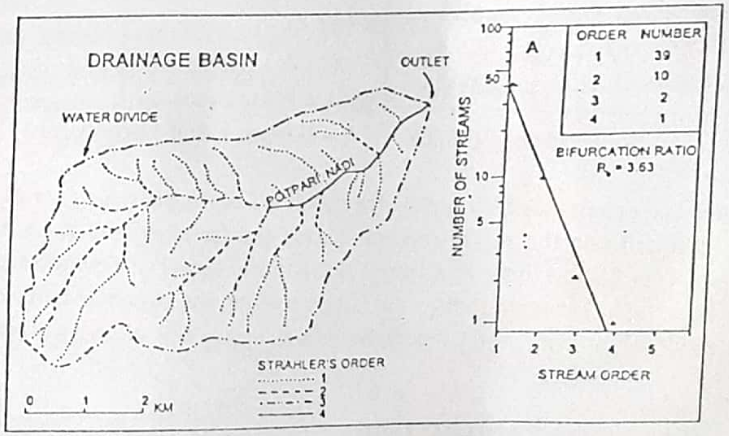

Fig. 2.1 A 4th order drainage basin. A. An example of Horton analysis of drainage network. The line shows the relationship between number of streams and stream order.

The shape and size of the drainage basin can conceivably affect stream discharge.

2.1). Many large rivers such as the Nile, Amazon, Mississippi, Mekong, Parana, Congo, Yangtze, Lena, Amur, Niger, Mackenzie, Volga, Ob, Euphrates, Danube, Darling, Zambezi and Ganges have drainage areas in excess of one million square km. Under a given climatic regime, the size of the basin determines the total volume of rainwater received and, hence, the total runoff produced. Therefore, large basins have large average discharge.

Table 2.1 Basin area, stream length and runoff of some major rivers of the world

Name of the river	Length (km)	Drainage basin area (thousand km^2)	Annual runoff (m^{3}s^{-1})
Nile	7950	2849	2222
Amazon	6275	7049	101181
Yangtze	5471	1169	4761
Congo	4666	3690	42853
Hwang Ho (Yellow)	4344	990	39996
Parana	4347	3100	19046
Niger	4187	2090	9301
Mackenzie	4053	1760	2539
Mississippi	3778	3230	18123
Indus	3218	963	5583
Ganges*	2414	1730	23095

Source: Snead (1980). * = Ganges + Brahmaputra

Basin shape determines how rapidly the runoff will reach the main river as well as the outlet. For circular basin the runoff reaches quickly and for elongated basin, such as the Narmada and Tapi Basins, there is a longer delay in the arrival of flow after heavy rains. Studies by Hack (1957) indicate that as the basins enlarge, the stream length increases and the basin become narrower and longer. Therefore, a majority of rivers have elongated basins.

2.2 DRAINAGE SYSTEMS AND PATTERNS

The study of the characteristics of drainage network of a particular region is approached in two ways e.g. (1) **descriptive approach** and (2) **genetic approach.** The descriptive approach involves the study of the characteristics of the forms and patterns of the streams of a given region while the genetic approach involves the investigation of the evolution of streams of a region in relation to tectonics, lithologies and structures. Thus, ***drainage system*** refers to the origin and development of streams through time while ***drainage pattern*** means spatial arrangement and form of drainage system in terms of geometrical shapes in the areas of different rock types, geological structure, climate conditions and denudational history e.g. trellis pattern, dendritic pattern, parallel pattern etc. The examples of drainage systems are consequent streams, subsequent streams, obsequent streams, resequent streams, antecedent and superimposed streams etc.

The origin and subsequent evolution of any drainage system in a region are determined and controlled by two main factors viz. (1) nature of initial surface and slope and (2) geological structure (e.g. folds, faults, fractures, joints, dips and strikes of rock beds and types of rocks). Streams of drainage systems are divided in two broad categories on the basis of the adjustment of the streams to the initial surface and geological structures e.g. (1) **sequent streams** (which follow the regional slope and are well adjusted to geological structures) such as ***consequent streams, subsequent streams, obsequent streams*** and ***resequent streams,*** and (2) **insequent streams** (which do not follow the regional slope and are not adjusted to geological structures) such as ***antecedent streams*** and ***superimposed streams.***

2.3 GENETIC CLASSIFICATION OF STREAMS

The position of every stream in a drainage network is determined by the nature of initial slope of the land surface and by the differences of rock resistance. Accordingly, the streams can be classified as ***consequent subsequent, obsequent, resequent and insequent streams*** (Johnson, 1932) (Fig. 2.2).

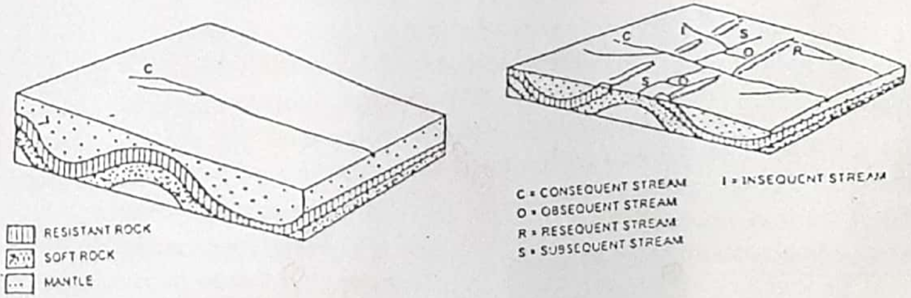

Fig. 2.2 Genetic classification of streams

Flowing water generally follows the slope of the land surface. Consequently, the courses of the streams and rivers are parallel to the direction of surface slope. Such a stream therefore is called a ***consequent stream.*** However, if a stream flows in a direction opposition to that of the consequent stream, it is denoted as obsequent [i.e. op(positecon) sequent] stream. ***Resequent*** [i.e. re(con)sequent] or secondary consequent stream is the stream that flows in the direction of the consequent stream but at a level lower than the initial surface. Such streams are generally younger that the consequent streams in age.

Sometimes, zones of weakness (faults, joints, etc.) in the underlying rocks may provide a more convenient path to the stream, giving rise to a subsequent stream. According to Johnson (1932) a subsequent stream is one that is 'sequent' to the underlying or substructure. In comparison, an insequent [i.e. in(con)sequent] or 'not consequent' stream does not exhibit any control of the underlying bedrock structures, and develops over homogeneous rocks or rocks with undetectable lithological differences.

2.4 DRAINAGE PATTERNS

The drainage pattern means the 'form' (geometrical forms) of the drainage systems and the spatial arrangement of streams in particular locality or region. The location, number and flow directions of different streams of a particular region depend on the nature of slope, structural control, lithological characteristics, tectonic factors, climatic conditions, vegetal characteristics etc. Since there are much variations in the environmental conditions of different regions and hence there are also spatial variations in drainage patterns. Though the drainage patterns of some regions may be similar but not the same, but there are some common characteristics which enable us to distinguish different drainage patterns. Generally, the drainage patterns are divided into the following types: (1) trellised pattern, (2) dendritic pattern, (3) centrifugal radial pattern, (4) centripetal pattern, (5) annular pattern, (6) barbed pattern, (7) indeterminate or confused pattern, (8) herringbone pattern, (9) pinnate pattern etc.

2.4.1 Dendritic Pattern

A *dendritic drainage pattern* is the most common form and looks like the branching pattern of tree roots. (Fig. 2.1). Dendritic drainage is commonly encountered in areas of uniform or comparable lithology and in areas with less prominent regional slopes. A notable characteristic of the dendritic pattern is the presence of tributary streams branching in all directions. Although the tributaries join the main stream at all angles, junction angles considerably less than 90° are prevalent. A variety of dendritic drainage is

joining the master stream at acute angles. This type of pattern is well-developed in narrow valleys with unusually steep slopes.

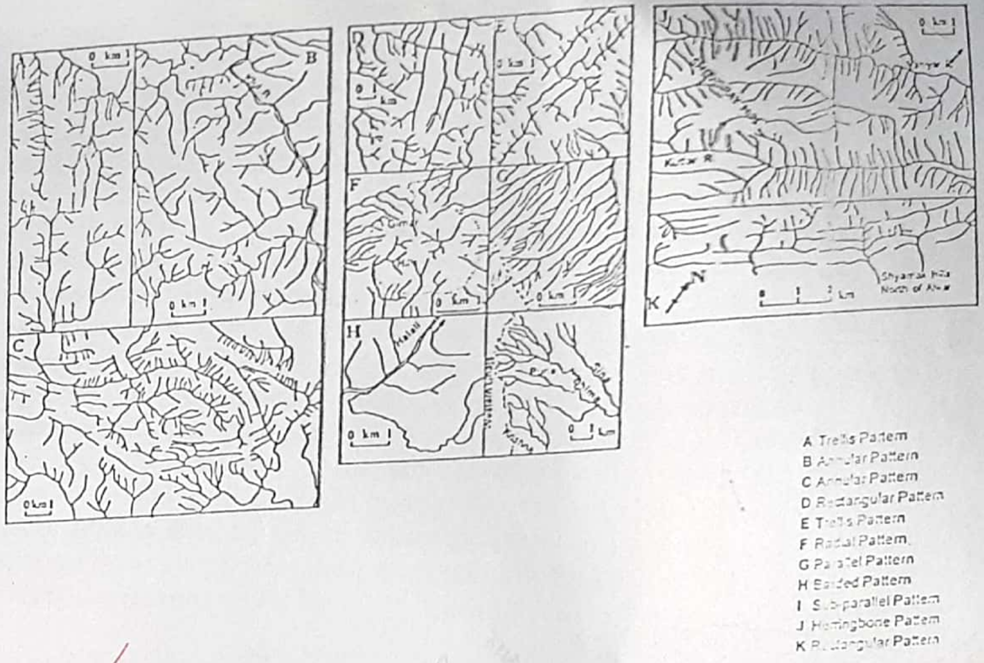

Fig. 2.3 Types of drainage pattern

2.4.2 Trellis Pattern

Trellis drainage patterns looks similar to their namesake, the common garden trellis. It is characterized by elongated tributaries flowing parallel or sub-parallel to the main stream, (Fig 2.3 A and E). The main primary and secondary tributaries join the main stream at right angles. Such patterns were first identified for the Ridge and Valley Province of the Appalachian Mountains of North America. The trellis drainage is a characteristic of folded mountains. Down-turned folds called synclines form valleys in which resides the main channel of the stream. Short tributary streams enter the main channel at sharp angles as they run down sides of parallel ridges called anticlines. Tributaries join the main stream at nearly right angles. Examples of this type of drainage are observed in Aravalli Hills near Abu, Rajasthan; in Cachar District, Assam; in Aizawl District, Mizoram; and in parts of Chotanagpur Plateau in India.

2.4.3 Rectangular Pattern

The *rectangular drainage pattern* is found in regions that have undergone faulting. Streams follow the path of least resistance and thus are concentrated in places were exposed rock is the weakest. Movement of the surface due to faulting off-sets the direction of the stream. As a result, the tributary streams make shape bends and enter the main stream at high angles. A rectangular drainage pattern displays orthogonal (right angle) bends in both the tributary as well as the parent streams (Fig. 2.3 D and K). This is typically developed in areas underlain by rocks with right-angled joints, fractures, lineaments and faults. Unlike the trellis pattern, the rectangular pattern is more regular and the tributaries are not necessarily elongated and parallel to the main stream. Striking examples of rectangular pattern include the Norwegian coast and the gorge of Zambesi, downstream of Victoria Falls (Zernitz, 1932). In India, such type of drainage pattern can be found in Shyamak Hills (north of Alwar, Rajasthan), on the Satpura Dome in Pachmarhi area (Madhya Pradesh) and in the hills to the east of Cuddapah town (Andhra Pradesh). ***Angulate pattern is*** a modified type of rectangular drainage which develops in areas where joints, faults, lineaments do not intersect at right angles. Consequently, the tributary streams following these weak zones join the main stream at an angle less than or more than right angle (i.e. acute and obtuse angle respectively).

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2.4.4 Radial Drainage Pattern

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The *radial drainage pattern* or ***centrifugal pattern*** develops around a central elevated point. It is formed by the streams, which diverge from a central higher point in all directions. It is obvious that dome structures, volcanic cones, batholiths and laccoliths, residual hills, small tablelands, mesas and buttes, and isolated uplands favour the development of ideal radial pattern (Fig. 2.4). The streams emerge at the central point of the aforesaid reliefs and drain down the slopes in all directions. Since the streams follow the slopes and hence they are basically consequent streams. These streams resemble the spokes of a wheel or the radii of a circle. If we take the entire drainage network of Sri Lanka, it exhibits the best example of radial drainage pattern at macro-level.

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2.4.5 Centripetal Drainage Pattern

The ***Centripetal or inland drainage pattern*** (Fig. 2.5) is opposite to the radial drainage pattern because it is characterized by the streams which converge at a point which is generally a depression or a basin. This pattern is formed by a series of streams which after emerging from surrounding uplands converge in a central low land which may be a depression, or a basin or a crater lake. The Kathmandu valley of Nepal presents an ideal example of centripetal drainage pattern wherein the tributary streams of the Baghmati converge in the tectonically formed circular basin. This pattern is typical in the western and southwestern portions of the United States where basins exhibit interior drainage. During wetter portions of the year, these streams feed ephemeral lakes, which evaporate away during dry periods. Salt flats are created in these dry lake beds as salt dissolved in the lake water precipitates out of solution and is left behind when the water evaporates away.

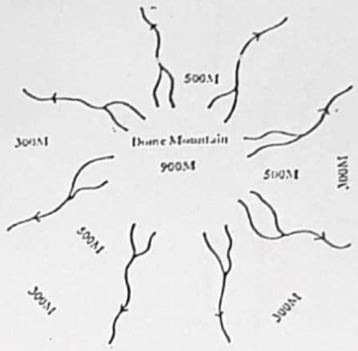

Fig. 2.4 Radial drainage pattern

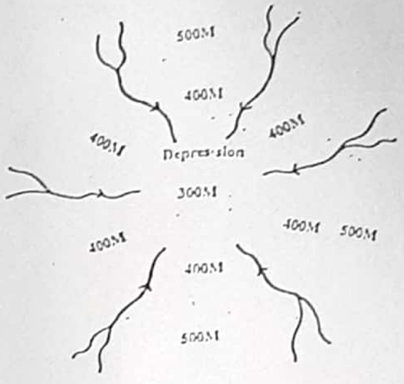

Fig. 2.5 Centripetal drainage pattern

2.4.6 Annular Drainage Pattern

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Annular pattern, also known as ***'circular pattern'*** is formed when the tributaries of the master consequent streams are developed in the form of a circle. Such pattern (Fig. 2.6) is developed over a mature and dissected dome mountain characterized by a series of alternate bands of hard and soft rock beds. The differential erosion of hard and soft rock beds results in the truncation of the beds which produces ***ringed belted structure*** wherein relatively resistant beds project outward whereas the weaker (soft) beds form circular clefts. The master consequent streams emerge at the top of the dome and radiate in all directions down the slope like radial drainage pattern whereas tributary streams develop in the clefts formed due to erosion of soft beds, assume arcuate shape and join the master consequent streams and thus annular drainage pattern is formed. At a much later date tributaries of circular subsequent streams, which join the radial consequent, are also developed and thus the drainage pattern becomes a special case of trellised pattern. Annular drainage pattern has developed over denuded domes in the Weald of England. The mature dissected Sonapet dome of Bihar, India presents an ideal example of annular drainage pattern.

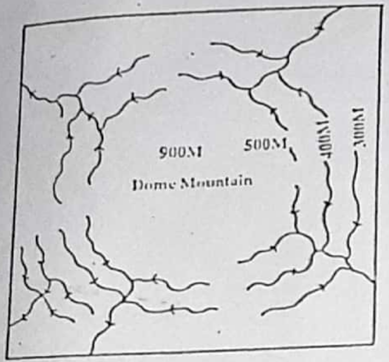

Fig. 2.6 Annular drainage pattern

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2.4.7 Pinnate Drainage Pattern

Pinnate pattern is developed in a narrow valley flanked by steep ranges. The tributaries originating from the steep sides of parallel ridges join the longitudinal master consequent occupying the valley at acute angles (Fig. 2.7). The drainage network of the upper Son and Narmada rivers denotes the example of pinnate drainage pattern. This pattern resembles the veins of a leaf.

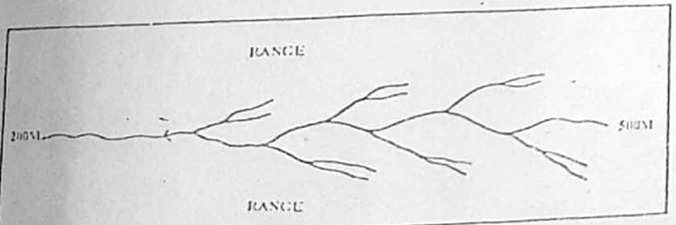

Fig. 2.7 Pinnate drainage pattern

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2.4.8 Barbed Drainage Pattern

Barbed drainage pattern, a rare kind of drainage pattern, which is usually observed in the headwaters and is limited in extent. In a normal stream, the junction angles of tributaries are such that they always point downstream. However, sometimes the tributary streams point upstream. This is referred to as barbed drainage pattern. Often the barbed pattern indicates control of geological structure or reversal of the drainage due to stream piracy or tilting of the surface because of tectonic movements. The tributaries join their master streams in a hook-shaped bend. Such pattern is generally developed due to river capture (Fig. 2.8).

Fig. 2.8 Barbed drainage pattern of the Tsangpo (Brahmaputra) River in Tibet

2.4.9 Herringbone Pattern

Herringbone drainage pattern, also known as *rib pattern* (like the rib bones of human beings), is developed in mountainous areas where broad valleys are flanked by parallel ridges having steep hillslide slopes. The longitudinal consequent streams, as master streams are developed in the longitudinal parallel valleys while tributaries, as lateral consequent, after originating from the hillslopes of the bordering parallel ridges join the longitudinal consequent almost at right angle. The courses of the tributaries are straightened because of slope factor and little distance between the ridges and the longitudinal consequent occupying the valleys and thus the tributaries are not allowed to adopt sinuous course and join the longitudinal consequent at acute angles (Fig. 2.9). The term herringbone has been derived from the pattern of bones of herring fish (mainly spine bones). The upper Jhelum river in the Vale of Kashmir receives numerous tributaries from both the sides and thus forms herringbone drainage pattern. The rivers occupying east-west trenches in the Himalayas form herringbone pattern. The Tamar Kosi, a left bank tributary of the Kosi river, the upper Rapti (a tributary of the Ghaghra river), the Rapti (another one), the left bank tributary of the Gandak river etc. have formed such drainage pattern.

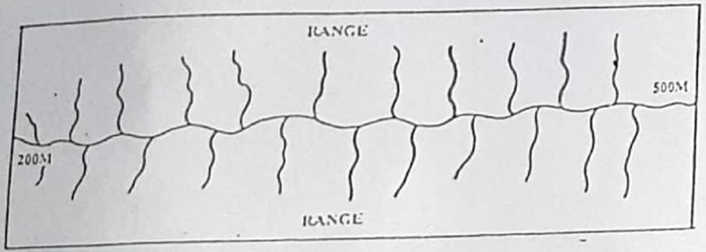

Fig. 2.9 Herringbone pattern

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2.4.10 Parallel Drainage Pattern

Parallel drainage pattern comprises numerous rivers, which are parallel to each other and follow the regional slope. This pattern is more frequently developed on uniformly sloping and dipping rock beds such as cuestas or newly emerged coastal plains. The western coastal plains of India represent several examples of parallel drainage patterns where the streams after taking their sources from the western flanks of the Western Ghats drain in straight courses towards west to empty into the Arabian Sea. Parallel drainage pattern has also developed on the Eastern Coastal Plains of India. It may be pointed out that a subparallel pattern is therefore essentially an *'initial drainage pattern'* (Fig. 2.10).

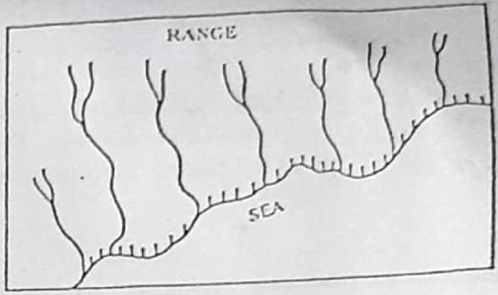

Fig.2.10 Parallel drainage pattern

2.4.11 Irregular Pattern

This drainage pattern, as the term implies, does not reveal any systematic arrangement or design of the main and tributary streams. Such a pattern is observed in regions that have recently experienced retreat of ice. Often the drainage in recently glaciated regions reveals anomalous and undeveloped network characteristics (Zernitz, 1932). Modified streams, abandoned valleys, discordant courses, and numerous lakes and swamps represent total or partial disarrangement of the former drainage system. In other words, the existing drainage is very different from that which preceded the last ice invasion.

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03 2.5 PHASES OF DRAINAGE NETWORK DEVELOPMENT

The drainage network, experiences an orderly development with the passage of time. Once the drainage is initiated over a newly developed land surface, it undergoes changes in terms of the number of tributary streams, stream length, and basin area. The growth of a drainage network closely resembles the growth stages of a tree, from the sapling stage to a fully-grown tree with large branches and numerous small branches.

Glock (1931) attempted to trace the sequence of drainage patterns during the development of a drainage network in a region characterised by simple rock structure and humid climate. He proposed a model of drainage network development and described five phases of the evolutionary development of a drainage network (Fig. 2.11). The drainage network was assumed to have been initiated on a newly established plain, formed either due to tectonic uplift or due to the recession of sea.

In the *initiation* phase, a skeletal drainage network is established on an undissected plain. The number of main streams is small and the inter-stream area is large. This is followed by a phase of ***elongation,*** characterised by the extension of all the major streams

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by headward erosion. The number of tributary streams and the average stream length increases. During the *elaboration phase* the small streams multiply rapidly. The network spreads, invades undissected interfluves and drainage density increases. Further development leads to the ***phase of maximum extension.*** This is the stage of fully developed network.

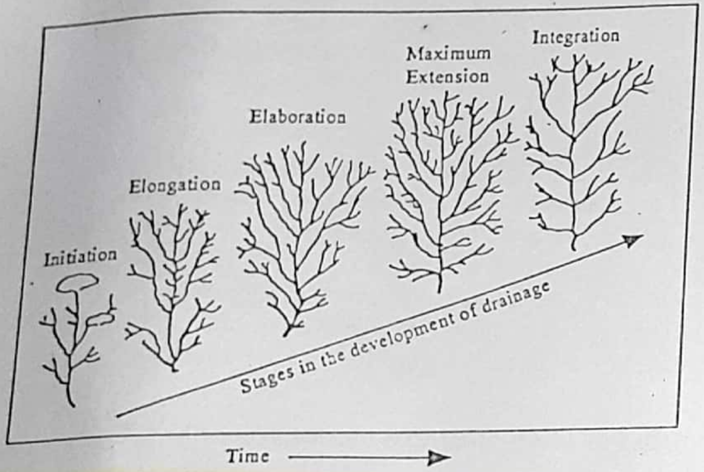

Fig. 2.11 Phases of drainage network Development

The final phase is the ***stage of integration,*** which is characterised by loss of small tributaries due to reduction in the overall relief. As the divides between streams are worn down, some streams shift laterally to swallow up neighbouring streams. In this way some streams become bigger. During this phase the number of smaller streams decreases to minimum, and the landscape is dominated by major streams. Like the initiation stage, in this stage also there is notable lack of streams over a large proportion of the land surface. This situation persists as long as the landscape remains undisturbed by tectonic movements or base level changes. The stages in the growth of a drainage network proposed by Glock have been demonstrated in flume experiments (Schumm, 1977).

Zernitz (1932) identified six common types of drainage patterns: dendritic, trellis, rectangular, radial, annular and parallel. The main characteristics, controlling factors and examples of these types of drainage pattern are shown in Table 2.2.

Table 2.2 Major drainage patterns Exam

Types of Drainage Patterns	Main Characteristics	Controlling Factors	Examples from India
Dendritic	Tree-like (Greek dendron, a tree)	Areas of comparable lithology	Common pattern; Ganga alluvial plains, Deccan Trap region
Trellis	Elongated tributaries flowing parallel or sub-parallel to main stream. The principal-tributaries join main stream at right angles	Folded rocks, in regions with elongated, linear features	Aravilli Hills, Cachar District, Aziwal District
Rectangular	Right angle bend in both tributary and parent streams	Rocks with right angle joints, faults, fractures	Shyamak Hills, Pachmari
Radial	Streams radiate in all directions from or towards a common center	Domed structures, volcanoes, isolated hills, islands, intermontane basins	Girnar Hills, Sambhar Lake
Annular	Ring-like (Latin annulus, a ring)	Mature dissected domes in alternate hard and soft sedimentary rocks	Giridih (Jharkhand)
Parallel	Parent and tributary streams flow parallel	Dominant regional slope, parallel faults and lineaments	On steep slopes in the Himalaya

Modified from Morisawa (1985)

2.6. RIVER AND STREAM

A *river* is the part of water flowing over land, constrained in a channel. All streams and rivers are supplied with water from rainfall. Whenever water falls on the Earth's surface as rain it flows down the slope as ***overland flow*** (Fig. 2.12). Down slope the runoff concentrates to form rills and gullies. The distance from the Crestline at which the concentration of flow occurs is the ***length of overland flow*** (Horton, 1945) (Fig. 2.12). Further down slope, several such small watercourses may unite to form ***streams.*** Several streams may join to form a larger body of flowing water known as a *river*. Most rivers flow into oceans, seas, lakes or join other rivers.

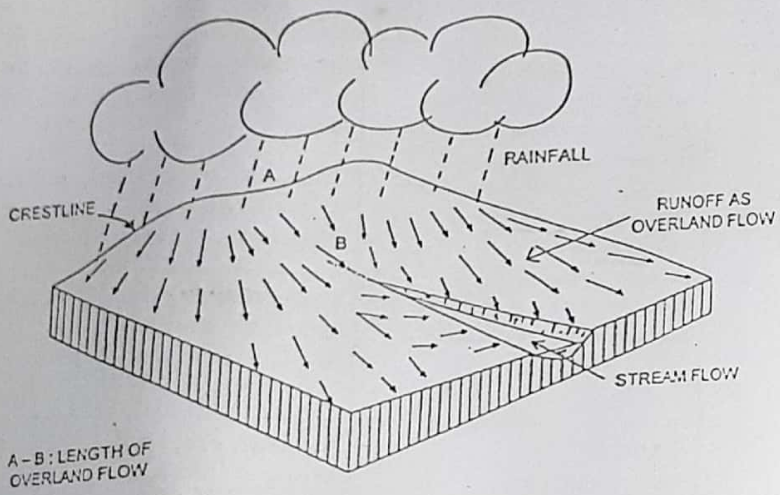

Fig. 2.12 Diagram showing the area of sheet flow, stream flow and the length of overland flow

In many regions, where the rainfall is well-distributed throughout the year and where there is contribution to the stream flow from groundwater or melting of snow ice the streams carry water thought the year. These are *perennial streams*. Most large rivers from the Himalayas are examples of perennial rivers. *Seasonal streams* are those that flow for a part of the year. Such streams are common in seasonally wet areas, such as the monsoon-dominated regions. Some streams flow only in direct response to rainfall, and carry water only during and immediately after heavy rains. These are *ephemeral streams*. The Luni River of the Thar Desert, India is an example of an ephemeral river. Rivers, such as the Nile, the Colorado, the Indus, and the Luni, that orginate in high rainfall region, but flow through dry regions for much of their course, are classified as *allochthonous* rivers.

Streams are important for several reasons

1. Streams carry most of the water that goes from the land to the sea, and thus are an important part of the water cycle.
2. Streams carry billions of tons of sediment to lower elevations, and thus are one of the main transporting mediums in the production of sedimentary rocks.
3. Streams carry dissolved ions, the products of chemical weathering, into the oceans and thus make the sea salty.
4. Streams are a major part of the erosional process, working in conjunction with weathering and mass wasting. Much of the surface landscape is controlled by stream erosion, evident to anyone looking out of an airplane window.
5. Streams are a major source of water and transportation for the world's human population. Most population centers are located next to streams.

2.7 TYPES OF RIVERS

Rivers are formed along more or less defined channels to drain from land all waters obtained by way of precipitation and melting of show from high altitudes. Their development is the work of ages. Along with water they carry and convey on to the sea sediment washed down from the catchment area and eroded from beds and banks.

There are mainly two sources from which water flowing in rivers is derived, viz, tidal and fresh water discharges. Tidal water centers at the lower end of a river and is derived from the tidal wave of the ocean. This supply is available all the year round with variations depending on the tides and freshet discharges. Fresh waters, entering the rivers from the upper and are also derived from the sea, but by a different process. The heat of the sun causes water from the sea to evaporate and collect in the form of clouds, which, condensing in the form of rain, falls to the ground and is then collected by brooks and rivulet, which feed rivers. The supply of fresh water is, however, variable and intermittent.

River reaches can be divided according to topography of the river basins as upper, middle and end reaches. The upper reaches comprise of the hilly and the submontane region, the middle reach is formed by the flood plain and the end reach covers the tidal portion and the delta region.

2.7.1 Upper Reaches of Rivers

2.7.1.1 Hilly reach incised rivers

In this type, the channel is generally formed by the process of degradation. The sediment which it transports is often dissimilar in character to that of the river bed, since most of it comes from the catchment due to denudation and soil erosion. The bed and the banks of the reach itself are usually highly resistant to erosion. As bed conditions do not determine the sediment load, the rate of transportation cannot be determined, as is usually done, as a function of bed characteristics.

These rivers are further characterized by the steepness of the slopes, the swiftness of the flow and the formation of rapids along their courses. They do not present a regular pattern of meanders because of varying resistances of bed and banks to erosion, which vary along their lengths.

2.7.1.2 Foothill submontance reach– boulder rivers

These are characterized by the steepness of their slopes and their beds consist of a mixture of boulders, gravel, shingle and sand. These rivers, moreover differ considerably from those carrying sand and silt in place of regular meandering courses, deep well defined beds and wide flood plains, boulder rivers tend to have straighter courses with wide shallow beds and shifting braided and interlaced channels. During a flood, the high velocity flow transports boulders, shingle and gravel downstream, but as the flood subsides the flow of materials is checked and the bed materials piles in heaps. The flow with reduced velocity then finds it more difficult to shift the heaps than to go round them and the channel thus wanders in new directions, often attacking its banks and widening the bed thereby.

When the river descends from the steep hilly region into the foothill area, the slope suddenly flattens resulting in considerable reduction in sediment transporting capacity. The sediment accordingly deposits forming an alluvial fan.

2.7.2 Rivers in Flood Plains (Alluvial Rivers)

Rivers in flood plains have the characteristics of meandering freely from one bank to the other and of carrying material, which is similar to that of the bed. Material gets eroded constantly from the concave banks of bends and deposits, either between two successive bends to form a bar, or along convex sides of successive bends. Once a stream with an erodible bed and sides deviates at any point from its linear course, the resulting unbalance of erosive power tends to increase the local deviation and sets a meandering pattern with the original course for its axis. The erosion of banks, the path of bed load movement and

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the location of deposits change significantly with change in stage. The shape of cross-sections and the slope of the stream are determined by the relative sediment load and the erodibility of bed and banks. During high floods these rivers inundate very large areas causing considerable damage.

Rivers in flood plains are further classified as aggrading degrading or stable. If a river is building up its bed, it is called an ***aggrading or accreting river.*** It the bed is getting scoured from year to year, it is called a ***degrading river.*** When a river carries down sediment which it receives, without either depositing the material or scouring the bed, it is called a *stable river.*

2.7.2.1 Aggrading type 10,M 15

A river builds up its bed because of a variety of reasons: heavy load, obstruction like a barrage or a dam across it raising the level of water and flattening the slope, extension of the delta at the river mouth, sudden intrusion of sediment from a tributary etc. Such a river is called an aggrading type. It has usually straight and wide reaches with shoals in the middle which shift with floods the flow being divided into a number of braided channels.

2.7.2.2 Degrading type 07,10

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This type of river is found either above a cut-off or below a dam (or a barrage). These result, respectively in the sudden lowering of the water surface upstream of the cut-off which increases its slope of flow and in the sudden diminution of its sediment load. The Colorado River, for instance, below the Boulder Dam has become a degrading type after the construction of the dam.

2.7.2.3 Stable type

This type of river is characterised by the stability of the alignment of channel and slopes as well as of its regime, which may change within a year, but shows little variation from year to year except, perhaps, that the river may migrate within its khadirs. Changes such as scouring and silting of the bed advancement of the death into the sea, and changes in bed and water slopes over a long period of time do take place but these are insignificantly small. Such rivers mould their characteristics in such a manner that most of the sediment load brought down by them is carried to the sea.

A river remains seldom of a single type. The same river may have either aggrading, degrading, stable and other river characteristics from its source to its mouth. Its nature depends upon the amount and size of sediment entering the river, its load carrying capacity and other factors. Even the same reach in a river may pass through various types depending on the variation of sediment load and discharge with time.

2.7.3 Lower Reach– Tidal and Delta Rivers

A river reach, in which periodic changes in water level occur due to tides, is called a ***tidal river.*** In its last journey to the sea before becoming tidal a river may split into branches and form a delta. This last portion is called a ***delta river.***

In its last reach, the river receives tidal water derived form the tidal wave of the ocean. The ocean water enters the river with the flood tide and the process is reversed during the ebb tide. The amount of water, which enters during the flood tide, ebbs out to the sea. The river undergoes thus, a periodical rise and fall in the level depending upon the nature of the tide. The distance up to which the tidal effect is felt depends on the slope of the river, the tidal range, freshet discharge, configuration of the river etc.

The delta river is rather a stage of a river than a type in itself. In this stage the river is nearing its outfall into the sea and is characterised by several branches, which multiply in number, as approaches the sea. On account of low velocities, the channels get silted and water levels rise, resulting in spills and eventual formation of new channels.

2.7.4 Other Types

2.7.4.1 Flashy rivers

River can also be classified according to the stage and nature of flood hydrographs. Thus a river is called ***flashy*** if the rise and fall of its floods are sudden.

In the case of flashy rivers the flood hydrographs are steep indicating thereby that the flood flow occurs all of a sudden. The flood rises and falls in a very short period of a day or two. A sizeable small flow is however maintained for some time till the end of the rainy season. Bed and banks of such rivers are in no way different from those of rivers in alluvial plains. There are several rivers of the flashy type in India in the State of Rajasthan, Andhra Pradesh, Tamil Nadu and Karnataka.

2.7.4.2 Virgin rivers

In arid zones, a river may completely dry up before joining another river or the sea. Such a river is called a ***virgin river.*** Waters in rivers of this type disappear due to high percolation and evaporation losses after flowing certain distance from their source. There are several virgin rivers in the States of Gujarat and Rajasthan.

2.7.4.3 Himalayan and non-Himalayan rivers

Rivers in the Indian sub-continent i.e. Himalayan region can also be classified as Himalayan and non-Himalayan. Rivers derived their waters from melting snow during the spring and summer and also from rains during the monsoon. These rivers are, consequently, more or less perennial and they can give dependable yields in the summer as well as in the monsoon.

The Himalayan rivers carry, generally, heavy sediment loads because of the soft friable Himalayan rock. This is further aggravated by the seismic character of the Himalayan zone, of which the north-eastern part is particularly active. Consequent upon a seismic disturbance, the friable rock loosens and landslips occur, thus increasing substantially the sediment load of the Himalayan rivers.

The non-Himalayan rivers in the Central and South India are not snow-fed. They get their supplies chiefly during the monsoon; they dry up practically in the summer. These rivers rise from the Aravali, Vindhya, Satpura and Sahyadri mountain ranges. Originating form these mountains the rivers run in all directions. The river Chambal runs to the north, Mahanadi to the east, Godavari to the south east, the Tapi and the Narmada to the west. Rivers in the south run similarly to the east and west. Peninsular rivers are mostly of incised type.

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2.8 RIVER CAPTURE OR STREAM PIRACY

The diversion of the part of the course of a river by another river is called ***stream diversion*** or ***stream capture*** or ***stream piracy.*** The river which captures the course of another river is called the ***capturing*** or ***captor stream*** while the part of the stream which has been divested of its course and water is called ***captured stream.*** River capture is a natural process which is more active in the youthful stage of the valley development because the streams are actively engaged in headward erosion and valley lengthening but river capture also occurs during mature and senile stages of the valley development through the process of lateral erosion and meander intersection. The stronger and more powerful streams (in terms of channel gradient, stream velocity and discharge and kinetic energy) capture the upper courses of weak and sluggish streams. Fig. 2.13 depicts the stages of the capture of the Saraswati river by the Yamuna river.

There are four major evidences of river capture viz. ***(i) elbow of capture, (ii) cols*** or ***wind gaps, (iii) water gaps,*** and ***(iv) misfit*** or ***underfit streams*** and ***valleys. The elbow of capture*** denotes the point (Fig. 2.14 E) where the course of the captured stream has been diverted to the course of the captor stream. Generally, the elbow of capture denotes sharp turn in the course of a river almost at right angle. ***The water gap*** denotes the deep and narrow valley in the form of a gorge formed by the captor stream through headward erosion across the ridge (Fig.2.14, WG).

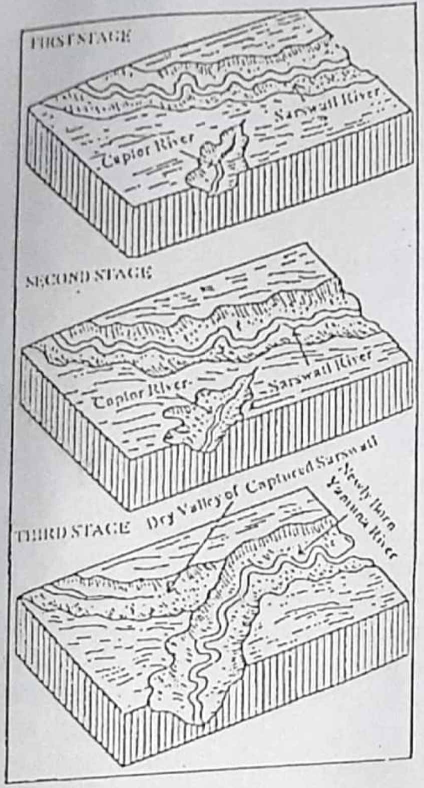

Fig. 2.13 Stages of the capture of the Saraswati river through the process of headward erosion

Wind gap is the dry portion of the beheaded stream just below the elbow of capture (Fig. 2.14, wg). The wind gap is also called as *col*. ***The misfit or under fit*** stream is the lower course of the captured stream. It is called misfit because of the fact that the former valley of the captured stream becomes too large and wide for the beheaded stream because

of substantial decrease in the volume of water due to diversion of its water to the captor stream.

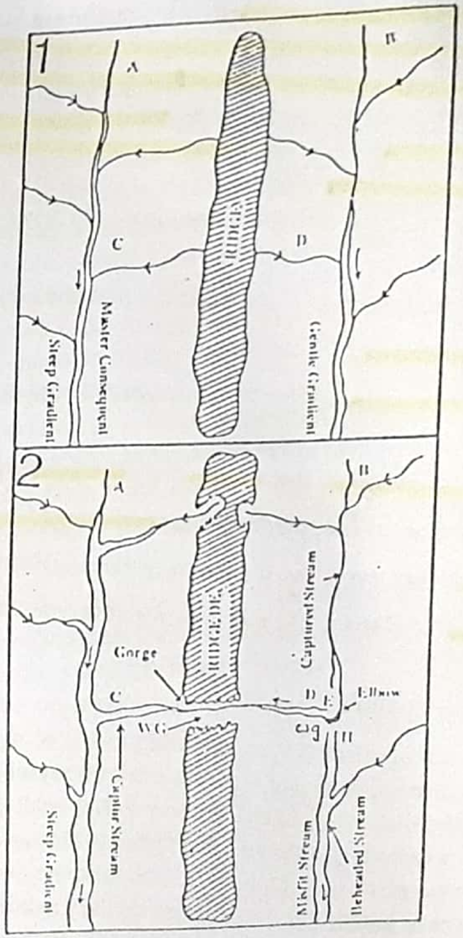

Fig. 2.14 Illustration of river capture through headward erosion. WG = water gap, wg = wind gap.

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2.8.1 Ideal Conditions for River Capture

Though the river capture is a natural process, but it does not take place in all circumstances rather it requires certain necessary conditions. In act, the process of river capture depends on *channel gradient, depth of river valley, volume of water, velocity and discharge, lithological characteristics and geological structures, stage of cycle of erosion or the stage of river development.* A particular river of a locality having deeper valley, more volume of water, steeper channel gradient and hence higher velocity and kinetic energy and flowing over less resistant and softer rocks than the other river of that region resorts to more powerful headward erosion than the latter, and thus may usurp the water and upper reaches of the weaker river.

It may be, thus, inferred that river capture occurs under the following conditions-

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1. Steep channel gradient,
2. Relatively narrow valley so that water may not spread in the otherwise wide and flat valleys,
3. Higher volume of water so that velocity and discharge may be sufficiently high,
4. Soft rocks so that the river may resort to rapid rate of headward erosion,
5. Deeper valley than the valleys of other neighbouring rivers,
6. Low sediment load so that the river may resort to active erosion etc.

2.8.2 Types of River Capture

It is apparent from the above discussion that the process of river capture is effected by erosion of different sorts viz. headward erosion (valley lengthening), vertical erosion (valley deepening of downward cutting), lateral erosion (valley widening), and intersection of meanders (lateral erosion). Headward and lateral erosion is the most powerful geomorphological process of river capture. It may also be pointed out that headward erosion is more effective in terms of river capture during juvenile stage (youthful stage) of river development while lateral erosion becomes more operative during mature stage. The capture of the course of a particular river by the other river through the intersection of meanders occurs mostly during late maturity and senile stage (old stage). Thus, the forms of river capture may be grouped in 3 broad categories viz. *(1) capture through headward erosion, (2) capture through lateral erosion and (3) capture through the intersection of meanders.*

2.8.2.1 River capture through headward erosion

Most of the river captures occur due to headward erosion. In the initial stage of their development most of the streams and their tributaries are engaged in active headward erosion resulting into continuous creeping or shifting of water divides and lengthening of their valley thalwegs. The nature and intensity of headward erosion of any stream largely depends on the potential energy (height of the divide) and the steepness of the side slope of the water divide. Generally, the side slopes of the divide are unequal. The streams originating from the steeper slopes of the divide having relatively softer rocks and more precipitation and relatively short channel lengths degrade their valleys through the process of valley deepening more powerfully and resort to headward erosion at more accelerated rate than those streams which originate from the other side of the divide having less steep slope, relatively resistant rocks and low precipitation. Consequently, the erosive power of the former becomes much more than the latter. The powerful stream pushes the water divide backward towards the side of gentle slope through active headward erosion. Prolonged headward erosion by more powerful stream flowing of the steeper hillside of the divide results in the coalescence of the sources of both the streams on opposite sides of the divides. Since the valley floor of the stream of the steeper side of the divide is lower than the valley floor of the stream of the gentler side of the divide and hence the former captures the headwaters of the latter.

The process of river capture may be explained with the help of an example. Consequent streams originate on the slopes of any uplifted landmass. The most active and the longest consequent is called the master consequent. 'A' is the master consequent (Fig. 2.14.1) while 'B' is the other consequent stream shown in Fig. 2.14. 'A' stream is flowing through steeper slope and channel gradient than B stream and thus the former has deepened its valley much more than the latter, with the result the valley floor of A stream is lower than the valley floor of B stream. It is, thus, apparent that A stream is more active than B stream. A few subsequent of lateral consequent streams emerge from the ridge (Fig. 2.14.1) and join the longitudinal consequent A and B streams at almost right angles. For example, C and D are the tributaries of streams A and B respectively. These two tributaries take their sources on both the slopes of the same ridge. The valley of C would be also deeper than the valley of D stream because the valley of the master stream of C (A) is deeper than the valley of the receiving stream of D (B). Thus, the headward erosion by C stream would be more active and vigorous than the headward erosion by D stream. The water divide is gradually pushed back (towards the source of the stream D) because of more active headward erosion by C stream. A time comes when the C stream cuts across the ridge and extends its course through deep and narrow valley (gorge) and captures the course of D stream (Fig. 2.14.2). Now the water of the upper course of the longitudinal consequent B stream also flows into the master consequent A stream via the integrated D and C tributary stream. Now the water of BEDC in the form of one channel drains into A stream.

This example illustrates the capture of two streams at two stages. First, D stream, a tributary of B stream, was captured by C stream, a tributary of a stream through active headward erosion. Secondly, the headwaters of B stream (from the source to E point, the elbow of capture) were diverted towards A stream via D and C stream due to fallout of the first stage. C-D streams now flow through deeply entrenched narrow valley known as gorge (Fig. 2.14.2). This narrow passage through the ridge is called *water gap* (wg in Fig. 2.14.2). B-E portion of the former B consequent stream has become *Captured stream* which turns at right angle forming an *elbow of capture* (E in Fig. 2.14.2). H-B portion of the former B consequent has now become a *beheaded stream*, the upper part of which is called *wind gap* (wg in Fig. 2.14.2) because of dry bed of the river due to capture of the upper portion of the river. The G-B portion of the former B consequent stream has now become *misfit or under fit river* because now the existing G-B stream is unable to adjust itself in its former valley because of marked reduction in the volume of water due to diversion of its headwaters to A stream via D-C streams as a result of river capture. There are two evidences which enable the investigators to identify the captured streams in the field viz (i) *elbow of capture* and (ii) *wind gap* just to the downstream side of the elbow. The erosional work of the *beheaded stream* becomes almost nil because of marked reduction in the volume of water. Some times, the valley of the beheaded stream becomes almost dry. On the other hand, the *captor stream* (Fig. 2.14, C and A) resorts to more vertical erosion resulting into accelerated rate of valley deepening because of marked increase in the volume of water due to additional supply of water of D stream and headwaters of B stream (B-E portion) because of river capture. It may be pointed out that C and D tributary streams were formerly flowing in opposite directions (Fig. 2.14 1) but now the waters of D stream flow in the direction of C stream. Thus, such streams of reversed flow direction are called *inverted streams.*

Example- A group of geologists and geomorphologists believe that the present drainage system of the Himalayas is the outcome of progressive river piracy during various stages of drainage development. The Arun Kosi, a head tributary of the Kosi river, has captured the Phung Cho, a southern tributary of the Tsangpo (the upper part of the Brahmaputra river is called Tsangpo) river. Two head-tributaries of the Ganga e.g. the Bhagirathi and the Vishnuganga have captured the source tributaries of the Sutlej river. The water divide between the tributaries of the Song river (a tributary of the Ganga river) and

the Asan river (A tributary of the Yamuna river) is only a few meters wide near Dehra Dun (Fig. 2.15). It is expected that the Song river may capture the Asan river and that the upper course of the Yamuna may be divided to the Ganga via the Asan and Song rivers.

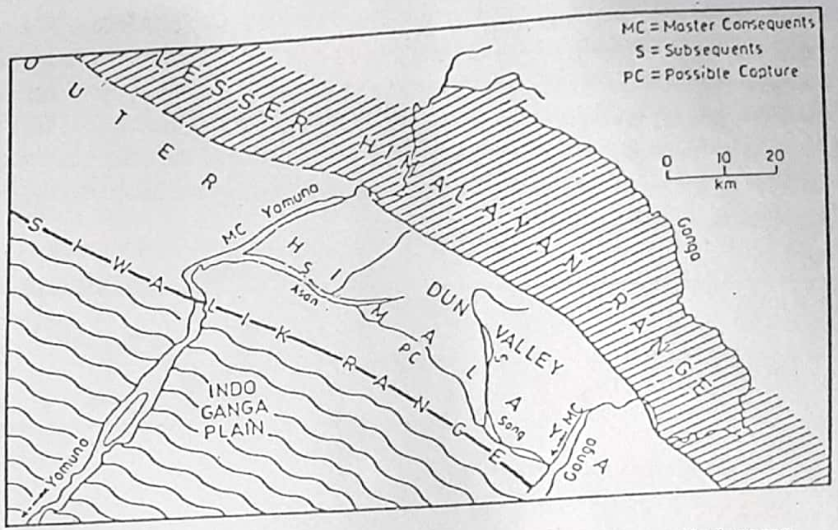

Fig. 2.15 Development of master consequent and subsequent streams in Dehra Dun Valley

2.8.2.2 River capture through lateral erosion

Lateral erosion and consequent valley widening become more active and significant during mature stage of river development than vertical erosion and valley deepening. The water divides between parallel streams developed on sedimentary rocks of the coastal plains are generally narrowed down due to lateral erosion and valley widening. The streams having more volume and drainage of water and relatively steeper channel gradient than the other streams resort to more lateral erosion due to which smaller parallel tributaries are consumed by the larger parallel streams. This process of river capture is called *stream abstraction* or *natural selection.*

2.8.2.3 River capture through the interaction of meanders

The stream adopts highly sinuous and meandering courses during their late mature and old stages of development because of the development of level to gentle slopes (0^0 to 5^0) over major part of the area concerned. The meanders of two closely spaced streams are gradually sharpened due to continuous lateral erosion and ultimately they intersect each other and thus relatively more powerful stream captures the waters of the other stream. The Belan river, a tributary of the Tons river (which is itself a tributary of the Ganges river), has captured the lower course of its tributary the Seoti river near Deoghat (about 80 km south of Allahabad city) through meander intersection and now has pushed its course through the course of the Seoti while its older course, now an example of a palaeochannel, has become quite narrow due to sedimentation and anthropogenic processes (cultivation) (Fig. 2.16). Due to of this unique process of river capture the confluence of the Belan-Seoti rivers has been pushed about 6 km upstream. The older (palaeo) valley of the Belan now has become misfit valley (Fig. 2.16).

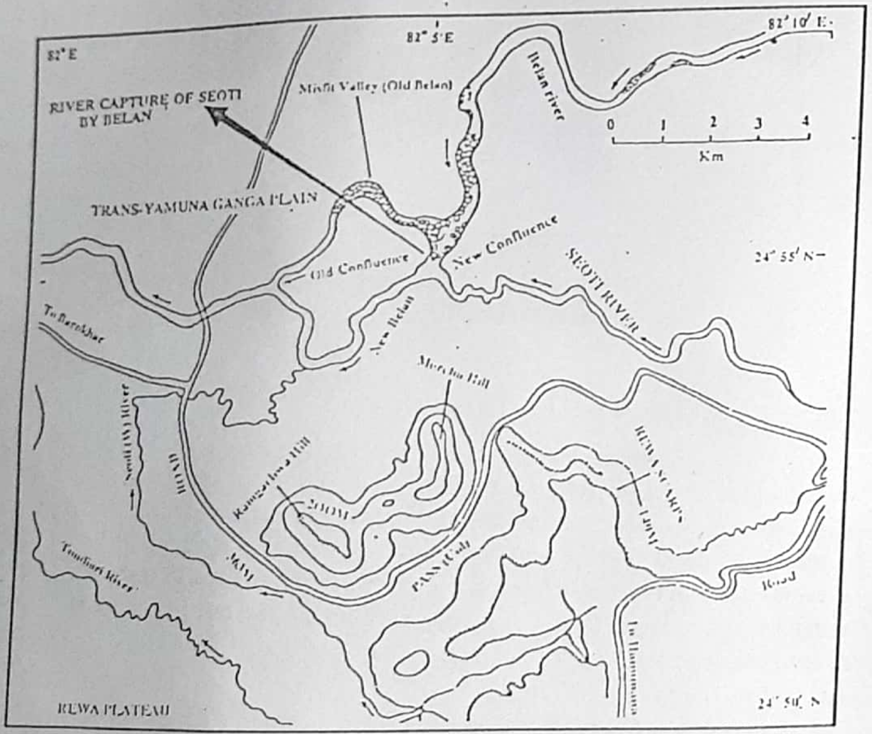

Fig. 2.16 Example of river capture through lateral erosion and consequent meander intersection

Numerous cases of river capture have occurred in the Himalayan region. In fact, the present drainage system of the Himalayas is, to greater extent, the result of progressive piracy. The headward erosion has been the most active process of river capture of the Himalayas and the Western Ghats (India). The water divide between the headwaters of the Savitri river (drainage into the Arabian Sea) and the Krishna river (draining into the Bay of Bengal) at the margin of the Mahabaleshwar plateau (Maharashtra, India) is very narrow. The Krishna river may capture the headwaters of the Savitri in near future. The process of river capture through lateral erosion and intersection of meanders is more active in the coastal plains and the great Northern Plains.

CHAPTER - 3

THE MORPHOMETRIC ANALYSIS OF DRAINAGE BASIN

3.1 THE CONCEPT OF MORPHOMETRY

The term '*morphometry*' connotes the meaning of '*measurement of forms*' derived from *morpho* (form) and *metry* (measurement). Therefore, the techniques related to the form measurements in geomorphology include a wide scope of measurement techniques of a large number of variables of spatial pattern and forms of the landforms i.e., the shape, size, relief, linear network and characteristics of drainage measured through different parameters to bring about weighage of the different aspects of the landforms. Therefore, the scope of morphometry is immense because many techniques, simple as well as complex, are evolving to assess the geometry and forms of the landforms with considerable importance attached to both forms and characteristics of slopes. In case of drainage basins, though the techniques of morphometric analysis are the same as that of any spatial analysis, the conditions are specific to a complete system, thus bringing about the interrelationships of this geometry and forms. They can be utilized for the derivation of many significant aspects of the genesis, evolution and characteristics of the landforms, though the degree of accuracy will largely depend upon the considerations of micro-details.

3.2 BASIN MORPHOMETRY

The basin morphometry includes the analysis of the characteristics of linear, areal and relief aspects of fluvially originated drainage basins.

3.2.1 Linear Aspects of the Basin

Linear aspects of the basins are related to the channel patterns of the drainage network wherein the topological characteristics of the stream segments in terms of open links of the network system (streams) are analysed. The drainage network, which consists of all of the segments of streams of a particular river, is reduced to the level of graphs, where stream junctions act as points (nodes) and streams, which connect the points (junctions), become links or lines wherein the numbers of all segments are counted, their hierarchical orders are

determined, the lengths of all stream segments are measured and their different interrelationships are studied. The nature of flow paths in terms of sinuousity is equally important in the study of linear aspects of the drainage basins. Thus, the linear aspect includes the discussion and analysis of stream order (μ), stream number (N_μ), bifurcation ratio (R_b), stream lengths (L_μ), length ratio (R_L), length of overland flow (L_g, sinuosity indices etc. Fig. 3.1 shows different components of a typical drainage basin.

3.2.1.1 Stream ordering

Stream ordering refers to the determination of the hierarchical position of a stream within a drainage basin. A river basin consists of its several branches (segments) having different positions in the basin area and they have their own morphometric characteristics and, therefore, it becomes necessary to locate the relative position of a segment in the basin, so that the hierarchical organization of stream segments is visualized. Thus, 'stream order is defined as a measure of the position of a stream in the hierarchy of tributaries' (L.B. Leopold, M.G. Wolman and J.P. Miller, 1969). It was Gravelius who made first attempt in 1914 to determine the orders of stream network wherein he attempted to trace the streams from the outlet to the source like an explorer.

(a) Gravelius' Scheme of Stream Ordering

Gravelius first , identified the trunk stream by tracing it from its outlet to its source on the basis of greatest width, discharge, headward branching and junction angles and thus the trunk stream was assigned the position of 1st order (Fig. 3.1 C). By applying the same procedure he designated order 2 to all the streams which joins the trunk stream of 1st order. Next, all of the streams joining 2nd order streams, were designated by order 3 and this procedure was continued till the most remote finger-tip tributaries were assigned the highest order. This scheme of stream ordering by Gravelius was not appreciated as the ordering was based on subjective decision of the investigator at each bifurcation and the hierarchical orders were not symmetrically related to the magnitude of a given segment or link.

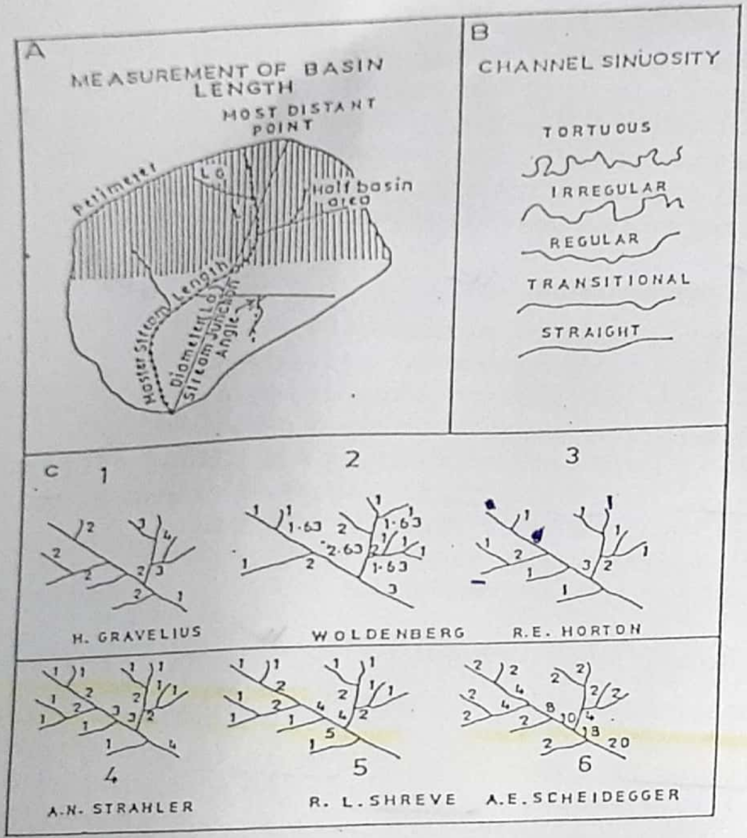

Fig. 3.1 A = Components of drainage basin; Lg = length of overland flow; L= length of master stream; Lca = distance from the mouth of the river to the centre of gravity of the basin; Lcu = 0.5 L ; Lo = longest horizontal and > straight distance from the mouth of the main river to the most distant point on the basin perimeter. After, R. J. . Chorley. B = Channel sinuosity. C = Methods of stream segment ordering, after M.J. Woldenberg, 1967.

(b) Horton's Scheme of Stream Ordering

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R.E. Horton, an American engineer, presented his scheme of stream ordering (1932, 1945) which was opposite to Gravelius' scheme. According to Horton ordering of stream begins from the finger-tip tributaries, which do not have their own feeders, rather they are [illegible]

independent in terms of supply of water. Such finger-tip streams are designated as 1st order streams. Two streams of first order, when join together, form 2nd order stream just below their junction. Similarly, two streams of 2nd order meet to make the stream of 3rd order and this process continues till the trunk stream is given the highest order (Fig. 3.1 C 3). Simultaneously, 2nd order streams may have other 1st order streams and 3rd order streams may have additional 1st order and 2nd order streams and so on. Thus, according to Horton's scheme when two streams of same order meet, they form the next higher order and each stream can receive tributaries of lower orders than its own order. In other words, the stream order increases only when two streams of same order join together. If a stream or streams of lower order join a steam of higher order, the order of the receiving stream does not increase. After all the streams of a drainage basin are classified in the first round, they are reclassified in order to determine the headward extension of the streams of different orders except the 1st order streams. For example, one of the two streams, which form 2nd order stream, is extended headward on the basis of length, linear extension, discharge and sometimes by choice (when both the streams are of the same length) and is renumbered as 2nd order stream (previously it was 1st order stream). Similarly, one of the two streams, which form a stream of 3rd order, is extended headward to water divide and is renumbered as 3rd order stream. This scheme of reclassification continues till the trunk stream of the highest order becomes the longest drainage line of the basin (Fig. 3.1 C 3).

Horton's scheme of stream ordering is difficult, tedious and time-consuming as it involves classification and reclassification of streams several times. Some of the finger-tip tributaries are given orders higher than one while other finger-tip tributaries of the 1st order with the same magnitude are not upgraded.

(c) Strahler's Scheme of Stream Ordering

A.N. Strahler (1952, 1953, 1957 and in Chow's 1964) modified the Horton's scheme of stream ordering by removing the problem of reclassification and renumbering of streams. According to him each finger-tip channel is designated as a segment of 1st order. At the junction of any two 1st order segments, a channel of 2nd order is produced and extends down to the point, where it joins another 2nd order segment whereupon a segment of 3rd order results and so forth' (A.N. Strahler, 1969). These streams may have additional stream segments of lower orders than their own order and thus these do not affect the classification (Fig. 3.1 C 4). It may be mentioned that the hierarchical order increases only when two stream segments of equal order meet and form a junction. The order does not increase if a lower order stream segment meets a stream segment of higher order. Strahler's scheme is popularly known as '*stream segment method*'.

Thus, the objections labeled against Hortonian scheme was overcome by Strahler's modifications. The advantage of this simple scheme is that it can be derived mathematically from the concepts of elementary combinational analysis (M.A. Melton, 1959) as 'it designates all unbranched segments as the same order, and it gives highest order to one segment rather than to the whole of the trunk stream' (K.J. Gregory and D.E. Walling, 1973). Strahler's scheme is simple and easy for application and it maintains the ordinal character of stream ordering and produces the same maximum basin order as that of the Horton's scheme but it suffers from the limitation (this is also in the case of Horton's scheme) in that the stream segments of lower order, when meet the trunk stream or the segments of higher order than their own, do not have the role to increase the order of the latter but the addition of a single 1st order segment in the upper reaches of the basin can raise the order of the trunk stream.

(d) Shreve's Stream-Link Ordering Method

Shreve's ordering method (1966, 1967) follows a hierarchic order, starting from the fingertip streams as of order 1, and increases into a cumulative order after its confluence with another stream. Only the exterior links are of the first order and goes on increasing in a cumulative manner. Therefore, if a link (order) of magnitude M_1 joins a link (order) of magnitude M_2 then the combination (*) of links M_1 and M_2 gives a downstream link magnitude of $M_1 + M_2$.

$$M_1 * M_2 = M_1 + M_2 \qquad \text{(Fig. 3.1 C 5)}$$

Thus, in Shreve's scheme each segment (link) has its own contribution in increasing the magnitude (i.e. stream order) of the segment which it meets. For example, if two 1st order (magnitude) stream links meet, 2nd magnitude (2nd order) is formed down the confluence. When two segments of magnitude 2 meet, the magnitude increases to 4 (2+2=4) down the confluence. If a segment (link) of magnitude 1 meets the segment of magnitude 4, next higher magnitude (i.e. 1+4=5) is formed down the confluence and so on.

Such an ordering system, referred to as the '*magnitude of a link*' has the advantages of involving all the links in a cumulative manner and thus provides a '*direct statement of the number of sources ultimately tributary to it.*'

Other stream ordering systems have been devised by many others of whom the methods of M.J. Woodenberg (1966), A.E. Scheidegger (1965) are quite well known.

3.2.1.2 Horton's stream laws

The most valuable utility of stream ordering system of Horton, modified by Strahler, is the establishment of empirical relations of stream orders with its different morphological parameters such as number, length slope and basin areas. These different laws of drainage composition are known as the "Horton's stream laws" (modified after by strahler) which are discussed below.

(a) Law of Stream Numbers

The law of stream numbers relates to the definite relationship between the orders of the basins and stream numbers. R.E. Horton's law of stream numbers (1945) states '***that the number of stream segments of successively lower orders in a given basin tend to form a geometric series beginning with the single segment of the highest order and increasing according to constant bifurcation ratio***'. For example, if the master stream is of 6th order and the bifurcation ratio is 4, then the number of stream segments from higher to lower orders (i.e. 6, 5, 4, 3, 2, 1) would be 1, 4, 16, 64, 256 and 1024 respectively. The law of stream numbers is expressed in the following form of negative exponential function model

$$N_\mu = R_b^{(k-\mu)}$$

where N_μ = number of stream segments of a given order
R_b = constant bifurcation ratio
μ = basin order
k = highest order of the basin

Example: (i) Number of stream segments of 1st order

$$= N_1 = 4^{(6-1)}$$

$$= 4^5 = 1024$$

(ii) Number of stream segments of 2nd order

$$= N_2 = 4^{(6-2)}$$

$$= 4^4 = 256$$

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Bifurcation Ratio (R_b) fx

Bifurcation ratio (R_b) which is related to the branching pattern of the drainage network, is defined as a ratio of the number of streams of a given order (N_μ) to the number of streams of the next higher order ($N_{\mu+1}$) and is expressed in terms of the following equation

$$R_b = \frac{N_\mu}{N_{\mu+1}}$$

where N_μ = number of streams of a given order

$N_{\mu+1}$ = number of streams of the next higher order

An example of calculating bifurcation ratio is shown in Table 3.1.

Table 3.1 Bifurcation ratio

Stream Order (μ)	Number of Streams (N_μ)	Bifurcation ratio, R_b
1	110	3.9
2	28	4.0
3	7	2.3
4	3	3.0
5	1	–

Bifurcation ratio, a dimensionless property of the drainage basin is supposed to be controlled by drainage density, stream entrance angles (junction angles), lithological characteristics, basin shapes, basin areas etc.

Horton further worked out the following equation (using constant bifurcation ratio) to find out the total number of the stream segments of the whole drainage basin–

$$\Sigma\mu = \frac{R_b^{k}-1}{R_b-1}$$

where, k = highest order of the basin

R_b = constant bifurcation ratio

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If the basin is of 5th order and bifurcation ratio is 4

So,

$$\Sigma N_\mu = \frac{4^5-1}{4-1}$$

$$= \frac{1024-1}{3} = \frac{1023}{3} = 341$$

Table: 3.2 Hypothetical Stream Number

Basin Order (μ)	Stream Number N_μ)	Constant bifurcation ratio (R_b)
1	256	4.0
2	64	4.0
3	16	4.0
4	4	4.0
5 = k	1	4.0

$\Sigma N_\mu = 341$

The following regression equation of negative exponential function helps in ascertaining the law of stream number

$$\log y = \log a - bx$$

where, y = number of stream segments

x = stream order

a = constant

b = regression coefficient

The regression line (Fig. 3.3) drawn on the basis of above regression equation involving number of stream segments (gully-rill segments) and stream order (gully order) of Deoghat gully (Table 3.3, Fig. 3.2, Allahabad District), plotted on semi-log graph paper, almost validates the Horton's law of stream number as stated above because the coefficient of correlation is (– 0.993) and the percentage variance explained is 98.65.

Table 3.3 : Morphometric data of Deoghat Gullies (1991)

Gully basin order (μ)	Number of gully segments (N_μ)	Mean length (m)	Cumulative mean length (m)	Basin area (m^2)
1	84	19.24	19.24	290
2	23	35.04	54.28	1560
3	7	46.85	101.13	5,980
4	1	256.00	357.13	56,130

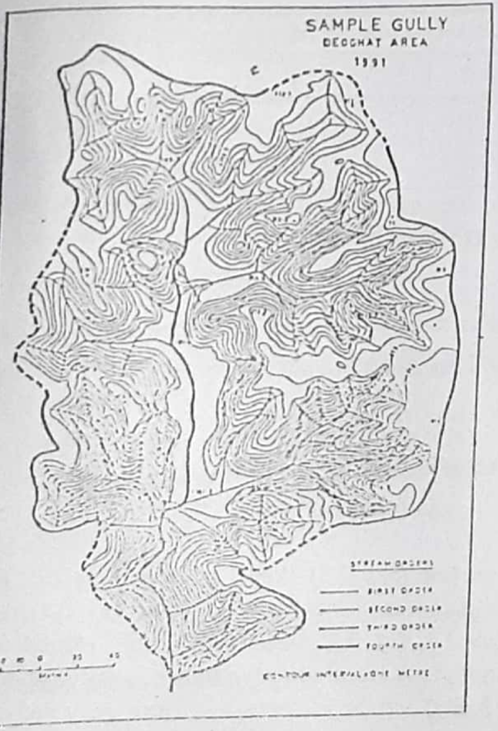

Fig. 3.2: Contour and drainage map with stream ordering of Deoghat gullies

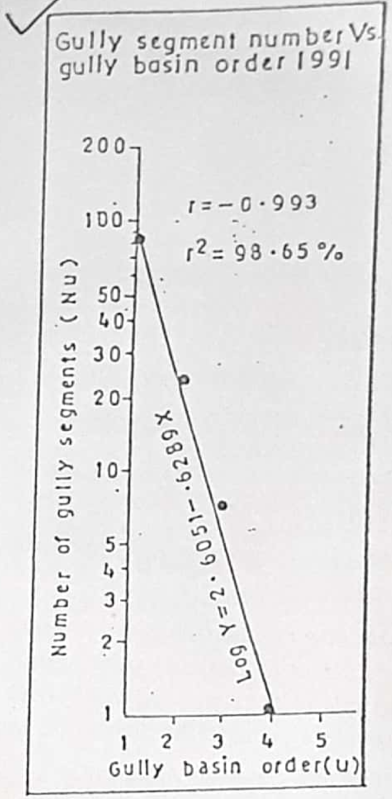

Fig. 3.3 Law of stream number–regression line of negative exponential function model: gully segment number vs. gully basin order.

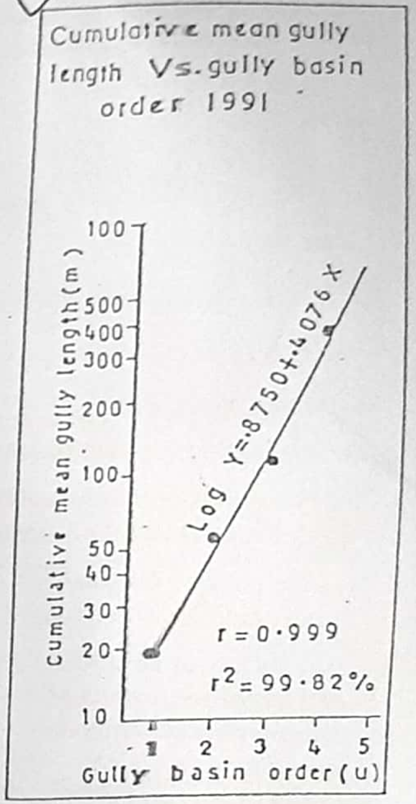

Fig. 3.4 Law of stream length–regression line of positive exponential function model: cumulative mean lengths of gully segments vs. gully basin order.

(b) Length Ratio and Law of Stream Length

The proportion of increase of mean length of stream segments of two successive basin orders is defined as length ratio (R_L) and is calculated according to the following equation

$$R_L = \frac{\bar{L}_\mu}{L_{\mu-1}}$$

when,

$$\bar{L}_\mu = \frac{\Sigma L_\mu}{N_\mu}$$

where,

$\bar{L}_\mu$ is the mean length of all stream segments of a given order (μ).

ΣL_μ is the sum of lengths of all stream segments of a given order.

N_μ is the number of stream segments of a given order.

The following relationships are generally noted between stream lengths and basin orders.

1. Total stream length of given order is inversely related to stream order i.e. total stream length decreases from the lower order to successive higher orders.
2. There is positive relationship between mean stream length and basin order i.e. mean length increases with successive increasing orders.
3. Horton's law of stream length (1945) states '*that the cumulative mean lengths of stream segments of successive higher orders increase in geometrical progression starting with the mean length of the 1st order segments with constant length ratio'* and the following positive exponential function model of stream length has been suggested

$$\bar{L}_\mu = \bar{L}_1 R_L^{(\mu-1)}$$

where,

$\bar{L}_\mu$ is the mean length of the 1st order.

R_L is constant length ratio.

It may be mentioned that this is a theoretical equation which may not be applicable in its totality for the drainage basins of natural system as the constant length ratio is of remote possibility in nature.

The regression line (Fig. 3.4) drawn on the basis of following regression equation of positive exponential function model involving cumulative mean gully lengths and gully basin order of Deoghat gullies (Allahabad district, India), plotted on semi-log graph paper, again almost validates the Horton's law of stream lengths as the coefficient of correlation is 0.999 and percentage of variance explained is 99.82.

$$\log y = \log a + bx$$

where,
y = cumulative mean lengths of gully segments
a = constant
b = regression coefficient
x = gully basin order

(c) Law of Stream Slopes

" The mean slopes of stream segments of successively higher orders in a given basin tend to form a geometric series decreasing according to a constant slope ratio"

The slopes of the streams can be measured from the vertical interval (V.I) and corresponding horizontal equivalent (H.I.) from the contours and length of the stream segments with the help of a rotameter from the contour maps. The relationship of order and slope may, therefore, be expressed as

$$R_S = \frac{S_u}{S_{u-1}}$$

where, S_u is the mean slope of the stream order under consideration. Therefore, the R_S may be worked out successively for the second and the first orders and so on. For any drainage system, the mean R_S may be worked out from $\frac{\Sigma R_S}{N-1}$ where N is the number of the stream orders. When the slope ratio is known, the slope of any stream segment can be worked out, like others as follows.

$$S_u = S_1 R_S^{(u-1)}$$

The slope ratio values generally vary from 0.3 to 0.6 and under no circumstance should exceed the value of 1 because the slope values of higher orders are progressively lower. Strahler is of the opinion that the slope ratio is characterised by a high degree of variability within large drainage basins.

The graphical representation of the stream order and corresponding slope values along X and Y co-ordinates on arithmetical and log-scales respectively show that the points are located along a straight line indicating a negative exponential function.

(d) Sinuosity Indices

The shape of the open link in terms of geometric structure of drainage line involves the calculation of deviation of observed path (O_L) from the expected path- almost a straight line (E_L) of a river from the source to the mouth. In fact, no river, in practice, shows straight path in terms of open link as many causative factors force the drainage line (stream) to deviate from the straight path. These factors may be *geological and hydrological controls, dip angles, slopes, absolute and relative reliefs etc.* Thus, sinuosity of a stream denotes the degree of deviation of its actual path from expected theoretical straight path (course). The analysis of deviation of the course of drainage line from the straight path, say sinuosity, may help considerably in studying the effect of terrain characteristics on the river course and vice versa. Simultaneously, the degree of sinuosity may give a vivid picture of the stage of basin development as well as landform evolution. A few models have been developed for the calculation of sinuosity indices as follows

1. S.A. Schumm's model (1963)

$$\text{Channel sinuosity} = O_L / E_L$$

where, O_L = observed (actual) path of a stream
E_L = expected straight path of a stream

On the basis of above equation Schumm identified 5 categories of channel sinuosity e.g. *straight course when channel sinuosity is 1.0, transitional course, regular course, irregular course and tortous course (when channel sinuosity is more than 20).*(Fig. 3.1B).

2. J. E. Muller's model (1968)

Muller proposed his model of sinuosity index in terms of hydraulic and topographic sinuosity, which requires the measurement of channel length (CL), valley length (VL) and the shortest distance between the source and the mouth of the river, i.e. air length (AL), and calculation of a few indices.

$$\text{Channel Index, } CI = \frac{CL}{AL}$$

$$\text{Valley Index, } VI = \frac{VL}{AL}$$

$$\text{Standard Sinuosity Index, } SSI = \frac{CL}{VL}$$

$$\text{Hydrological Sinuosity Index, } HSI = \text{\% equivalent of } \frac{CI - VI}{CI - 1}$$

$$\text{Topographic Sinuosity Index, } TSI = \text{\% equivalent of } \frac{VI - 1}{CI - 1}$$

The value of unity (1.0) of standard sinuosity index (SSI) is indicative of ***straight river course*** whereas index values between 1.0 and 1.5 put the river in ***sinuous*** shape and the value more than 1.5 represents a ***meandering course.***

The hydrological and topographical sinuosity indices (HSI and TSI) can be used as significant morphometric tools in searching out the causative factors of the sinuosity and also in determining the stage of the basin development. During early stage of basin development, if other factors remain constant, the TSI (more than 60%) dominates over HSI and after the removal of pronounced relief controls in the late mature and old stages, the hydrological sinuosity (more than 60%) scores over topographical sinuosity. Thus, sinuosity indices explain the hydrological and topographical characteristics of drainage basins.

3.2.2 Areal Aspects of the Basin

Basin area is very important morphometric attribute as it is related to the spatial distribution of a number of significant attributes such as *drainage density, stream frequency, drainage texture, slopes, absolute and relative reliefs, dissection index etc.*, that is why H.W. Anderson (1957) has termed it as a 'devil's own variable because almost every watershed characteristic is correlated with area. The drainage basin area is delineated on the basis of water divides and the areas of all stream segments of each order are measured with the help of digital planimeter. All of the ground surface, which directly feeds the 1st order segments, are included in the areas of 1st order basins. The area of 2nd order stream segments includes the area of 1st order segments plus the areas of inter-basins, which are triangular patches of ground surface contributing directly to the 2nd order segments. The same principle works for all the increasing successive order segments. Thus the basin area becomes automatically cumulative from the 1st order to the successive higher orders.

The areal aspects of the drainage basin include the study of basin perimeter, geometry of closed links i.e. basin shape, law of basin area, law of allometric growth, stream frequency, drainage density, drainage texture etc.

3.2.2.1 Geometry of basin shape

The geometry of basin shape is of paramount significance as it helps in the description and comparison of different forms of the drainage basins and it is also related to the functioning of the units of the basins and its genesis. The ideal drainage basin is usually of pear shape but since it is dependent on the size (of the basin) and the length of the master stream of the basin and basin perimeter, which are themselves dependent on other variables such as absolute reliefs, slopes, geological structure and lithological characteristics etc. and hence a wide range of variation in basin shape is bound to happen. Thus, various methods have been suggested to calculate the shapes of the basins. On an average 3 sub-categories of basin shapes have been recognized viz. *(i) circular, (ii) elongated,* and *(iii) indented.* A compact shape may be non-elongated, non-indented, or slightly indented, whereas a non-compact shape may be elongated, non-elongated, non-indented or highly indented. Different popular methods of computation of basin shape are as follows

1. Horton's form factor (F) (1932)

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

where,
F = form factor indicating elongation of the basin shape
A = area of the basin
L = length of the basin

The value of 'F' varies from 0 (highly elongated shape) to the unity i.e. 1 (perfect circular shape). Thus, the higher the value of F, the more circular the shape of the basin and vice-versa.

2. Stoddart's (1965) Elipticity Index (E)

$$E = \frac{\pi L^2}{4A}$$

where,
E = elipticity index
π = 3.14
A = area of the basin
L = length of the basin

The value of 'E' varies from 1 to 0. It is apparent from these two equations that 'E' is inversely proportional to 'F'.

3. V.C. Miller's Circularity Index (C) (1953)

$$\left[C = \frac{\text{area of the basin}}{\text{area of the circle with same perimeter as the basin}}\right]$$

or,

$$C = \frac{4\pi A}{\rho^2}$$

where, ρ = basin perimeter

The value of 'C' varies from 0 (a line) to 1 (a circle). The higher the value of 'C', the more circular shape of the basin and vice versa.

4. S.A. Schumm's (1956) Elongation Ratio (R)

$$\text{Elongation Ratio,} \quad R = \frac{\text{diameter of the circle with same area as basin}}{\text{basin length}}$$

$$R = 2\sqrt{\frac{\frac{A}{\pi}}{L}} = \frac{2}{\sqrt{\pi}}\sqrt{\frac{A}{L^2}} = \frac{2}{\sqrt{\pi}}\sqrt{F}$$

or
$$F = \frac{\pi}{4} R^2$$

Thus, Schumm's 'R' is proportional to the square root of Horton's 'F'. The value of 'R' varies from 0 (highly elongated shape) to unity i.e. 1.0 (circular shape). Thus, the higher the value of R, the more circular shape of the basin and vice versa.

3.2.2.2 Law of Basin perimeter, Basin length and Basin area

Basin area, basin perimeter and channel length are significant morphometric variables which determine the shape, size and genetic aspect of drainage basins. Basin perimeter can be directly correlated with the square roots of basin area and increase or decrease in the former indicates increase or decrease in the latter. The coefficient of correlation between these two variables of 30 small drainage basins (of S.E. Chotanagpur, Bihar, India) standing at 0.99 is very strong positive correlation which is significant at 1 per cent probability level. Similarly, coefficients of correlation between basin perimeters and channel lengths and between square roots of basin areas and channel lengths being 0.89 and 0.98 respectively are again significant at 1 per cent of confidence level. The significant relationships among these variables speak the story of genetic aspect of basin development. The first order segments of the basins notch down the watersheds from which they take their sources through headward erosion. This process helps in the proportionate increase of basin area and the backwearing of watersheds (water divides) favours the increase of stream length and basin area alike. The backwearing of divides simultaneously increases the basin perimeter. This law works in the region of homogeneous lithology and geological structure, climate and plant cover but significant variation in relief characteristics upsets the smooth functioning of basin development and introduces departures from the above law.

(a) Area Ratio (Ra)

Area ratio denotes proportion of increase of mean basin areas between two successive orders and can be calculated by the following equation as suggested by A.N. Strahler (1969)

$$Ra = \frac{\bar{A}_\mu}{\bar{A}_{\mu-1}}$$

where, $\bar{A}_\mu$ is mean area of a given order of the basin

When, $\bar{A}_\mu = \frac{\Sigma A_\mu}{N_\mu}$

where, N_μ = number of all segments of a given order

ΣA_μ = total area of all stream segments of the same order.

Since the area becomes cumulative with increasing orders and hence area ratios decrease with increasing orders within the basin.

(b) Law of Basin Area

It may be stated that the basin area becomes cumulative from 1st order to successive higher orders and the trunk stream (master stream) of the highest order represents the total area of the whole basin. A.N. Strahler (1969) paraphrased Horton's law of stream length into law of basin area and postulated that, '*the mean basin areas of successive higher stream orders tend to form geometric series beginning with mean area of the 1st order basin and increasing according to constant area ratio*' and suggested the following equation of the law of basin area

$$\bar{A}\mu = \bar{A}1 \ R_a^{(\mu-1)}$$

where, $\bar{A}1$ is the mean area of the 1st order and
Ra is the constant area ratio.

The plot (Fig. 3.5) of mean basin areas on a constant ratio scale (logarithmic scale) on the vertical axis against stream order on an arithmetic scale on the horizontal axis involving the following regression equation produces a straight line of regression of positive exponential model.

$$\log y = \log a + b x$$

where,
y is the mean basin area
a is constant
x is basin order
b is regression coefficient

The above law almost holds good in the case of Deoghat gullies (Allahabad district, India) as the correlation coefficient is 0.994 and percentage of variance explained is 98.96 per cent. But the fitted function (Fig. 3.5) shows considerable underestimation in the case of basin areas of 1st, 2nd and 4th order gully segments and an overestimation in the case of 3rd order basin areas. It may be mentioned that whenever the area ratio within different orders of a particular basin becomes more or less stable, the law of basin area comes nearer to truth but when area ratio registers large variation, the law of basin area loses its validity. Thus, the relation of geometric series may not be tenable in crude sense but the linear relationship between these two variables is no doubt validated.

Distinguish 07 both the drainage density and stream frequency. ✓ 13

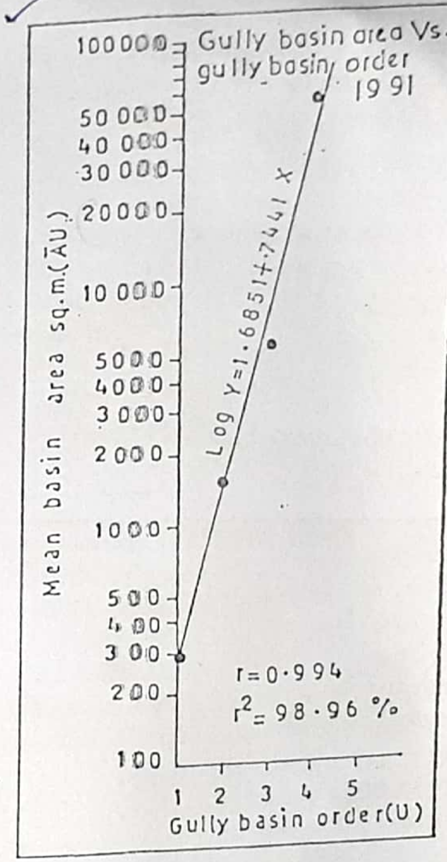

Fig 3.5 Law of basin area- regression line of positive exponential function model

(c) Stream Frequency

Stream frequency or drainage frequency is the measure of number of streams per unit area (may be square meter, square kilometer and so on). For the computation of stream frequency (SF), the basin is conveniently divided into grid squares (more commonly one square mile/kilometer) depending on map scale and aerial coverage of the basin and the number of streams in each grid is counted, tabulated and quantified. The data of stream frequency are classified into certain categories depending upon the nature of data.

spatial pattern of stream frequency is studied through isopleth (Fig. 3.6A) or choropleth maps. The general categories of stream frequency are (i) very poor (SF_{VP}), (ii) poor (SF_{P}.), (iii) moderate (SF_{M}), (iv) high (SF_{H}) and (v) very high (SF_{VH}).

(d) Drainage Density

Drainage density refers to total stream lengths per unit area. R.E. Horton (1945) defined drainage density as a ratio of total length of all stream segments in a given drainage basin to the total area of that basin and thus it can be derived as follows

✓ $$D_d = \frac{L_k}{A_k}$$

where, L_k = total lengths of all stream segments of a basin
A_k = total area of the basin

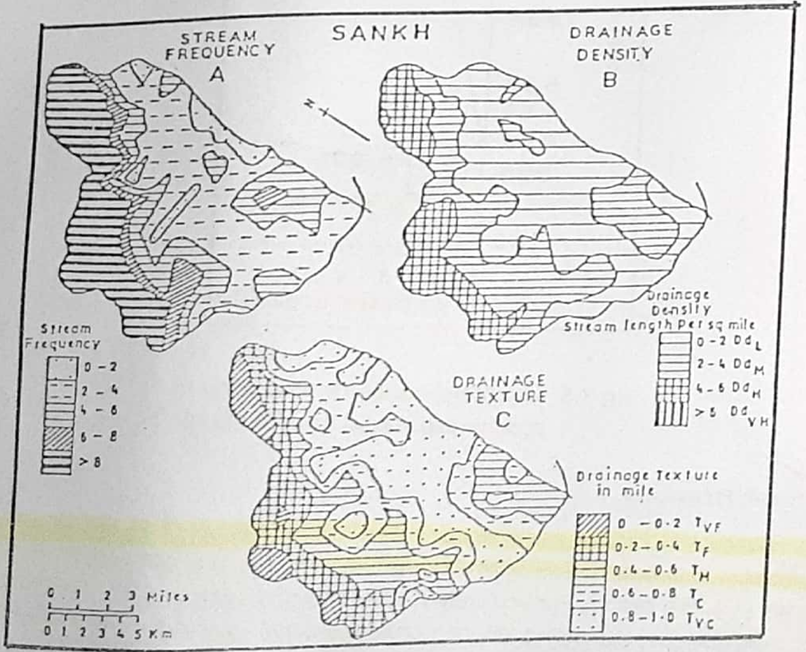

Fig. 3.6 (A) Spatial patterns of strearn frequency, (B) drainage density and (C) drainage texture of Sankh basin, Ranchi plateau, Bihar, India.

Horton's method (as given above) yields only a single value (of drainage density) for the entire basin and hence it cannot be applied for the study of spatial variations of drainage density within a given basin. The simplest way to calculate drainage density on a regional scale is to divide the basin into grid squares of one square mile or one square kilometer each and to measure the total stream lengths in each grid square and to group the derived data into drainage density categories viz. (i) very low (Dd_{VL}), (ii) low (Dd_{L}), (iii) moderate (Dd_{M}), (iv) high (Dd_{H}) and (v) very high (Dd_{VH}) drainage density categories and to prepare isopleths (Fig. 3.6 B) for the study of spatial distributional pattern.

It may be pointed out that the measurement of stream lengths in grid square (with the help of opisometer or threads) is very tedious, difficult and time consuming procedure and hence the tedium of measurement of stream lengths per unit area to calculate drainage density has diverted the attention of interested workers in this field to explore alternative methods of rapid estimation of drainage density.

(e) Drainage Texture

'An important geomorphic concept is drainage texture by which we mean the relative spacing of drainage lines' (G.H. Smith, 1950). Horton (1945) defined drainage texture on the basis of stream frequency (number of streams per unit area). In fact, the term *'drainage texture'* has been used loosely and no successful attempt has been made to search out a quantitative parameter for its calculation. According to Savindra Singh (1976, 1978) the term drainage texture must be used to indicate relative spacing of the streams in a unit area along a linear direction. Thus, he attempted to find out a new parameter in terms of drainage texture (Savindra Singh, 1976, 1978) to replace the derivation of drainage density. According to him, drainage texture refers to relative spacing of streams per unit length in grid squares (one mile × one mile or one kilometer × one kilometer). The derivation of drainage texture is quick and easier method, as it involves only the counting of stream crossings along the four edges of each grid and its two diagonals rather than measuring the lengths as is done in drainage density. The following equation (Savindra Singh, 1981) is suggested to calculate drainage texture:

$$Dt = AS = \frac{1}{(t+p)/2}$$

where, Dt = drainage texture
AS = average spacing between two streams

$$t = \frac{(t_1 + t_2)/2}{\sqrt{2}}$$

when, t_1, t_2 = number of intersections between the stream network and grid square diagonals

and
$$p = \frac{P_1 + P_2 + P_3 + P_4}{4}$$

where P_1 to P_4 = number of intersections between the stream network and grid square edges.

The data of drainage texture, so derived (on the basis of above equation) are classified into five Dt categories e.g. *(i) very coarse drainage texture, Dt_{VC} (above 0.8), (ii) coarse drainage texture, Dt_C (0.80-0.6), (iii) moderate drainage texture, Dt_M (0.6 - 0.4), (iv) fine drainage texture, Dt_F (0.4 - 0.2), and (v) very fine drainage texture, Dt_{VF} (0.2 - 0.001),* values indicate stream spacing in mile or kilometer in grid squares. Isopleths (Fig. 3.6 C) are prepared on the basis of computed data of drainage texture of a given basin for the study of its (drainage texture) spatial patterns.

CHAPTER - 4

RIVER VALLEYS, GRADED CURVE AND PROFILE OF EQUILIBRIUM

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4.1 RIVER VALLEY

A river valley is an elongated depression between hill or mountain ranges occupied and developed by a river. There is a definite relationship between the size of the rivers and the valley size. Large rivers create large valleys and small rivers produce small valleys. The shape and size of the valley are determined by the lithology, geological structure, climatic conditions and the geomorphic history of the region.

4.1.1 River Valley Development

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A part of the total rainfall water received at a place is absorbed in the land and another part is evaporated in the air. Rest of the water flows on the surface as *Runoff.* If the surface is like an inclined roof, the water will flow in the form of sheets. There are very few such land surfaces. *Rills* are formed even if there are small irregularities on the land surface. These rills develop into bigger rills which turn into streams and big rivers. Small furrows formed initially change into gorges which turn into river valleys.

River valley development takes place in three ways:

1. Valley lengthening
2. Valley deepening
3. Valley widening

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4.1.1.1 Valley lengthening

Valley lengthening depends upon the followings:

(a) *Head Erosion:* A stream begins to cutback. This increases the area of the stream where it diverts towards itself the water of springs, rills, etc. This activity is called *head erosion.* This head erosion work continues till a hard rock intervences. Sometimes the decrease of slope also stops head erosion. The tributaries of rivers on the opposite slope may reduce the work of head erosion of the river of this side of a divide. Head erosion increases the length of a stream.

(b) ***River meandering:*** It increases the length of a river. A stream creates many meanders in its course by erosion or deposition of sediment at various places. This makes the river flow in a zig-zag course. This is known as river meandering. It also increases the length of the stream.

(c) ***Mouth expansion:*** A stream deposits sediment at its mouth where it meets the sea. It makes the mouth extend towards the sea. The river Nile in Egypt has extended its mouth hundreds of km away to the sea.

4.1.1.2 Valley deepening

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The deepening of valley depends upon the following:

(a) ***Steep slope:*** Due to steeper slope, the flow of a river increases resulting in the deepening of its channel.

(b) ***Hard Rocks and Dry Climate:*** If the rocks around its course are hard and the climate is dry, the deepening of valley takes place slowly. More deepening takes place when the rocks are soft and the climate is more humid.

(c) ***Rise of River Course:*** If endogenetic forces raise the course of stream slowly, the river valley deepens. For example the Brahmaputra to the south of Namcha Barwa is thousands of metres deep.

(d) ***Rolling of Rock Fragments:*** Valley is also deepened on account of the rolling of rock fragments on its floor.

(e) ***Mechanical Friction:*** Water in the river with its fast flow deepens the valley by mechanical friction.

(f) ***Solution action:*** Valley is deepened by solution action.

(g) ***Pot holes:*** Pot holes also deepen the valley.

(h) ***Weathering:*** Weathering at the floor of the valley also deepens its channel.

4.1.1.3 Valley widening

Valley widening accompanies valley deepening. The widening of valley depends upon the following:

(a) ***Slumping:*** Water enters holes and cracks of the rocks near the sides of the rivers. This water lowers parts of the rocks close by. The weight of rocks increases by the entry of water into rocks. Due to the percolation of water into

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rocks, the pressure exerted by water increases and weakens the rocks. When the lower parts of rocks are eroded deeply, the upper parts collapse under their own weight and due to the *narrowing* of their lower part. This is known as slumping. Slumping broadens the valley at sides.

[illegible]

(b) ***Gulley Formation:*** The rain sweeps down the rock flour lying on the sides of the stream into the running water. This forms many ***gulleys*** on the banks, steepens the slopes and widens the valley.

(c) ***Vegetation and Animals:*** Vegetation and animals also widen the valley. The roots of plants loosen the soil of the banks. When the trees are uprooted, they loosen and displace soil and rock fragments. The goats uproot the grass while grazing near the banks. The hoofs of grazing animals also loosen the soil. The loosened soil reaches the river and in the end widens the valley.

(d) ***Glaciers:*** Glaciers while flowing down the valley erode the walls and carry the sediment along. This widens the valley.

(e) ***Meandering:*** A stream has rarely a straight course. It moves in a zig-zag course. It cuts one bank more than the other at each bend. After some time, the bends are broken down. The valleys widen themselves by meandering.

4.2 GRADED CURVE OF A RIVER AND PROFILE OF EQUILIBRIUM

4.2.1 Longitudinal Profile and Graded Curve

The longitudinal course of a river from its source to mouth is called longitudinal or simply long profile or valley thalweg. In fact, long profile of a river represents channel gradient of the river from its source to the mouth. Each river tries to develop such a longitudinal course (profile) that it may be able to transport the bed load downstream. The longitudinal channel course is generally smooth curve which rises upstream. A river is supposed to ultimately remove topographic irregularities by penultimate stage (monadnock stage) and to develop smooth curve from source to mouth. The maximum limit of vertical erosion (valley deepening) is determined by grand base level which represents sea level. Thus, rivers always try to erode their valleys down to base level of erosion near sea coast and the valley floor becomes concave in such a way that it rises upstream or headward. Thus, the rivers always try to develop smooth concave curve of their channels. The concavity of long profile of a river results from the fact that there is minimum erosion in the upper and lower courses of the river while there is maximum erosion in the middle segment. Lack of required amount of erosion tools (load) and water in the source segment and gentle gradient and very low flow velocity in the lower segment of a river are responsible for minimum erosion whereas sufficient load, channel gradient and flow velocity in the middle course of a river cause maximum erosion of valley floor. This is why a river develops a smooth concave curve of longitudinal course. When a river develops such a course that channel gradient is such that resultant flow velocity is able to transport entire load, the resultant longitudinal curve of valley thalweg is called graded curve and the river after attaining graded curve is called graded river and the long profile of the river becomes profile of equilibrium as there is balance between transporting capacity of the river and total load to be transported i.e. balance between available energy and work to be done (Fig. 4.1).

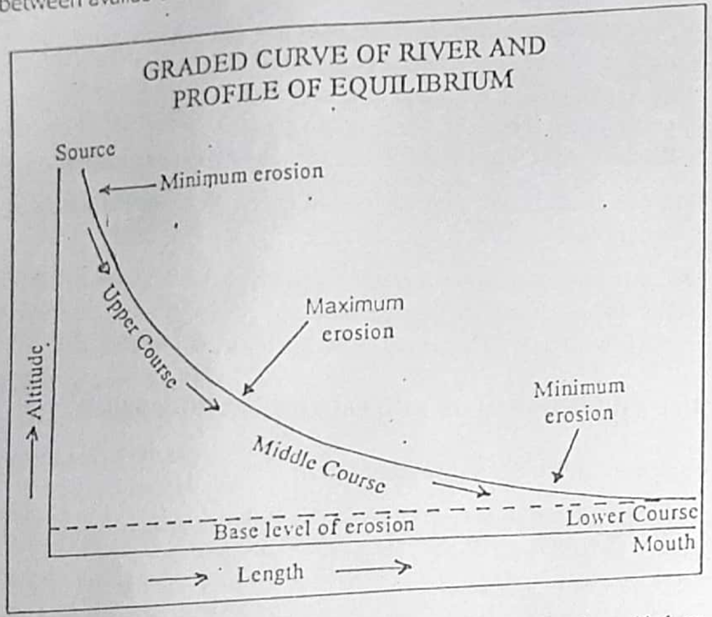


Fig. 4.1 Long profile of a river: graded curve and profile of equilibrium

4.2.2 Concept of Grade

The usage of the term ***'grade'*** in fluvial system does not simply means gradient or slope but means continuous curve of descent of a stream floor downstream which has such a gradient (slope) throughout longitudinal course of the stream that it can transport all the loads downstream. The river having attained such condition is called ***graded river*** and its curve as a graded curve. It is generally believed that G.G. Gilbert was first to use the word

'grade' in 1876 followed by W.J. McGee in 1891. W.M. Davis in 1894, H. Gannett in 1896 and W.D. Johnson in 1901, but Davis seems mainly, and perhaps wholly, responsible for that deductive elaboration of the concept which has promoted as voluminous and so recurrent a discussion.

According to Davis 'it is evidently desirable to employ the term 'grade' for the balanced condition of a mature or old river ... the balance between erosion and deposition ... is brought about by the changes in the capacity of a river to do work, and in the quantity of work that a river has to do. The changes continue until the two quantities... reach equality, and then the river may be said to be graded.

G.H. Dury (1966) has summarized the concept of grade as conceived by W. M. Davis as follows:

1. Grade is the balanced condition of a mature or old river: (the balance is that between capacity to do work, and quantity of work to be done. It is expressed by an equivalence of erosion and deposition.
2. The slope of the graded river is the slope (profile) of equilibrium: this slope permits the most effective transport of load.
3. Once the graded condition is attained, slope can be altered only by changes in the volume/load relationship: such change, operating slowly, is expectable in the normal cycle.
4. Load increases in quantity and coarseness during youth, in quantity but probably not in coarseness during maturity, and after full maturity decreases both in quantity and in coarseness.
5. Grade is first established in downstream reaches, where valley deepening reduces downstream gradient, until eventually the excess capacity of the river to do work is wholly offset.

According to, J.E. Kesseli (1941) '*a graded stream be taken as one without waterfalls or rapids. That is to say, he defines grade in terms of transporting power, load, velocity, or tendency to cut or fill*'.

According to J. H. Mackin (1948) '*a graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of load supplied from the drainage basin. The graded stream is a stream in equilibrium, its diagnostic characteristic is that any change in any of the controlling factors will cause a displacement of the equilibrium in a direction that will tend to absorb the effects of the change.*' According to him transporting power of the stream depends on velocity which depends on slope. It is inferred from Mackin's writing, that his *graded stream neither cuts (erodes) nor fills (deposits).*

4.2.3 Controlling Factors of the Graded River

Several factors like channel gradient, volume of water, discharge, flow velocity, quantity and nature of sediments (load), base level of erosion, lithology etc. are considered significant variables which are responsible for the grading of a river and attainment of graded curve and profile of equilibrium.

L.B. Leopold and T. Maddock (1953) have classified variables which control hydraulic geometry of a stream into 3 broad categories viz. **(1) independent variables, (2) semi-dependent variables, and (3) dependent variables.** ***Independent variables*** include *stream discharge, sediment load and ultimate base level of erosion.* It is argued that stream has little control over these factors; rather it must adjust to them. ***Semi dependent variables*** comprise *channel width, channel depth, bed roughness, grain size of the sediment load, velocity and channel behaviour* i.e. tendency of a river for meandering or braiding its course. These are semi-dependent in as much as they are partly determined by three independent variables, but they are also capable of mutual self-regulation in a river. The shape of the cross section (width/depth ratio) determines the distribution of velocity and of shear; for a given width and discharge, total load depends on the ratio of velocity to depth; and velocity/depth ratio is provided in part by adjustment of bed roughness, which is itself a function of grain-size and of suspended-sediment concentration. Changes in be roughness, which itself is determined by grain-size, introduce changes in velocity/depth ratio. According to Leopold and Maddock, *differences in the concavity of longitudinal profile of a stream are directly related to differences in the relationship of velocity and depth to discharge.* Meandering of the streams depends on nature and velocity of moving water of the channel, size and shape of channel, erodibility of riparian tracts, bedload and suspended load, discharge etc. On the other hand, meandering influences (increases) channel length, which in turn decreases channel slope (gradient), which determines velocity (low channel gradient → low velocity; steep channel gradient → high velocity) and velocity in turn determines transporting capacity of the stream (high velocity → high transporting capacity; low velocity → low transporting capacity). Thus, meandering property of a river is both dependent and independent variable. ***Dependent variable*** includes a single variable viz. downstream slope of the water surface.

4.2.4 Grading of River Channel and Profile of Equilibrium

It is evident from the above discussion that grading of a river denotes perfect balance between transporting capacity of the river and total load to be transported by it. In other words, at each and every point of the longitudinal course of the river transporting capacity is such that total sediment load can be transported downstream or velocity of the river is such that erosional and depositional works are balanced. The river having attained such condition throughout its course is called ***graded river.*** It may be mentioned that the graded condition is not suddenly attained rather it is attained slowly and gradually. It may be further pointed out that it is not only the slope (channel gradient) factor which is most important for grading of a river but a critical adjustment among volume of water, discharge, velocity, slope and sediment load is also prerequisite condition.

Let us take the case of variation in sediment load and related adjustment of river channel. If the supply of sediment load decreases in any part of the river, more energy becomes available for valley incision because the river is under-loaded. Thus, resultant valley incision causes decrease in channel gradient. This condition continues till the eroded materials are transported downstream. Such condition, when erosion exceeds deposition, is called ***stage of degradation*** wherein channel gradient becomes less than general slope denoting inequilibrium condition. Contrary to this, if sediment load increases and exceeds the transporting capacity of the river, there occurs deposition of extra sediments, which the river is unable to transport downstream.

This condition is called ***stage of aggradation*** (when deposition exceeds erosion) wherein slope increases and this condition continues (i.e. slope continues to increase) till the slope becomes such that resultant velocity provides required transporting capacity so that all tile sediment load is transported downstream. Thus, if balance (adjustment) between transporting capacity of the river (available energy) and total load to be transported downstream (work to be done) is attained, the river is said to be graded.

Alternatively, if sediment load and channel gradient remain constant, any increase in the volume of water will increase discharge and velocity which will increase transporting capacity and hence the rate of erosion will be accelerated leading to the ***stage of degradation*** and consequent inequilibrium condition. Conversely, if volume of water decreases, the discharge and velocity will also decrease which would result in decreased transporting capacity of the river and resultant deposition of sediments leading to the development of the stage of aggradation and inequilibrium condition.

If sediment load and volume of water remain constant, increase in channel gradient will lead to increase in flow velocity and erosion and hence there would be the ***stage of*** *degradation*. On the other hand, decrease in channel gradient would result in decrease in velocity and deposition of sediment load leading to the development of the ***stage of aggradation***.

Thus, it may be concluded that the course of a river is said to be ***graded course*** or ***graded curve*** when there is balance between velocity (and hence transporting capacity) and sediment load to be transported downstream. The longitudinal profile of such a graded river is called graded profile and profile of equilibrium indicating a condition of balance between erosion and deposition throughout longitudinal course of river i.e. from its source to mouth.

It is necessary to point out some misconceptions about graded curve, graded river and profile of equilibrium.

1. Grade is a condition, not an altitude or a certain slope angle. A graded river is in a steady state only with regard to short-term changes. Over a time scale of millions of years, typical of time intervals in which landscapes evolve, the potential energy of an undisturbed river system gradually approaches zero, and the rate of change of the system also decreases. The river remains at grade, but the characteristics of the graded condition change with time.
2. Graded river does not mean steep or low gradient. A river may be graded at higher gradient while the other river may be graded at lower gradient.
3. A graded river, in fact, is seldom loaded to the capacity. Thus, a graded river, in reality, is not such river which neither cuts (erodes) nor fills (deposits). A graded river does not mean that there is balance between erosion and deposition in each and every part of the longitudinal course of a river because there is every likelihood that erosion may be dominant in one segment of the river while deposition may be most active in the other part of the same river.
4. It has been repeatedly discussed above that in order to attain graded stage of a river there must be adjustment (balance) between transporting capacity and sediment load to be transported. But question arises, adjustment between what? Whether in power (energy) or quantity? Generally, it is believed that there should be adjustment between transporting power of a river and sediment load to be carried by the river downstream. It is inferred from this corollary that if there is decrease in sediment load, that part of river energy which was previously expended in transporting the load, is now spared and is expended in erosional work resulting in increased rate of erosion. It may be conceived on this basis that if there is total absence of sediment load in a particular river, it would have maximum corrasive power (capacity) but this inference is erroneous because it is not only the flow velocity and sediment load of a river which alone control erosion and deposition. Thus, the energy spared from transportation of sediment load may not be a factor of erosion because erosion becomes negligible in the absence of load. Not only the total mass of the load but the size or calibre of load are responsible for corrasive capacity (power) of the stream. In spite of steep channel gradient and hence high velocity and less quantity of sediment load there is minimum erosion in the upper segment (course) of a river. Similarly, high load but gentle channel gradient and hence low velocity cause minimum erosion in the lower reach (segment or course) of a river. Contrary to these two conditions, there is maximum erosion in the middle reach of the river because of availability of required sediment load, flow velocity and channel gradient. This is why the erosion level (valley floor) of the river from its source to mouth is not straight but is smooth curve (Fig. 4.1)

5. The gradual decrease of slope of graded curve of a river downstream may be theoretically sound but in practice it seldom occurs as some parts of the river may be graded while other parts may be ungraded.
6. Grading of the river begins near the mouths of the rivers and proceeds upstrearn. The overall grading of the river is controlled by grand base level of erosion which is determined by sea-level. Besides, there are some local and temporary base levels which represent lakes, confluences of tributary streams, resistant rock beds etc. The maximum vertical erosion (valley incision) near the mouths of the rivers is determined by grand base level i.e. sea level. General grading of the river from its mouth to source is attained in stages having a time span of millions of years. When sea-level becomes permanent base level for the entire span of a river and all the local and temporary base levels are eliminated from a river course, then the river attains its general grading.
7. Generally, graded curve of a river is considered regular from source to mouth but a few geomorphologists do not subscribe to this view point. For example, J.H. Mackin is of the view that there is variation in slope gradient of a graded river. The longitudinal course of a river does not consist of single regular graded curve but consists of several segments but each segment has such slope that the resultant velocity is able to transport all sediment load downstream. Thus, according to Mackin a graded profile is, in fact, transportation slope. Such profile is neither influenced by corrasive power nor by the resistance of bedrock. A graded curve can never be a mathematical curve.

8. A graded stream does not mean, as understood by some geomorphologists, that it has attained its lowest gradient or minimum slope over which it flows. It is also believed by many that after the attainment of profile of equilibrium, vertical erosion or valley incision by the stream stops and the profile of equilibrium denotes limit of vertical erosion but such connotations are erroneous. The slope of graded river changes with time because there is variation in the quantity and calibre of sediment load, volume of water, discharge etc. but it is also true that the changes are so gradual and slow that a river, once graded, remains graded except some temporary disturbances.

4.3 DISTURBED AND REGRADED CURVE

As already stated above a graded curve and profile of equilibrium is the result of adjustment between volume of water, transporting capacity (velocity) and sediment load. In fact, the graded profile of a river is in a delicate balance. A slight change in any of the independent, semidependent and dependent variables (as elaborated earlier) which control and determine the grading of a river may disturb the equilibrium condition of the river and the river again tries to regrade its course according to new conditions. Decrease or increase in sediment load influences deposition and erosion. A river deposits sediments when there is increase in sediment load and decrease in the volume of water. Conversely, a river starts eroding its valley when there is decrease in sediment load or increase in the volume of water. Thus, a river always tries to develop profile of equilibrium by making adjustment (balance) between erosion and deposition. This balance is so delicate that a slight change in any part of a river or river system causes disturbance and the graded curve (balance or equilibrium) is disturbed with the result the river has to readjust with new conditions. If a river succeeds in attaining rebalance the curve of such a river is called *regraded curve* and its profile is called *regraded profile* of equilibrium.

The disturbance in the graded profile of a river may be caused due to a variety of factors but increase or decrease in channel gradient is the most significant causative factor. Changes in channel gradient are generally effected by *rejuvenation* and *deposition* of sediments.

4.3.1 Effects of Rejuvenation

Rejuvenation simply means sudden and phenomenal increase in the erosive power of the streams and consequent accelerated rate of downcutting (valley incision) caused by steepening of channel gradient either due to negative change (fall) in sea level or upliftment of land mass in a river course. Rejuvenation may be effected either at the mouth of the river or in the middle course or in the headwaters of the river.

4.3.1.1 Rejuvenation at the mouth of a river

Rejuvenation at the mouth of a river occurs when there is fall (negative change) in sea level after the river has developed graded curve and profile of equilibrium (Fig. 4.2, AB curve). Consequently, the graded profile of the river is disturbed because channel gradient is steepened at the mouth of the river due to lowering of sea level which results in the acceleration of flow velocity. Thus, the erosive power of the river increases and hence the river starts fresh vigorous valley deepening at its mouth according to new base level of erosion determined by new sea level (B'). Now the river tries to develop its new curve according to new sea level (B') which is lower in height than the old sea level (B). The rejuvenated river starts regrading its course from its mouth and the mechanism of regrading proceeds upstream. Wherever the new curve intersects the old curve, break in long profile is formed. Such breaks are called ***nick points*** (Fig. 4.2) or ***head of rejuvenation***. These nicks recede upstream as the mechanism of regrading of the river course proceeds upstreams. Ultimately, all such nick points (water falls) are eliminated and the entire span of longitudinal profile of the river is regraded and profile of equilibrium is reestablished.

It may be mentioned that regraded profile is at lower gradient than the old graded profile (Figs. 4.2 and 4.3).

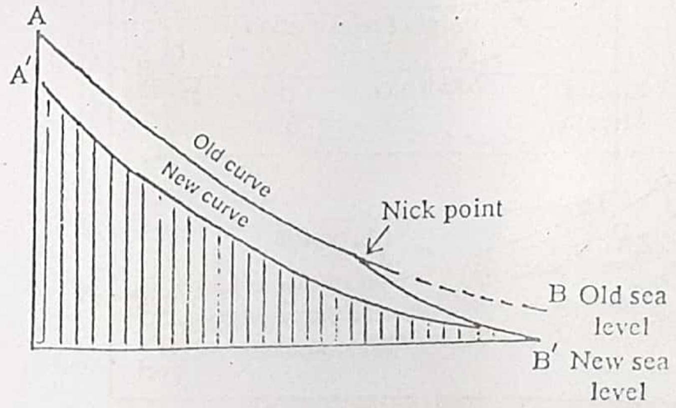


Fig. 4.2 Regrading of disturbed graded curve due to rejuvenation at the mouth of river caused by fall in sea level

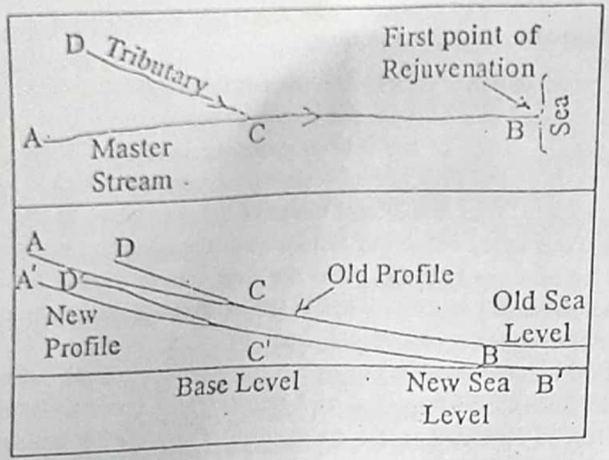


Fig. 4.3 Regraded profile at low gradient after rejuvenation at the mouth of the river due to fall in sea level

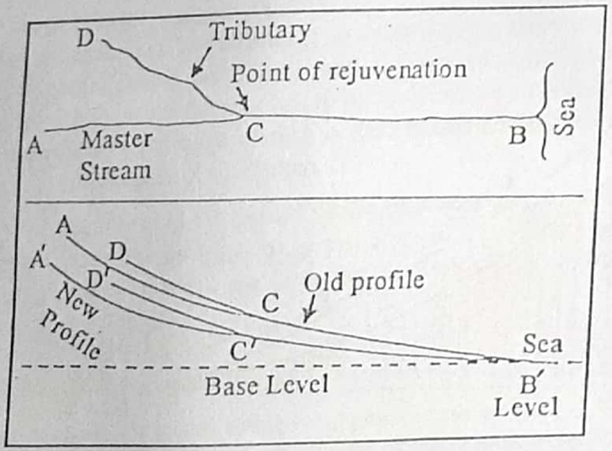


Fig. 4.4 Disturabance in the graded profile because of rejuvenation in the middle course (at point C) and regarading ofthe river (A' B' and C' D').

4.3.1.2 Rejuvenation in the middle course of a river

The rejuvenation in the middle course of a graded river down the confluence of a tributary occurs when the supply of sediment load by the concerned tributary (D, Fig. 4.5) to the receiving master stream decreases significantly and thus the master stream down the confluence becomes underloaded and available extra energy, which was previously spent in transporting the sediment load, is spared and is now expended in erosional work, with the result erosive power of the stream is increased, which causes rejuvenation and thus the previously graded profile gets disturbed. The master river now degrades and deepens its valley downstream from the confluence, with the result the gradient of upstream section is steepened, which causes headward erosion. Headward erosion continues until the gradient of upstream section of the river is adjusted to the previous gradient and the entire span of the long profile is regraded. It is apparent From Fig. 4.4 that the river is regraded at lower gradient and height. The channel gradient of A' B' (new graded curve) is lower than the channel gradient of AB (old graded curve).

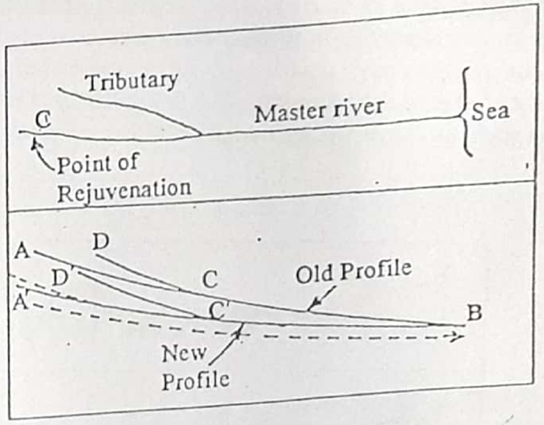


Fig. 4.5 Disturbance in the graded profile of the river due to rejuvenation in its headwater section and attainment of regraded profile (A'C'B)

4.3.1.3 Rejuvenation in the headwaters of the river

Significant decrease in the supply of sediment load in the uppermost section, say headwaters, of the stream results in increased erosion as the stream becomes underloaded and hence the headwater section is rejuvenated (Fig. 4.5). Since the supply of sediments has decreased in the headwaters of the river, this condition (decrease in sediment load) prevails throughout the entire span of longitudinal course of the river. Consequently, the entire span of the river valley is deepened so that sediment load produced by increased erosion equals the transporting capacity of the river. Whenever the river becomes able to attain this condition, the disturbed graded curve is regraded and the river reattains its profile of equilibrium. It may be pointed out that under such situation the river is regraded at the same gradient of old profile (Fig. 4.5 ACB) but at lower height (A'C'B').

4.3.2 Effects of Deposition

Deposition of extra sediments results in increase of the level of valley floor and hence there is decrease in channel gradient, with the result the graded curve of the river gets disturbed. Sedimentation at the mouth of the river which drains into the sea, results in the formation of delta provided that other conditions are favourable (i.e. sea wave, are not very active). Gradually delta grows seaward and thus the length of longitudinal course of the river also increases. Lengthening of river course lessens channel gradient, which results in marked decrease in velocity and transporting capacity of the river, with the result the river has to deposit sediments in all parts of its course in order to regrade its course at higher elevation. As the delta grows in size, deposition by the river also increases in all parts of its course. AD curve (Fig. 4.6) denotes previously graded (old) curve. The length of the river A-D has extended upto E (ADE) due to delta formation. Due to availability of required sedimentation the river has regraded its curve (A'C'E) though at higher elevation but with the same channel gradient.

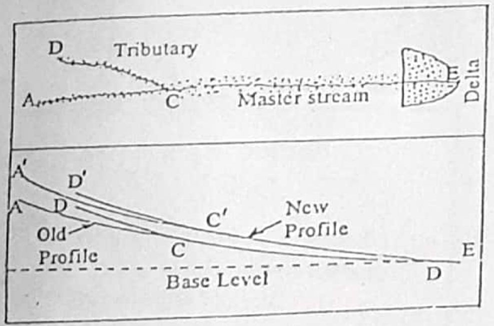


Fig. 4.6 Disturbance in the graded profile due to delta formation and attainment of regraded profile (A'C'DE) al higher elevation

If volume of water, sediment load, and slope remain constant, the graded condition of a river becomes more or less permanent but if any juvenile tributary stream meets the master stream and brings sufficient sediment load, the master stream becomes unable to transport additional sediment load downstream, with the result additional sediments are deposited down the confluence resulting in the increase in channel gradient and consequent disturbance in the graded curve of the river. Sedimentation in the downstream section from the confluence with the juvenile tributary stream results in decrease in channel gradient in upstream section. Consequently, sedimentation in the upstream section from the confluence continues until the entire span of the longitudinal course attains such slope which allows transportation of all sediment load. Thus, the river is regraded but at higher elevation.

It is, thus, apparent that graded curve of the river is disturbed by a host of causative factors but the river tries to remove such obstacles which disturb its graded profile and ultimately regrades its profile. The regraded curve may be at higher elevation or lower elevation, depending on local conditions.

CHAPTER - 5

CHANNEL MORPHOLOGY

Channel morphology or river channel morphology includes the consideration of (1) channel geometry or channel cross-sectional characteristics (e.g. channel length, channel width, channel depth, wetted perimeter, channel slope, channel bends (meanders) etc., (2) channel fluid dynamics (e.g discharge, velocity etc.) (3) hydraulic geometry, (4) channel types, (5) channel bed topography or channel bed configuration, (6) channel patterns etc.

5.1 CHANNEL GEOMETRY OR FORM

Channel geometry representing the size and shape of cros-sectional and longitudinal channel form includes *channel width, channel depth, wetted perimeter, channel slope, channel bends, shape of channel, thalwegs and their interrelationships.* A ***river channel*** represents water course of a river confined within the limits of valley walls on both the sides (Fig. 5.1 A).

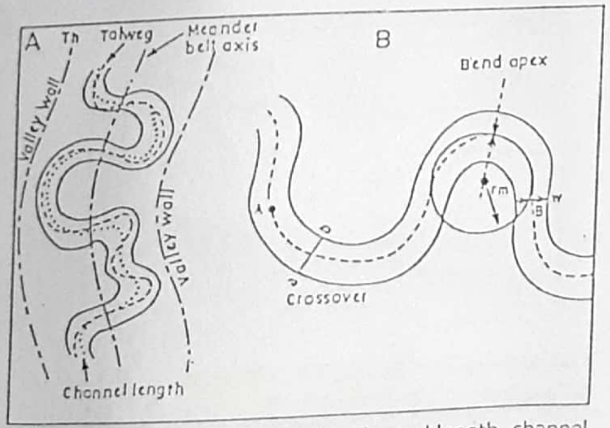


Fig. 5.1 Channel form- valley walls, channel length, channel thalweg, meander belt axis, crossover, curvature of radius (rm) and channel width (W)

Rivers in humid regions are called ***effluent streams*** because they receive contributions of groundwater. Rivers in arid regions generally lose water to the ground in addition to losing it by evaporation, and often they dry up entirely without reaching the sea. These are called ***influent streams.*** Thus, based on this criterion river channels are divided into ***effluent*** and ***influent channels.***

Channel width (W) at any given point along the course of a river represents straight cross-sectional distance of channel representing stage of the river (i.e. level of water). It is, thus, apparent that channel width varies with changes in volume of water and discharge. The ***bankfull stage*** of the river denotes maximum channel width. Thus, channel width considerably changes in the rivers having seasonal regime of rainfall (e.g. rivers in the regions of Monsoon and Mediterranean type of climate). It may be mentioned that the cross-sectional configuration of the valley also determines channel width. It is customary to think that if the cross-sectional shape of the channel is irregular, channel width increases with increasing discharge and volume of water (Fig. 5.2 C) but if the channel shape is rectangular, no appreciable change in channel width occurs in spite of gradual increase in discharge and volume of water (Fig. 5.2 B). The maximum channel width is associated with bankfull stage of discharge (Fig. 5.2 A). The depth of channel denotes vertical distance from the water level in the channel to the channel bed. ***Maximum channel depth*** is measured from the level of water of bankfull stage of the river to the lowest point of the channel bed (Fig. 5.2 A) while ***mean channel depth*** (d) denotes average of channel depths taken at different stages of the channel (i.e. gauge levels). The coarser materials lying on the river bed are called ***bed load*** (Fig. 5.2 A). ***Wetted perimeter*** (p) denotes cross-sectional distance of the wetted portion of the valley (Fig. 5.2 A).

The shape of the channel of a river from source to mouth is considered as longitudinal profile or simply long profile which is generally a concave upward profile in the case of perennial rivers. The gradient or slope of channel in downstream direction is called *channel gradient.* Different long-profiles are related to long-term geological development-influenced by tectonic history, base-level change, and climatic change. The degree of concavity increases with relief but excessively concave profiles are associated with rivers which have extended over Quaternary estuarine sediments as sea-level retreated or by flow diversion. Under-concavity relates to lithological controls on runoff and sediment supply. Concavity tends to be more accentuated if the downstream increase of discharge is rapid, and to approach linearity where discharge increases slowly, such as within permeable catchments.

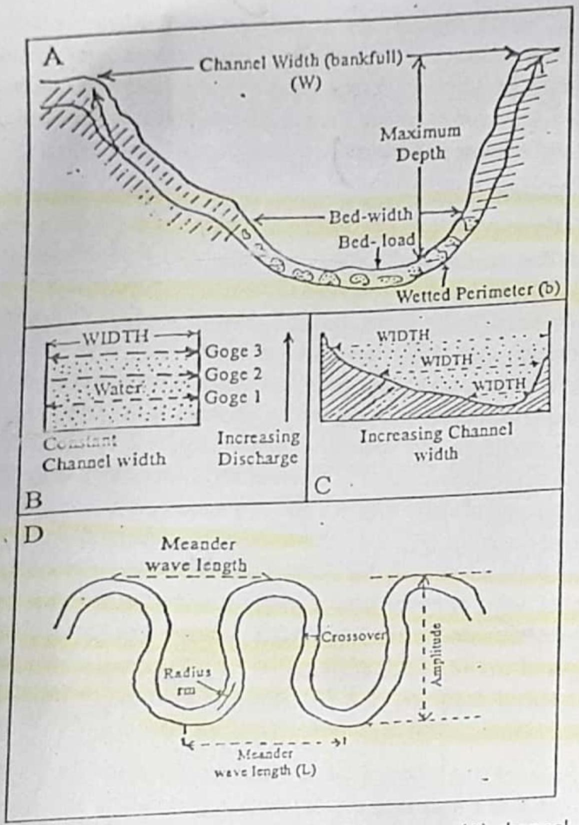


Fig. 5.2 Definition of different channel shapes- (A) channel width, channel depth, wetted perimeter, (B) (C) relationship between discharge and channel width (D) meander properties.

The shape of the longitudinal segments of a river channel is considered in terms of sinuosity which refers to departure of actual channel course from the expected theoretical straight line. Thus, the longitudinal shape of the channel ranges from straight (rarely possible) through sinuous to meandering shapes. A meandering shape is described by its different characteristic features viz. *meander wavelength, meander height, meander amplitude, convex and concave banks, radius of curvature* etc. (Fig. 5.2 D). Interrelationships are being described in the following section.

5.1.1 Hydraulic Geometry

The analysis of the *relationships among stream discharge, velocity, channel shape, sediment load, channel width, channel depth, channel slope etc. is called **hydraulic** geometry of a river channel*. The cross-sectional area of the channel is measured by multiplying channel width by channel depth while stream discharge is measured by multiplying cross-sectional area at the gauging station by average velocity of water current.

$$\text{Discharge, } Q = w \times d \times v$$

where,
w = channel width
d = average channel depth
v = average velocity

Channel morphology is the result of mutual interactions of four broad categories of variables viz. (1) **fluid dynamics** (which include velocity, discharge, roughness and shear stress); (2) **channel character** or **channel configuration** (e.g. channel width, channel depth, channel slope, channel shape, channel pattern etc.); (3) **sediment load** (amount and calibre); and (4) **bed and bank materials** (composition and character i.e. coarse, fine, medium etc.). The overall geometry of a river channel is controlled by the independent variables of discharge and load, i.e. the climate and geology of a watershed. It may be mentioned that the variables, as referred to above, which determine channel morphology by their mutual interactions, are also subjected to change by mutual adjustment. M. Moriswa has observed that, Adjustment mechanisms include erosion or deposition in the channel to change its form, slope or pattern and creation and movement of bed forms. Scour (erosion) of the bed will result in a lower gradient, increased depth of channel and decreased water velocity. Scour (erosion) on the banks will increase the channel width and decrease velocity and depth with given discharge. On the other hand, if the channel becomes sluggish and deposits sediments, the channel bed rises and hence channel depth decreases but channel gradient increases which results in increased velocity downstream.

L. B. Leopold and T. Maddock (1953) described hydraulic geometry i.e. variations in channel forms as power function of discharge as follows

$$w = a\,Q^b$$

$$d = c\,Q^f$$

$$v = k\,Q^m$$

where,
w = channel width
d = channel depth
v = channel velocity (mean)
a, c, k = constants
b, f, m = exponents
$a \times c \times k = 1.0$
$b + f + m = 1.0$

Channel Bed Topography

The bed topography of a river channel refers to configuration of the river beds in terms of positive and negative features e.g. presence or absence of riffles and pools, sand bars and sand islands, shoals, sand dunes etc. Such depositional and erosional (pools) features developed on channel beds are the result of interactions of channel flow and transport of sediment load both as suspended sediment load and bed-material load. A *pool* is characterised by a water surface profile less than the mean stream (channel) 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. It may be pointed out that if the volume and discharge of water increase resulting in high gauge level, the slope of water surface over riffles and pools is neutralised. According to Petts and Foster (1985) 'a riffle is a topographic high area produced by the lobate accumulation of relatively coarse sediment, and a pool is a topographic low, usually characterised by finer material'. Spatially, riffles are wider and shallow while pools are narrow but relatively deep.

5.1.2 Channel Types

2005 On the basis of lithological characteristics of the region through which the river has developed its course, the river channels are divided into two broad categories viz. (1) bedrock channels, and (2) alluvial channels.

5.1.2.1 Bedrock channels

*** 08 *Bedrock channels* are also called *erosional channels* and simply rock channels as they have been developed on well consolidated rocks, popularly called as *bedrocks*. They occur wherever potential rates of removal exceed sediment supply (i.e. erosive power or erosion rates are very high, streams are underloaded as sediment supply through erosion of banks and beds falls short of transporting capacity of the streams); in high mountain areas with steep slopes, glaciated hardrock regions, and in areas undergoing active tectonic uplift. There is a wide range of variation in the size of bedrock rivers as they may be as long as

several hundred kilometers in length and as small as a few hundred meters. There are many such long rivers of the world which are partly bedrock channels and partly alluvial channels. For example, the upper reaches of the Indus, the Sutlej, the Ganges, the Yamuna, the Gandak, the Kali, the Tista, the Brahmaputra etc. located in the Himalayas are bedrock streams whereas their middle and lower reaches are alluvial channels. The Colarado river (USA) presents a very fine example of bedrock channels, which has cut a 1380 m deep and 12 km wide valley representing the best example of a canyon known as *Grand Canyon* between Kaibab and Coconino plateaus in Arizona state (USA). उदाहरण

The channel morphology of bedrock channels is largely determined by structural and lithological controls. The erosional work of the bedrock channels is performed by the mechanism of corrosion (dissolution of soluble materials), corrasion and hydraulic action. *Corrosion* or *solution* involves the dissolution of soluble materials through the mechanism of disintegration and decomposition of carbonate rocks. Most of the salts are removed from the bedrocks through carbonation and are suspended in river water. *Corrasion* or *abrasion* involves the removal of loosened materials of the rocks of valley walls and valley floors with the help of tools of erosion (i.e. boulders, cobbles, pebbles, gravels etc.). The nature and magnitude of abrasion depends on nature, size, amount and calibre of erosion tools. Boulders, cobbles and pebbles of various sizes and angularity are by far the most important tools of erosion which are generally called *drilling tools*. Lateral abrasion causes valley widening while the vertical erosion through *pot-hole drilling* leads to valley deepening and net increase in valley depth. *Hydraulic action* involves the breakdown of rocks of valley sides due to the impact of water currents of the channel. 9

Most of the rock channels have least sinuosity, rather they have almost straight course because of least erosion of rock banks but the valleys are very deep and narrow, at places forming gorges and canyons due to accelerated rate of downcutting of valley floors. The long profile of the bedrock channels is characterized by stepped reaches indicating frequent breaks in slope, called as nick points. Most of the nick points of the bedrock channels are structurally controlled and not by rejuvenation. These nicks or breaks are always associated with rapids and waterfalls which are succeeded by pools and potholes in the channel floor. These rapids and falls recede upstream as the stages of cycle of erosion advance and are completely eliminated by penultimate (monadnock stage) stage of landscape development.

5.1.2.2 Alluvial channels *** 08

Alluvial channels develop in the regions of sedimentation or alluviation i.e. where thick deposits of sediments of mostly fluvial origin have taken place i.e. the Ganga-Yamuna plain of north India. They also develop in the broad coastal plains having fluvial (sub-aerial) as well as marine deposits. It may be pointed out that alluvial channels are characterized by degradation (erosion of beds and banks), aggradation and again degradation. This means the deposited materials are reworked by the channels during coming wet season. Alluvial channels are also characterized by sinuous to meandering and braided channel patterns, depositional and erosional bed topographic features such as pools and riffles, shoals, sand bars, point bars, sand islands, sand dunes etc.

It may be pointed out that since alluvial channels are formed over such deposited materials which are highly erodible and hence these change in form and pattern with time. H. W. Shen and S.A. Schumm (1981) has described six types of temporal changes in natural alluvial channels (Fig. 5.3). It is evident from Fig. 5.3 that there is shift of transverse bars in straight channel (A) while there is alternate bar shift downstream within the channel in B. It is also apparent from Fig. 5.3 B that though the channel is straight but channel thalweg also shifts position within the channel. With the march of time the river develops highly meandering course where two sides of the meanders come very close to form narrow meander neck and ultimately the meander neck is cut off and the channel is straightened (Fig. 5.3 C). Besides neck cutoff, the channel changes its position in several other ways viz. through ***chute cutoff*** (Fig. 5.3 D), ***meander shift*** (Fig. 5.3 E) or by ***rapid channel diversion***, known as ***avulsion*** (Fig. 5.3 F). According to E.J. Hickin and G.C. Nanson (1975) *the factors which are responsible for changes in alluvial channels and rate of meander migration include water discharge, water surface slope, character of the boundary (bank) material, height of the concave bank, vegetation, the ratio of radius of channel curvature to channel width, sediment supply etc.*

The shortening of channel length through the mechanisms of meander cutoff and chute cutoff leads to increase in channel gradient which results in increased scour of sediments upstream and deposition of sediments in downstream reach. From the stand point of degree of temporal channel changes, alluvial channels are divided into two types viz. (1) **stable channels** and (2) **unstable channels**. Normally, straight channels are considered relatively stable but **braided channels** are called unstable because of frequent changes in the positions of bars and islands and even their disappearance at times.

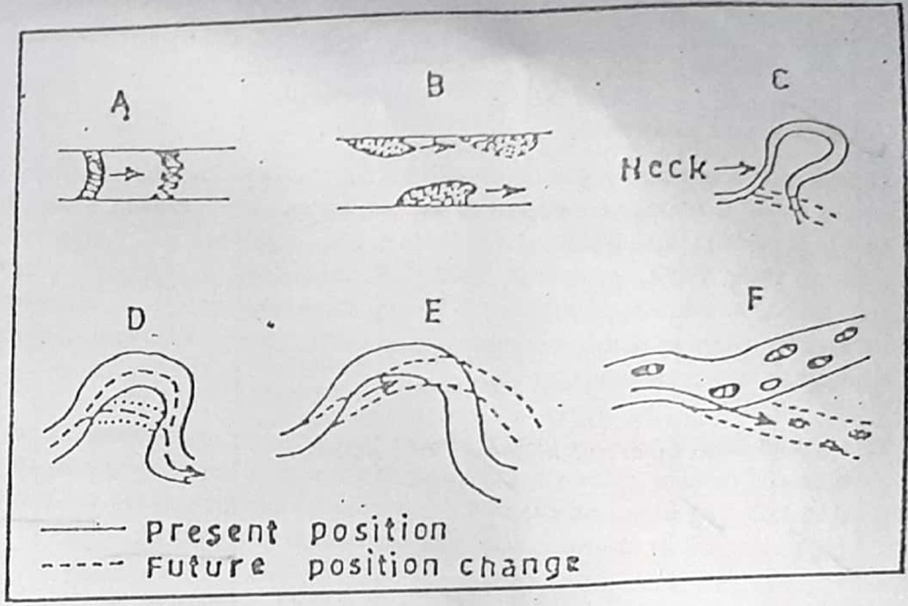


Fig. 5.3 Types of temporal channel changes : (A) transverse bar shift ; (B) alternate bar shift; (C) neck cutoff; (D) chute cutoff; (E) meander shift ; (F) avulsion (rapid channel diversion),

Alternatively, alluvial channels are also classified on the basis of those variables which influence and control channel morphology e.g. water discharge and sediment load, both type, and amount and nature of their transport. It is generally observed that in the event of large water discharge, alluvial channel also becomes large, whereas the shape and pattern of channel are influenced by the proportion of total sediment load mainly bedload. Thus, five types of alluvial channels are recognized viz. (1) **suspended-load channel** with straight course and uniform depth; (2) **mixed-load straight channel** with sinuous thalweg and small coarse sediments; (3) **suspended-load channel** with high sinuosity, uniform channel width, stable banks ; (4) **meander-braided transition channel**, characterized by large sediment load having greater proportion of sand, gravel and cobbles, wide and shallow channel, variable channel width, chute cutoffs and shifts in thalweg and meander ; (5) **bed-load channel**, representing bar-braided stream, is characterized by unstable condition, large sediment load of fairly larger size and coarse in texture, erodible bank materials, migrating gravel bars and islands etc.

5.1.3 Channel Pattern

Channel pattern is usually associated with alluvial channels. The channel pattern or map view of a river is usually considered as straight, meandering or braided. Several attempts have been made by the geomorphologists (e.g. L.B. Leopold and M.G. Wolman, 1957, S.A. Schumm, 1968, 1972, A.D. Miall, 1978, B.R. Rust, 1978, D.I. Brotherton, 1979, R.I. Ferguson and A. Werritty, 1983 etc.) to classify alluvial channel Patterns on several criteria viz. sinuosity, channel stability, number of channels (single or multi-thread), slope-discharge relationships, sediment load type etc.

1. **Leopold and Wolman (1957)** divided river channels basically into 3 types on the basis of sinuosity index viz. (1) **straight channel**, when sinuosity index (SI) is less than 1.05, (2) **sinuous channel**, when sinuosity index is between 1.05 and 1.5, and (3) **meandering channel**, when sinuosity index is more than 1.5.

$$SI = \frac{L_C}{L_V}$$

where, L_C = channel thalweg length

L_V = valley length

Alternatively, sinuosity index has been defined by J.C. Brice (1964) as follows:

$$SI = \frac{\text{Length of Channel}}{\text{Length of meander belt axis}}$$

2. S.A. Schumm **(1963, 1972)** classified alluvial channels on the basis of sediment load types (viz. suspended load, mixed load and bed load) into 3 major types e.g. (1) suspended **sediment load channels**, (2) **mixed load channels**, and (3) bed load channels and presented their main characteristic features (Table 5.1) as follows.

Table 5.1 Classification of alluvial channel patterns (Schumm, 1963)

	Stable	Depositing (deposional behaviour)	Eroding (erosional behaviour)	Supended load 100%	Bedload 0	M 100%
1. Suspended load Channels	W/D ratio<7 Sinuosity > 2.1 Gradient gentle	Major deposition on banks narrowing	Dominant bed erosion widening minor	85	15	30
2. Mixed-load channels	W/D ratio7 – 25 Sinousity 2.1-5 Gradient moderate	Initial major deposition on bank followed by deposition on bed	Initial bed erosion by channel widening	65	35	8
3. Bedload channels	W/D ratio > 25 Sinuosity > 1.5 Gradient moderate	Bed deposition + island formation	Widening dominant, little bed erosion	30	70	0

3. **A. D. Miali (1978)** presented almost identical classification of alluvial river channels as presented by S.A. Schumm (Table 5.1) but with some additional criteria of morphological characteristics. M. Morisawa (1985) after amalgamating the classificatory schemes of Schumm (1963 b) and A.D. Miall (1978) presented a unified classification of alluvial channels in 1985 wherein 5 major categories of channel patterns (Table 5.2) have been identified on the basis of morphological characteristics, sinuosity index, sediment load types, and erosive and depositional behaviour e.g. (1) **straight channel**, (2) **sinuous channel**, (3) **meandering channel**, (4) **braided channel**, and (5) **anastomosing channel.**

It may be mentioned that the scheme of alluvial channel classification of Leopold and Wolman was based on two criteria viz. **channel sinuosity** and **channel multiplicity** but they could not suggest quantitative parameter for the quantification of channel multiplicity as they did provide for channel sinuosity and thus their scheme could not provide basis for making distinction between channel meandering and channel braiding. B.R. Rust (1978) attempted to provide quantitative parameter in the form of channel braiding index to quantify channel multiplicity (number of braids in a river valley) so that the inherent shortcoming of Leopold-Wolman's scheme may be overcome.

Braiding Parameter, BP = number of braids in one meander wavelength

Table 5.2 Classification of river channel patterns (M. Morisawa, 1985)

Type	Morphology	Sinuosity	Load-type	Erosive behaviour	Depositional behaviour	Width/ Depth Ratio
1. Straight	Single channel with pools and riffles, meandering thalweg	<1.05	Suspension mixed or bedload	Minor channel widening and incision	Skew shoals	< 40
2. Sinuous channel	Single channel, pools and riffles meandering thalweg	>1.05 <1.5	Mixed	Increased channel widening and incision	Skew shoals	< 40
3. Meandering channel	Single channels (may be inner point bar channels)	>1.5	Suspension or mixed load	Channel incision, meander widening	Point bar formation	< 40
4. Braided channel	Two or more channels with bars and small islands	>1.3	Bedload	Channel widening	Channel aggradation, mid-channel bar formaiton	> 40
5. Anastomosing channel	Two or more channels with large, stable islands	>2.0	Suspension load	Slow meander widening	Slow bank accretion	< 10

In order to avoid the problem of stage-dependence, B.R. Rust defines the perimeter of a braid as the mid-line of the channels surrounding each bar or island but the braid order should be stated in any survey (Fig. 5.4). Classification of alluvial channel patterns by B.R. Rust is shown in Table 5.3

Table 5.3 Classification of alluvial channel patterns (B.R. Rust, 1978).

Channel classification	Single-channel (braided parameter < 1)	Multi-channels (braided parameter >1)
1. Low-sinuosity (<1.5)	Straight	Braided
2. High-sinousity (> 1.5)	Meandering	Anastomosing

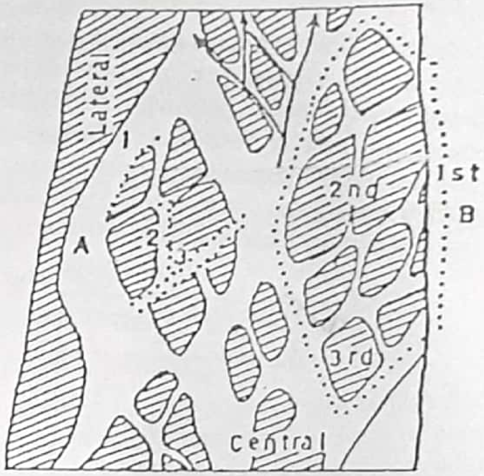
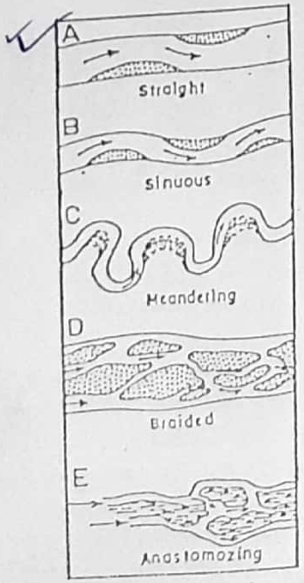


Fig. 5.4 Channel braiding: (A) Channel orders viz. order I, order 2, and order 3, (B) Bar orders viz. Ist, 2nd, 3rd.

~~It~~ is apparent that Rust identified an additional channel pattern as **anastomosing pattern** whereas Leopold and Wolman (1957) considered anastomosing pattern as a synonym for braided pattern but S.A. Schumrn (1963 b) accepted braided and anastomosing patterns as separate alluvial channel patterns and distinguished them on the basis of channel parameter. *'A braided pattern is one where the many divided channelways are always shifting* (Fig. 5.5 D). *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 channelways separated by bars or islands'* (M. Morisawa, 1985) but in the case of anastomosing channel pattern bars or islands are stabilized by growth of vegetation mainly weeds and grasses (Fig. 5.5 E).

R.I. Ferguson and **A. Werritty** (1983) identified a transitional class of **wandering gravel rivers** having low to medium sinuosity and combining features of both meandering and braiding with wide, shallow channels, flanked and locally divided by expanses of bare gravel but lacking the degree of channel division characteristic of true braided rivers.

It may he concluded that alluvial channels may be divided into five principal types viz. straight channel pattern, sinuous channel pattern, meandering channel pattern, braided channel pattern, and anastomosing channel pattern (Fig. 5.5) but it may be emphasized that different channel patterns are part of continuum, determined by energy conditions in relation to local constraints. Experimental studies have demonstrated that the complete range of river patterns from straight through meandering to braided is dependent on stream power which in turn, reflects sediment load and discharge.



5.5 Types of alluvial channel patterns - (A) straight, (B) sinuous,

5.1.4 Shape of Stream Channels

Shape refers to the configuration or form of the cannel in cross-section. The shape of the channel is determined by its width and depth. It is therefore often measured by the ratio of water surface width to mean depth. The ratio is known as the ***form ratio*** (Schumn, 1977). Narrow and deep channels have low form ratio, and shallow, wide channels have high form ratio. The form or shape of the channel determines the area of friction between the flowing water and the channel bed and banks represented by wetted perimeter. Consequently, shallow channels are less efficient because the loss in stream energy increases with increase in wetted perimeter (i.e. frictional area). In narrow channels the wetted perimeter is smaller and so the rivers are more efficient.

Four generalisations regarding the channel shape can be made (Leopold et al., 1964).

1. Most rivers have roughly parabolic cross sections.
2. River channels are asymmetrical at bends.
3. Rivers increase their width-depth ratio in the downstream direction.
4. Big rivers have relatively large width-depth ratio.

The shape of a channel at a given cross-section is a function of three variables

1. the discharge and its variations
2. the quantity and nature of the sediment
3. the nature of materials through which the river flows.

Marked seasonality in discharge or periodic occurrence of high floods is associated with channels with high width-depth ratios. This control is clearly demonstrated by the channel of Brahmaputra River, for example, which has an unusually high width-depth ratio.

Alluvial streams transport predominantly the same type of material as the material forming the channel in the lower reaches. These rivers are called ***rivers in flood plains***. Streams in flood plain exhibit great freedom in meandering within their permanent banks, (commonly known as *khadirs*). A typical cross-section of river with flood plain is shown in Fig. 5.6 to a greatly exaggerated vertical scale. The width of the flood plain between the permanent banks, i.e. width of valley, varies considerably depending on the size of the stream and other factors; the width of the valleys in large streams can be as large as a few kilometers.

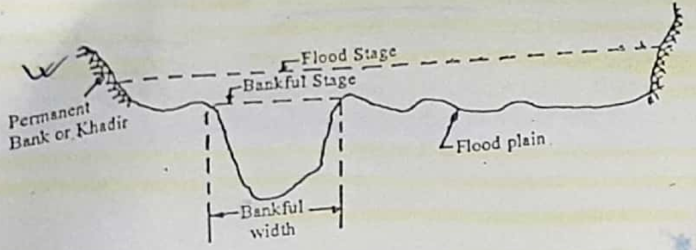


Fig 5.6 Typical cross section of a river with flood plain

The flood plains usually slope away from the main stream and towards the khadir. The reason for this is that during the floods, river water rises above the banks and as it moves away from the main current, its velocity is reduced. As a result a large part of the sediment load of the stream gets deposited as the bank line is passed. Hence the land close to the stream builds up and creates a lateral slope as mentioned above.

Most of the alluvial stream channels are found to be relatively wide and shallow. If the channel is deep and narrow, the banks become unstable due to higher velocities and the consequent high shear stresses along the sides. The material that is eroded from the sides drops on the bed and thus a narrow and deep channel tends to widen until the velocities near the sides are too low to cause further erosion. We know, that the side slopes and hence the shape will be a function of the nature of the material forming the channel, i.e. its sediment size, specific weight and cohesivity. If the slope of the stream is large, it will naturally produce higher velocities and hence the channel would be relatively wide. Since the sediment transport rate increases with increase in slope, a similar statement can be made regarding the dependence of cross- sectional shape on sediment transport.

Lacey gave a relationship between wetted perimeter and dominant discharge as

$$P = 4.75\sqrt{Q}$$

in which P is perimeter expressed in m and Q the dominant discharge in m^3/sec, and showed that, within certain limits, the wetted perimeter does not depend on slope, sediment size or sediment load. According to him, the sediment size only governs the

shape. Lacey found that natural channels have a tendency to assume a semi-elliptical shape. The coarser the sediment flatter is the semi-ellipse and greater is the width at the water surface. Finer the sediment more nearly does the section approximate to a semi-circle. Fig. 5.7 shows the cross-sectional shapes for various sized materials for the same dominant discharge. Checks using river data have shown that the coefficient in the Lacey's equation varies between 3.56 and 6.05.

However, Lacey's equation for perimeter with a constant coefficient is used in many countries as a handy design equation.

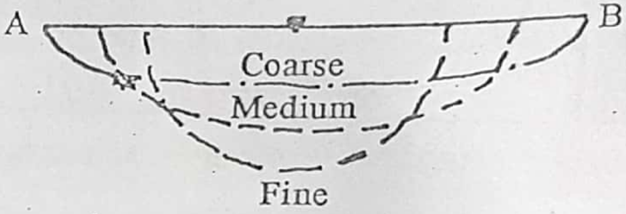


Fig. 5.7 Effect of sediment size on channel section

5.1.5 Channel Pattern or Plan Form

Unlike the term drainage pattern, which refers to a drainage network, the *channel pattern* or *planform* refers to the shape or configuration of a single river as seen from the sky. The term *'planform'* denotes the plan geometry without any reference to the associated processes. Like channel gradient and cross-section, channel pattern is a mechanism for adjustment of the river to the amount and variations in the sediment and discharge conditions.

Three basic types of channel patterns are usually recognised (Fig. 5.8) *straight, braided* and *meandering* (Leopold and Wolman, 1957). A fourth type, the *anabranching (or anastomosing)* channel pattern has been added in recent years.

09 - Distingush between ① Pool & riffle
(ii) sin & tortesity

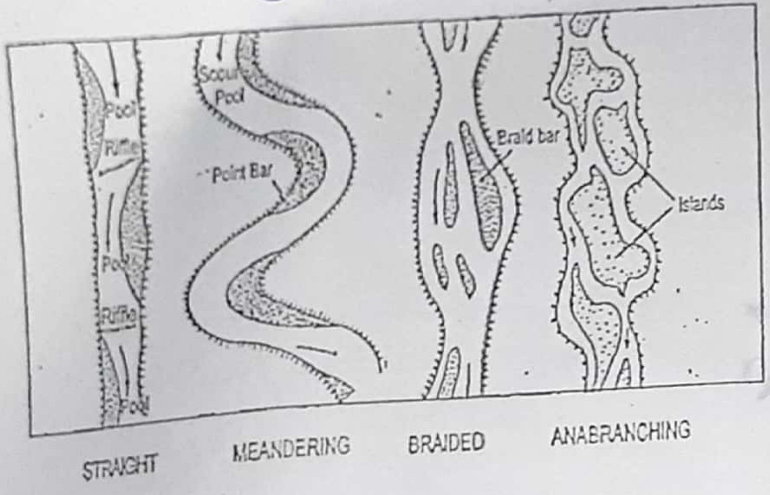


Fig. 5.8 Main river channel pattern

5.1.5.1 Straight channel

Truly straight channels scarcely exist outside the laboratory. Where they do occur, the channel is usually controlled by a linear zone of weakness in the underlying rock, like a fault or joint system. In natural system straight channel may he possible up to the stretches of 100 meters or so. Even in straight channel segments water flows in a sinuous fashion, with the deepest part of the channel changing from near one bank to near the other. (Fig. 5.5). Velocity is highest in the zone overlying the deepest part of the stream. It may be mentioned that in natural system the channel always tries to deviate from theoretical expected straight path. This deviation from straight path has been described by geomorphologists as channel sinuosity

Sinuosity is the ratio between channel length (CL) and valley length (VL). The channel length is determined along the channel between two points on a river, and valley length is the straight line distance between the same two points

$$\text{Sinuosity index (SI)} = \frac{CL}{VL}$$

Channels are defined as straight when sinuosity index is less than 1.05 and sinuous when it is between 1.05 and 1.5.

① [illegible] (sinuosity)

Although perfectly straight channels are rare in nature, short straight reaches are not uncommon. If such straight reaches occur they usually have steep slope and show a strong control of geological structure such as lineaments, faults, fractures, etc.

In a straight channel the flow is not straight and parallel to the banks but invariably shows a tendency to follow a winding path through alternate bars formed on each bank (Fig. 5.8). In addition, a straight river displays an undulating channel bed. The change in the flow depth is due to the alternate occurrence of deeper reaches, known as ***pools,*** and shallower reaches known as ***riffles.*** Pools are areas of slower flows and riffles are areas of faster flows. Several studies show that the pools and riffles are not randomly located but are spaced at regular intervals, about 5-7 times the mean width of the channel.

5.1.5.2 Meandering pattern

A ***meander*** is a bend in a stream. Because of the velocity structure of a stream, and especially in streams flowing over low gradients with easily eroded banks, straight channels will eventually erode into ***meandering channels.*** A straight channel having sinuosity index more than 1.5 is defined as meandering and is the most common channel pattern to be found anywhere along the longitudinal course of a river mainly alluvial rivers.

The word *meander* comes from the name of the river *'Maiandrose'* in Turkey, which is characterized by a sinuous path. Figure 5.9 shows a typical meandering stream. It is difficult to demarcate clearly between straight channels and sinuous channels which can be called meandering channels.

Terms like sinuosity and tortuosity have been introduced to provide a quantitative basis for the classification of streams into straight and meandering streams. *Sinuosity* of a stream is defined as the ratio of thalweg length to the valley length. Joglekar defines *tortuosity* as

$$\text{Sinuosity} = \frac{\text{Thalweg length}}{\text{Valley length}}$$

$$\text{Tortuosity} = \frac{\text{Thalweg length - Valley length}}{\text{Valley length}} \times 100$$

Leopold and Wolman have arbitrarily classified streams with sinuosity greater than 1.5 as meandering streams. Analysis of several American streams has shown that sinuosity varies between 1.0 and 2.80. For the Indus River the sinuosity varies from 1.02 to 1.45 over 1500 km, while it varies from 1.08 to 1.53 for the River Ganges.

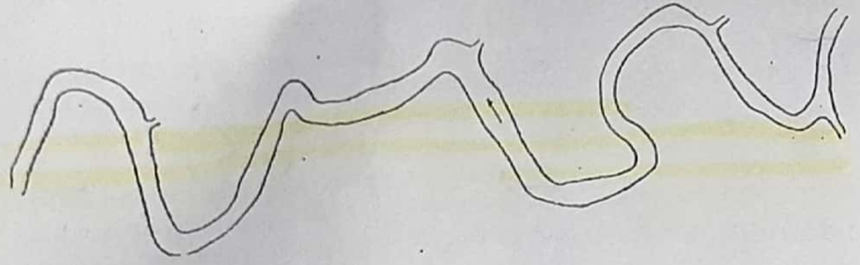


Fig. 5.9 Gomti river at Lucknow (India)- meandering river

Pools, point bars, and asymmetrical cross-sections at the bends are some of the characteristic features of a meandering channel (Fig. 5.8). Pools are associated with the meander bends, and point bars occur inside of the meander bend.

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. It may be pointed our that if the volume and discharge of water increase resulting in high gauge level, the slope of water surface over riffles and pools becomes almost the same. According to Petts and Foster (1985) *'a riffle is topographic high area, produced by the lobate accumulation of relatively coarse sediment, and a pool is a topographic low usually characterized by finer material.'* Spatially, riffles are wider and shallow while pools are narrow but relatively deep.

Pool-riffle sequences introduce variations in channel forms viz. channel width, channel depth, and velocity. Generally, pools develop at concave bank and riffles at crossover of the channel (Fig. 5.10) in sequential manner i.e. pools all riffles occur in alternate manner (e.g. pool → riffle → pool → riffle and so on). The channel cross section is asymmetrical at pools while it is symmetrical at riffles (Fig. 5.10). Generally, the channel depth is greater at pools than at riffles but as the discharge increases, gauge level (stage) also increases and hence the difference of channel depths at pools and riffles decreases (Fig. 5.11).

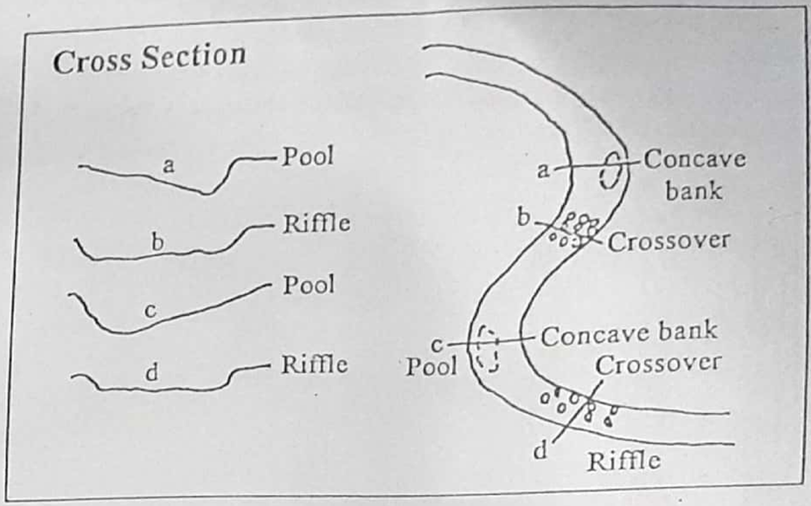


Fig. 5.10 Sequence of pools and riffles in river channel

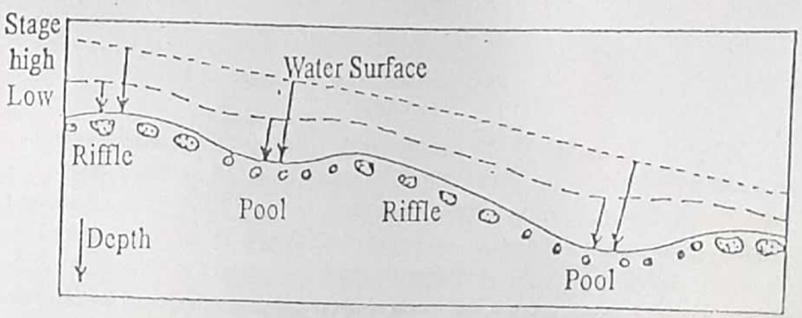


Fig. 5.11 Channel depth at pools and riffles at low and high stages of gauge levels

It has been observed that spacing of pools and riffles almost remains the same even the materials of riffle may move downstream due to flow velocity. In fact, spacing of pools and riffles has been shown to be regular in both meandering (curved) and straight reaches, with the distance from pool to pool (or riffle to riffle) approximating 5-7 times the mean width of the channel. Meanders are often associated with a frequency of one riffle-pool sequence per bend. However, more complex meander forms have been found to contain additional riffles and pools.

E.A. Keller (1972) proposed a five-stage model of the development of meandering channel and pool-riffle sequence on the basis of evidences of regularity in the spacing of pools and riffles (Fig. 5.12).

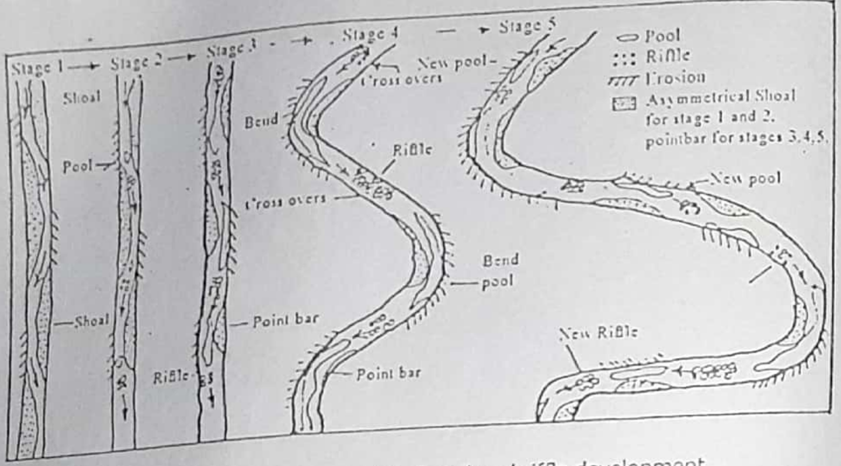


Fig. 5.12 Five-stage model of pool and riffle development as presented by E.A. Keller

K. S. Richards (1982) has formulated a theory of meander development based on hydraulic principles, (Fig. 5.13) wherein he has described three possible stages in the development of meandering reach. **First stage** (Fig. 5.13 A) is characterized by sequence of faster and slower eddy flow at bankfull discharge in straight reaches having channel sinuosity index of 1.0. **Second stage** is characterized by the formation of pools and riffles which are generally spaced at 5-7 mean channel widths (Fig. 5.13 B). The development of pools and riffles produces undulating channel bed which causes variations in flow velocity downstream. Lateral oscillation of channels increases sinuosity index and development of moderate bends in the channel (Fig. 5.13 B) with sinuosity approaching 1.1. It may be mentioned that pools favor the formation of bends while straight reaches develop over riffles. Pool to pool or riffle to riffle spacing increases to 5-7 times the mean channel width. **Third stage** is heralded by the development of ideal meander belts wherein one meander

wave length (L) is equal to 10-12 mean meander widths (Fig. 5.13 C). Once a meandering pattern has been established, it is likely to persist, unless some really powerful disturbing factor comes into operation. But although a great deal is known about the behavior of meandering streams and about their statistical properties, it is still not possible to define the ultimate cause of meandering.

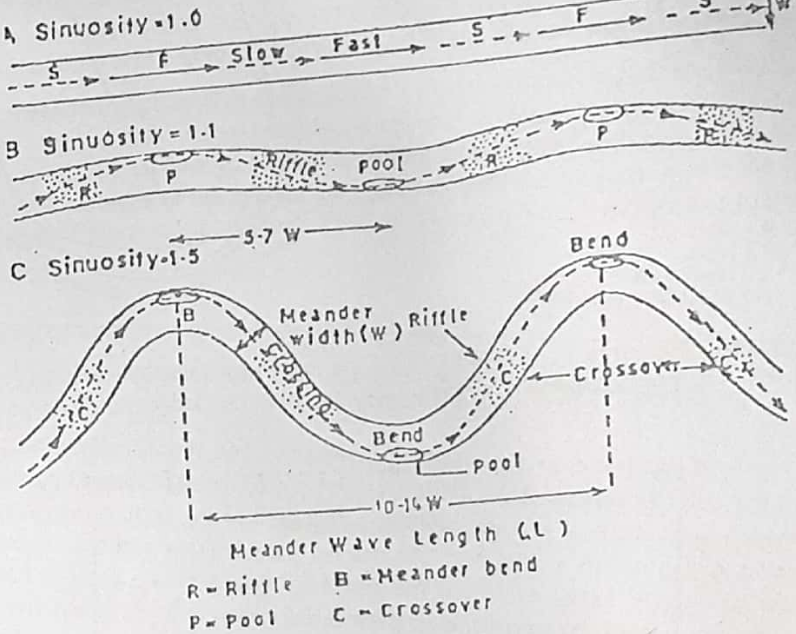


Fig. 5.13 Stages of development of meandering reaches- (A) straight reach, (B) sinuous reach, and (C) meandering reach.

A meandering river displays several morphological characteristics (Fig. 5.14). Studies show that the meander wave length, the meander radius, and the channel width are related to dominant discharge, which could be identified as the bankfull or mean discharge. The size and sinuosity of meandering channels are related to discharge, channel slope, and amount of fine material present in bed and banks. Schumm (1960) has shown that high sinuosity of channel is associated with a significantly higher proportion of silt and clay in the bed material. It should be noted, however, that streams meander even with coarse bedload

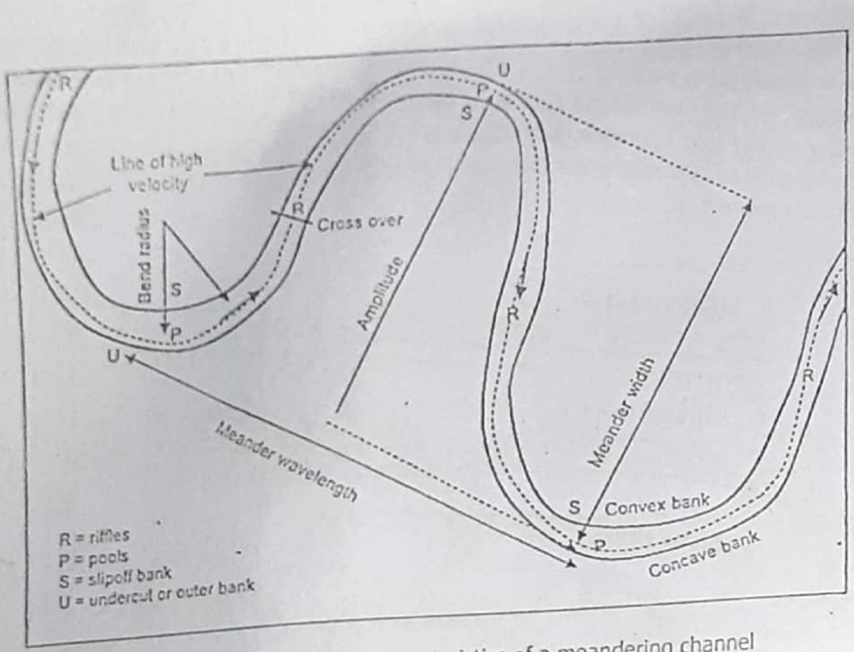


Fig. 5.14 Morphological Characteristics of a meandering channel

Fig. 5.14 shows that in a meandering channel the, line of maximum velocity is closer toward the outer or concave bank. This is responsible for lateral erosion by undercutting. The eroded bank material is transported and deposited to the next convex bank on the same side, giving rise to a point bar. The channel shifts laterally and the sinuosity of the meandering channel increases. When the maximum erosion of the concave bank occurs slightly downstream of the meander axis, the meanders migrate down valley. The migration of channel is one of the main reasons for the formation of cut-offs and ox-bow lakes.

Geometry of Meandering Streams

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Meanders have been classified by Chitale as *regular* and *irregular* and also as *simple* and *compound*. **Regular meanders** are a train of bends of nearly the same curvature and frequency. **Irregular meanders** are deformed in shape and may vary in amplitude and frequency. Simple meanders have bends with a single radius of curvature, whereas *in* Compound meanders, each bend is made up of segments of different radii and varying angles. If the meanders are irregular and compound, meander characteristics will change along the length of the stream considerably and it may be difficult to define average meander characteristics.

Meander geometry

The rivers developing the meandering characteristics generally possess certain amount of symmetry of the sinuosity (S.I, more than 1.0) with distinctive length and amplitude. The sinuosity of a channel may, however, vary with considerable variations in the amplitudes and meander lengths over a section of a channel. Therefore, the idea of measuring the symmetry of both arcs and respective symmetry of the sequence of arcs comes up.

A meandering channel is characterised by arcs with varying meandering amplitude. Therefore, the section of the meandering channel under study may have a number of meander axes. The channel is, therefore, divided into sections with meander axes and the perpendicular distance of the apex of the curvature from the meander axis is the arc height and the linear distance from one end of the curvature from the meander axis to the other is the arc length.

Symmetry of arcs

Symmetry of arcs can be measured for any specified section of a channel by measuring the arc lengths and arc heights and form ratio (Fig. 5.15).

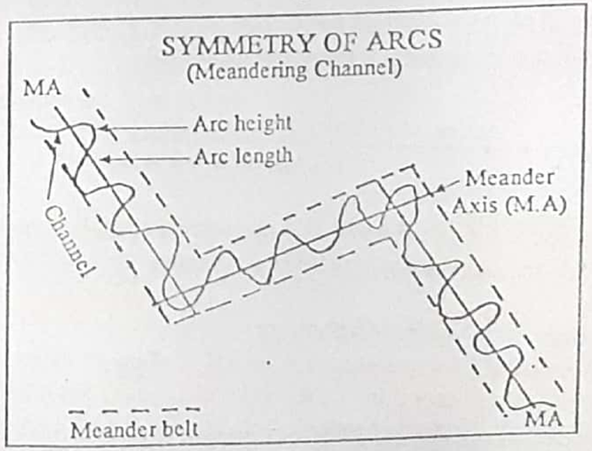

Fig. 5.15 Symmetry of arcs

$$\text{The form ratio} = \frac{\text{arc length}}{\text{arc height}}$$

After calculating the mean values and mean deviations of the arc lengths, arc heights and form ratios, the symmetry, of each of these components can be measured by the following formulae.

$$\text{Arc length symmetry} = 100 - \frac{\text{Mean deviation of arc length}}{\text{Mean arc length}} \times 100\%$$

$$\text{Arc height symmetry} = 100 - \frac{\text{Mean deviation of arc height}}{\text{Mean arc height}} \times 100\%$$

$$\text{Form ratio symmetry} = 100 - \frac{\text{Mean deviation of form ratio}}{\text{Form ratio}} \times 100\%$$

These values of percentage symmetry are based on the mean deviation values of each component. The higher is the value, the greater is the symmetry. The mean deviation values can even be substituted for the standard deviation values.

In reality, there hardly exists a perfect symmetry of the meanders though similar meander amplitudes may be obtained for certain lengths of channels. The quantitative evaluation, of repetition of symmetry is measured as follows:

$$\text{Repetition of Symmetry} = \frac{\text{Number of arc length with less than 25\% deviation from mean value}}{\text{Number of arcs in the reach}}$$

In order to find out such values for any meandering channel, it would, therefore, be convenient to divide the channel into sections of similar meander amplitudes.

Empirical Relations in Meander Morphology

Probably, the most exhaustive quantitative empirical relations of meander geometry and discharge conditions are obtained from the works of Leopold, Wolman & Miller besides many other such derivations by other experts. Only some of the most widely used empirical relations are given below. Hydrological relationships have been treated separately.

In the meandering channel, some interesting empirical relations of the amplitude of meander (A), wave length (λ) and wetted perimeter (P) with the width of the channel (W), radius of curvature (r_m) and the discharge (Q) have been worked out. Each of these bivariates are exponentially related.

Amplitude of meanders: The empirical relationship has been established with the width by different authorities in alluvial valleys as follows:

$$A \propto W$$

$A = 2.7\, W^{1.1}$ ... After Leopold & Wolman, 1960.

$A = 18.6\, W^{0.99}$ ... After Inglis, 1949.

$A = 10.9\, W^{1.04}$ ... After Inglis, 1949.

$A = KW^{0.98}$ ... After Knighton, 1972.

The relations are worked out generally in alluvium channels and show considerable disparities.

The amplitude is, however, poorly correlated with meander length or wave length and even with other parameters like depth, radius of curvature or discharge.

Meander length (or wave length): It is generally expressed by the Greek letter λ which is found to be correlated with a larger number of channel morphologic forms and hydrology, mainly discharge. The linear relationships have been worked out by a number of authorities and some such relations are given below.

$$A \propto W, r_m, Q$$

$\lambda = 10.9\, W^{1.01}$ ... After Leopold & Wolman, 1960.

$\lambda = 6.6\, W^{0.99}$ ... After Inglis, 1949.

$\lambda = KW^{1.06}$ ... After Knighton, 1972.

$\lambda = 4.7\, r^{0.98}$ ... After Leoplod & Wolman, 1957.

From the above relations it is quite apparent that the values considerably vary but certain generalisations can be made, such as, the meander length is about 7 to 10 times the channel width and about half the radius of curvature (r_m).

Characteristics of a meandering river

1. A meandering river is a graded river. As a graded stream it slowly alters the straight course to meandering by lengthening its course and reducing its gradient. It also reduces greatly its load carrying capacity as the actual bed load in motion is less in a curved channel than in a straight one. The curved channel is also longer than a straight one and much of the bed load is locked up in alluvial deposits adjacent to the channel for long periods of time.
2. The outside bank of each meander loop tends to be deep and under cut and the short straight segment between adjacent loops is rather wide and shallow.
3. The pool and riffle pattern are commonly found along the stream course of a meander.
4. The thalweg of a meandering reach is close to the outer side of each bend and crosses over near the point of inflection between the banks. Like the thalweg, stream lines of maximum velocity also moves downstream, crossing over from one bank to the other.
5. Meandering streams, in general, have gradients between about 20 cm/km and about 10 cm/km.
6. Back-water eddy with deceleration of flow are developed at the inner edge of bend where deposits occur. Moreover the separation causes the stream lines of flow to impinge on the outer bank of the downstream edge of the curve.

Deformed Meanders

Meanders of regular shape forming one after another in succession are not very common in rivers. Interference in the natural processes developing regular meanders is often caused by natural constraints which lead to deformed meanders. Such constraints could be of varied types.

1. Local accelerated erosion of banks composed of pockets or local stretches of sand or highly erodible alluvium.
2. Resistance to bank caving due to the presence of compacted silts or clays, which have acquired a greater degree of consolidation than that of the surrounding alluvium.
3. Resistance to bank caving due to revetment, or erodible materials such as a rock, kanker, etc. Fig. 5.16 shows a regular pattern of meanders, as well as deformed meanders, formed due to revetment and rock outcrops on the banks.

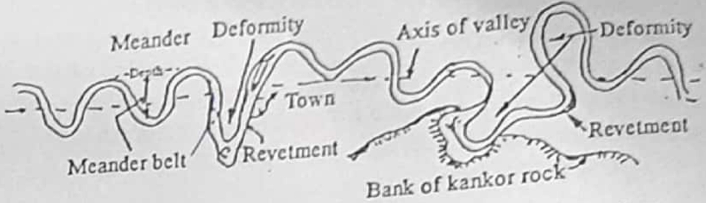

Fig. 5.16 Deformed meander pattern due to obstructions

Cutoffs

A neck is the upland between opposing meanders of a stream. A cutoff occurs when the neck between river meanders is eroded away and the meanders join to shorten the length of the channel. The slope of the channel increases as well when the river shortens its length.

Mark Twain aptly described the process and effect of river cutoffs when he wrote:

"The Mississippi is remarkable in another way– its disposition to make prodigious jumps by cutting through narrow necks of land, and thus straightening and shortening itself. More than once it has shortened itself thirty miles at a single jump! These cut-offs have curious effects: they have thrown several river towns into the rural districts, and built up sand bars and forests in front of them. The town of Delta used to be three miles below Vicksburg: a recent cutoff has radically changed the position, and Delta is two miles above Vicksburg."

~ *Life on the Mississippi* ~

It has been mentioned earlier that the meander pattern is not stationary but moves slowly in the downstream direction. During the development of meanders there is also a gradual lengthening of the meanders, which imparts lateral movement to the meanders. Increased frictional losses and bank resistance tend to halt the lateral movement. When the bend and the bank resistance become too large for continued stretching of the loop, it is easier for the flow to cut across the neck than to flow along the bend, resulting in a cutoff. Usually narrow and small side channels are available within the neck of the meander loop. These side channels are either part of the main channel when the stream was flowing along this course or are formed by spilling of floods over the banks. Cutoffs may develop along these small side channels. As contrasted to the natural cutoff described above, a cutoff may be artificially induced for one purpose or the other.

09- Distinguish betwon neck cutoff and chute cut of.

Natural Cutoffs

The development of a small narrow channel at the neck into a major natural cutoff primarily depends on the assistance this channel receives from the major flood in increasing its cross section. If a large flood lasts for a relatively long time, the channel gets sufficient time to develop a narrow channel into a full waterway. Development of such a natural cutoff requires two to three years or probably even more. A typical cutoff is shown in Fig. 5.17.

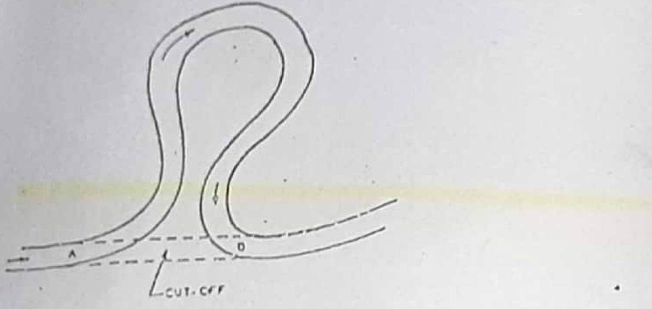

Fig. 5.17 A Typical Cutoff

Types of Cutoffs

10, 06, 5, 09

10, 06, 05, 09

Cutoffs are generally of two types: (1) loop or neck cutoffs (2) chute cutoffs.

Loop or neck cutoffs occur when progressive bank erosion at the neck of acute bends as shown in Fig. 5.18 and are more common.

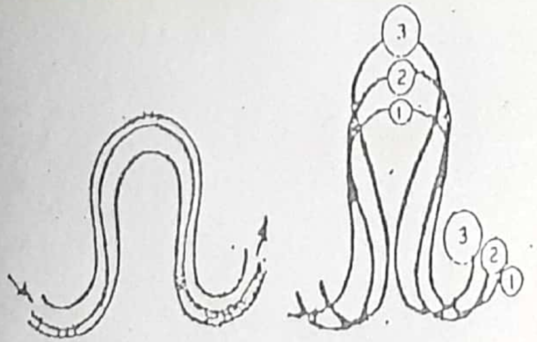

Fig. 5.18 Progressive Bank Erosion in Acute Bends Leading to a Cut off

A river increases its curvature by eroding the concave banks, until either, the velocity of the stream is so reduced that the banks cease to be further eroded or, the arms of the loop with a very narrow neck cut into one another and a cut-off occurs. This side channel through which the current has broken through has the same total fall as the old channel around the bend. Current velocities in the side channel are consequently relatively very great and hence it enlarges until accommodates the entire discharge and the former curved channel gels silted up.

A chute cutoff occurs normally across the base of a flat meander and is less common than neck cutoff. A river flowing along curved paths, such as shown in Fig. 5.19, has shallow side channels beside its main course; these side channels may be either, remnants of an old course or, caused by floods spilling over its bank. During high stages excessive deepening of the pools occurs, supplemented by a growth of bars at the inflections, which accentuates the tendency of water to take to side channels. As floods begin to fall, these tendencies predominate with the result that the discharge through the main curved channel is considerably reduced, while the side channels draw comparatively large discharges. The side channel thus seeks to enlarge itself to accommodate the large discharge while the bend in the main channel continues to silt because of extended bars. The cut-off is completely formed when the short-circuited bend draws little or no water.

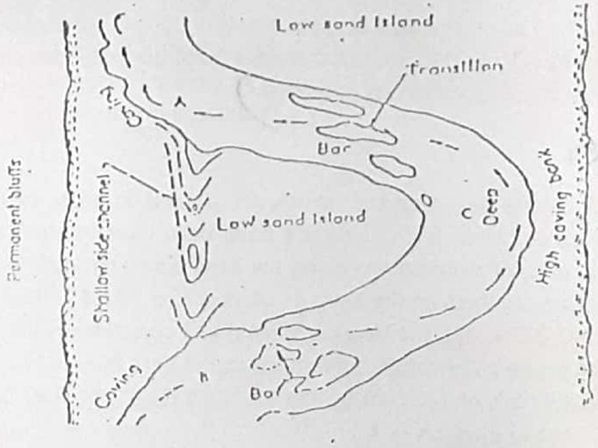

Fig 5.19 Development of a Chute Cut off

12,10 08,07

Cutoff Ratio

For flow around a bend, the ratio of length of the bend to that of the chord viz. ACB/AB in Fig. 5.20. when a cut off occurs is called a the *cutoff ratio.*) This ratio varies according to the type of the cutoff and characteristics of the river. A cutoff does not therefore necessarily occur for any fixed value of the ratio but is possible if the conditions are favourable.

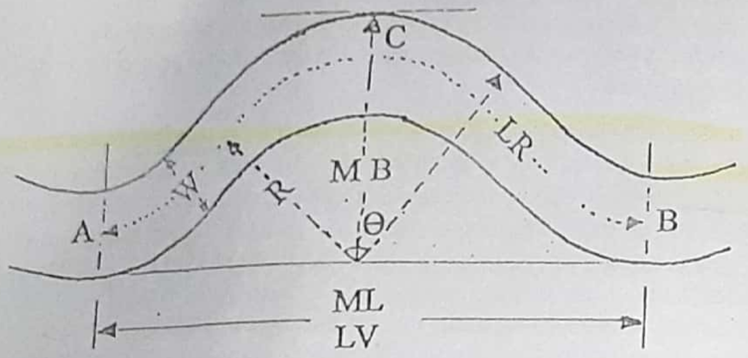

Fig. 5.20 Cut off Ratio

It may occur for cutoff ratios varying between 1.7 to 3.0 in the case of rivers in which a cutoff results due to development of a side channel. Where development of a cutoff takes place due to a loop cutting itself, the ratio is, generally, very light. In some of the Mississippi cutoffs, the value was as high as 8 to 10. But there are numerous instances, where cut-offs did not take place even when its value was exceeded.)

Artificial Cutoffs 5

Many times artificial cutoffs are executed on alluvial streams in order to reduce flood heights and flood periods. Also, artificial cutoffs have been used to shorten the travel distance and increase ease of maneuvering along the bend during navigation. Such cutoffs have been made in large numbers on the lower Mississippi river (U.S.A.), the Missouri river (U.S.A.), the Tisza river (Hungary), the Hai river (China) and several rivers in New Zealand. During the nineteenth century 112 cutoffs were made on the Tisza River in Hungary thereby shortening the original length of 1200 km by 455 km. As a result, the river bed has been lowered at various points by as much as 2.3 m.

The following recommendations made by Pickles will be found useful in the design and execution of artificial cutoffs:

10,08,07, 12,11,10, 15

1. The pilot channel should be tangential to the main direction of river flow approaching and leaving the cut.
2. The pilot channel is usually made on a slight curve, the curvature being less than the dominant curvature of the river itself.
3. Entrance to the pilot channel is made bell-mouthed. Such transition at the exit is considered unnecessary because the cut develops first at the lower end and works progressively upstream.
4. The cut, when unlikely to develop because of coarseness of the material or of low shear stress, should be excavated to mean river cross-section.
5. The width of the pilot cut is unimportant as the cut ultimately widens due to scouring. Hence, in practice, the width is determined by consideration of the type and size of the dredging equipment used.
6. When a series of cutoffs is to be made, the work should progress from downstream to the upstream.

Effects of Cut-off

(The changes that take place in alluvial rivers after cutting off the bends can be divided into two categories: immediate changes and long-period changes.)

(When a cutoff is executed, the length of channel is appreciably reduced between the neck points of meander loop, i.e. between A and B in Fig. 5.21. As a result the water surface slope in this reach will increase.)

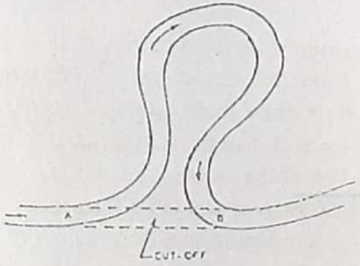

Fig. 5.21 A typical cutoff

Another effect of cutoff is exhibited during conditions of varying discharge. The lower stages in and above the cutoff lead to reduced storage and the peak discharge downstream of the cutoff is likely to be higher than in the absence of the cutoff. If tributaries join the river immediately downstream of the cutoff, the peak discharge downstream of the tributaries may be more or less than the peak discharges before execution of cutoff, depending on whether the peaks from the main river and the tributaries are synchronized or not.

Wherever a river succeeds in establishing a cut-off, there follows a period of total chaos, for miles above and below the newly formed short cut. Banks start caving, new channels are formed, some old channels get silted up, until at last, probably during low stages, there is a temporary stability for a few months. With the next floods again the agitated period of adjustment commences until, equilibrium is finally established.

Downstream stage changes, as may appear to occur are merely temporary and disappear rapidly as the channel adjusts itself to its new alignment. A temporary bar growth at the lower end of the cut of channel is likely to occur, because of the deposit of detritus scoured out from the enlarging cut-off channel. The bar lasts rarely for more than one or two low water seasons after the cut-off has been formed. It is therefore, reasonable to support that the downstream stages are not permanently affected by the cut-off since it causes no increase in the discharge of the river.

Besides their effect on stages, cut-off cause local changes in the direction of currents which may be occasionally radical. These currents may in their turn cause bank caving both above and below the cut-off, which is sometimes violent and extensive. As soon as the channel adjusts itself to the new conditions imposed by the cut-off caving, decreases to its normal proportions. The extent and character of the channel changes, following a cutoff, depend to a large extent upon local conditions. No general rule, therefore, can be proposed.

5.5

Ox-bow Lakes

If erosion on the outside meander bends continues to take place, eventually a meander bend can become cut off from the rest of the stream. When this occurs, the cut off meander bend, because it still a depression, will collect water and form a type of lake. The lakes thus formed due to impounding of water in the abandoned meander loops are called *ox-bow or horse-shoe lakes*. Oxbow lakes are typically crescent shaped- like that of an oxbow. When the curvature of the meander loops is so accentuated due to lateral erosion, the meander loops become almost circular and the two ends of meander loops come closer, consequently, the streams straighten their courses and meander loops are abandoned to form ox-bow lakes (Fig. 5.22). It may be pointed out that the formation of oxbow lakes owes to erosion (straightening of river course through the intersection of two ends of meander loops at the meander neck due to lateral erosion) and deposition both filling and plugging of cutoff ends of meander loops through deposition (Fig. 5.22). There is frequent sedimentation (alluviation) of oxbow lakes during floods and thus they are converted into swamps in due course of time.

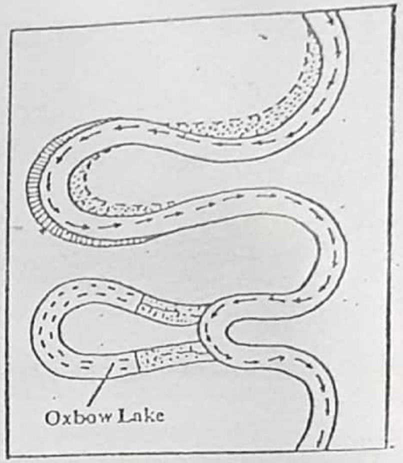

Fig. 5.22 Formation of oxbow lakes due to sharpening of meander loop

[illegible]

Point Bars and Scrolls

Point bar is yet another major feature associated with meandering channels. The crescent-shaped bar occurs on the inside of the meander bend (Fig. 5.8), and is formed by lateral accretion of sediments towards the inner bank. Migration of point bars gives rise to a series of ridges known as scrolls.

5.1.5.3 Braided stream

[illegible]

A braided stream can be defined as one which flows in two or more channels around alluvial islands. Fig. 5.23 shows a typical braided reach of an alluvial stream. Field observations and laboratory investigations by Leopold and Wolman throw some light on the sequence of events leading to braiding and the hydraulic relationship between divided and undivided reaches of the stream. Their study shows that a braided pattern develops after

07-06- Diff betn braided & distributary stream,

local deposition of coarser material which cannot be transported under local conditions existing in the reach. This coarse material becomes the nucleus of a bar and subsequently grows into an island made up of coarse as well as fine material. The formation of the bar deflects the main stream towards the banks and causes erosion.

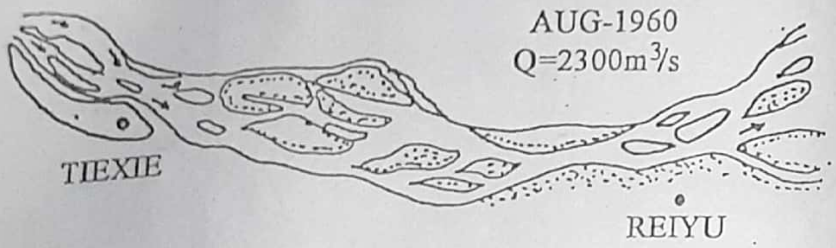

Fig 5.23 Typical braided reach of the Yellow river

A distinctive characteristic of braiding pattern is multiple channels. There are however two types of multichannel streams; one is the interlaced multichannel stream separated by islands at low stages giving an appearance of a hair braid. At high flow stage, the islands may get submerged and the stream may flow from high bank to high bank. This is called a *braided pattern.*

14

The other kind of multichannel stream is of *distributary type* in which several separate channels branch out of the parent stream as in case of a river building an alluvial fan or a debris cone. All these multichannels again combine at the foot of the cone. Distributary type multichannel stream is also formed in building up of delta where all these different channels finally disappear into sheet flow at sea end. Fig. 5.24 schematically shows the braided pattern as distinct from distributary channels.

The braided stream channel contains bars and islands, and the degree of braiding can be expressed by the percentage of reach length that is divided by one or more islands or bars. J.C. Brice (1964) has devised a braiding index to determine the degree of braiding.

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

If the value is more than 1.5 then the channel is referred as the braided channel. The cross sections of the braided stream are wide and shallow i.e. they have a high width/depth ratio.

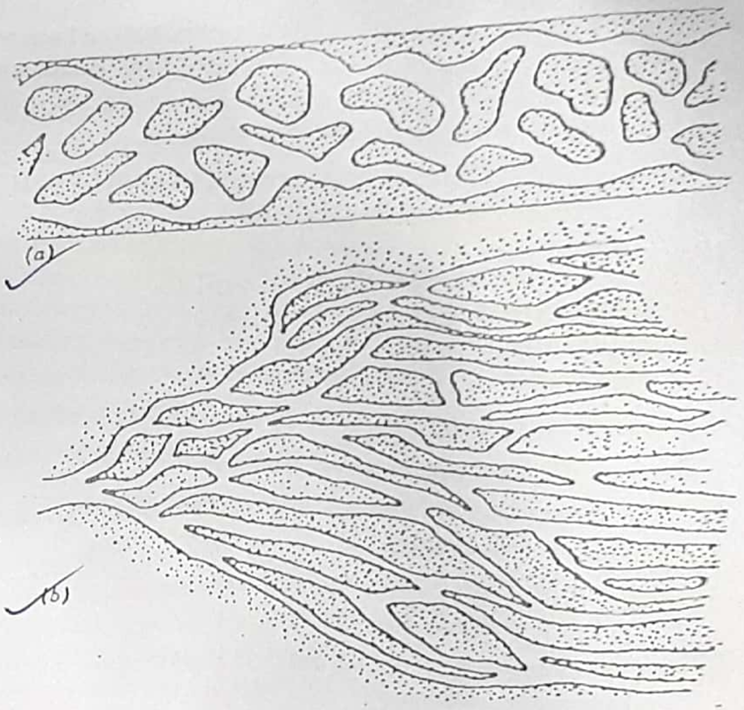

Fig. 5.24 Braided and distributary channel

Braided streams are found mainly in three contrasting environments:

1. Semiarid regions of relatively low relief and the streams are formed by the runoff of the mountain areas.
2. The glacial outwash plain where the source of water is the melting ice front.
3. Mature stream in mountain areas-arid, temperate or even periglacial. The stream gradient is steep.

The bars, which separate the channelways, are divided into two main types viz. (1) longitudinal bars, and (2) transverse bars wherein longitudinal bars are diamond-shaped and are composed by gravels while transverse bars are tabular in shape, flat-topped and covered with bedforms. In fact, many such bars seem to be dune fields which were covered at high flows and appear as bars when the discharge receded and these are composed of sands.

Very heavy bedload is carried by braided rivers. J.M. Coleman (1969) noted very high sediment load carried by the Brahmaputra (i.e. 7 million tons per day at the time of peak discharge, 607.7 million tons as mean annual, 696.5 million tons as maximum annual and 530.9 million tons as minimum annual load). He also observed large sand waves as 7 to 16 m high with a wavelength of 183 – 914 m. The average rate of downstream movement of bed forms including sand waves on the Brahmaputra bed was noted by him as 204 m over 24 hours while maximum rate of migration was recorded as 640 m in 24 hours.

Several causes have been assigned to the development of braided pattern. 12, 13

1. incompetence of the river to transport bedload.
2. high single channel resistance to flow to move the bedload.
3. formation of bars and islands.
4. highly erodible banks.
5. fluctuations in discharge change.
6. sediment transport, bank erosion and channel scour i.e. high energy environment.
7. steep channel gradient.
8. abundant and coarse bedload etc.

6.

According to Leopold and Wolman (1957) *'braiding is not indicative of excessive bedload since they found aggradation can take place at constant slope without braiding. This means that braiding is not a matter of lack of capacity but lack of competence'.* This is in agreement with Schumm's statement that *'high suspended loads are transported in meandering (sinuous) channels whereas bedload transport requires a straight or braided system'.* According to Leopold and Wolman the braiding of a river channel begins with the deposition of a mid-channel bar or island which bifurcates the channel and thus diverts the flow of water towards the banks having erodible materials. Consequently, the banks are eroded leading to widening of channel width. Bank erosion increases sediment load which causes further deposition and formation of additional bars and islands which in turn further divide the channels and process continues. The wide shallow, cross-sections develop

multiple secondary-circulation cells and bars form at points of channel-bed flow convergence. Excess energy is rapidly dissipated by a large increase in friction associated with the combined greater width and lesser depth of the multi-thread channel.

Generally, braided channel patterns are associated with alluvial fans, delta, glacial outwash plains, and the regions which are characterized by marked seasonal variation in stream discharge because of seasonal regime of precipitation.

From investigations in many different regions the following differences between the braided and meandering channels have been recognised:

1. A meandering river has a single channel and a braided river has multiple channels.
2. For a given discharge, a braided channel has steeper slope than a meandering channel.
3. A braided channel generally has coarser material than a meandering channel.
4. A braided channel is broader and shallower than a meandering channel.
5. A braided channel is characterised by frequent bank erosion, and thus is more unstable than a meandering channel.

These differences suggest that braiding represents a high-energy environment.

10, 08, 11, 12

Characteristics of Braided Pattern

(a) Aggradation

Since braided pattern emerges when bed load transport is heavy, braiding of channels is often associated with tendency for aggradation. Braiding channels however, need not always experience aggradation. For instance, Brahmaputra river upsteam of Gauhati is having intensely braided pattern as shown in Fig. 5.25 but is not having an aggrading trend.

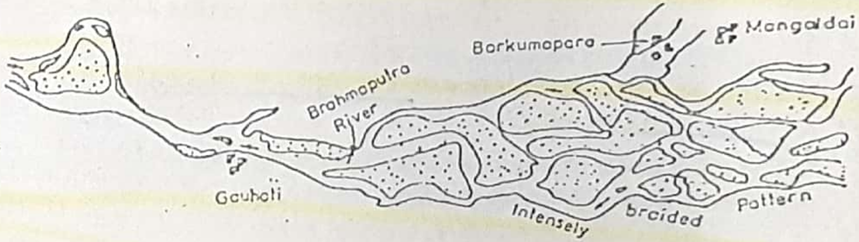

Fig. 5.25 Braided pattern in the Brahmaputra river

(b) Channel Alignment

Heavy bed load, generating a wide and shallow cross-section, was seen to be the basic reason for formation of braiding pattern. Associated characteristics were found to be steeper slope, coarser bed material and higher velocities. All these factors being unfavourable for meander formation, the alignment of braided channels is more or less straight, subject to constraint of valley boundaries.

(c) Movement of Islands

Islands in braided rivers get eroded on their upstream faces and build up on the downstream faces. The islands therefore appear to be unstable and moving downstream. The rate of this apparent movement is slow and depends on several factors like frequency and duration of high floods, size and gradation of material forming the island, its susceptibility to erosion, vegetal cover which retards velocity, clay content which retards erosion, etc. Tendency for movement of islands therefore can be significant in some rivers and not noticeable in others.

(d) Bank Erosion

Islands in some of the braided rivers have a tendency to movement of islands, the channel along the bank gets squeezed causing increase in discharge concentration, thus leading to local bank erosion.

5.1.5.4 Anastomosing channel pattern

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Anastomosing channel pattern is a special type of braided pattern (Fig. 5.5 D and E). Both are characterized by multiplicity of channels i.e. multithread pattern. These two patterns are distinguished on the basis of stability of bars and islands and channelways as in braided pattern sand bars and islands change their positions and divided channelways also register frequent shifting. On the other hand, an anastomosing pattern is one where there are many channels but they are stable and retain their identities with changing discharge and time.

5.1.5.5 Anabranching pattern

Anabranching channel pattern is one where the anabranches (offshoots) rejoin the original trunk or unite with a next-neighbouring trunk, some times after a distance of tens of miles (Fig. 5.26). Anabranch means off shoots of a stream which rejoin the trunk or tributary streams. According to Schumm (1977) *'anastomosing channels are distinct from the anabranched channels, as they have major distributaries that branch and rejoin the main channel. The individual branches of anabranching and anastomosing channels can be meandering, straight, or braided'.*

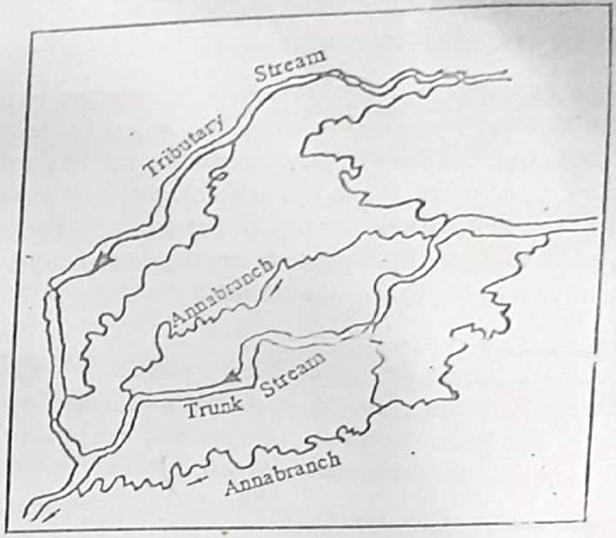

Fig. 5.26 Anabranching channel pattern

Anabranching patterns have been observed in cold temperate, humid tropical and semi-arid regions. Geomorphic situations favouring the development of anabranching river patterns include intermontane valleys, low gradient fans, lacustrine plains and alluvial plains. According to Nanson and Knighton (1996) anabranching rivers are characterised by-

1. flood-dominated flow regimes
2. banks that are resistant to erosion [illegible]
3. river mechanisms to constrict channels and induce avulsion. Avulsion is the sudden shift or diversion of a river to a new course at a lower level on the flood plain, during flood.

Such rivers are able to efficiently transport their sediments by reducing the width-depth ratio (i.e. by increasing the depth) and consequently by concentrating shear stress and stream power. Thus, the rivers are able to maintain or increase their sediment throughput without significantly increasing the channel gradient.

5.2 VARIABLES IN STREAM PROBLEMS

While studying the behaviour of alluvial streams it is necessary to know the important variables that are involved in the phenomenon. This aspect has been well discussed by Kuiper. Leaving aside the variables which characterize the sediment and water, and remain essentially constant (e.g. ρ_s, ρ_f, g and temperature), the more important variables are: water discharge Q, bed material transport rate Q_T, representative size of the bed material d, stream slope S, width to depth ratio r characterising the shape of cross section, and ratio of stream mileage to valley mileage, M_l, characterising the shape of the stream in plan, i.e. meander pattern.

It is necessary to find out which of the above variables are independent and which are dependent. Of these variables r and M_l are certainly dependent variables, whereas the water discharge, Q, and bed material size, d, are certainly independent variables. Hence the question remains about two variables namely Q_T and S.

In the upper course of the stream the slope of the land and hence the slope of the stream is determined by geologic factors and S can be treated as an independent variable so far as stream behaviour is concerned. Thus Q, S and d determine the magnitude of the sediment transport rate Q_T in the upper course of the stream and Q_T becomes a dependent variable. In the lower course of the stream Q, Q_T and d become the independent variables and hence the slope S becomes a dependent variable along with r and M_l.

5.3 DOMINANT DISCHARGE

It has been pointed out earlier in this chapter that the flow in alluvial streams differs from that in regime channels in several respects. The most important difference between the two lies in the fact that, while regime channels are designed to carry a fairly constant discharge, alluvial streams carry extremely varying discharges and sediment loads. The ratio of maximum to minimium discharge can attain values as high as 1000 or more in many streams. Flashy streams and streams in semi-arid regions are likely to have very high values of this ratio. Table 5.4 gives values of this ratio for some streams. Similarly the variation in sediment load can also be very large. During low flows there may be little sediment transport, while during high flows the stream may carry high sediment loads with a wide range of sediment size.

The braided stream channel contains bars and islands, and the degree of braiding can be expressed by the percentage of reach length that is divided by one or more islands or bars. J.C. Brice (1964) has devised a braiding index to determine the degree of braiding.

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

If the value is more than 1.5 then the channel is referred as the braided channel. The cross sections of the braided stream are wide and shallow i.e. they have a high width/depth ratio.

Table 5.4 Ratio of maximum to minimum discharge of some streams

Columbia (U. S. A.)	28.7
Mississippi at St. Paul (U.S.A.)	23.5
Danube a the head of Delta (Rumania)	14.3
Elbe at Hamburg (Germany)	7.8
Rohone below mouth of Durance (France)	38.0
Volga at Rybinsk (Russia)	32.0
Indus at Kalabah (Pakistan)	53.0
Ganges at Farakka (India)	34.6
Mahanadi at Naraj (India)	108.0
Nile at Cairo (Egypt)	48.5
Yangtze at Chihkiang (China)	22.1
Mekong at Kratie (Cambodia)	35.3
Sutlej at Rupar (India)	113.0
Ravi at Madhopur (India)	411.0
Ujh at Chak Basti (India)	2400.0
Irrawadi at Saiktha (Burma)	48.8

The wide variation in stream flow, indicated in Table 5.4, makes it difficult to choose a representative discharge in studying the stream characteristics. Different methods have been suggested by different investigators for the choice of a representative discharge. Inglis introduced the concept *of dominant discharge*. According to him, there is a dominant discharge and gradient, to which a channel returns annually. At this discharge, equilibrium is most closely approached and the tendency to change is the least. This condition may be regarded as the integrated effect of all varying conditions over a long period of time. In other words, dominant discharge is that hypothetical steady discharge which would produce the same result (in terms of average channel dimensions) as the actual varying discharge. Inglis found that for north Indian rivers the dominant discharge was nearly the same as the bankful discharge and recommended that the dominant discharge be taken to be half to two-thirds of the maximum discharge. This may not be true in the case of other rivers.

Blench designates that discharge as dominant discharge, which is equalled or exceeded fifty per cent of the time. The U.S.B. R. defines the dominant discharge as the discharge that will carry the greatest sediment load of material coarser than 0.0625 mm with respect to time. This discharge has been found to be slightly greater than the median discharge. Ackers and Charlton define the dominant discharge as that constant discharge which would produce the same meander length as produced by the varying discharge.

A little reflection will show that the dominant discharge, which determines the average channel dimensions, need not correspond to the steady discharge which would yield the same annual sediment transport as that due to the varying discharge. From this point of view the concept of dominant discharge is of questionable significance. Leopold and Maddock prefer to use a discharge of a particular frequency of occurrence for comparing the hydraulic geometry of streams. For several American streams investigated by Leopold and Maddock, it was found convenient to use the mean annual discharge for studying the variation of hydraulic geometry along the river. For these streams the mean annual discharge was found to be equalled or exceeded about twenty five per cent of the time. Nixon has used the bankful discharge of a stream for comparing the geometry of streams in England and Wales. For regime streams in these countries Nixon found the frequency of bankful discharge to be approximately the same and having an average value of 0.6 per cent. As this frequency is a function of the climatic conditions and the drainage characteristics which are highly variable, departures from the above value are likely in many streams. For instance, the recurring interval of the bankful discharge is found to be 1.5 years for several American streams. Schaffernak has introduced the term *bed generative discharge*, defined as the discharge that transports the largest volume of coarse material. *

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Fig. 5.27(a) shows the frequency-discharge curve for a given stream. Fig. 5.27(b) shows the relationship between the water discharge and sediment transport.

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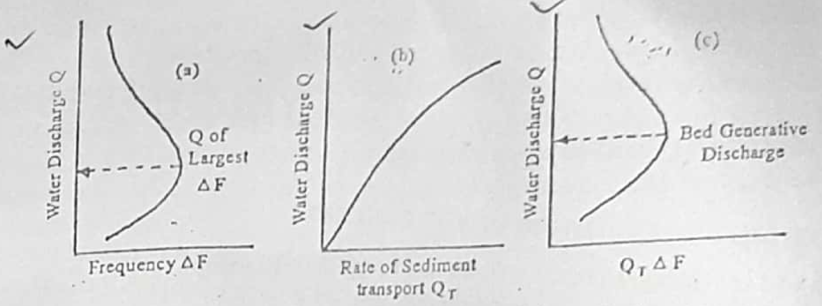

Fig. 5.27 Determination of bed generative discharge

In Fig. 5.27(c) the abscissa is obtained by multiplying the frequency ΔF *of* a particular discharge Q by the corresponding sediment transport rate Q_T. The discharge which gives the maximum value of Q_T ΔF *is* the bed generative discharge and is supposed to influence the channel geometry. NEDCO recommends finding the depth D_0 corresponding to the dominant discharge using the equation

$$D_0 \int_0^T Q_B \, dt = \int_0^T Q_B \, D dt$$

$$\text{or,} \qquad D_0 = \frac{\int_0^T Q_B \, Ddt}{\int_0^T Q_B}$$

in which Q_B is the bed load transport rate. Gondalfo found that the bed generative discharge is greater than the discharge corresponding to the average sediment transport rate and that the latter is greater than the mean annual discharge. The definition of dominant discharge according to U.S.B.R. is the same as that of bed generative discharge by Schaffernak except that in the latter case there is no restriction on sediment size.

CHAPTER – 6

CYCLE OF EROSION

6.1 ORIGIN AND EVOLUTION OF THE CONCEPT

At the end of nineteenth century Davis has envisaged the concept of cycle of erosion which has been regarded in the geomorphological field as a basic concept in the landform study. According to him the landforms undergo a progressive change from the initial through sequential to ultimate form by the processes of denudation within a definite period. Therefore, the heights of landforms like hills, plateaus, plains are gradually lowered down and the form of land surface is developed depending upon the degree of processes of erosion.

The earth's surface is affected by two types of forces viz. (i) endogenetic forces and (ii) exogenetic forces wherein endogenetic forces create vertical irregularities on the earth's surface by forming several types of relief features of different dimensions whereas exogenetic processes originating from the atmosphere (rivers, wind, glaciers, sea waves, groundwater, periglacial processes etc.) try to remove the vertical irregularities created by the endogenetic forces and ultimately become successful in bringing down the reliefs to low featureless plain called as a peneplain. The whole period of the creation of relief features by endogenetic processes and their destruction by exogenetic processes is called cycle of erosion which Davis defined as follows, "Geographical cycle is the period of time during which an uplifted landmass undergoes its transformation by the process of land sculpture ending into a low featureless plain- a peneplane".

The concept of 'geographical cycle' of Davis was severely criticised by Germa geographers and the term 'cycle' was described as confusing and hence untenable. Walthe Penck though accepted the basic concept of cycle of erosions but rejected the Davisian mod of geographical cycle and propounded his own model of cycle of erosion. Inspite of sever criticism in Germany the Davisian model of geographical cycle of erosion was adopted b most of the contemporary and subsequent geomorphologists all over the world. It may b safely argued that Davisian model of cycle of erosion, say the first general theory of landfor development, dominated the entire field of geomorphology and geomorphologic investigations right from its inception in 1899 to 1950 throughout the world.

6.2 GEOGRAPHICAL CYCLE OF DAVIS

W. M. Davis (1894) established the well-known principle that the 'landscape can be analysed in terms of structure, process and stage. Structure means the underlying rocks on which the landforms are fashioned. Processes include mechanical and chemical weathering, mass movement, rainwash, river erosion, wave attack, glacial action etc. which are responsible to shape the landforms. Stage refers to the time during which these processes are acting on a definite rock structure. In this context in describing the life cycle of the landscape he used some new terms *youth, mature and old age.* Of course these ages are relative terms and cannot be related to an actual time scale. Land features are different in three different stages.

Davis theory may be expressed as follows-

"There are sequential changes in landforms through time (passing through youth, mature and old stages) and these sequential changes are directed towards well defined end product-development of peneplain."

Davis postulated his concept of **'geographical cycle'** popularly known as **'cycle of erosion'** in 1899 to present a genetic classification and systematic description of landforms. His 'geographical cycle' has been defined in the following manner.

" Geographical cycle is a period of time during which an uplifted landmass undergoes its transformation by the process of land sculpture ending into low featureless plain or peneplain (Davis called peneplane)."

According to Davis three factors viz. structure, process and time play important roles in the origin and development of landforms of a particular place. These three factors are called as **"Trio of Davis"** and his concept is expressed as follows–

"Landscape is a function of structure, process and time."

Structure means lithological (rock types) and structural characteristics (folding, faulting, joints etc.) of rocks. **Time** was not only used in temporal context by Davis but it was also used as a process itselfleading to an inevitable progression of change of landforms. **Process** means the agents of denudation including both, weathering and erosion (running water in the case of geographical cycle).

6.3 PENCK'S MODEL OF CYCLE OF EROSION

It may be pointed out that German scientist Walther Penck pleaded for the rejection of Davisian model of geographical cycle based on time-dependent series of landform development and presented his own model of 'morphological system' or 'morphological analysis' for the explanation of landscape development. The main goal of Penck's model of morphological system was to find out the mode of development and causes of crustal movement on the basis of exogenetic processes and morphological characteristics. The reference system of Penck's model is that the characteristics of landforms of a given region are related to the tectonic activity of that region. The landforms, thus, reflect the ratio between the intensity of endogenetic processes (i.e. rate of upliftment) and the magnitude of displacement of materials by exogenetic processes (the rate of erosion and removal of materials.)

According to Penck landform development should be interpreted by means of ratios between diastrophic processes (endogenetic, or rate of uplift) and erosional processes (exogenetic, or rate of vertical incision).

Following are the basic premises of Penckian model of landscape development–

1. The morphological characteristics of any region of the earth's surface is the result of competition between crustal movement and denudational precesses.
2. Landscape development is time-independent.
3. Tectonic movements can be explained and their casual factors may be ascertained on the basis of morphological characteristics.
4. The shape of the hillslope depends on relative rates of valley incision by rivers and removal of debris from hillslope.
5. There are three crustal states
    (i) State of crustal stability when there is no active displacement,
    (ii) State of initial dome uplift in a limited area followed by widespread uplift and
    (iii) State of extensive crustal upliftment.
6. There are three states of adjustment between crustal movement and valley deepening.
    (i) If crustal upliftment remains constant for longer period of time, the vertical erosion by the river is such that there is balance between the rate of upliftment and erosion,
    (ii) If the rate of uplift exceeds the rate of valley deepening, then the channel gradient continues to increase till the rate of valley deepening matches with the rate of upliftment and the state of equilibrium is attained when both become equal, and
    (iii) If the rate of valley deepening exceeds the rate of crustal upliftment, then the channel gradient is lowered to such an extent that the rates of upliftment and erosion become equal and the state of equilibrium is attained.
7. Upliftment and erosion are always coexistent.

The Penck's model of landscape development, as pointed out in the beginning, could not be correctly interpreted because of its publication in obscure German language and wrong interpretation of his ideas by English translators. Penck's morphological system was severely criticised in the USA in the same way as the 'geographical cycle' was criticised in Germany. His concept of long continued upliftment and tectonic speculations could not find any support but his concepts of slope development and weathering processes are definitely of much geomorphological significance.

6.4 NORMAL CYCLE OF EROSION

The cycle of erosion by fluvial processes (running waters or rivers) is called normal cycle of erosion because of the fact that fluvial processes are most widespread (covering most parts of the globe) and most significant geomorphic agent. Even water also plays important role in glacial, and arid regions. W. M. Davis considered humid temperate areas as the most normal case for fluvial cycle of erosion but this claim is debatable.

The normal cycle of erosion begins with the upliftment of any landmass with reference to sea level. As the land rises, the rivers are originated and their erosional work starts. The rate of uplift in the beginning far exceeds the rate of erosion with the result absolute relief (absolute altitude from sea level) and relative relief register increase. After some time upliftment of the land stops and erosion becomes more active. The land area, tectonically, remains stable i.e. there is crustal stability for long period of time during which there is neither upliftment nor subsidence of land area. There is progressive development of river valleys in sequential order and the whole land area progressively passes through three successive stages of youth, mature and old (senile or penultimate) and is ultimately transformed into low featureless plain of undulating surface. Thus, the penultimate end product of normal cycle of erosion is called *peneplain* which is characterized by undulating surface with residual convexo-concave low hills known as *monanocks, unakas* and *mosores.* Thus, the land area has to pass through the successive stages of its development right from the upliftment of landmass to its transformation into peneplain of exceedingly low reliefs.

W. M. Davis has divided the whole duration of normal cycle of erosion into three successive stages of youth (juvenile), mature (equilibrium) and old (penultimate or senile) and each stage has been further divided into three substanges e.g. early, middle and late (for example, early youth, middle youth and late youth and so on). Thus, the landscapes also become young, mature and old with the advancement of normal cycle of erosion. Like landscape development through three successive stages, the development of river valleys also passes through three successive stages of their development and the rivers become young or youthful rivers, mature rivers and old rivers. The following are the characteristic features of successive stages of the normal cycle or erosion.

1. It has been found that certain streams exhibit alternating reaches of youth and maturity. If the geological formations consist of erosion-resistant rock, the stream takes a longer period to attain a graded profile. On the other hand, the stream may attain maturity earlier in stretches having geologic formations susceptible to erosion.
2. In their natural state, many streams show a condition of apparent equilibrium as exhibited by the stability of their alignments and slopes. Available data over a period of years do not show significant changes in the mean characteristics of the stream. In contrast to such stable streams there are also streams such as the Yellow river in China, the Brahmaputra in India and Bangladesh and the Kosi rivers in India, which can be classified as unstable streams.

The Yellow river is a peculiar stream carrying as much sediment as water during floods; its silt content is of the order of 50 percent by weight. The stream is estimated to carry about 1260 million cubic meters of sediment annually from its drainage area. The river is unable to carry such heavy load to the sea. Much of it gets deposited within the dikes constructed for controlling the floods thereby resulting in a gradual rise of stream bed within the dikes. The Kosi river in India is also extremely unstable. It is widely known for the changes in its course. It shifted laterally from east to west through 110 km over a period of 200 years.

6.5 VARIOUS STAGES OF STREAMS

The various stages of streams are determined by the characteristics they exhibit. The following are the characteristic features of successive stages of normal cycle of erosion:

6.5.1 Youth Stage

According to generally accepted concepts, a young stream is always able to erode its channel in the vertical direction, the slope of a young stream is always greater than the slope necessary to carry the sediment load coming into it. Because of its ability to cut its bottom downwards, a young stream usually flows through V-shaped deep ***gorges*** or ***canyons***. There is no flood plain for young streams and they occupy the entire floor of the valley at all stages. Other characteristics of the young stream include presence of rapids and waterfalls, steep and varying gradients, and presence of lakes. Streams meandering may exist but these are closely confined in valleys. According to Johnson early youth ends when the lakes are eliminated and middle youth ends when falls and rapids are eliminated.

6.5.2 Mature Stage

The stream becomes mature when it stops cutting down the bed and starts widening. Vertical corrasion reduces and the lateral erosion becomes significant, as a result the broad stream divides gradually and becomes sharp and ridge-like in form. A considerable portion of flood plain is found along the valley floods. Lakes and swamps of the youth stage, as found in interstream areas, have been eliminated.

Another important feature is the reduction of the relief or in other words a decrease in the vertical height (relief) separating interfluve summits and valley floors. This is the reverse form of the youth when the valley bottoms are lowering down by vertical Incision and initial surface remains as unaffected stream-divide.

The long profile of the river becomes even more gentle and Davis suggested that a river attains a graded condition during this early mature stage. Meanders may be conspicuous and they are free to shift their positions over the flood-plains.

The slope of the stream is reduced to such an extent that the hydraulic conditions are just adequate to transport the sediment brought from the upstream reaches and that resulting from bank erosion. If sediment load is in excess of the transport rate of the stream, sediment is deposited in the upstream reaches and the stream slope reduced. Hence a mature stream adjusts its slope delicately. It is in the stage of maturity that the streams follow sinusoidal of meandering path in plan. According to Lobeck, full maturity is attained when the width of the valley floor equals the width of the meander belt. The width of the meander belt, in turn, is approximately ten to twenty times the width of the river.

A ***mature stream*** is many times known as a ***graded stream, poised stream, balanced stream, stream in regime*** or ***stream in equilibrium***. Mackin has defined a graded stream as follows.

> *A graded stream is one in which over a period of years, slope is delicately adjusted to provide, with the available discharge and with prevailing channel characteristics, just the velocity required for the transportation of*

the load supplied from the drainage basin. The graded stream is a system in equilibrium.

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Lobeck lists the following characteristics of mature streams:

1. Flood plain with natural levees; নদীতীরের বাঁধ
2. Meanders with abandoned meander scrolls, cut offs and oxbow lakes; [illegible]
3. Width of the valley equal to or greater than width of meander belt;
4. No rapids of falls
5. Slow moving currents of muddy water;
6. Subdued valley walls, with deep soil cover and few rock outcrops; and [illegible]
7. No lakes except oxbow lakes.

[illegible]

6.5.3 Old Stage

A stream whose tributaries are all mature or graded is known as an *old stream*. There are no significant changes in the characteristics of mature and old rivers. Usually in old age the valley is wider than in the mature stage because of the lateral migration of the mender-belt across the flood plain.

By extensive lateral erosion a broad and gently sloping, both laterally and longitudinally, valley is formed. In course of time these nearly level valley floor are covered by the flooding alluvium and form a flood-plain over which the stream *flows in* meandering course. Interstream areas are reduced in height and the stream- divides become smooth and rounded hills.

Lakes, swamps and marshes are present in the flood plain, not in the interstream areas as in youthful stage. Davis has postulated that at the end of old stage an extensive slightly undulating plain is developed at or near the base level of erosion and it is termed ***peneplain***. Here relief is almost destroyed and the initial surface remains as few residual isolated hillocks which are referred to as ***Monadnocks***.

The ultimate aim of all this transformation is to erode the landmass to such an extent that movement of sediment ceases. This stage is achieved after millions of years. During this period, no portion of the stream is in equilibrium in the strictest sense, because the material is being continually eroded from the high regions and brought down to low regions. However, since engineers concerned with river problems think in terms of a few hundreds of years at the most, hydraulically the stream can be considered to be in equilibrium, even though geologically it is not so.

CHAPTER - 7

FACTORS AND PROCESSES

The land surface is sculptured by the river action and there are mainly three types of rive
action e.g. erosion, transportation and deposition. The running water of the river erodes the
rocks of the bed and bank, then these materials are transported by the stream flow and
lastly sediments are deposited. Most of the fluviatile landforms of the earth surface are the
result of these three actions. Depending upon the climatic, lithologic and the velocity of the
flow the stream acts through different processes in different places along a river course.

7.1 FACTORS INFLUENCING RIVER ACTIONS

The nature and extent of river erosion, transportation and deposition are influenced by various factors.

1. **Climate:** It controls the nature of river flow i.e. whether it is perennial, non-perennial, ephemeral or intermittent. The nature of precipitation determines the volume and the velocity of a river. The erosive power of a river largely depends upon the velocity. It has been estimated that if the velocity be doubled the erosive power will increase four times; because it is seen that keeping all other factors constant the velocity varies as the square of the abrasive power of a river.
2. **Surface relief:** It denotes the height of the surface unit above the base level of erosion which determines the potential erosion power of the river. Therefore, greater erosion is found in the highland region compare to the low-land which is near to the base level of erosion. On the other hand deposition is prominent in the low-land region.
3. **Nature of bed rock:** It is common that the river erodes mostly those areas where bed rocks are soft or of poor resistance to erosion. The solubility of the materials composing the bed rock also determines the rate of erosion. If the bed rock is composed of non-soluble materials, the river cannot erode them easily. On the other hand if the river flows over a soluble bed rock like limestone, then the river erosion is maximum. Maximum deposition is expected to occur in the lower reach of a river if it is flowing over easily soluble or erodable rock beds.
4. **Structure:** Nature of river actions depends upon the rock structure. Horizontally layered sedimentary rocks are more easily eroded away than that of the vertically aligned one. In uniclinal structure where the inclinations of the rock beds are in river flow direction,

there, greater erosion is desirable. In the folded region fractures are commonly found in the anticlinal crest due to tension which supports greater erosion. On the other the synclinal valley is the zone of compression which resists erosion to some extent.

5. **Presence of joints & fissures:** Presence of joints and fissures in the bed is the most determinant factor of river erosion, transportation & deposition. On a highly jointed and fissure dominated area, water can easily penetrate to a greater depth and flow to a large area horizontally. As a result a great area will be exposed to erosion. By subsequent weathering & erosion highly jointed bed rock supplies fragments of rocks which act as tools for erosion and later deposited as sediments.

6. **Load:** The actual erosion & transportation power of water in a river is to some extent modified by the transport materials along its course. A riiver is only effective as a geomorphic agent when it has the ability to carry sediments. The load may be in solution (dissolved), suspension or bed load form. Along with velocity of a river water the size and shape of the load are also the most important factors of river erosion, transportation and deposition. Apart from size and shape, the hardness of the load is another determining factor in river mechanism. If the loads are of physically hard material, mechanical erosion occurs mainly and greater erosion supports maximum transportation as well as deposition. On the contrary, soft materials can do very little erosion as they are likely to be worn down easily. Reverse is true in the case of bed rock.

7. **Nature of the wetted perimeter:** The river in a broader channel of shallow depth, i.e. greater wetted perimeter or small hydraulic radius (Fig. 7.1), exerts lesser erosion than a river in a deep narrow channel with large hydraulic radius or minimum wetted perimeter (Fig. 7.2).

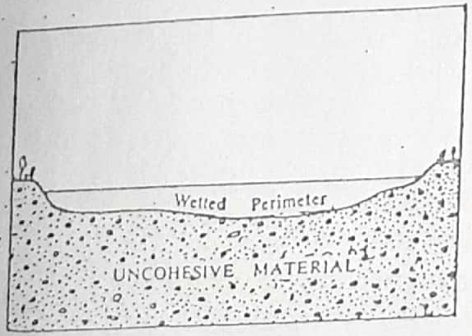

Fig. 7.1 Small hydraulic radius

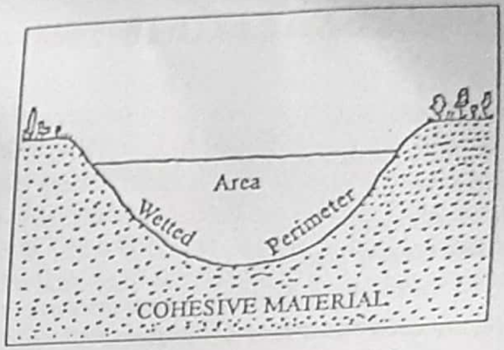

Fig. 7.2 Large hydraulic radius

8. **Nature of river regime:** Rivers which have great variations in velocity and volume ca perform more erosion than those which have uniform flow throughout their life histor Rivers of landslide-prone areas support more erosion, transportation & deposition tha any others of landslide free areas. Landslides disturb the normal flow of a river an supply huge ready sediments. Floods may occur sometime, due to major landslides, i those river courses. During floods the volume of a river becomes tremendous whic supports almost double velocity power. Therefore, river is more destructive at times o flood. Two rivers of same volume and catchment area but with a different basin slope, perform different erosion, transportation and deposition.

9. **Nature of the river current:** Irregularities on the river bed and side-walls creates many changes in direction and velocity of there currents. River with greater whirling currents imparts more erosion and supplies greater loads of transportation & deposition. Constricted flow, i.e. in some parts of river the valley widths are shortened by the presence of hard rock across its course, exerts greater erosion and -presence deposition just on the down slope of it.

10. **Time:** Evolution history of the river is a most noticeable factor in erosion, transportation and deposition. If any river is situated within an intermittently uplifted area then that river holds a complex erosional, transportation and depositional processes. River in a youth stage does more erosion than deposition and the river of old age has more deposition than erosion. Transportation is noticed in every stage but with different magnitudes. Different geological times deserve different river actions. Nature of river erosion, transportation and deposition during carboniferous period differs from the

Pleistocene (glacial) period. Besides actions, the magnitudes of mechanism also differ from period to period.

11. **Nature of the river water composition:** The presence of some dissolved materials and gases in river water are very important factors. Though water is a good solvent still its dissolving power is more when there are same suitable materials in solution with it. Temperature of the water controls the buoyancy of the loads. In cold water the rate of buoyancy of suspended load is greater. Mixing of water of different temperature and characters determines the nature of erosion, transportation and deposition.

12. **Human interferences:** Since human civilization, man utilizes the river in many ways. To control its hazards man constructs- dams, canals, embankments on its course. These human interferences have marked impact on its normal processes of development. As a result of these non-desirable erosion & deposition side by side, disturbed transportation have been noticed.

CHAPTER - 8

FLUVIAL GEOMORPHOLOGY

The work of running water in the from of ***surface runoff*** or ***overland flow*** and streams is most important of all the exogenetic of planation processes (e.g. groundwater, sea waves, glaciers, wind, periglacial process etc.) because the running water is the most widespread exogenetic process on this planet earth. The landforms either carved out (due to erosion) or built up (due to deposition) by running water are called ***fluvial landforms*** (both erosional and depositional) and the running waters which shape them are called ***fluvial processes*** which include overland flow (surface runoff) and stream flow.

The rainwater reaching the earth's surface becomes ***surface runoff*** when it spreads laterally on the ground surface. The surface runoff becomes a stream when water flows from certain height down the slope under the impact of gravity. Streams are generally divided in four broad categories viz. perennial or permanent streams, non-permanent or seasonal streams, intermittent streams and ephemeral streams. The geological works of fluvial processes or rivers are called ***three-phase work*** comprising ***erosion, transportation*** and ***deposition***. The fluvial landforms are divided into two major groups e.g. **(1) erosional landforms** and **(2) depositional landforms**. The landforms resulting from progressive removal of the bedrock mass are called erosional landforms e.g. various types of valley (viz. gorges, canyons, broad and flat, mature and senile valleys, multi-storied valleys etc.), pot holes, rapids and waterfalls, structural benches, terraces, meanders etc. The landforms shaped by the deposition of different types of eroded materials become depositional landforms such as alluvial fans and cones, natural levees, flood plains, terraces, deltas etc.

8.1 EROSIONAL WORK OF RIVERS

The word '*erosion*' has been derived from a Latin word, '***erodere***' which means to gnaw. Erosion is, in fact, a dynamic process which involves the removal of geomaterials from the rocks and other deposited materials. Stream erode because they have the ability to pick up rock fragments and transport them to a new location. Though weathering greatly assists in the erosion of rocks but it is not a prerequisite condition as remarked by W.D. Thornbury, "*It is true, of course, that weathering is a preparatory stage and may make erosion easier, but it is not prerequisite to nor necessarily followed by erosion*". In fact, "*erosion is that process in which various erosive agents (running water-river, wind, glacier, periglacial, sea* *waves and groundwaters) obtain and remove rock debris from the earth's crust and transport them for long distance"*(Savindra Singh, 1973).

The erosional work of the rivers depends on *channel gradient, volume of water, velocity and thus kinetic energy, water discharge, river-load (tools of erosion) etc.* The quantity, size and calibre (angularity) of erosional tools (river load) largely control the nature and magnitude of fluvial erosion. The erosional tools of fairly big size and high calibre (with high degree of angularity) help in active down cutting of valleys. The size of river load is of paramount significance because if the load consists of very fine sediments, they move with the water in suspension (suspended sediment load) and hence become passive in fluvial erosion but if they are of fairly big size, they roll down along the valley floor and help in valley deepening. The amount of load should be of optimal level i.e. the rivers should neither be overloaded nor underloaded because if the river is overloaded in relation to its transporting capacity, it would start deposition of additional load and if the river is underloaded, the erosional work becomes negligible. The following relationships may be identified between the rate of fluvial erosion and river load:

1. Erosion becomes minimum in the absence of required amount of river load (underloaded river).
2. Erosion also becomes minimum when the river has maximum load (overloaded river).
3. Erosion becomes maximum when the river carries load according to its transporting capacity.

The law of erosion states that the rate and amount of erosion increases before the attainment of equilibrium between the transporting capacity of the river and its load while it decreases after the attainment of their equilibrium condition.

It may be pointed out that besides the river load, velocity and channel gradient are also significant parameters which effectively control fluvial erosion. Erosion becomes maximum when the river having steep channel gradient and optimal amount of load of good size and high caliber flows with high velocity. The velocity of water flow depends on *(i) channel gradient and (ii) volume of water.* Normally, the erosional power of the stream is proportional to the square of the velocity which [*erosional power* $\propto$ *(velocity of the stream)*^{2}] means if the velocity is doubled, the erosional power of the streams increases four times, if the velocity is increased 4 times, the erosional power increases 16 times and so on. Besides, lithological and structural characteristics of geomaterials also affect the nature and magnitude of fluvial erosion.

8.1.1 Types of Fluvial Erosion

The erosional work of the rivers is performed in two ways viz. ***(i) through chemical erosion and (ii) through mechanical erosion.*** Chemical erosion involves corrosion or solution and carbonation while mechanical erosion comprises corrasion or abrasion, hydraulic action and attrition. Fluvial erosion is also divided into ***(i) vertical erosion or down cutting (which leads to valley deepening) and (ii) lateral erosion (which causes valley widening).***

1. Corrosion or Solution

Corrosion or solution involves the dissolution of soluble materials through the processes of disintegration and decomposition of carbonate rocks. The soluble materials are removed from the parent rocks and are mixed with the running water of the streams. Most of the salts are removed from the bedrocks through the process of carbonation and are suspended in river water. According to the estimate of Murray every cubic mile water of the river contains about 7,62,587 tons of suspended minerals of which about 50 per cent is calcium carbonate. On an average, the world rivers discharge about 6,500 million cubic miles of water into the oceans every year. On the basis of Murray's estimate it may be inferred that about 5 billion tons of minerals are removed from the bedrocks by the world rivers each year and these minerals are carried to the seas and oceans in solution.

2. Abrasion or Corrasion

The removal of loosened materials of the rocks of valley walls and valley floors with the help of erosional tools (boulders, pebbles, cobbles, gravels etc.) is known as ***Abrasion*** or ***Corrasion***. The erosional tools or river loads move down the channel gradient along with water and thus strike against the rocks which come in contact with them. The repetition of this mechanism weakens the rocks which are ultimately loosened and broken down. Thus, abrasion is the mechanism of breakdown of rocks occasioned by erosional tools carried by the rivers. The nature and magnitude of abrasion depends on the nature, size and calibre (angularity) of erosional tools. Boulders, cobbles and pebbles of various sizes and angularity are by far the most important tools of erosion which are generally called ***drilling tools***. The erosional mechanism of abrasion operates in two ways e.g. *(i) vertical erosion leading to the erosion and deepening of valley floors and (ii) lateral erosion leading to the erosion of valley walls.* Lateral abrasion causes valley widening while vertical abrasion leads to valley deepening wherein the erosional tools drill the valley floor through the mechanism of ***pothole drilling*** resulting into the formation of numerous pot holes (cylindrical depressions) of various sizes in the valley floors. Vertical abrasion (down cutting) becomes more effective during the juvenile stage (youthful) of river and valley development when channel gradient and velocity are very high.

3. Attrition

Attrition is the mechanical tear and wear of the erosional tools in themselves. The boulders, cobbles, pebbles etc. whole moving with water collide against each other and thus are fragmented into smaller and finer pieces in the transit. Thus, the rock particles are so broken down that ultimately they are comminuted into coarse to fine sand particles which are transported down the channel in suspension.

4. Hydraulic Action

It involves the breakdown of the rocks of valley sides due to the impact of water currents of channel. In fact, hydraulic action is the mechanical loosening and removal of materials of rocks by water alone. It may be pointed out that chemical weathering, abrasion and hydraulic action are so intimately interrelated that it is unwise to think of pure hydraulic action without chemical erosion and abrasion.

8.1.2 Erosional Landforms

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The significant landforms resulting from fluvial erosion by streams include ***river valleys, water falls and rapids, pot holes, structural benches, river terraces, meanders, peneplains*** etc.

1. River valleys

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The valleys carved out by the rivers are significant erosional landforms. The shape and dimension of fluvially originated valleys change with the advancement of the stages of fluvial cycle of erosion. The valley formed in the youthful stage of fluvial cycle of erosion and in the initial stage of valley development is V-shaped having steep valley side slope of convex element. The valley is very deep and narrow, both the valley sides meet together at the valley floor and thus water always touches the valley sides. Such type of V-shaped valleys are the result of accelerated rate of downcutting (vertical erosion or valley deepening). The valleys are gradually widened due to lateral erosion with the advancement of the stage of cycle of erosion and they become quite broad with flat valley floor and uniform or rectilinear valley side slopes during mature stage of valley development and fluvial cycle of erosion. They are further transformed into very broad and shallow valleys having concave valley side slope of very gentle gradient during old stage. V-shaped valleys are divided into two types viz. (a) **gorges** and (b) **canyons.**

(a) **Gorges:** Gorges and canyons represent very deep and narrow valleys having very steep valley side slopes say wall-like steep valley sides. It is difficult to draw a line of distinction between these two types of valleys. Normally, a very deep and narrow valley is called a gorge and the extended form of a gorge is called a canyon. Gorges are formed due to active down cutting of the valleys through the mechanism of pothole drilling during juvenile (youth) stage of the fluvial cycle of erosion. Gorges are also formed due to recession of waterfalls. Most of the Himalayan rivers have carved out deep and narrow gorges.

(b) **Canyons:** Canyons are extended form of gorges. Canyons represent very deep, narrow but long valleys. The steepness of the valley sides depends on the nature of the rocks. Relatively resistant rocks alternated by soft rocks give birth to undulating valley sides. The Grand Canyon of the Colorado river in the state of Arizona (USA) having a length of 482.8 kilometers and depth of 2088.3 m is one of the most important canyons of the world. The Indus river has cut across the Himalayan ranges and flows through 5181.7 m deep gorge and canyon.

2. Waterfalls

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Waterfalls or simply falls are caused because of sudden descents or abrupt breaks in the longitudinal course of the rivers due to a host of factors e.g. *variation in the relative resistance of rocks, relative difference in topographic reliefs, fall in the sea level and related rejuvenation, earth movements etc.* A ***waterfall*** may be defined as a vertical drop of water of enormous volume from a great height in the long profiles of the rivers. ***Rapids*** are of much smaller dimension than waterfalls. Generally, they are found upstream from the main falls but they are also found independently.

3. Pot Holes

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The kettle-like small depressions in the rocky beds of the river valleys are called potholes which are usually cylindrical in shape. Pot holes are generally formed in coarse-grained rocks such as sandstones and granites. Eddies are found and the water whirls around and produces depressions by plucking the sediment up. This makes the depressions deep and cylindrical. Sometimes these depressions look like discs and are known as ***pot holes*** (Fig. 8.1). Stone pieces also enter the pot holes along with the water and help water in boring and cutting the holes. These stone pieces are called ***grinders.*** Pot holing or pothole drilling is the mechanism through which the grinding tools (fragments of rocks e.g. boulders and angular rock fragment) when caught in the water eddies or swirling water start dancing in circular manner and grind and drill the rock beds of the valleys like drilling machine and thus form small holes which are gradually enlarged by the repetition of the said mechanism. During the process of grinding, these grinders are themselves rounded and are eroded into small pieces. When a grinder becomes small another grinder enters the pot holes. Hence, *every pot hole contains at least one grinder*. These pot holes have a diameter varying from few centimeters to many meters. The depth of a pot hole is greater than its diameter. Pot holes as deep as 7.6 meters have also been located. When these pot holes grow in size, they are called ***plunge pools***. The pot holes and the plunge pools do not exist for a long time in soft beds but they are pretty stationary in hard rocks. Gradually many pot holes and plunge pools form on the bed of the stream. At the time of the flood the water flow becomes very strong very strong and breaks down the walls between adjacent pot holes and plunge pools and the sediment is carried away. Due to the destructions of the pot holes and plunge pools, the floor of the stream is lowered and the stream becomes deeper. Pothole drilling is the effective mechanism of valley deepening. The deepening of the stream floor by the destruction of pot holes, etc., is an important phenomenon in the development of the river cycle.

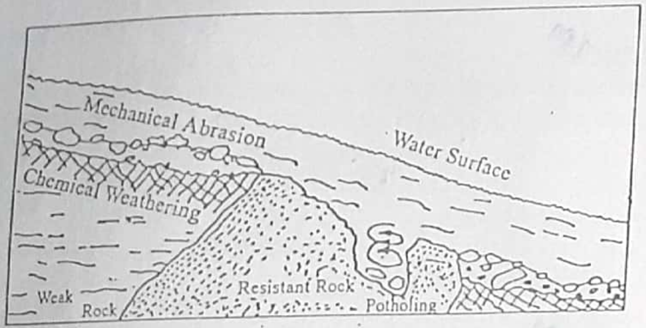

Fig. 8.1 Pot hole formation

Some people call these pot holes and plunge pools as ***Devils Punch Bowl or Witches Cauldron*** because they think that such formations are due to the work of supernatural power.

IM 4. River Terraces ✱✱✱ Exam

Stream terraces are elevated portions of a floodplain created when the stream down cuts and creates a new floodplain at a lower elevation. Stream terraces are important indicators

of environmental change. Down cutting can be initiated by uplift of the land surface due to tectonic activity, increased flow, or a loss of sediment load.

Some times, the river valleys are frequented by several terraces on either side wherein they are arranged in step-like forms. River terrace is a former flood plain abandoned when the river by deepening its channel could no longer inundate this surface. The term terrace includes the flat tread and the scarp (Fig. 8.2). Flood plains are generally formed when lateral channel migration is prevalent and downcutting is negligible. Such a situation occurs in the absence of tectonic movements or changes in base level or climate. However, any change in climate or sea level or tectonic uplift may lead to rejuvenation and downcutting by rivers. Under these changed conditions the old flood plain is converted into a terrace by river incision (Fig. 8.2 A). All terraces therefore are basically erosional features, although the terrace material may be depositional.

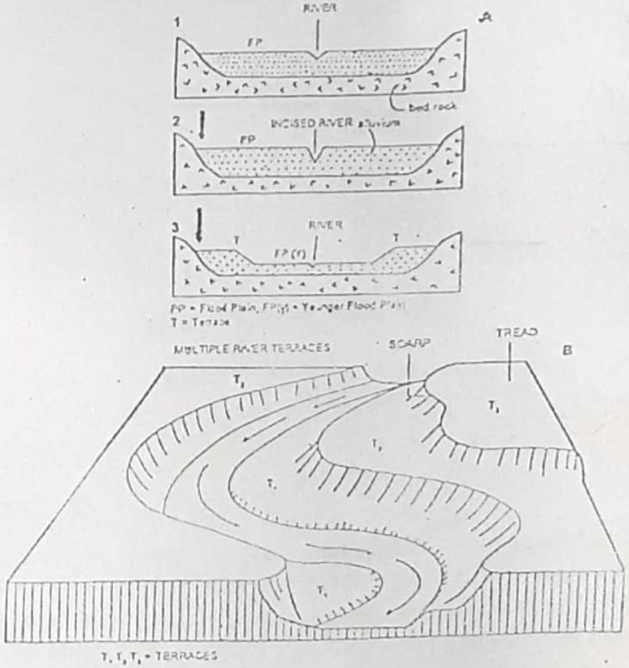

Fig. 8.2 River Terraces (A) stages in the development of river terraces. (B) Multiple terraces

5. Straight Fluting

It is most interesting erosional feature within the river bed. It is mainly found where grinding is quite powerful but more directional in minimum turbulent current. Sometimes it is accompanied by pothole at the front edges.

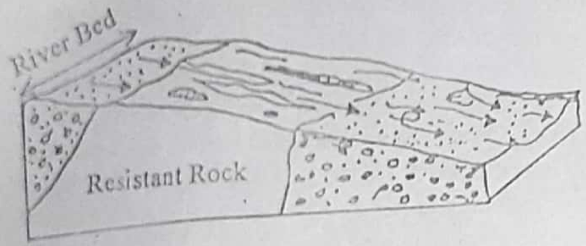

Fig. 8.3 Straight Fluting

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6. Gully

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The formation of gullies is the beginning of stream erosion. Gully erosion is the most important headward erosion process. When gullies form on hill sides, they incise deeply into the slope. Recession of the head cut leads in time to the coalescence of the individual gully sections and the formation of a unified channel. In other word gullies grow to ravines and the ravines develop into valleys (Fig. 8.4).

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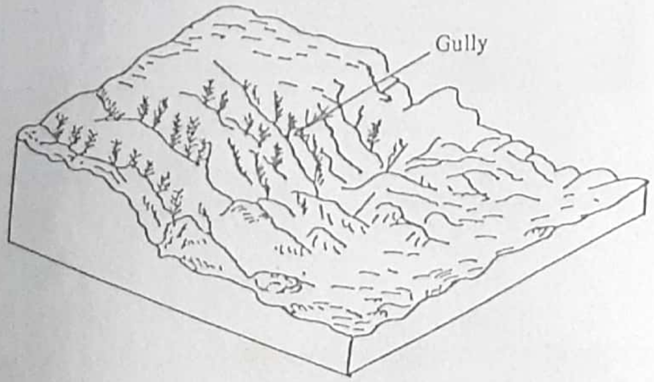


Fig. 8.4 Gully

7. Knickpunket or Knickpoint

It is an interesting feature which denotes the history of a river. It originates in the case of falls of base level. There are some raised surfaces in the valley and plains. The surfaces are formed by erosional activity. Scientists think that these landforms have been formed by upliftment, before the cycle of erosion was completed. On account of the upliftment, the section of the river at the upliftment attains youthful stage and the peneplain which existed before the upliftment, begins to be eroded. The remnants of the eroded peneplain is called *Knickpunket* (Fig. 8.5). The American scientists do not agree with it. They think that these are the remnants of the resistant areas which have stood the erosional activity.

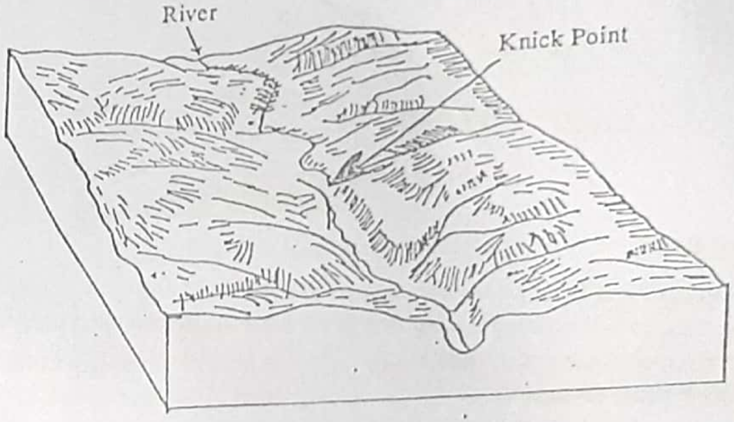


Fig. 8.5 Knickpoint

Nickpunket is known as *knickpoint* in English. These are also known as ***rejuvination head.*** The river accelerates erosion due to rejuvenation so that the nickpoint recedes. Springs or rapids are formed at the nickpoint

8. Plunge Pool

Sometimes a waterfall, cataract or rapid may develop at the knick point which is the break in the long profile of the river. Due to the fall of the high flush of water from the top, plunge pools are prominently developed at their bases (Fig. 8.6), the sizes of which vary with the size and the force of the falling water above them. This bowl-shaped feature is known as *deep pool.* In such cases, the basai pool easily extends backwards to undercut the feature which may latter collapse the hanging above portion to effect the retreat of the waterfall.

This process generally leaves behind a narrow, steep-sided valley which represents the headward progression of the waterfall. The Noa-kali-kai falls near Cherapunji, Meghalaya, India is a good example of this.

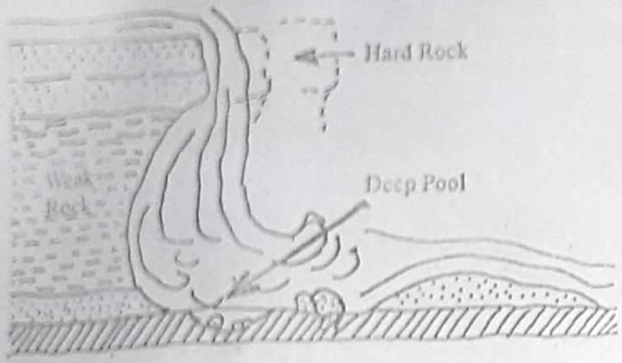
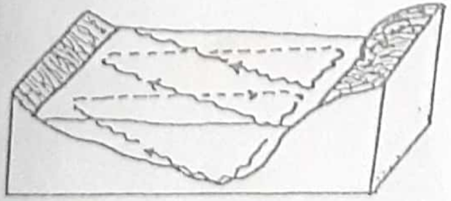


Fig. 8.6 Plunge Pool

9. Undercut Bank

Evidence of an undercut bank is very common on the astride of any river mainly from her mature stage. Due to undercutting by river flow at the base the overhanging bank will slump down to the river or come under mass wasting. By this process oscillation of meander or widening of river width takes place.

The mechanism by which a meandering stream erodes outer banks seems related to the helicoidal (spiral) flow (Fig. 8.7).



Helicoidal Flow

Fig. 8.7 Undercut bank

10. Karst Landform Features

Chemical erosion is the real importance in the development of valleys in limestone rocks; landforms like gorges, dry valley, cave, karst window, uvalas etc. are most remarkable erosional features (Fig. 8.8).

Fig. 8.8 Karst landform features

11. Monadnock

It is a typical land feature in riverine environment. Along with weathering and other erosional processes fluvial erosion is most spectacular for its development. The rounded small scattered hills of the old stage of a river valley are known as monadnocks.

12. Cuesta: In the old age, the valley has already been eroded to a plain but there are a few landforms which act as interruptions to the uniformity of the place. They have a gentle dip-slope on one side and a steep escarpment slope on the other side. The gentle dip-slope is towards the mouth of the river while the steep escarpment slope faces the direction of the origin of the river. Such features are known as ***Cuesta.*** Penk think that a cuesta is formed by an upliftment in the course of the river. Others have a different opinion. They think that the cuestas are the remnants of the resistant part of the land which could not be eroded by the river.

13. Pools and Riffles

Pools and riffles, along the stream channel are the smallest erosional features in the crystalline rock areas. These are formed due to the erosion of the sediment dunes in the river beds by the stream flow. During the low flow, resistance to flow is great, and the rate of sediment transport is reduced then the formation of pools and riffles are maximum. These are temporary features, as during high flow the bed surface becomes smooth or plain (Fig. 8.9).

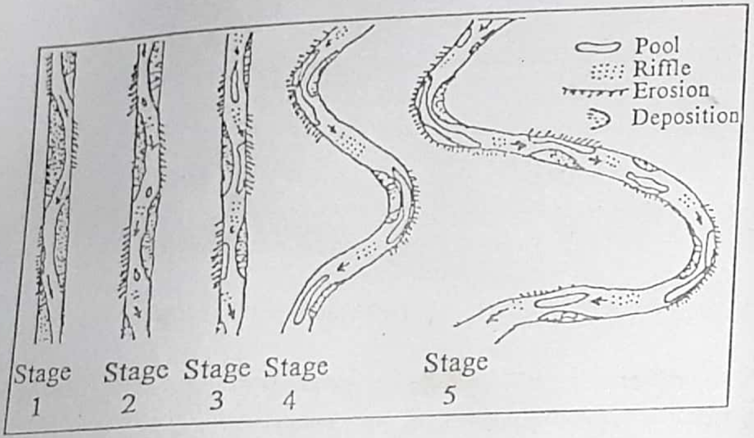


Fig. 8.9 Pools and Riffles

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8.1.3 Effects of Degragation

Degradation downstream of a dam or elsewhere has both beneficial and harmful effects. These effects are briefly discussed below.

1. For a given discharge, the tail water level is lowered as a result of degradation. If a hydraulic jump is formed below the spillway to dissipate the energy, the lowering of tail water will move the hydraulic jump downstream. In the extreme case the jump may not form on the apron and endanger the safety of the apron. This was observed on the Wisconsin river at Prairie Du Sac Dam (USA).
2. In case of dams on pervious foundation, the lowering of tail water level will increase the effective head, which is the difference between head and tail water levels. This increase must be anticipated at the time of design in the calculation of uplift pressures.

3. Increase in effective head means that greater head is available for power generation in case of a hydroelectric scheme. Such an increase in head may be anticipated and suitable provision made in the design. An increase in power due to such an increase in head has occurred at Praire Du Sac Dam on the Wisconsin river in U.S.A.
4. Lowering of the stream bed by degradation increases the capacity of the river channel to carry the flood flow, thereby lowering the high flood level of the river. Creating artificial degradation by construction of big reservoirs was a method that had been suggested as a possible solution to the flood problems of the Yellow river in China and the Kosi river in India.
5. Lowering of the water level due to degradation reduces the height of ground water table in the adjoining areas.
6. Lowering of water level may expose pile foundations of bridges, abutments and other structures to air and this may lead to deterioration of piling.
7. Degradation also causes lowering of water level at the existing irrigation intakes and thus makes the diversion of water for irrigation more difficult.
8. Degradation may cause substantial lowering of the bed in navigable rivers and in the extreme case locks may become inoperative.

8.1.4 Problems Associated with River Erosion

River is the most important gift of the almost all civilizations. Men utilise its water in many ways and cultivate on its deposited alluvial floors. But sometimes the erosion of the river generates many problems to man.

1. In down-cutting process channels are fingering deeper and deeper into the bed rock which support valley widening as secondary effect. In valley widening process mass wasting in uncohesive lithology, weathered mantle creeping etc. on valley sides are common. Villages, cultivated plots and forest wealth on the hill slope are damaged very often by these processes.
2. The headward erosion process of river trunk stream as well as some major tributaries supports the gradual extension of river basin area. Recession of the head cuts and gully erosion within the basin area encroaches the interfluves areas. Agricultural plots, settlements, forest belt on such an interfluve area are facing the problems of existence. For example, the gully erosion on the banks of Silai river, Midnapur district of West Bengal, India, is an alarming problem of the cashew nut jungle.

3. Water routes provide easy means as well as low cost of transport. Men utilise almost all navigable rivers for their communication purposes. But knick point, which is characterised by waterfalls, causes hindrance in navigation along routes.

4. Due to undercutting processes the banks on concave sides of a meander collapse. At some critical angle the bank slope becomes unstable and the upper part of the bank slides down or falls in. Settlements, agricultural plots, forest, communication lines like roads, telegraphic poles, railway lines etc. on such undercut sides of a meander have problems of permanent existence.

5. Sometimes the incision process of the river erodes away some valuable minerals in underneath structure. It is noticed that rivers erodes even the gold bearing and other important economic rock veins through their down cutting process. Subarnarekha river of Chotanagpur plateau has eroded away numerous valuable minerals.

6. Road networks, settlements and economic activities may be disrupted if the underlying limestone is eroded by river's chemical action. A bridge on a karst region is sometimes weakened by gradual enlargement of underneath solutional cavities through river water action.

7. Erosion caused on the right bank of the Ganges in Murshidabad district of West Bengal and drying up of the river's channel along the left bank might create border line problem between India and Bangladesh.

8.2 TRANSPORTATION WORK OF RIVERS

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The products of erosion are carried by the stream flow from one place to other. River transports not only its own erosional products but also the materials added to the flow due to landslides, slumping, avalanches or due to the carrying of the Wind. If we analyse the silt carrying capacity of the Ganges (90.000 tons/day), the Brahmaputra (more than 1,000,000 tons/day) and the Indus (1,000,,000 tons/day) then one can understand what a large quantity of materials can be transpored by the river.

The sediment load carried by the rivers is divided into (i) *suspended load* or *wash load,* and (ii) *bedload.* The bed load consists of particles of various sizes & shapes and is transported in total or partial contact with the channel bed by the mechanism of traction or saltation while suspended load involves finer particles which are kept in suspension in the fluid (water).

8.2.1 Methods of Transportation Work of Rivers

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Rivers transport their load in four different ways e.g. **(1) by traction, (2) by saltation, (3) by suspension and (4) by solution.**

1. **By traction:** The heavier and large rock fragments like gravel, pebbles, etc., are forced by the flow of water to roll on the floor of the channel. These fragments can be seen rolling, slipping and bumping. This is known as traction.

2. **By Saltation:** The fragments of the rocks move onward by jumping continuously. This is called saltation.

3. **By suspension:** When the rock fragments fall in the stream, their weight is reduced by the buoyancy of water. Usually the relative density of rock particles is 2.5. Their weight in the water is reduced by 2/5. The reduced weight of the fragments keeps them in suspension. The suspended rock particles are clay or silt. 90% of the load in the Mississippi river is found in suspension. Huang Ho (Yellow river of China) during floods is reported to have carried an amount of sediment equal in weight to the water that carried it. The amount of suspension in the rivers of dry areas is much more than that in humid areas.

4. **By Solution:** Some parts of the rock fragments are dissolved in the stream water. The dissolved substances of the underground water also enter the stream water later on.

8.2.2 Factors Affecting the Transport Power of a River

The transport of materials is influenced by three factors (1) velocity of the flow, (2) nature of the stream flow and (3) density and the buoyancy of the rock materials.

1. **Velocity:** Transporting power of a river varies directly as the sixth power of its velocity, that means when the velocity is doubled then the transporting power increases 64 times. This is suitable mainly for the transportation of the coarse materials and not the fine materials.

2. **Nature of the river current:** Suspended finer materials are carried by the river current easily. The heavier materials of the bottom can be transported by the forward current of the stream. In the pocket depressions i.e. in the potholes the whirling or roller currents are developed by which the materials are lifted up from the bottom. In the meandering channel by the helical flow the materials are transported from the steep side slope to the sloping sides of the stream. As the velocity is maximum at the central part of the stream because of less friction therefore maximum transportation of the particles is found at this central forward moving current.

3. **Density and buoyancy of the rock materials:** It is well known that every object loses its weight when it is immersed in the water. Thus the solid materials which have low specific gravity can remain suspended and easily carried by the river water. But the heavier materials deposit at the bottom and are also transported by the water as they are lighter in weight under water. If the water has not such buoyancy property then it is really difficult for the stream to carry large sized boulders. The presence of salts in river water increases the density of it which produces more buoyancy thus facilitating the transportation of the river.

The total load of a stream váries greatly from time to time and from place to place. The energy of a stream is not constant during flood the energy as well as the volume and velocity increase rapidly. Therefore the capacity of the stream to move the load has also increased. If the velocity is doubled then the capacity is eight times and it can transport huge load.

The availability of load of a stream largely depends upon nature of the topography on which it flows. In the clay dominant area rivers carry considerable amount of suspended loads, particularly during and after torrential rain. In the limestone and chalk area the solution loads are comparatively large. In the sand and gravel covered region, due to little tractional movement, amount of bed loads are also maximum. The nature of load and the process of transportation may also be affected by the distance from the stream source. In the source region stream generally flows over the steep gradients so that the amount of bed load of coarse material is maximum which can be transported easily by traction. Further downstream the size of the load decreases by different erosional processes and the loads are carried by saltation and suspension. In the mouth of the river particles become finer when the suspended loads are dominant. Lastly, time or stage of a river determines the nature and amount of stream loads. During the youth stage the relief is maximum and the rapid recession of steep slope determines the load of both coarse and fine. In the old age when the base level of erosion remains stable, relief is reduced and then the amount of total load of a stream will be decreased and the stream contains mainly the finer materials.

8.2.3 Transporting Power of a River

The size and amount of load and the velocity of streams determine their transporting power. The velocity of streams depends on channel gradient, form and nature of valley floors and valley walls, sinuosity of river course and volume and discharge of water. Steep channel gradient, less sinuous course, smooth valley floor and required amount of volume

of water increase the velocity of streams which in turn increases the transporting power of the streams.

G.K. Gilbert has propounded a law of stream transportation based on the relationship between stream velocity and its transporting power. The law is known as ***Gilbert's sixth power law*** according to which the transportation power of the streams is proportional to the sixth power of their velocity. In other words, if the stream velocity is doubled, the transportational power of the stream increases 64 times. This law can be expressed in the following form.

$$\text{Transportation Power} \propto (\text{stream velocity})^6$$

8.2.4 Competence and Capacity of a river

There are two characteristics of a stream relating to transportation: (i) Competence and (ii) Capacity.

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1. **Competence:** The competence of a river is measured by the largest rock fragment that stream can transport. The competence is proportional to the velocity of stream. The greater is the velocity of a river, the greater is its competence, *i.e.*, the larger and heavier fragments will be transported. Competence is proportional to the *sixth power* of the velocity of a stream. If the competence and the velocity of a stream are reproduced by C and V respectively:

$$C \propto V^6$$

Table 8.1 expresses the relation between the competence and the velocity of a stream.

Table 8.1 Relationship between the competence and the velocity of a stream

	Transported Material	Velocity of Stream (m/sec.)
1.	Fine sand particles	0.2
2.	Ordinary sand particles	0.3
3.	Coarse sand particles	0.4
4.	Gravel	0.6
5.	Pebble (Diameter 2.5 to 6.35 cm)	1.6
6.	Boulder (Diameter more than 25.4 cm)	11.7

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2. **Capacity:** The capacity of a stream is measured by the total load of the stream. If the rock fragments of the load are of ordinary type, the capacity is proportional to the *third power* of its velocity. If the fragments are finer, the capacity is proportional to a *higher power* and if the fragments are coarser, it is proportional to a *lower power* of its velocity.

The Mississippi river transports about 516 million tons of rock flour suspended in its water every year. It is estimated that all the rivers of USA, together transport every year about 800 million tons of sediment. If this sediment is loaded into and ordinary goods train, the length of the train is so much that this train would make 6 rounds of the earth along its equator. The rivers of the world transport so much dissolved material that it can cover the surface of the earth at the rate of 62 tons per sq. km. Total sediment transported is six times that of this quantity.

8.3 DEPOSITIONAL WORK OF RIVERS

Sudden changes in velocity can result in deposition by streams. Within a stream we have seen that the velocity varies with position, and, if sediment gets moved to the lower velocity part of the stream the sediment will come out of suspension and be deposited. Other sudden changes in velocity that affect the whole stream can also occur. For example if the discharge is suddenly increased, as it might be during a flood, the stream will overtop its banks and flow onto the floodplain where the velocity will then suddenly decrease. This results in deposition of such features as levees and floodplains. If the gradient of the stream suddenly changes by emptying into a flat-floored basin, an ocean basin, or a lake, the velocity of the stream will suddenly decrease resulting in deposition of sediment that can no longer be transported. This can result in deposition of such features as alluvial fans and deltas.

When the stream comes down to plain, its slope becomes gentle. This reduces the energy and the competence of the stream. As the competence decreases, the rock fragments begin to settle down. First larger fragment settle and, then, they are followed by smaller fragments. Due to the decreasing energy which hampers transportation the rock-flour starts settling down. This activity is known as ***deposition***. The deposition is not only dependent upon slope but also upon the amount of water. Deposition takes place either due to decreasing slope or the fall in the amount of water of the stream.

The deposition of load carried by the streams is effected by the following factors:

1. Decrease in channel gradient
2. Spreading of stream water over larger area

3. Obstructions in channel flow
4. Decrease in the volume and discharge of water
5. Decrease in the velocity of streams
6. increase in the load etc.

It may be pointed out that aforesaid factors of river deposition may be grouped into two categories:

1. decrease in stream velocity and
2. increase in river load.

The decrease in stream velocity reduces the transporting power of the streams which are forced to leave additional load to settle down. The stream velocity is decreased because of decrease in channel gradient (effected by subsidence of land or tilting of land due to diastrophic forces, expansion in the delta of the master stream, increase in sinuosity of the river course and tendency of streams to attain graded stage due to more and more erosion), spreading of water over larger area (due to decrease in channel gradient and overtopping of river banks at the time of floods), obstructions in the channel flow (due to damming of streams through accumulation of debris caused by landslides, formation of sand dunes in the river beds of alluvial streams, accumulation of logs and other wood pieces carried by the streams across the valley and transverse to the direction of channel flow, and sudden deposits of huge volume of materials), and decrease in the volume and discharge of water (caused by decrease in annual precipitation and consequent surface runoff due to climatic change, substantial loss of water through evaporation in hot dry regions, downward seepage of river water, diversion of substantial volume of water to other streams due to river capture, diversion of water through canals for irrigation, braiding of stream channels etc.).

Increase in river load is effected through

1. Accelerated rate of erosion in the source catchment areas consequent upon deforestation and thus increase in the sediment load in the downstream sections of the rivers,
2. supply of glacio-fluvial materials,
3. supply of additional sediment load by tributary streams,
4. gradual increase in the sediment load of the streams due to rill and gully erosion etc.

Fluvial sediments are laid down, and depositional landforms are developed at three dominantly or partially subaerial location: (1) topographic discontinuities, (2) valleys and the (3) margin of water bodies.

1. Topographic discontinuities are created by faulting, tectonic movements, glacial overdeepening, marine abrasion etc. Depositions of the moving water occur at these places and form the deposition of such features as alluvial fans, screes and talus slopes.
2. Valley fills develop the flood plains and terraces.
3. Where the velocities of transporting currents are decreased then sedimentation occurs in standing water bodies as water margin deposits. Deltas and beach deposits are the major landform here.

8.3.1 Factors Responsible for Deposition

As we have seen there are many factors which tend to modify or lessen the transporting ability of a stream. The loss of transporting capacity may be due to the decreased gradient, decreased volume, increased amount of load or damming of the channel, for instance.

A stream-gradient may change when the stream flows from one rock type to another. Furthermore, stream length may increase with the same vertical fall, as in a meander. Gradient of the stream is suddenly decreased when a stream descends from a steep mountain front on to a plain or when it moves into a still body of water. In all these cases a decrease in gradient causes a loss of transporting ability and deposition of the load.

Decreased volume supports decrease in velocity when an increase in vegetative cover promotes infiltration and detention of rainwater through storage. It may also occur from a change in climate whereby less rain is supplied to a stream. Volume of water decreases downstream as the river loses water by evaporation or seepage.

Decrease in volume may also occur if a river is naturally diverted by another stream due to piracy or if it is artificially diverted by men. Again loss of competence and deposition of the load will occur as a result of its decrease in discharge.

Deposition may also occur when the load supplied to a stream exceeds its competency or capacity. Excessive load is often provided from glacial outwash or accelerated erosion of a denuded watershed. Sometimes a steeper more turbulently flowing tributary bears boulders which the main stream is incompetent to carry and so these are deposited at the junction.

When grain size is increased beyond the competency, then deposition may also occur. It may be competent to entrain and carry the particles to the point of encounter but may be incompetent further downstream and may thus deposit the particles.

As soon as the river enters the plain from its upper course, its valley becomes more widened and lateral erosion is greater than, its vertical corrosion and stream deposition occurs. A great variety of depositional landforms is formed by the river in the lower course.

8.3.2 Problems Associated with Deposition

Men utilise the river water in various ways but varying deposition of it generates many problems which actually hinder the optimum utilisation of the river. In the following paragraphs a few problems will be discussed briefly.

1. Due to the deposition the channel bed rises up and during heavy rain the bed cannot hold the water; it overflows and causes flood. One of the main causes of the flood in Bangladesh is the rising of the stream beds.
2. Due to deposition shoals are developed in the midst of the river bed which hampers the navigability of the river. In some cases it increases the cost of navigation, because for the presence of shoals the boats take a sinuous route.
3. Heavy deposition in the mouth of the river disturbs the port facility.
4. In the Southern part of Bangladesh due to the deposition in the creeks, saline water overflows and flooded the cultivated fields.
5. Frequent changing course of the river due to deposition disturbs the existing economy and livelihood pattern.
6. Shoal deposition diverts the main flow of water into different courses of various widths, which sometimes creates problems of navigation.

8.3.3 Depositional Landforms

Rivers deposit sediments in different parts of their courses and thus form various types of landforms.

The depositional landforms can be classified into two groups: *(a) Features formed within the main channel and (b) features formed outside the main channel.* The former includes various types of bars: viz. channel bars, meander bars, delta bars etc. The latter includes natural levee, back swamp deposits, valley fill deposits, flood plain, meander scroll deposits etc

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1. Alluvial Fans and Cones

Most important depositional features of the piedmont are the alluvial fans. In the upper reach of a river in the mountainous region, the slopes are steep and the flow has a high velocity. Sediment concentration is therefore also high. At the foothills the river descends into the plains where the slope suddenly becomes flat and the velocity drops. As a result, the capacity of flow to carry sediment reduces appreciably. The sediment then deposits and causes bed aggradation. When the bed is raised, the river shifts laterally. By this process a cone shaped delta is built by the river which presents the shape of a fan. This formation is known by the term ***alluvial fan*** (Fig. 8.10). There is sorting of materials in the alluvial fans. The size of sediments decreases outward from the apex (which is towards the hills) of the fans towards their outer margins (distal side).

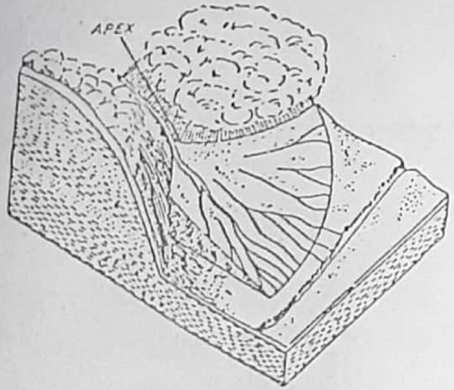

Fig. 8.10 Alluvial Fan

Causes of Deposition of Alluvial Fan

1. The most popular theory of fan initiation is that a drastic reduction in gradient between the eroded valley and the receiving plain causes deposition of load.
2. The break of slope changes the hydraulic geometry of the main channel. It increases the channel width, decreases the depth and flow velocity and causes the deposition of some of the transported materials.
3. Sometimes the changes in the direction of trunk wash or the increasing friction and decreasing velocity, debouching of the flow from the constricted channel create fans at different places down the slope.

Morphology of alluvial fans

The shapes of alluvial fans are usually semi-circular of arcuate, the apex of which is located at the mouth of narrow opening through which the stream comes out of the hills and enter the surface of low height and gentle slope. The shape of alluvial fans is described in two perspectives, planimetric and volumetric. The planimetric consideration involves two dimensional shape whereas volumetric perspective involves three dimensional shape of the fans. The alluvial fan, in planimetric prespective, is similar to the shape of a sector of a circle. In volumetric perspective an alluvial fan has a shape of a part of a cone. The longitudinal profile of an alluvial fan is concave at its apex while the transverse profile (which is parallel to the mountain front) is convex. Though the size of alluvial fans varies significantly but generally the diameter of fans ranges from a few kilometres to several hundred kilometres.

Many times these alluvial fans increase in height by the deposition of the sediment of the fans and their slope becomes steeper. Such formations are called *Alluvial Cones* (Fig. 8.11). Usually the alluvial cones are found in semi-arid areas.

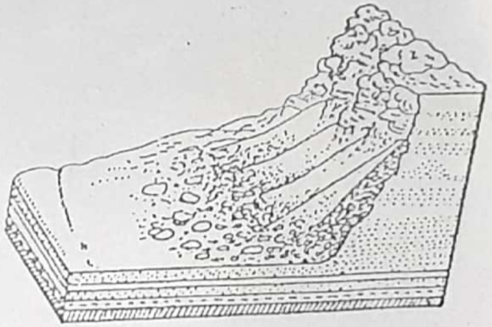

Fig. 8.11 Alluvial Cone

The slopes of fans are much gentler than those of alluvial cones. Larger alluvial fans have average slope of less than one degree but smaller fans are characteritized by gentle to moderate slopes (5 degree). Alluvial cones have average slopes of about 15 degree. Alluvial cones are made of coarser materials than the alluvial fans.

The apex of alluvial fan is at the mouth of the gorge from where the stream emerges. The stream does the following three things in the fan:

1. Many layers of the sediment deposited by the stream are formed.
2. The process of grinding the angular sediment into rounded forms starts.

3. It has been found that finer particles accumulate near the periphery and the bigger and rougher fragments of rocks are deposited near the apex.

Classification

Fans can be of two types, dry or mudflow fans formed by ephemeral streams flow and wet fans formed by perennial stream flow.

(i) Dry Fans

Bull (1968) graphically summarised his observations on modern dry fans and recognized the different conditions of fan morphology. It occurs near the mountain front and the fan surface is undissected (Fig. 8.12). It is also found when deposition is at the toe of the fan and water and sediment move to this location through a fan head trench. It is commonly found on the arid region.

Fig. 8.12 Dry Fan

(ii) Wet Fans

Wet fans are formed by the fluvial action. The Kosi River in India has built a large wet fan (Gole and Chitale 1966), which provides an interesting contrast to the dry fans. The Kosi river draining from the high Himalayas, delivers a tremendous sediment load to the Ganges piedmont area, where it has constructed the large Kosi fan. During the period 1736 to 1964 the Kosi River shifted 115 km from east to west, and in this process about 9,000 square kilometres of land were reworked and laid waste as a result of sand deposition and bank erosion (Fig. 8.13).

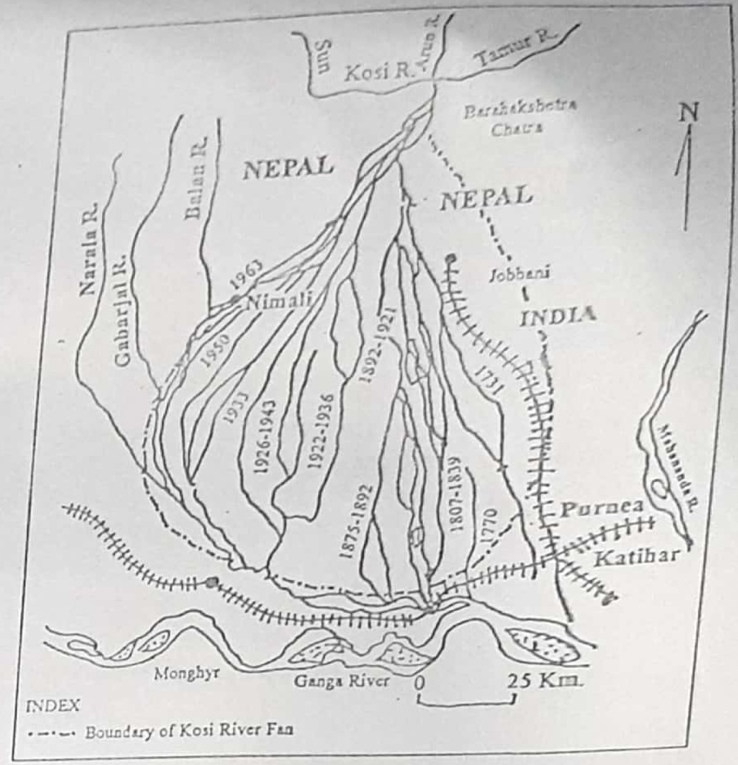

Fig. 8.13 Wet Fan

Geographical Importance of Alluvial Fan 15

The following describes the geographical importance of alluvial fans:

1. Cities develop near the peripheries of alluvial fans. Many such towns can be seen in the upper Rhone valley.
2. Water is available for irrigation from these fans. Various branches of the stream in the fans provide water for irrigation.
3. The water of the fans goes to the lower layers by seepage. Water can be pumped up from these layers even when there is no water available on the surface of the fans. रिसाव
4. Fertile soil is available in these fans in the semi arid fans. There is a series of alluvial fans from apex to the periphery. Agriculture is developed in these fans.

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2. Flood Plain

A *flood plain* is the relatively flat area that borders a stream which is periodically inundated with water during high flow periods. In their youthful stage, the stream broadens its valley instead of deepening it. As a result the width of the streams increases a lot, when the flood time comes, the speed of the stream increases. Its capacity to carry sediment also increases. When the water of the stream goes out of the valley, its speed is reduced and it deposits the sediment. The area in which a stream spreads its sediment is called *Flood Plain.* These plain have become very fertile as a result of fresh deposition of sediment continuously. Floodplain agriculture has given rise to many of the great world civilisations. The flood plains of the Sindh, the Ganges, the Nile etc. are known and are fertile.

Flood-plains are continuously constructed and destroyed by fluvial processes. Mainly three types of deposits are found in the flood plain *(1) Colluvium, (2) Channel deposits and (3) Overbank deposits.* The colluvium found near the valley walls, which are deposited from the valley side slopes by mass movements. It is poorly sorted, angular pieces of bed rock imbedded with the finer materials. Depending on the river basin environment, colluvium may comprise up to 20-25% of the flood-plain deposit.

Meandering channels shift laterally over the existing sediments and build up newer point bar, channel and levee deposits. The flood-plain thus gradually increases in size.

Flood-plain materials are mainly laid down by the vertical and lateral accretion of the channel. These are the result of the decession of flow causing lack of competence and therefore, larger particles are dropped from the bed load. Main flood-plain features are the natural levees, backswamps, sloughs, meander scroll, crevasses and splays, flood-plain placers etc (Fig. 8.14). Hopp (1971) classified the valley sedimentary deposits, the list of which is given in Table 8.2

B = Bluffs F = Flood Plain A = Alluvium
O = Oxbow Lake L = Levce
Y = Yazoo Stream

Fig. 8.14 Flood Plain of a River

Table 8.2 Classification of flood-plain deposits

Place of deposition	Name	Characteristics
Channel	Transitory channel deposit	Primary bed load temporarily at rest; part may be preserved in more durable channel, fills or, lateral accretions.
	Lag deposits	Segregations of larger or heavier particles, more persistent than transitory channel deposits.
	Channel Fills	Accumulations in abandoned or aggrading channel segments; ranging from relatively course bed load to fine-grained ox-bow lake deposits.
Channel Margin	Lateral accretion deposits	Point and marginal bars that may be preserved by channel shifting and added to over-bank flood-plain by vertical accretion deposits at top.
Overbank flood plain	Vertical accretion deposits	Fine-grained sediment deposited from suspended load of overbank flood water including natural levee and backland deposits.
	Splays	Local accumulations of bed load materials, spread from channels onto adjacent flood-plains.
Valley margin	Colluvium	Deposits derived chiefly from unconcentrated slope wash and soil creep on adjacent valley sides.
	Mass movements	Earth flow, debris avalanche, and landslide deposits commonly intermix with marginal colluvium; mud flows usually follow channels but also spill over bank.

3. Bars

Along the stream channel are likely to be found numerous deposits of sand and gravel commonly designated by such names as channel bars, point bars, diagonal bars, delta bars, transverse bars etc.

Channel bars are located in the stream course and are perhaps most characteristic of braided streams.

Point bars are called meander bars. As water rounds a meander, the water swings toward the outside bank where erosion is concentrated and then spirals toward the inside banks. As the water spirals toward the inside of the meander it is slowed by frictional drag imposed by the bed of the channel. This causes deposition of alluvium on the inside bank to form a bar. A *point bar* forms on the inside bank of a meander and rising from the channel as an accumulation of alluvium. As the channel meander continues to erode laterally, a succession of bars with intervening swales form called **bar and swale topography.**

Longitudinal bars are common in gravel-bed rivers. *Transverse bars* occur from one bank by avalanche and extend downstream and lateral margins. *Diagonal bars* are aligned perpendicular to the flow and are formed of horizontal gravel strata. Other types include *linguoid bars* which are large-scale ripple-like forms in sandy sediments, these migrate downstream.

4. Natural levees

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A *Natural levee* is a narrow ridge of alluvium deposited at the side of the channel. They are highest near the river and slope gradually away from it (Fig. 8.15). During flood period the whole plain, from one valley wall, to the other, is under water and the water current is most rapid along the deep line of river channel. Silt bearing water spreads out and mingles with shallow flood waters on either side. It quickly loses its velocity and much of the silt and sand settle along both sides of the river channel. During flood period such type of deposition occurs year after year and as a result a slightly higher ground is formed known as *natural levee* on both sides of the river.

It may be pointed out that not all the streams build natural levees. Levees are formed due to deposition of sediments during flood periods when the water overtops the river banks and spreads over adjoining flood plains. Long ridges of low height are formed parallel of the river valleys. Average height of natural levees is within 10 meters. The natural levees of the Mississippi river ranges between 6 m and 7.6m. Natural levees limit the lateral spread of river water except during severe and widespread floods. Natural levees are more or less stabilized landforms which attract human settlements. Some times, natural levees are also

used for agricultural purposes because water table of groundwater in that area is very high. Generally, natural levees help in checking the floods but when breached they cause severe catastrophic floods inflicting heavy loss of human health and wealth. Since the channel is more of less confined within the natural levees and hence there is continuous sedimentation which causes gradual rise of the river beds (valley floor).

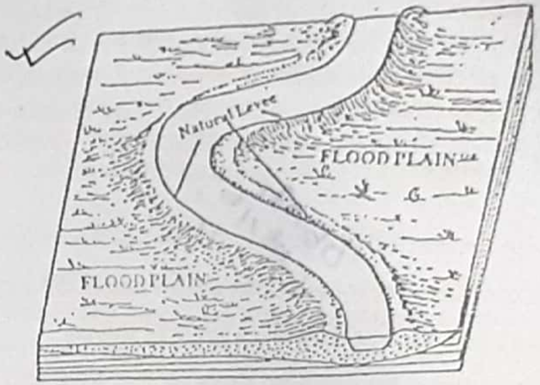

Fig. 8.15 Natural Levees

Natural levees may sometimes prevent a tributary from joining the main river. Consequently, such a tributary flows parallel to the main river, behind the natural levee, for considerable distance before it finds a suitable place to meet the main river. Such tributary streams are referred to as *yazoo streams*, after a stream of the same name flowing into the Mississippi River. A number of such yazoo streams occur along the Ganges River (for example, between the confluence of Gandak and Kosi Rivers) and some of its major tributaries. Where the levee is not well developed, a river in spate may take a shorter and straighter course across a meander but not its neck. This short course is known as *chute.*

Natural levees are especially noted on the Yellow River in China near the sea where ocean going ships appear to sail high above the plain on the elevated river. Natural levees are also present on the Rio Grande River in Colorado's San Luis Valley.

Breach of natural levees in such situation causes sudden catastrophic floods because the river water gushes in the flood plains and settlements with high velocity beyond imagination. Such cases of breaches of natural levees and consequent severe floods are very often reported from the Yellow river (formerly the Hwang Ho) of China. This was the reason that the Hwang Ho was called 'Sorrow of China'.

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5. Delta

The depositional feature of almost triangular shape at the mouth of a river debouching either in a lake or a sea is called *delta*. The word 'delta', derived from Greek letter, was first used by Greek historian Herodotous (485-425 BC) for the triangular depositional feature at the mouth of the Nile river. Whether small or large, almost every river forms delta. The size of delta of major and small rivers all over the world varies from a few square kilometres to thousands of square kilomeres (e.g. the Ganges delta in Bangladesh and India, which is the largest delta in the world). The size of delta depends on the *rock characteristics, vegetal cover, rate of erosion, amount of annual rainfall etc.* The depth of sediments has been reported to be hundreds of meters. For example, the average depth of sediments in the Mississippi delta is about 610m. The shape of delta also varies from one river to the other. Common shapes of delta are arcuate shape, bird-foot shape, elongated shape etc.

Conditions for Delta Formation

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The ideal favourable conditions for the formation and growth of delta include

1. suitable place in the form of shallow sea and lake shores,
2. long courses of the rivers (i.e. long rivers so that they bring enough amount of sediments),
3. medium size of sediments (because if the sediments are very fine, they would be carried in the sea in suspension for longer distances and if they are very coarse, they would soon settle down at the sea bottom, and hence no delta would be formed),
4. relatively calm or sheltered sea at the mouths of the rivers (so that ocean currents, strong waves or high tidal waves do not interfere with the natural process of gradual sedimentation and delta formation,
5. large amount of sediment supply,
6. accelerated rate of erosion in the catchment area of the concerned river.
7. almost stable condition of sea coast and oceanic bottom (because sea coast subjected to frequent emergence or submergence caused by tectonic movements does not allow regular sedimentation and thus disfavours delta formation.

It is therefore clear that a delta is formed only when the rate of deposition of sediment is greater than the rate of removal of sediment by sea waves and tidal currents.

Delta Formation

The formation of delta starts with the deposition of sediments if the aforesaid favourable conditions are available. The sedimentation takes place regularly at the mouth of the river, on the sides of stream channel, in the bed of the river and in front of river mouth where the river debouches in the sea. Thus, an extensive fan is formed which slopes towards the sea. Several such fans are formed at the mouth of the river. These fans gradually grow towards the sea. Ultimately, these fans are coalesced and a delta is formed. These deposits obstruct the free flow of main river and hence is divided into several branches. This process of segmentation of main stream is known as ***bifurcation***. Thus, the main channel is bifurcated into numerous small and narrow sub-channels which are called ***distributaries*** and the stream with numerous distributaries is called braided stream.

Factors affecting Type, Shape and Progress of Delta

Deltas are built out of the materials transported from catchment basins. Hence the delta building activities of a river will depend on the nature of the catchment area and also on the nature of the small streams feeding the river.

Total annual rainfall and its distribution are other factors affecting the quantity of sediment. If a part of the catchment is snow-fed, glaciers supply a heavy sediment load because of their considerable grinding power.

Coming down to the river mouths, the tidal range has a great effect on the progress of the delta. If the total range is high, the solids, brought down by the flood carriers, are continuously churned and prevented from settling down; they are transported up the tidal creeks and utilized for raising the delta already formed, and hence, the seaward progress of the delta is checked. If on the contrary, the tidal range is very low, the progress will be rapid.

Littotal drift affects the progress of the delta to a very great extent. It may be defined as the movement of sediment along the coast by the means of currents, primarily induced by waves striking the coast obliquely. The material in the littoral drift is available from several sources; sediments, brought by the flood carries eroded material from shores, etc. If the delta is subject to a littoral drift, its seaward progress will be naturally checked as sediment brought down by the stream will be continuously carried away.

Other factors such as coastal currents, cyclones, human interference, etc., also effect the delta formation.

Alluvial Fans and Deltas

The alluvial fans resemble deltas but there are two main differences between them:

1. The flow of water in an alluvial fan is suddenly decreased but it decreases slowly in delta. This results into slow but more systematic deposition in a delta.
2. The surface of the lake or sea is within the limit of the deposition of the river but there is no such limit in an alluvial fan. It is because of this that the upper part of the delta is more distinct than the alluvial fan.

Types of Delta

Deltas may be classified according to their plan view as either high destructive or high constructive deltas.

1. ***High destructive deltas*** are those where the sediments are continuously removed by the wave and tidal currents. As a result the distributaries do not become blocked and tend to remain stable in position.
2. ***Wave influenced deltas*** are those where there is a rapid removal of debris by strong long shore wave currents and make a flat delta. The delta of San Francisco river of Brazil is one such.
3. ***Tide influenced deltas*** are generally funnel-shaped where the distributaries are open and straight by strong tidal scour. The deltas of the Ganges, Niger & Mekong are of these types.
4. ***High constructive deltas*** are those where due to the large supply of debris ধ্বংসস্তূপ from the river form a broadly curving shoreline resembling the alluvial fan. e.g. Nile river.

Names of the deltas are usually derived from the shape of the delta. The formation of them largely depends on the relationship of two main factors of delta-building. viz. (i) the rate of sedimentation (ii) the degree of marine forces acting on these sediments.

Economic Importance of Delta

Deltas are economically very important. On account of the deposition of alluvium in the delta every year, the deltas become very fertile. Agriculture is practiced very successively. A great population found in deltas depends upon agricultural production. The deltas of the Ganges, the Sindh, the Brahmaputra, the Nile, the Hwang Ho, etc. are intensely populated. The people of the deltas have to face the problems of marsh, floods, transports etc.

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6. Back Swamp

Back swamps are located a distance away from the stream channel on the floodplai When water spills over onto the floodplain, the heaviest material drops out first and fine material is carried a greater distance. The fine-grained alluvium holds much water ar drains rather slowly creating wetland areas. Back swamps are important "sponges" th retain water that might cause severe flooding downstream.

8.4 INSTABILITY OF RIVERS

Downward movement of meanders is common in alluvial rivers. Sideways shift in the rive course is associated with alluvial fan formation. In these processes, the river instability i manifest in horizontal plane. Vertical instability occurs when rivers are dammed resulting i bed aggradation on account of sediment deposition on the upstream and bed retrogressio due to scour on the downstream. Even if the river is not disturbed through human agenc and is incised and hence not so free to permit changes, instability can be prevalent in bec form, which may assume sizeable dimensions and migrate at measureable rates. Instability is thus inbuilt in river morphology and the river constantly tries to adjust to changes in flow, sediment load and boundary characteristics to achieve dynamic equilibrium.

8.4.1 Kind of River Instability ০৬,০৭, ০৮,০৯,১০

Chitale and Garde (1984) classified river instability as autogenic meaning inherent in the river regime or allogenic in response to system change brought about as a result of human activity. Some illustrations are as follows:

8.4.1.1 Autogenic instability 15

1. Lateral shifting and changing of channel positions accompanied by aggradation inherent in activity of building of an alluvial fan.
2. Erosion on concave bank and sediment deposition along convex bank inherent in progressive downstream movement of meander train or in cutoff forming hairpin bends.
3. Shoaling due to flocculation and increase in salinity due to reduction in tidal influx.
4. Flattening of slope due to extension of delta.

8.4.1.2 Allogenic instability

1. As a result of construction of waterway caused by bridge or a barrage;
   Increase in meander belt and formation of cut off immediately upstream and straightening of river course immediately on downstream.

2. As a result of ponding at weirs and barrages;
   Aggragation and flattening of slope on upstream and degradation on downstream.

3. As a result of construction of dam for water storage;
   (a) Aggragation on upstream and degradation on downstream.
   (b) Reduction of channel capacity on downstream.
   (c) Terrace formation and change of channel shape on downstream.
   (d) Change of channel pattern and hydraulic geometry on downstream.

4. As a result of flood embankments;
   change in river water and bed levels and in river slope.

5. As a result of bank protection work over long reaches;
   change in sediment transport rate and associated changes.

6. As a result of man made cut offs;
   steepening of slope causing accelerated bed scour and bank erosion on upstream.

7. Increase in sediment load due to land slides, dumping of mining debris etc.

8. Decrease in sediment load due to very effective sediment excluders.

9. Increase in channel flow due to flow from return channel.

10. Decrease in channel flow due to diversion.

11. Change in base level for tributary (this can happen if the main river shifts laterally).

8.4.2 Implications of River Instability

Study of river instability is important since it can affect performance, functioning and even safety of engineering structures. Some examples are cited below:

1. Aggradation may cause rise in flood levels, reduction in free board and increase inundation rise in ground water levels in the vicinity, increased evaporation, etc.

2. Shift in channel position and meander progression may render water intakes dry and in fructuous.

3. Retrogression may result in undermining of foundations, reduction of depth o submergence of pumps, reducing efficiency of stilling basins; channel widening (bed is unerodible), cutting off of meanders, coarsening of bed material, etc. ma also be emphasised that aggradation or degradation in main channel can induc changes in the tributaries or sub-tributaries and hence one has to carefully stud the reasons for instability of a stream because the culprit can be somewhere else.

CHAPTER - 9

MAN AND RIVER

From pre-historic times river has been one of the many life sustaining sources. However, when the all important human intelligence was absent on earth, the animals who inhabited the earth then, failed to utilise the various river sources. The advent of human civilisation opened up a new era for the rivers. The gradual progress of science has also helped in the proper utilisation of river. Now, river is not only an inspiration for the poets for writing poetry, but an inspiration for all of mankind for sustaining life. The three stage of the river help in different ways. It is a source of hydel-power, domestic and industrial use, navigation and so on. In the following pages we will discuss briefly about the various uses of river resources.

9.1 VARIOUS USES OF RIVER RESOURCES

9.1.1 Irrigation

The, largest use of river water in the world is irrigation. For the growth of plants, water must be available in appropriate quantities and at the right time. Irrigation, therefore, is vital to stabilise agriculture and augment production for all areas where the rainfall is less than 1,000 to 1,150 mm. Since ancient period irrigation was extensively practiced in India. The points of extensive irrigation systems were found in the oldest city Harappa and Mohen-jo-daro. In the Vedas, rituals were prescribed for the inaugural ceremonies of channels. Ruins of some of these ancient works are found in Cauvery river basin area. During Moghal periods two canals from the Yamuna river (Eastern and Western) and one canal from the Ravi River were constructed. In 1854 upper Ganges canal was constructed at Hardwar for irrigation. Other irrigation canals of this period are the Sirhind canal, Lower Sohang and Para canals, Lower Chenab canal of Punjab and the Lower Ganges canal, the Agra Canal, the Betera canal of U.P.

In early 20th century large irrigation works have been done in India e.g. the Nizam Sagar Project on the river Maniira, Mettur dam across the Cauvery, Bikaner canal from the river Sutlej in the State of Bikaner etc.

Irrigation was practiced along the Tigris and the Euphrates river valleys from ancient times. Extensive cultivated areas of about 396,580 hectares are well irrigated from these

two rivers. In Indus basin area link canals have been built to transfer water from the Jhelum and the Chenab to the Ravi and the Sutlej and there has been considerable development of ground water also for irrigation. Wheat of Afghanistan is widely grown depending upon the irrigation water of Amudarya river. The Mississippi river of USA provides irrigation at about 4 million hectares of land. In Sudan about 2 million hectares of land is irrigated by the Nile river water. Though the climate is torrid in Rajasthan but after the installation of Rajasthan main canal project a large area has been brought under cultivation. In the kharif season the farmers are producing cotton, clusterbean, sugarcane and groundnut on about 25 lakhs hectares and wheat, grain, rapes and mustard on 2.50 lakh hectares in rabi season.

9.1.2 Hydropower-

Another most important -ways in which water is utilised is hydropower generation. For the development of the hydropower some important geographical factors are necessary i.e. the amount of water of the river, availability of water through out the year, velocity of the stream, shape of the land etc.

The total hydropower potential in the world is estimated at 4,200 million kW. U.S.A. has generated largest hydropower in the world. and the important generating centers are the Niagra falls, Tennese river basin and Colorado river basin area. The total hydroelectric potential of the Colorado river basin is estimated at 41 million kW, The then U.S.S.R. occupies the second place in hydropower generation. The important power stations are on the river Dniper, Niva river, Arnur river, Shir and Volkhov river. The generating capacity of the U.S.S.R. is 170 million kW Japan has the third position in the world for generating the hydropower depending upon which the small' and cottage based industries of the country have developed.

9.1.3 Navigation

River transport is by far the cheapest means of navigation. Navigability of the river depends upon some geographical factors like *(1) steady and calm flow of river, (2) snow-free, (3) deep and wide river course, (4) perennial character etc.*

The Ganges was navigable for boats from the mouth to Benaras and also through Padma upto Dhaka. Depending upon this route a Hooghly industrial belt was developed along the river. But now due, to the siltation of this course navigation is practically extinct except for country boats in a few reaches of the upper and lower Ganges stretches. Brahmaputra river was also once navigable from Sadya onwards to Calcutta. But now due to siltation the steamers can go up to Neamati, 320 Km upstream of Guwahati. In the northern region of West Bengal the Torsa, the Tista and the Mahananda are navigable by small country boats in reaches. The Narmada is navigable up to 160 Km from the mouth, the Tapti is navigable upto 25 Km from the mouth, the Subarnarekha is navigable for 30 Km and the, Mahanadi up to 416 Km from the mouth. The Godavari is navigable up to a distance of 306 Km upstream from the mouth and the Krishna to about 40 Km.

The Mississippi-Misouri river of USA is navigable about 3,200 Km at a stretch and large amount agricultural products, industrial goods and the Coal of Pennsylvania are transported through this river. In Russia, through the river Volga many products are transported between south and north Russia. Ruhr industrial belt of Germany was developed along the side of the Rhine river and coal, cement, iron, wood, steel etc. are transported through this river. In UK the cargo ship easily reaches to the centre of the cotton producing region through the 56 Km Manchester canal. Beside this Tames, Mercy, Hamber, Severn are also navigable.

The early civilization of China was developed along the side of the Yang-Sikiang river, about 2530 Km of which is navigable. All agricultural products, minerals and forest products of China are transporting through this river to the Ports of Pacific Ocean.

9.1.4 Industrial Use

Industries require water, therefore, the development of the industries along the side of the river is most preferable. In the north-east industrial belt of U.S.A., the water of St. Laurence river and five lakes are widely used. In U.S.S.R., all the industrial belts like Moscow- Tula region, Ural region, Leningrad region, Ukrain region use the water of the rivers Volga-oak, Oab, Ladoga-odega Lake, Dneister-Dnipper river respectively. In India the iron and steel industry of Jamshedpur uses the water of river Subarnarekha.

River water is not only used for the production but also for the disposition of the waste materials. Such type of disposition by industries is, now-a-days, responsible for increasing the pollution of the rivers.

9.1.5 Domestic Use

River water is used for drinking and other domestic purposes. River is also a rich source of fishes and other aquatic lives. The important river fishes are Hilsa, Parse, Bhangar, Ruhi, Rutilam etc.

9.2 CHANNEL BEHAVIOUR UNDER HUMAN INFLUENCE

From the above discussion it is cleared that man uses the river for various purposes and he has a tendency to change the environment to suit himself. Effects of these human influence on the river are not, always good and the hydrological characteristics of the river have, changed greatly. Owing to the pressure of population and to serve the needs of advancing civilization extensive deforestation is going on. Larger and larger areas are being opened up to find room for the growing population and cultivation. Extensive forest on the hill slopes are being cut rapidly and often indiscriminately to meet the needs of modern civilization. Even the under growth is being destroyed due to excessive grazing by the cattle. Intensive deforestation is increasing the silt charges of the river bed, thus raising the flood levels. Owing to the formation of shoals and trickle flow in dry weather navigation is also affected. Some naturalogists suggest the intensive agriculture in Rajasthan by the canal water would loosen and erode: the valuable and precarious topsoil that presently supports extensive grassland.

To keep the river flow steady or navigable and to make the flood free zone many flood controlling measures like longitudinal embankments, dams and barrages have been constructed on the river. These measures have some adverse effects also.

9.2.1 Effect of Embankment on River Bed Level

Firstly, due to the construction of longitudinal embankments on both sides of a river, flood water will be controlled to some extent and the river bed will be filled up with silt as the water level will not reach flood plain. This incident happens in case of Damodar and other tidal rivers of Sundarban areas. The tidal water of these rivers flooded the lower part of Bengal and made them unfertile. Therefore, by the construction of longitudinal earthen embankments, the overflow of the saline water from the tidal river has been stopped. But due to the deposition of silt the river beds are being filled up. This is the case of such tidal rivers like Bidyadhari, Kultigang, Piali etc. of South 24- Paraganas of West Bengal, India.

Secondly, due to the construction of longitudinal embankment, down stream aggradations will be more prominent. The river flow is obstructed and instead of further meandering straight course will develop. The rejuvenation features like terrace will disappear due to salutation in the river beds.

Thirdly, the construction of longitudinal embankment causes decrease in cross sectional area of the leveed stream. The velocity will increase due to the constriction of the flow and large hydraulic radius, thus the rate of discharge will be greater than before the construction of embankment.

Fourthly, the tendency to scour is intensified because of greater velocity arid the tendency to deposit sediment is lessened. The scouring is more active on the bed than on the banks and the genera effect is to lower the bed of the stream. If the discharge is high then the velocity- measurement curve will be steeper.

In an embanked river, the stream hydrograph will form a sharp peak during the flood stage. During other periods the hydrographs will form a rounded shape. About 900 Km long longitudinal embankment has been constructed along the river Brahmaputra but it cannot stop the flood frequency of the river.

Fifthly, if there is any crack in the embankment the water of the river will enter in its flood plain and will create a swampy land. Due to construction of embankment the flood-plain will be ill drained because the rain water cannot flaw to river, giving rise to a swampy land. Bordering the Hooghly-Bhagirathi levee from Katwa to Howrah there is a number of low lying swampy lands most of which have been filled up with alluvium and reclaimed for agriculture. Some of the prominent marshes of this part are bekol marsh, Dankuni marsh, Bargachia marsh, Hurburia marsh and the Khanakul low land.

9.2.2 Effect of Dam and Barrage on River Bed Level

Firstly, due to construction of a dam or a barrage, the flow of water is checked, as a result the rate of deposition of silt in the downstream decreases. The silt carried by the tidal water from Bay of Bengal are being deposited in the bed of river Hooghly. It is generally observed that the duration of *'ebb tide'* in a tidal river is much longer than that of the flow tide, and shoals are created as the 'carrying capacity of the *'flow tide'* is more than the *'ebb tide'.*

Secondly, due to the construction of a dam, velocity increases in the upstream and gradually decreasing in the downstream, as a result the velocity curve takes a smoother shape and same can maintain the graded condition.

Thirdly, in the upper reaches due to construction of dam, there is a local change in base level. In the lower reaches, the velocity drops and causes deposition, channel filling etc. The deposition also cause, decrease in slope.

Fourthly, due to less velocity, huge sedimentation occurs in the reservoirs to the dam reducing the depth of the reservoirs which may cause flood sometime.

One theory has been advanced that the impounding of water reduces longevity of the dams and barrages and the capacity to hold water in the reservoir. Therefore, the flood problem in the lower reaches becomes acute and the channel deteriorates.