Module

2

The Science of Surface and Ground Water

Lesson
9
Geomorphology of Rivers

Instructional Objectives

On completion of this lesson, the student shall be able to learn the following:

1. The components of a fluvial system
2. Mechanics of sediment erosion, transportation and deposition by rivers
3. Causes of riverbed aggradation and degradation
4. Bar formation in rivers
5. Causes of meandering, lateral migration and river width adjustment of rivers
6. Relationships between velocity, perimeter, slope, velocity, etc. of alluvial rivers

2.9.0 Introduction

In the previous lesson, we discussed the mechanics flowing water. In the earth system, this water may be thought of as the water flowing downhill after a splash of rain, which carries with it some amount of soil that has been eroded by the action of flowing water. The flowing water of river moving down to the ocean also carries huge amounts of sediment which have been accumulated from other smaller streams joining the river.

In general, the water moving over the land surface is the dominant agent of land space alteration. Near surface weathering provide sediment load for the flowing streams. Some of the load gets deposited along the path of the river and only a fraction of the total material waste from the lands is carried by the rivers to the sea. In fact, the land space evolves essentially due to the water flowing over it in small rills and gullies, joining to form small streams, which combine to form rivers. The process of these watercourses eroding and conveying water is a continuous process and has been going on since the formation of this planet and the elements surrounding it. Hence rivers are ever changing but in a man’s lifetime it may not be much depending on the land space through which it passes. The general adjective fluvial (from Latin fluvial meaning river) is applied for the work done by river and fluvial system applies to all the area draining a particular river extending from the drainage divides in the source areas of water and sediment, through the channels and valleys of the drainage basin, to depositional area such as the coasts.

In this lesson, it is intended to understand the flow and sediment transport behaviour of natural channels and rivers. More applied theories of sediment dynamics and their application to natural rivers and artificial channels have been discussed in Lesson 2.10.

2.9.1 The fluvial systems

Conceptually the fluvial system of the river valley can be divided into three main zones (Figure 1), and described as under:

1. An ***erosional zone*** of runoff production and sediment source
2. A ***transport zone*** of water and sediment conveyance, and
3. A ***depositional zone*** of runoff delivery and sedimentation

FIGURE 1. The three zones of a fluvial system

In the first or upper zone the erosional process predominates and the stream and riverbeds are generally degraded. The streams join together at Confluences and their slopes are generally steep. The bed material is characteristically composed of boulders, cobbles or gravels.

The second (middle) zone is characterized by near equilibrium condition between the inflow and outflow of water and sediment. The bed elevation in this equilibrium zone is fairly constant and the river generally flows in a single channel- there are few confluences or branching (as in the last zone) the sediment material generally composes gravels and sands of various sizes.

The lower zone is characterized by net sedimentation and riverbed aggradations. There is branching of the river into channels and the slope of these channels is rather flat. The bed material generally composes of fine sand to silt and clay.

2.9.2 Sediment erosion, transport and deposition by river

It is amply clear that since rivers play a decisive role in land form evolution, the force of water is intricately connected to the dislodging of soil and rock particles and their conveyance. Where the power of water becomes less, it is forced to deposit the particles on its way.

When water flows over a surface, there exists a shear stress at the interface (Figure 2).

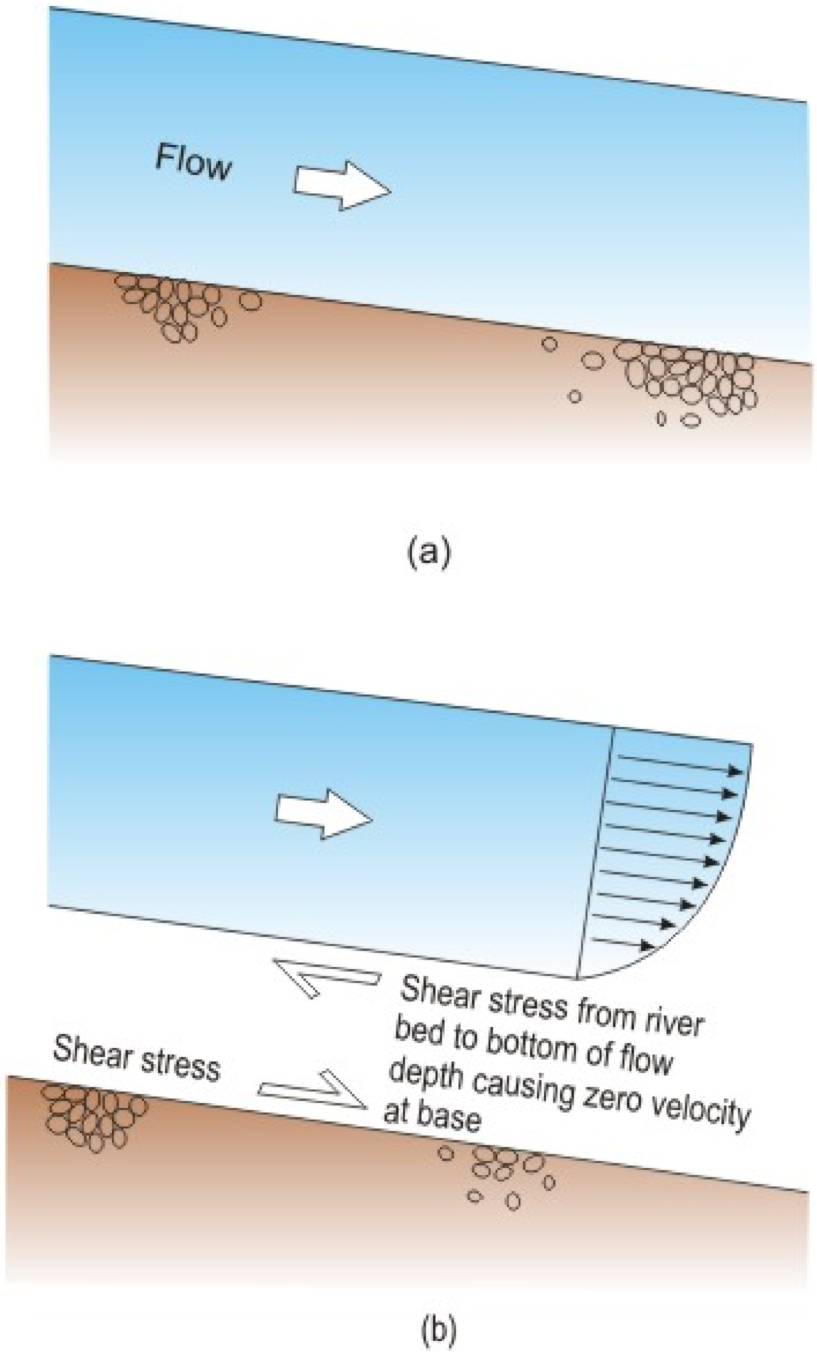


Figure 2. Interaction of forces between flow and riverbed
(a) General view
(b) Free body diagram showing shear stress at flow base-river bed interface.

Mathematically, the shear stress may be expressed in terms of the flow variables of a flowing river. If ***S_0*** is the slope of the channel bed, ***V*** is the velocity of flow and ***h*** is the water depth at a point then the shear stress (τ_0) at the interface of the water and the streambed is given as

$$\tau_0 = \rho g h S_f \tag{1}$$

Where S_f is the slope of the energy grade line (EGL) shown in the Figure 3. EGL represents the total energy of the stream at any point given by:

$$E = Z + h + \frac{V^2}{2g} \tag{2}$$

For explanation of the terms, one may refer to Lesson 2.8, and hydraulic text books like Ven Te Chow "Open Channel Hydraulics" (1959: McGraw Hill).

If the momentum of the moving water, its hydrostatic pressure its downstream weight component of water and the bottom friction are equated, the following equation results:

$$S_f = S_0 - \frac{\partial h}{\partial x} - \frac{v}{g}\frac{\partial V}{\partial x} - \frac{1}{g}\frac{\partial V}{\partial t} \tag{3}$$

From the equation (3) one may find S_f and evaluate shear stress (τ) using equation (1).

In deriving equation (3) it is assumed that the flow variables are not uniform and unsteady if they are not so then the derivatives with respect to the spatial dimension ***x*** and time ***t*** vanish, thus simplifying the equation to

$$S_f = S_0 \tag{4}$$

This is the case of the uniform flow and the corresponding equation for the shear stress (τ_0) is given as

$$\tau_0 = \rho g h S_0 \tag{5}$$

Thus, knowing the shear stress, it is possible to find out whether it is sufficient to dislodge a particle of diameter ***d_s*** from the streambed by a method suggested by Shields (Julien, 1995).

First, the dimensionless particle d_* is found out by the following formula

$$d_* = d_S \left[\frac{(G-1)\,g}{\nu^2} \right]^{1/3} \qquad (6)$$

Where ***G*** is the specific gravity of the sediment particle; ν is the kinematic viscosity of the fluid and ***g*** is the acceleration due to gravity. In some books, ***G*** is expressed as S_g.

The ratio of the shear force to bed particle defines the shields parameter τ_* as

$$\tau_* = \frac{\tau_0}{(\gamma_s - \gamma)\,d_S} = \frac{{u_*}^2}{(G-1)\,g\,d_S} \qquad (7)$$

Where τ_0 is the boundary shear stress and u_* is the shear velocity defined as

$$u_* = \sqrt{\frac{\tau_0}{\rho}} \qquad (8)$$

In equation (7), γ_s and γ are the specific weights have the sediment particle and water respectively. Note that τ_* depends on τ_0 , and which again is the function of S_0 (or S_f). Whether τ_* is competent enough to dislodge a particle depends on a critical value of shear stress given for particle of given diameter and density as given in Figure 3.

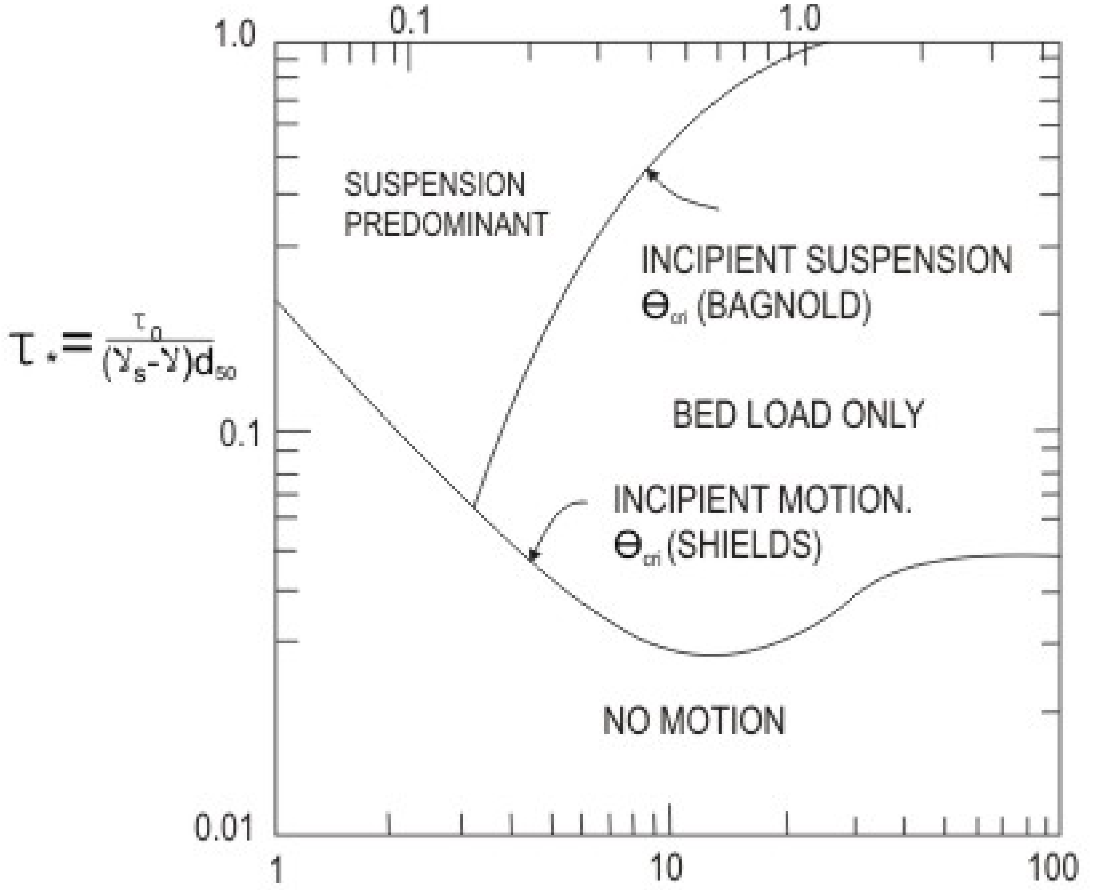


Figure 3. Particle motion diagram $d_* = d_{50}\left[\frac{(G-1)g}{v}\right]^{1/3}$

d_{50} : Mean diameter of particle(grain size)
G : Relative Density of particle
g : Accaleration due to gravidy
γ_s : Unit weight of sediment
γ : Unit weight of water
v : Kinematic viscosity of water
τ_* : Shields parameter or entrainment function

The parameter τ_{*c} given in Figure 3 is the critical value of Shields parameter corresponding to the beginning of the motion ($\tau_* = \tau_c$). This value of shear stress τ_c of certain particle sizes are as in the following table:

Particle Type	Diameter ***d***d_s (mm)	Critical Shear Stress τ_c (N/mm^2)
Cobble	130	111

Grand	8	5.7
Sand	0.25	0.194

Once the sediment particles are dislodged they get carried so long as τ_* is larger than τ_{*c} it may be remembered that in a natural stream, uniform flow rarely exists and the flow variables vary along the stream as the cross section and slope changes. However, if the shear stress τ_* may be sufficiently large it would continue to convey sediment particles of size smaller than a certain size **d_s**.

2.9.3 Riverbed degradation

Channel degradation refers to the general lowering of the bed elevation that is due to erosion. In some cases, the bed material is fine and degradation will result in channel incision as shown in Figure 4.

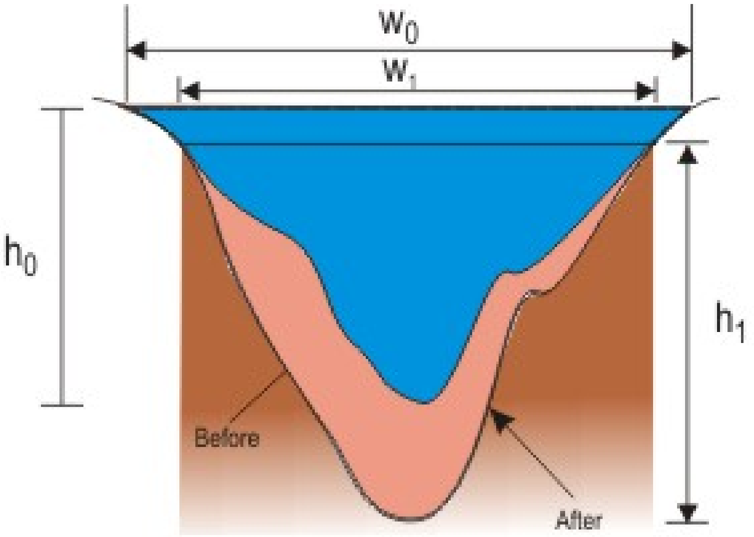


Figure 4. River cross section for bed degradation. Original river width w_0 and river depth h_0 befor degradation ; After degradation width changed to w_1 and depth to h_1

The phenomenon of degradation occurs when the sediment load being transported by a river is less than sediment transporting capacity of the river and the excess sediment needed to satisfy the capacity of the river will be scoured from erodable riverbed. Degradation results in channel incision and milder slopes, often this phenomenon is observed downstream of a dam constructed on a river (Figure 5).

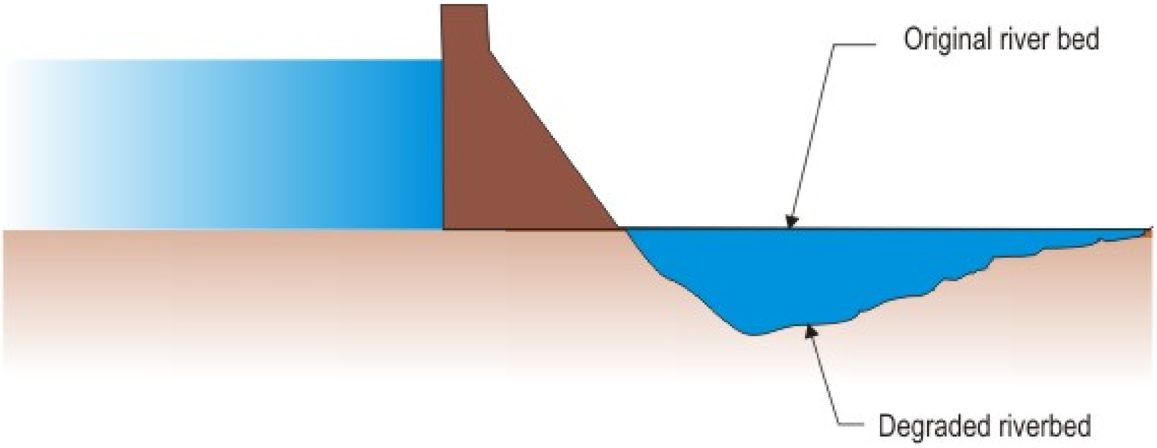


Figure 5. Longitudinal river profile showing river bed degradation along length of river below a dam

Dams constructed on rivers alter the equilibrium of flow of water and sediment in alluvial channels. Reservoirs tend to decrease the magnitude of flood flows by moderating them as a flood flows through, and conversely, they increase low flows by releasing the stored flood water at that time. The clear water release from the dam also causes the reach below the dam to degrade in the form of a wedge starting below the dam. The magnitude and extent of the degradation below the dams depends on the reservoir size and operation and on the size and availability of the alluvium below the dam.

A phenomenon related to streambed degradation is ***armouring***, where the coarsening of the bed material size results during degradation as finer particles get washed away. When the applied bed shear stress is sufficiently large to mobilize the large bed particles, degradation continues when the bed shear stress cannot mobilize the coarse bed particles, an ***armour layer*** forms on the bed surface. The armour layer becomes coarser and thicker as the bed degrades until it is sufficiently thick to prevent any further degradation.

2.9.4 River bed aggradation

When the sediment transporting capacity of a river at a point becomes less than the sediment load being carried, as a result of reduction the velocity due to an increase in cross section or reduction in slope of the river, the excess sediment get deposited on the river bed. As a result the riverbed rises, the phenomenon being termed as ***aggradation***. Often this phenomenon is noticed on the upstream of a dam (Figure 6), where the velocity of water in the reservoir is reduced as a result of increase in flow depth.

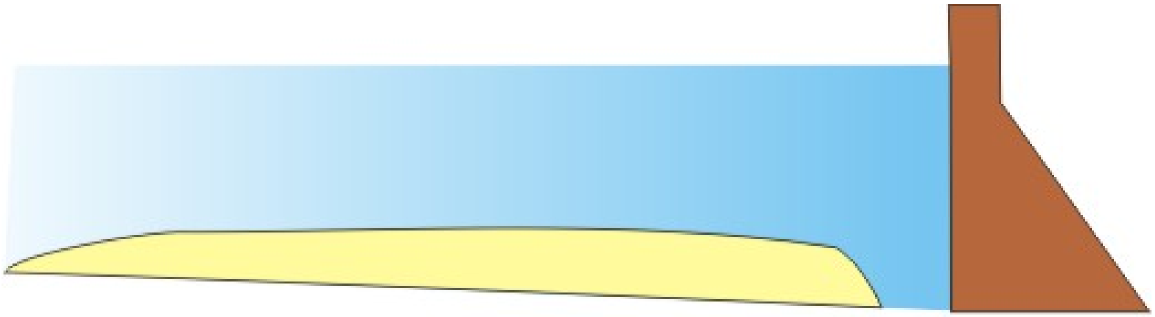


Figure 6. Longitudinal river profile showing sediment deposition on riverbed in the reservoir behind a dam

Channel aggradation may also occur in a river reach if due to geological reasons (say, increase of erosion of the catchment) the sediment load being conveyed to the river increases than that can be carried by the river in equilibrium. As a result the riverbed rises (Figure 7a) and forces the channel to carve out its path in a braided fashion (Figure 7b)

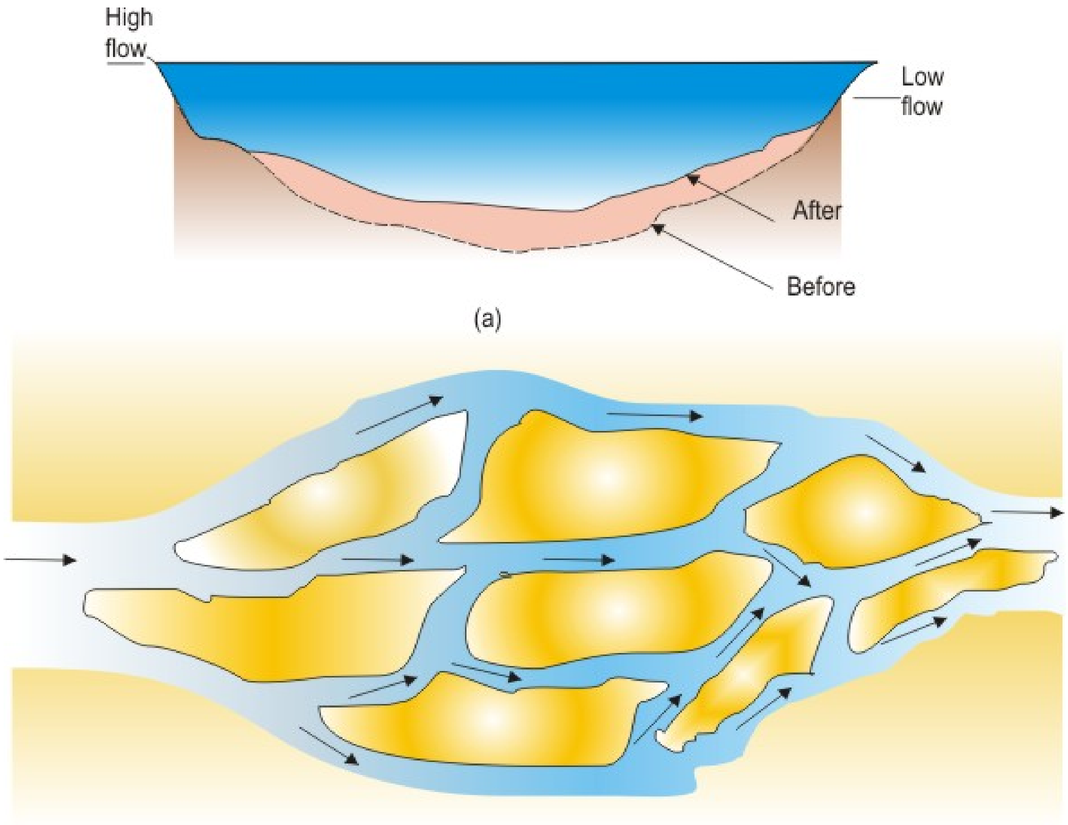


Figure 7. Effect of increase of sediment load in a river (a) Channel aggravation ; (b) Braiding

(b)

For ***braided rivers***, there is a tendency for stream to widen and become very shallow with bars subjected to rapid changes in morphology. At high flows braided streams have a low sinuosity and often appear to be straight at low flows, numerous small channels weave through the exposed bars.

Aggradation also occurs in a channel when there is a decrease of bed slope for example as the river emerges from the hills and enters relatively flat land. This has occurred markedly in the river Kosi, which has forced the river to change its course by more than a hundred kilometer westward in the last 200 years.

2.9.5 Bar formation in alluvial rivers

Bars refer to large bed forms on the bed of a river that are often exposed during low flows (Figure 8) these deposited segment mounds are not static and often get transported under high flows. They may again appear when the flow subsided but may not necessarily at the same location as the earlier ones.

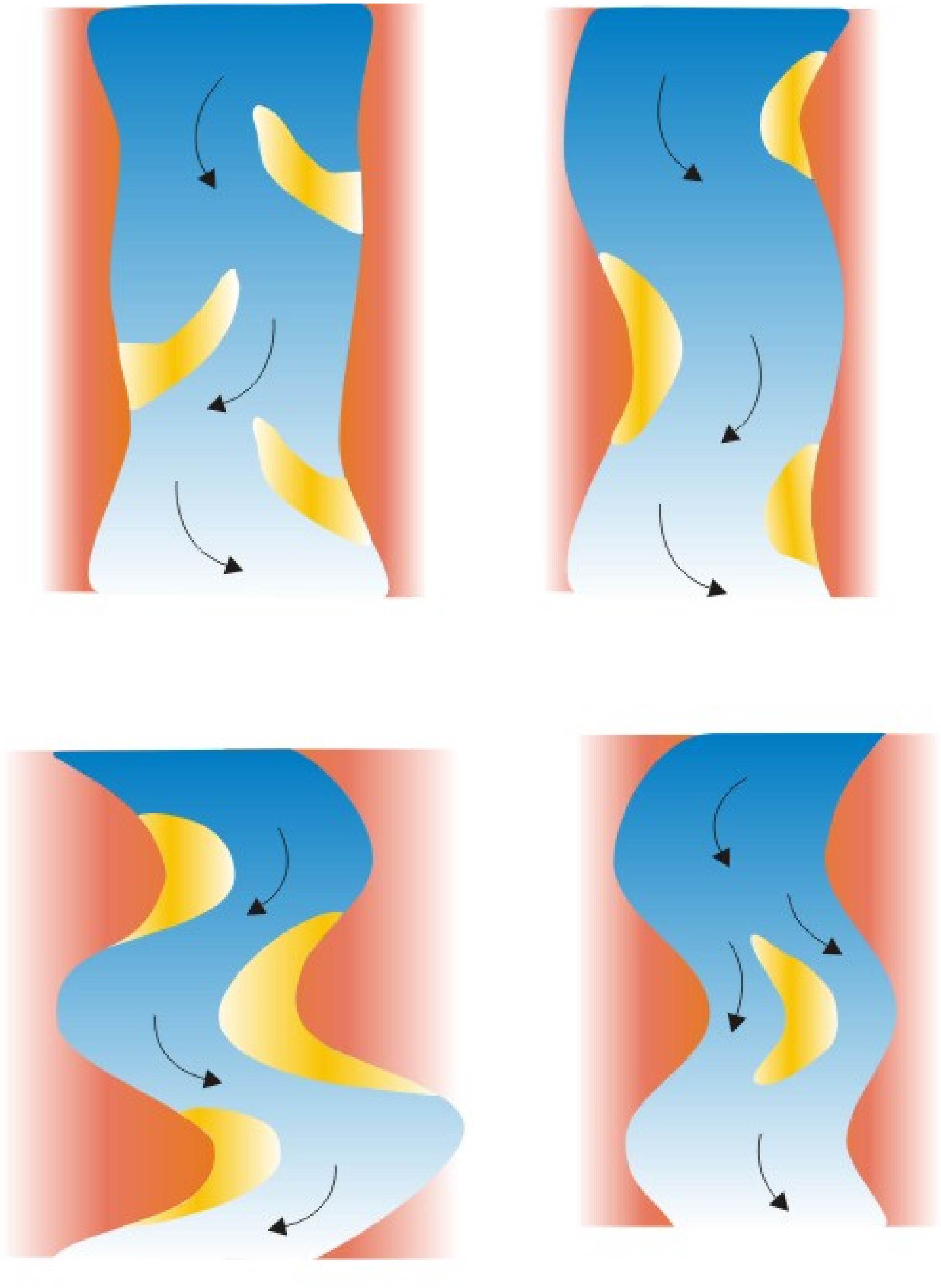


Figure 8. Bar for motion in rivers : (a) Alternate bars ; (b) Point bars ; and
(c) Mid-channel point bars

Alternate bars form in straight channels with deposits alternation from right bank to left bank. This type of bar forms where the Froude number of the river flow is high and the Shields parameter is close to incipient motion. Point bars form due to the presence of secondary flow of river bends (Figure 9).

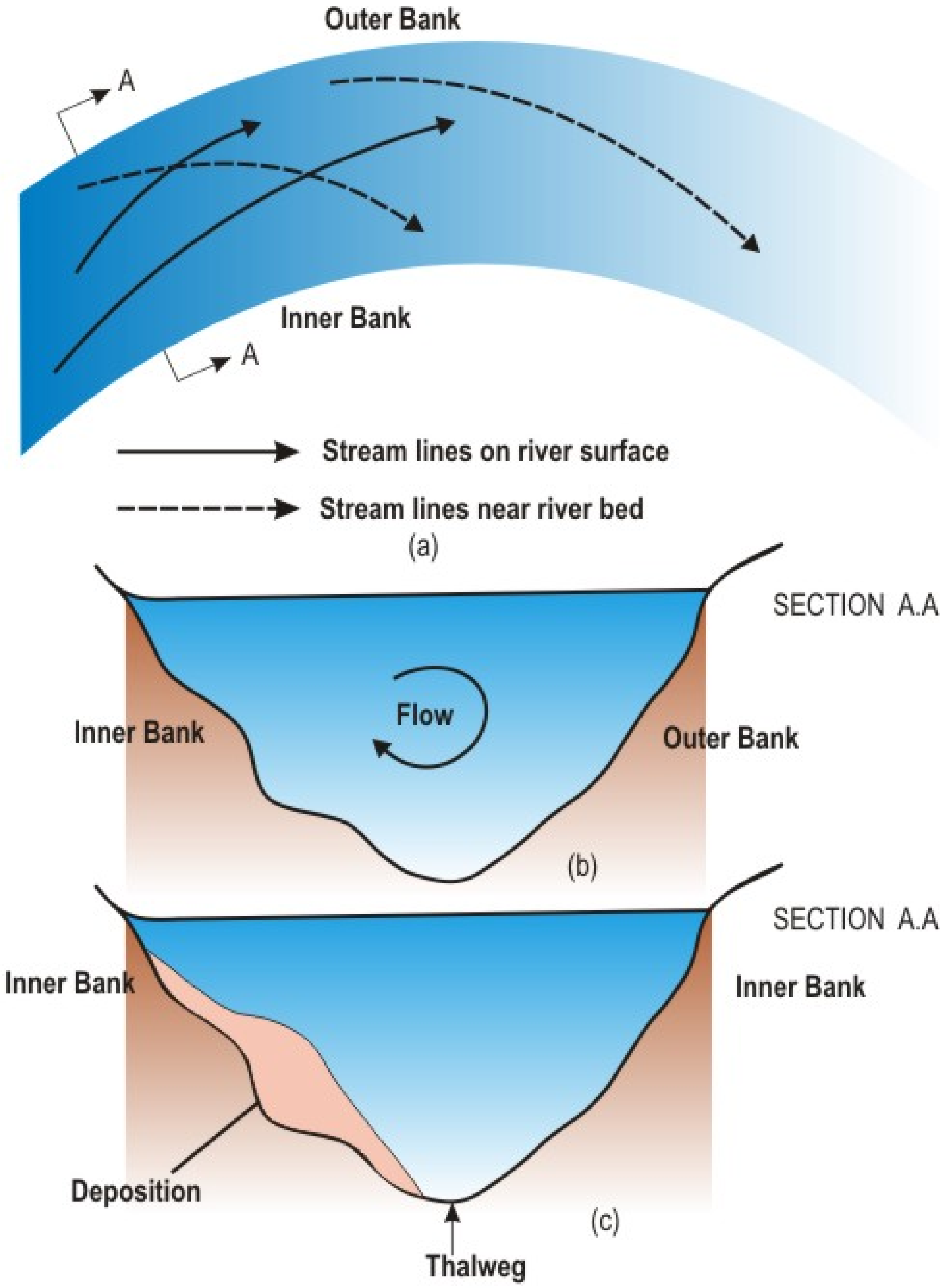


Figure 9. Secondary flow in river beds (a) Streamlines in plan at different levels ;
(b) Rotation movement of water in river cross-section ; and
(c) Effect of secondary flow : deposition on inner bank(compare point bars in fig 8 b)

As may be seen from the figure at river bends, there is a perceptible flow in a plane perpendicular to the river flow direction. At the outer bank the secondary flow causes erosion and at the inner bank it causes deposition, thus giving rise to point bar formation. The locus of the deepest points of the river along the length is called the thalweg. Most thalwegs pass through a succession of ***pools*** in the channel bed that are separated by ***riffles*** which might be sedimentary bed forms or bed rock ledges. The pools and riffles of the streambed cause the thalweg to have an irregular slope, rising and falling in the downstream direction.

2.9.6 River meandering

A river that winds a course not in a straight line but in a sinusoidal pattern (Figure 10) is called a ***meandering*** river.

Figure 10. A meandering river

It is the continued action of the secondary flow developed on the river bends that cause further erosion on the outer bank and deposition on the inner bank. The meandering action increases the length of the stream or river and tends to reduce the slope.

Many scientists have suggested different reasons for meandering to happen. The principles of external hypothesis have been used to explain the phenomenon like that of minimum variance proposed by Langbein and Leopold in 1962. The minimization involves the planimetric geometry and the hydraulic factors of depth, velocity and local slope. Mathematical explanations have also been put fort by Yang in 1976 that started the time rate of energy expenditure explains the formation of meandering streams. Other like Maddock (1970) and Chang (1984) use the principle of minimum stream power Julien (1985) treated meandering as a variation problem in which the energy integration corresponds to the functional variational problem, the solution of which is the sine-generated curve.

Quantitavely, scientists like Chitale (1970) argue that the primary cause of meandering is excess of total sediment load during floods. A river tends to build a steeper slope by depositing the sediment on the bed when the sediment load is in excess of that required for equilibrium. This increase in slope reduces the depth and increases the width of the river channel if the banks do not resist erosion. Only a slight deviation from uniform axial flow is then required to cause more flow towards one bank than the other. Additional flow is immediately attracted towards the former bank, leading to shoaling along the latter ascending the curvature of the flow and finally producing meanders in its wake.

2.9.7 Lateral movement of rivers and its bank instability

Channel meandering is a result of an ongoing bed and bank deformation by the flow in a self formed alluvial channel thus the meander sinuosity increases with the passage of time (Figure 11).

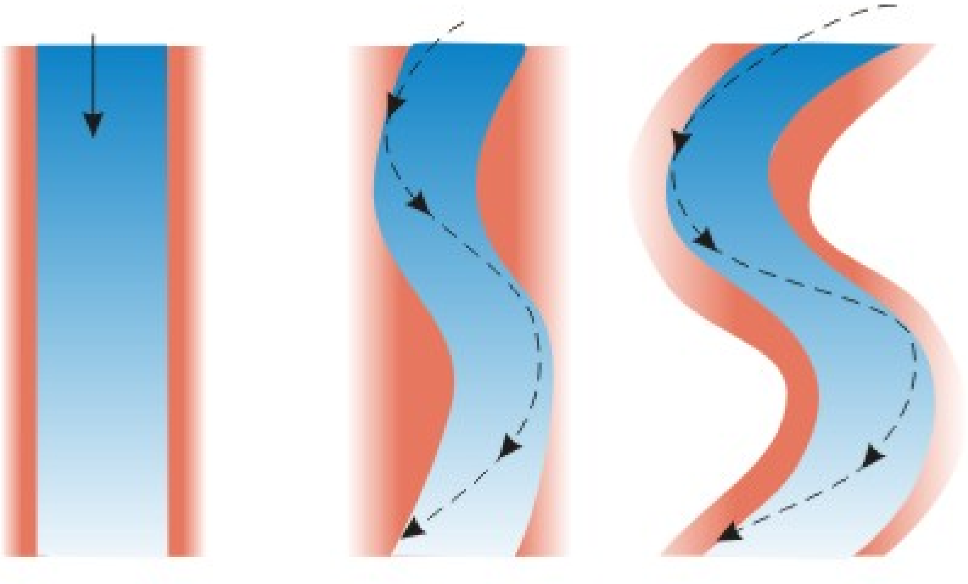
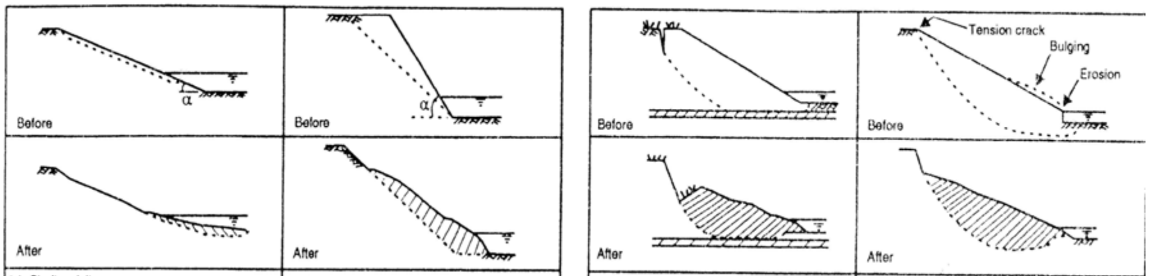


Figure 11. Sinuosity for a straight and meandering river (a) Straight: Sinuosity = 0; (b) Sinuosity = 1.1 ; and (c) Sinuosity = 1.5

In the above figure it is clear that the increase in sinuosity of a meandering river is associated with riverbank retreat. In some rivers, like Kosi the river has shifted or migrated laterally over large distances (predominantly in the westward direction). Here too the action is due to riverbank retreat, though the river doesn't display meandering significantly hence bank erosion is inseparably connected to lateral river migration.

Bank erosion consists of the detachment of grains or assemblages of grains from the bank, followed by fluvial entrainment. Though the riverbed may be composed of non-cohesive alluvial material the banks, on the other hand, may be composed of cohesive or non-cohesive soils. Cohesive, fine-grained bank material is easily eroded by the entrainment of the aggregates or the crumbs of the soil rather than individual particles, which are bound tightly together by electro-mechanical cohesive forces. Non-cohesive bank material is usually detached grain by grain and may leave a pronounced notch marking peak stage achieved.

When a section of bank-line fails and collapses lots of bank material slide or fall towards the toe of the bank. They may remain there until broken down insitu or entrained by the flow. Mass failures can be analyzed in geotechnical slope stability terms or as the result of fluvial and gravitational forces, which overcome resisting forces of friction, interlocking and cohesion, some of the bank failure modes are given in Figure 12.

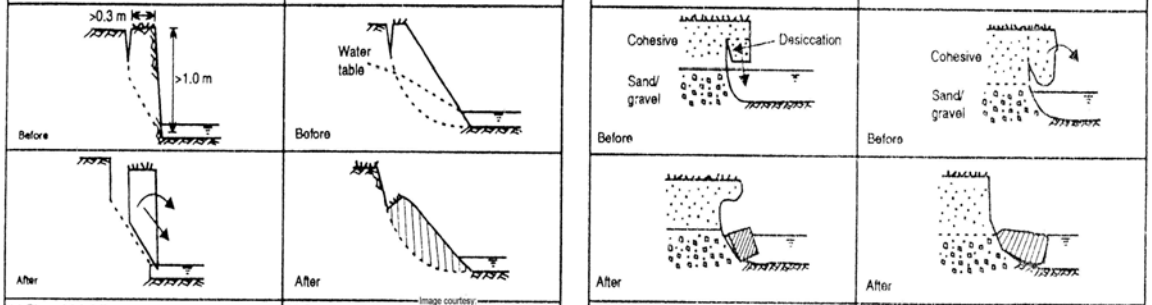


(a) Shallow failure
- shallow bank angle
- usually in non-cohesive banks
- failure nearly parallel to slope at $\alpha = \phi'$
- water seepage from bank can substantially reduce stable α
- vegetation will normally help stabilise against failure

(b) Planar failure
- steep or vertical bank angle
- frequently (but not always) in non-cohesive banks
- water table/channel water level usually low relative to bank height

(e) Rotational failure with weak zone
- failure surface dictated by position of weak zone
- see also comments for type (d)

(f) Massive rotational failure/landslide
- erosion of river bank threatens stability of whole valley side
- very large volume of slipped material
- tension cracks up valley side, bulging above toe, or noticeable movement are signs of potential failure



(c) Planar/slab failure
- steep or near vertical banks
- deep tension cracks
- Failure occurs by sliding and/or toppling
- failure more likely if crack fills with water
- little affected by groundwater table

(d) Rotational failure in homogeneous material
- usually on moderately high or steep banks
- usually in cohesive material
- tension cracks reduce stability particularly when water-filled
- significantly affected by position of water table
- failure may extend beyond toe, see also type (e)

(g) Failure of composite bank (in tension)
- occurs only where upper cohesive layer overlies erodable sand/gravel
- failure by tension of lower part of overhanging block

(h) Failure of composite bank (as beam)
- occurs as type (g)
- failure with upper soil in tension, followed by rotation
- after failure block usually remains intact with vegetation towards river
- failure can also be by shear

FIGURE 12. Modes of bank failure

Image courtesy: CR Thorne, RD Hey and MD Newson (Eds.) Applied Fluvial Geomorphology for River engineering and Management

2.9.8 River width adjustment

With increase or decrease of predominant flow and sediment load of a river, there is a change in river bed level, as discussed in 2.9.2 to 2.9.4. Although changes in channel depth caused by aggradation or degradation of the river bed can be simulated, changes in width cannot. When attempting to model a natural system like fluvial morphology this is a significant limitation because channel cross section usually changes with time, and adjustment of both width and depth (in addition to changes in planform, roughness and other attributes) are quite common.

River with adjustments may occur due to a wide range of morphological changes and channel responses. It may be widening (Figure 13) or narrowing (Figure 14).

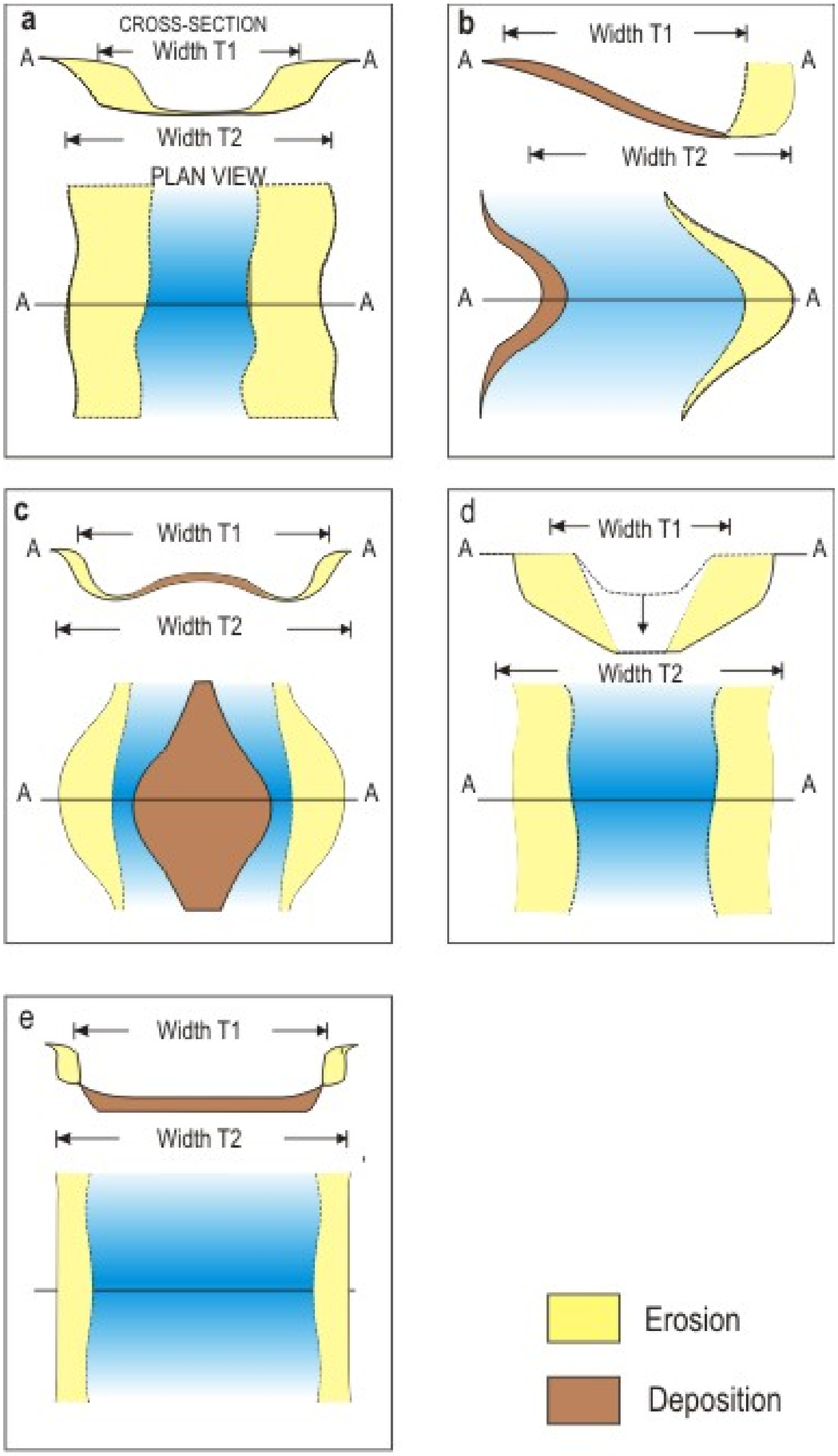


Figure 13. Modes of channel widening
Adapted from ASCE Task Committee , 1998 paper

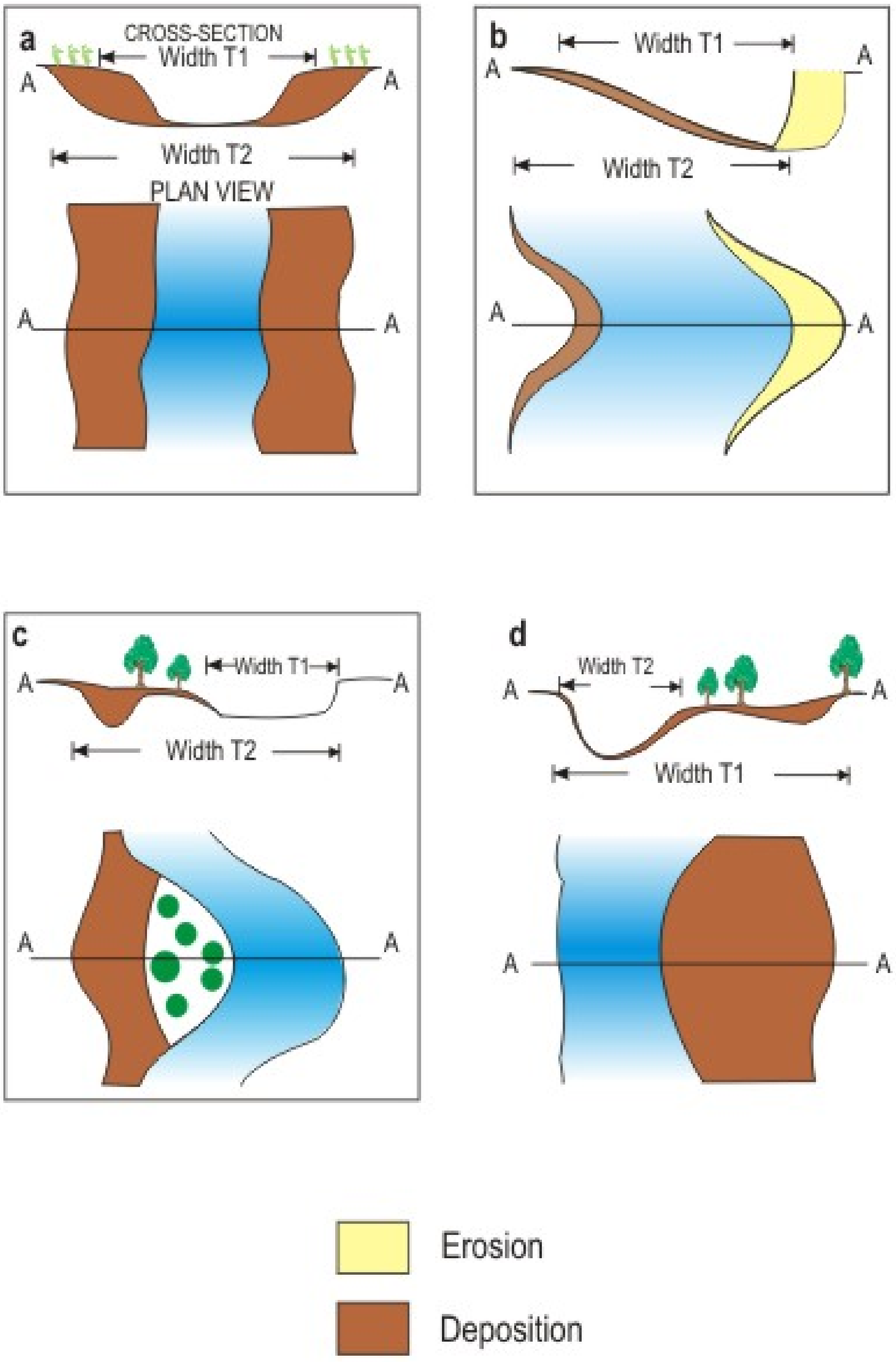


Figure 14. Modes of channel narrowing
Adapted from ASCE Task Committee , 1998 paper

Widening can occur by erosion of one or both banks without substantial incision (Figure 13a). Widening in sinuous channel may occur when outer bank retreat, as in a meandering channel Figure 13b. In braided rivers, bank erosion by flows deflected around growing braid bars is a primary cause of widening (Figure 13c). In degrading streams widening often flows the incision of the channel when the increased height and steepness of the banks causes then to become unstable (Figure 13d). Widening in coarse-grained, aggrading channels can occur when flow acceleration due to a decreasing cross sectional area, coupled with current deflection around growing bars, trigger bank erosion (Figure 13e).

Narrowing of rivers may occur through the formation of in-channels ***berms***, or ***benches*** at the margins (Figure 14a). Berm or bench often grows when bed levels stabilizes following a period of degradation and can eventually lead to creation of new, low- elevation flood plain and establishment of narrower quasi equilibrium channel. Narrowing in sinuous channels occur when the rate of alternate or point bar growth exceeds the rate of retreat of the cut bank opposite (Figure 14b). In braided channels, narrowing may result when a marginal ***anabranch*** (on offshoot channel) in the braided system is abandoned (Figure 14c). Sediment is deposited in the abandoned channel until it merges into the floodplain. Also, braided bars or islands may become attached to the floodplain, especially following a reduction in the formative discharge (Figure 14d). Island tops are already at about the flood plain elevation and attached bars are built up to flood plain elevation by sediment deposition on the surface of the bar, often in association with establishment of vegetation.

2.9.9 Hydraulic geometry of alluvial rivers

Width, depth, average velocity, average longitudinal bed slope of a natural river depends on many factors like discharge and sediment variation throughout the year and over the years, type of bed material and their variation in the river bed, type of bank material. There have been numerous attempts to find some relations between all the variables, which may be grouped as under (ASCE, 1998):

1) Regime theory and power law approach
2) External hypothesis approach
3) Tractive force methods.

The first of the three methods is traditionally the oldest and some of the initial contributors like Kennedy (1885), Lindley (1919), and Lacey (1929) based their hypotheses on research carried out on small rivers and artificial channels in India. Other noted contributors were Simons and Albertson (1963) and Blench (1969). The latter also based his study on the data gather from Indian rivers. Of the various formulas proposed so far by different researchers, the one by Lacey is quite popular in India though it has its own limitations as pointed out by Lane.

In fact, the data that was analyzed by him pertained to stable artificial channels of north India which were flowing through sandy materials and where carrying relatively small amount of bed material load. The following equations, which were originally presented by Lacey in FPS units, are being given here in terms of SI units

$$P = 4.75 \sqrt{Q} \qquad (9)$$

$$R = 0.47 \left(\frac{Q}{f_1}\right)^{1/3} \qquad (10)$$

$$S = 0.0003 \ f_1^{5/3} / Q^{1/6}$$
(11)

$$U = 0.516 \ f_1^{5/3} / Q^{1/6} = 10.8 R^{2/3} S^{1/2}$$
(12)

$$f_1 = 1.76 \sqrt{d_{50}} \qquad (13)$$

In the above expressions, the variables stand for

- ***P:*** Wetted Perimeter (m)
- **R:** Hydraulic Radius (m)
- ***S:*** Channel Slope
- ***U:*** Average Velocity (m/s)
- ***Q:*** Discharge (m^3/s)
- ***f_1:*** Silt factor, a term used to define the fineness or coarseness of the channel bed material.
- ***d_{50}:*** Median size of bed material in mm

In India, hydraulic engineers have used these equations often for rivers, small and large. For wide rivers, the equations for ***R*** in terms of discharge ***q*** (discharge per unit width) obtained by combining the first two equations is used in the following form:

$$R = 1.35 \ ((q^2 / f_1)^{1/3} \qquad (14)$$

A critical analysis of the formulae proposed by Lacey shows that sediment load is not included as one of the independent variables in the equation along with Q and d. Secondly, it has been pointed out by other researchers, that since the formulae of Lacey was based on data from channels of north India where the base is alluvial and banks are cohesive, the proposed equations are applicable largely to channels and canals with sandy bed and cohesive bars. Further the regime equations, as the equation proposed by Lacey are generally called, correspond to a given bank full discharge.

In the recent years the work by Julien and Wargadalam (1995) has attempted to refine the regime approach within a framework based on the governing principles of open channel flow. After studying data from 835 non-cohesive alluvial rivers and canals they arrived at the following relationship

$$h = 0.2\ Q^{0.33}\, {d_{50}}^{0.17} {S_f}^{-0.17} \tag{15}$$

$$W = 1.33\ Q^{0.44}\, {d_{50}}^{-0.11} {S_f}^{-0.22} \tag{16}$$

$$U = 3.76\ Q^{0.22}\, {d_{50}}^{-0.05} {S_f}^{0.39} \tag{17}$$

$$S_f = 0.121\ Q^{0.33}\, {d_{50}}^{-0.83} {S_f}^{0.33} \tag{18}$$

These are the simplified formulae of the more detailed ones and have been showed to agree quite well measured data. The variable sin the above equations are defined as follows

- ***h:*** Flow Depth (m)
- ***W:*** Water surface width (m)
- ***U:*** Average Velocity (m/s)
- ***S_f:*** Friction Slope
- ***d_{50}:*** Median slope of bed material (m)

The simplified equations proposed by Julian and Wargadalam are suitable when τ_* = 0.047, when Manning's equation is generally applicable to describe flow in the river. Higher segment transport implies higher velocity and slope and reduced width and depth. It may be recalled that Shield's parameter τ_* is defined as:

$$\tau_* = \left(\frac{\gamma\, h\, S_f}{(\gamma_S - \gamma)\, d_{50}} \right) \tag{19}$$

Two other approaches that have been proposed for describing the hydraulic geometry of an alluvial river are based on height following theories:

a) Extremal hypothesis
b) Tractive force approaches

These have been more commonly applied in the recent years. But the method proposed by Lane in threshold channel theory has also been used often to design canals in alluvium. This has been discussed in Lesson 2.10.

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