The **bankfull discharge** is that flow at which the channel is completely filled. Wide variations are seen in the frequency with which the bankfull discharge occurs, although it generally has a return period of one to two years for many stable alluvial rivers. The geomorphological work carried out by a given flow depends not only on its size but also on its frequency of occurrence over a given period of time.

The flow in river channels exerts hydraulic forces on the boundary (bed and banks). An important balance exists between the erosive force of the flow (driving force) and the resistance of the boundary to erosion (resisting force). This determines the ability of a river to adjust and modify the morphology of its channel. One of the main factors influencing the erosive power of a given flow is its **discharge**: the volume of flow passing through a given cross-section in a given time. Discharge varies both spatially and temporally in natural river channels, changing in a downstream direction and fluctuating over time in response to inputs of precipitation. Characteristics of the flow regime of a river include seasonal variations in discharge, the size and frequency of floods and frequency and duration of droughts. The characteristics of the flow regime are determined not only by the climate but also by the physical and land use characteristics of the drainage basin.

**Valley setting**

Channel processes are driven by flow and sediment supply, although the range of channel adjustments that are possible are often restricted by the valley setting. The influence of channel substrate and vegetation on bank erosion and channel migration have already been mentioned. The valley slope is also significant, affecting the steepness of the channel, which, together with discharge, determines stream power. Channels that flow over very gentle gradients can sometimes be extremely restricted in the adjustments they can make because so little energy is available. Another control on channel adjustment is the degree of **valley confinement**. While some channels are able to migrate freely across a wide floodplain, others are confined to a greater or lesser extent by the valley walls.

**THE FORM OF A CHANNEL**

When the stream beds turn gentler due to continued erosion, downward cutting becomes less dominant, while lateral erosion of banks increases; a consequence of this is that the stream channel widens, and that hills and valleys surrounding the stream channel are reduced to plains over time. The shape and form of the channel itself also change down the course of a river, and are dependent on the gradient, flow rate and sediment load of the stream at different points. *Four main types of alluvial channel form can be identified*: straight, meandering, braided and anabranching. Bedrock channels also exhibit a wide variety of forms. However, with so many environmental variables influencing channel form, a range of different channel forms and behaviour is possible and not all rivers fit neatly into one of these categories – there are many examples of transitional rivers that have characteristics associated with more than one channel type.

**Channel substrate**: the material in which the channel is formed. An important distinction can be made between bedrock and alluvial substrates (Figure 2.33).

- **Bedrock channels**, as their name suggests, are sections of channel that are cut directly into the underlying bedrock, while

- **alluvial channels** are formed in **alluvium** – sediment that has previously been laid down in the valley floor by rivers. Alluvium can include a mixture of unconsolidated particles ranging in size from boulders, gravels and sands to finer deposits of silts and clays. Where the valley floor is wide enough, material laid down in the channel, together with silt deposited by floods, form a **floodplain** adjacent to the river channel.
ALLUVIAL CHANNEL FORM

Characteristics of alluvial channels

Channels usually lined with alluvium
Removed & carried further downstream during flood
Re-deposited during wane
Erodible channel boundaries (alluvial banks & bed)
Transport Capacity ≤ Sediment Supply
Storage can be quite high
Input ≥ Output

Figure 2.33: Alluvial channels are formed in alluvial deposits formerly laid down by fluvial processes.

Alluvial channel form

Four main types of alluvial channels are generally recognised: straight, meandering, braided and anabranching.

The previous sections have considered the controlling influence of the driving variables and boundary conditions on channel form and behaviour. Each of these controls varies across a continuous range. For instance, slopes range from steep to gentle, valleys from confined to unconfined, and sediment loads from suspended to mixed to bedload dominated. Many different combinations are possible, leading to the immense variety of fluvial forms and behaviour that is seen globally.

The continuum of alluvial channel types is illustrated in Figure 2.41 on p 30. In general terms, different channel types exist along an energy gradient, ranging from high energy braided channels through meandering and straight to low-energy anastomosing channels (a sub-set of anabranching channels). Floodouts and chains of ponds are found in low-gradient arid environments, where downstream reductions in discharge result in a dwindling supply of energy. This continuum can be related to the channel controls, since stream power integrates channel slope and flow regime. It also influences the type of load that the channel can carry, which in turn determines the substrate and stability of the channel. Like all channel classifications, the one shown in Figure 8.10 is, by necessity, a simplification of reality. While some channel reaches typify, say, a braided form, many have characteristics that are associated with more than one type. In fact, it has been suggested that channels with an intermediate form might be the norm rather than the exception (Ferguson, 1987). Although there is a continuum of forms, thresholds do exist between them. For example, there is a meandering–braiding threshold, above which rivers braid and below which they meander. Rivers that are close to this threshold, such as many of those in the South Island of New Zealand, have alternating meandering and braided reaches.

Straight channels

Most single-channel rivers and streams follow a winding path and straight channels are rare. Even where they do exist, variations are usually seen in flow patterns and bed elevation. Straight channels are relatively static, with rates of channel migration limited by a combination of low energy availability and high bank strength. This is especially true where the channel banks are formed from more resistant material, such as cohesive silts and clays.

Meandering channels

In large flood and delta plains, rivers rarely flow in straight courses. Loop-like channel patterns called meanders develop over flood and delta plains. In contrast to braided rivers, meandering rivers typically contain one channel that winds its way across the floodplain. As it flows, it deposits sediment on banks that lie on the insides of curves (point bar deposits), and erode the banks on the outside of curves.
Figure 2.34: Meandering Burhi Gandak river near Muzaffarpur, Bihar, showing a number of oxbow lakes and cut-offs

A meander is not a landform but is only a type of channel pattern. Their formation is due to:

(i) propensity of water flowing over very gentle gradients to work laterally on the banks;
(ii) unconsolidated nature of alluvial deposits making up the banks with many irregularities which can be used by water exerting pressure laterally;
(iii) coriolis force acting on the fluid water deflecting it like it deflects the wind.

When the gradient of the channel becomes extremely low, water flows leisurely and starts working laterally. Slight irregularities along the banks slowly get transformed into a small curvature in the banks; the curvature deepens due to deposition on the inside of the curve and erosion along the bank on the outside. If there is no deposition and no erosion or undercutting, the tendency to meander is reduced. Normally, in meanders of large rivers, there is active deposition along the convex bank and undercutting along the concave bank.

Figure 2.35: Meander growth and cut-off loops and slip-off and undercut banks

Meanders occur most commonly in channels that lie in fine-grained stream sediments and have gentle gradients, but also form in a variety of bedrock substrates. Associated with moderate stream powers, alluvial meanders may develop in gravels, sands, or fine-grained silts and clays. Meanders are scaled to the size of the channel, with wider spaces (longer wavelength) for larger channels. The degree of meandering varies greatly, from channels that only deviate slightly from a straight line to sequences of highly convoluted meander bends. Variations are also seen in the regularity of meander bends. Meandering channels evolve over time as individual bends migrate across the floodplain. Erosion is usually focused at the outside of meander bends, which gradually eat into the floodplain as the channel migrates laterally. At the same time, deposition on the inside of the bend allows the channel to maintain its width. Cut-offs – short sections of abandoned channel – indicate the path of former meander bends.

Circumstances favourable for meandering to occur include a gentle slope (< 2%), a relatively low sediment load and cohesive banks. Meandering rivers change their course gradually. In the progress of their migration, they create floodplains much wider than the channel itself, as it erodes the cut bank, which is the outside loop of the meander, while deposition takes place on the point bar, which is on the inside loop of the meander. Meandering alluvial systems are also characterized by seasonal flooding and the deposition and build-up of very fertile soil.
Figure 2.36: Meander morphology, with erosion causing cut banks and deposition forming point bars.

Streams generally **erode on outer (cut) bank** where **velocity is greatest**, and **deposit on the inner sides of bends** where **velocity is less**. Meanders tend to grow as the flow erodes the banks, favouring development of meandering channels. Successive point bar deposits create a floodplain, while cut banks migrate closer to each other, causing cut-offs and the formation of oxbow lakes. These processes all add to the migration of the stream and the building up of alluvial deposits that form a floodplain.

Figure 2.37: Flow velocity in meander bend and in cross-section of meandering stream

We therefore encounter lateral erosion of the floodplain with meandering systems. The **streamway or meander belt is also called the Channel migration zone, defined by the area across which the river is prone to move.**

**Meander geometry**

Various methods are used to quantify the geometric characteristics of meandering channels. These are based on measurements that can be made in the field, from maps, aerial photographs and, increasingly, satellite images. The spacing of meander bends, or **meander wavelength (l)**, can be determined by measuring the channel width ≈ 10 to 14 x wavelength as in figure below.

The **sinuosity ratio** gives an indication of how ‘bendy’ a channel is and can be worked out by measuring the length of a channel reach and dividing this by the straight line distance along the valley. Channels with a sinuosity ratio of less than 1.1 are described as **straight**, those between 1.1 and 1.5 are **sinuous**, and **meandering** channels have a ratio of more than 1.5.
Although widely used, these descriptions are somewhat arbitrary, since they are not based on any physical differences. There is a tendency for the thalweg, or line of fastest flow, to shift from side to side along the channel (See figure 2.37). This is seen even in straight channels, and is often associated with the development of riffles, pools and alternate bars.

Since the distance between successive meander bends varies, a mean wavelength is calculated for several meander bends along the reach of interest. Meander wavelength is more strongly related to channel width than to bankfull discharge. This is because secondary circulation within the channel, which is significant in meander development, is controlled by channel size. Interestingly, a similar relationship is seen for small supraglacial streams that flow over the surface of glaciers: they often develop meanders, despite the absence of sediment. There is a well established relationship between channel width and meander wavelength, which is usually \( \approx \) ten to fourteen times the bankfull width (See figure 2.38).

Figure 2.38. The relationship between channel width and meander wavelength.

Meander wavelength can also be influenced by the channel substrate, and longer wavelengths are associated with gravel channels than for silt and clay channels of a similar size. The reason for this is that cohesive banks allow the development of a narrower cross-section with tighter bends (Schumm, 1968). An indication of the ‘tightness’ of individual bends can be determined by fitting a circle to the centre line of a meander bend: the radius of this circle is called the radius of curvature \((r_c)\). To allow comparison between channels of different sizes, the tightness of bends is usually expressed as the ratio between the radius of curvature and the channel width at the bend \((r_c/w)\). Observations have shown that many bends develop an \(r_c/w\) ratio of 2 to 3. For bends that are tighter than this, flow separation leads to increased energy losses (Bagnold, 1960).

In cross-section, the form of the channel varies along its length. Meander bends are associated with asymmetric cross sections since scouring and bank steepening occur at the outside of the bend, while deposition occurs on the inside of the bend. The cross-section is more symmetrical at riffle sections.

Braided channels

Braided channels have substantial inputs of bedflow from upstream catchments. When sediment supply exceeds the transport energy in a stream, it is unable to move all the available load and tends to deposit the coarsest sediment, causing one or more central bars to form, which divert the flow towards the banks. This flow in turn increases lateral erosion on the banks, causing more deposition and bar formation. Braided channels tend to form in streams with a highly variable discharge, easily erodible banks, and/or a high sediment load and they are characterised by numerous channels that split off and rejoin each other to give a braided appearance.

Figure 2.39. Braided channel segments of Son (left) & Gandak (right) rivers.
They usually carry coarse-grained sediment down a steep gradient and have a high total load, with bedload typically being more than 11% of the total load. Braided rivers are usually wide and relatively shallow (they have a high channel width to depth ratio). As the valley widens, the water column is reduced and more and more sediment gets deposited as islands and lateral bars, resulting in the development of separate channels of flow.

Deposition and lateral erosion of banks are essential for the formation of a braided stream pattern. The appearance of a braided channel varies with changing flow conditions, with many bars becoming partly or wholly submerged during high flows, giving the appearance of a single wide channel. At low flows, extensive areas of bar surface may be exposed. Braided rivers, are associated with high rates of energy expenditure, which is involved in the transport of large volumes of sediment. They often have steep channel slopes, although there are several examples of large braided rivers that flow over low gradients. Erodible banks are also required for the channel to become wide enough to allow for the growth and development of channel bars. Braided channels are highly dynamic, with frequent shifts in channel position. Modifications, such as the dissection and reworking of bars and the formation and growth of new bars, occur over relatively short periods of time (days to years). The presence of bars leads to complex patterns of flow within the channel, and there can be sudden shifts in the location of sub-channels. Individual channels can be abandoned or reoccupied in the space of a few days.

Anabranching channels

With anabranching channels the flow separates into two or more distinct channels, and this channel form is rare in comparison to braided and meandering channels. The separate channels, called anabranches, are typically cut into the floodplain, dividing it up into a number of large islands with an elevation similar to the surrounding floodplain. Usually the island positions remain relatively fixed over many years or decades and are well vegetated, where climatic conditions allow this. Individual anabranches can themselves be straight, meandering or braided, with the flow in each ranch reasonably independent of the surrounding branches. Unlike braided channels, rates of lateral channel migration are usually very low, but new channels can be cut when floodwaters breach the channel boundary and spill out on to the floodplain. Other channels are abandoned as the flow is diverted elsewhere, or when they become infilled with sediment.

Anabranching channels occur in flood-dominated regimes, and usually have banks that are relatively resistant in comparison with the available stream power. It is the most diverse channel type which is found in many different environments – cold, dry, wet, semi-arid, tropical and sub-arctic, and it occurs in substrates ranging from coarse to fine-grained alluvium and in various energy regimes. They are nevertheless comparatively scarce.

Colour Plates 8 and 9 both show examples of a subset of low-energy anabranching channel that is referred to as anastomosing. Although most research on anabranching channels has so far been focused on anastomosing channels, anabranching channels represent the most diverse of the four main channel types.

When considering channel form, individual reaches of channel are usually considered. This is because of the downstream changes in channel size and shape that are brought about by factors such as increasing drainage area and variations in channel substrate. Therefore different channel patterns may be found along the same channel. At the reach scale – (a few metres to a few hundreds of metres) – there is a homogeneity of form. In addition to the variation in the channel planform patterns described above, variations are also seen in cross-sectional shape and channel slope. For example, braided channels tend to be relatively wide and shallow in comparison to meandering channels, which have a narrower, deeper cross-section. Headwater streams in mountainous areas typically flow in steep channels, with frequent waterfalls, pools and rapids. This is in contrast to rivers that flow across lowland floodplains, where the channel slope is much more gentle. Fluvial forms also exist at the sub-channel scale. These include channel bars, pools excavated by localised scour, and periodic features such as dunes and ripples that form on the bed of sandy channels. Certain groupings, or assemblages, of these features are associated with different channel types.
Why do rivers anabranch?

Anabranching channels are often associated with very low slopes and, because little energy is available, the range of possible adjustments is somewhat limited. Although the slope cannot be increased, form adjustments can lead to a reduction in flow resistance, thus increasing the energy available for transporting sediment. It has been demonstrated that two or more channels with a low width-to-depth ratio (narrow and deep) are more hydraulically efficient than a single channel (Nanson and Huang, 1999), because the combined hydraulic radius of the multiple channels is greater (more hydraulically efficient) than for a single channel carrying the same flow.

Anabranching channels are usually formed by erosion, when avulsion leads to the incision of a new channel into the floodplain. Avulsion occurs during high flows, when one of the banks is breached and water spills out onto the floodplain. If flow is sufficiently concentrated, a new channel can be incised, eventually rejoining another channel further downstream. Some anabranches are only active during flood flows, acting as a distributory system for dispersing and storing water and sediment (Nanson and Huang, 1999). Individual anabranches are abandoned when they become infilled with sediment, perhaps as a result of a blockage or because the flow is diverted elsewhere. In some cases, anabranching may develop as a result of sediment deposition, when flow is concentrated by the development of bars or ridges within a relatively inefficient channel (Wende and Nanson, 1998).

Anastomosing channels

There is some confusion surrounding the terminology of these multi-channelled forms, which are sometimes referred to as anastomosing. The nomenclature used by Nanson and Knighton (1996) will be used here, where the term anabranching is used to describe all planforms that are characterised by more than one separate channel. Anastomosing will be used to describe one particular subgroup of low-energy anabranching channels.

General controls on channel morphology

<table>
<thead>
<tr>
<th>Channel Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight Channels</td>
<td>Typically steep, low-sediment supply</td>
</tr>
<tr>
<td>Braided Channels</td>
<td>Typically high sediment supply</td>
</tr>
<tr>
<td>Meandering Channels</td>
<td>Typically low to medium slope and moderate sediment supply</td>
</tr>
<tr>
<td>Anastamosed Channels</td>
<td>Typically reflect vegetation influences</td>
</tr>
</tbody>
</table>

**Straight Channels**

Straight channels are rare. They form where streams are confined by topography or follow geologic structures. Generally mountain streams.

**Braiding favoured by:**

- High slope
- High sediment load
- High discharge variability
- Erodible (non-cohesive) banks

Figure 2.40: Alluvial channel type as function of bedload supply and diameter, and stream energy
To determine whether a given length stream will have a straight, meandering, braided, or anastomosed form, the following figure is helpful:

*Figure 2.41 The continuum of variants of channel planform. After Brierley and Fryirs (1992), adapted from Church (1992) and Schumm (1977).*
Sediment particles are deposited when there is a reduction in the competence and capacity of the flow. The process takes place at a very small scale and involves individual grains, although depositional forms can be observed over a wide range of spatial scales, from the smallest bedforms to vast floodplains and deltas. Thresholds for deposition are associated with the fall (or settling) velocity; the deposition of suspended sediment occurs when the fall velocity dominates over turbulent diffusion. Fall velocity is also affected by the viscosity and density of water. Because there is also a close relationship between fall velocity and particle size, the coarsest sediment is usually deposited first, leading to sediment sorting, which is both a vertical and horizontal gradation of sediment, from coarse to fine. These are both influenced by changes in suspended sediment concentration. In addition, finer material can be transported as agglomerations of sediment called flocs, which have a greater fall velocity than the individual particles forming them. In the case of bedload transport, the near-bed flow conditions are significant. Bedload deposition occurs where the bed shear stress drops below the critical shear stress (Shields’s parameter) required to transport particles of a given size.

The different circumstances that lead to sediment deposition include:

- **Reductions in flow discharge** which are seen as flows recede, or along dryland rivers, where downstream losses are caused by high rates of evaporation and percolation.
- **Decreases in slope** which can be localised, or involve a gradual reduction over a longer length of channel and cause a reduction in average flow velocity and stream power.
- **Increases in cross-sectional area** cause the flow to diverge and become less concentrated. Flow resistance increases because there is more contact between the flow and channel boundary. There is a large increase in cross-sectional area when overbank flows occur.
- **Increases in boundary resistance** are associated with vegetation and coarse bed sediment. When overbank flows occur, velocity is reduced by the increased roughness of the floodplain surface, leading to the deposition of suspended sediment.
- **Flow separation**, which causes sediment to become decoupled from the flow.
- **Obstructions to flow.** Sediment often accumulates behind obstructions. These include boulders, outcrops or islands of bedrock, woody debris and man-made structures such as bridge piers, dams and flow control structures. Changes in the supply of sediment are also important. For example, sediment tends to accumulate immediately downstream from scour zones caused by flow convergence, when the material scoured from the channel bed is deposited immediately downstream. At a larger scale, increases in the supply of sediment to a channel reach are caused by changes within the upstream drainage area (Chapter 5).

**Depositional environments**

Deposition dominates in the deposition zone, where there is a decline in gradient and low energy levels, but limited deposition also occurs in the production and transfer zones of the fluvial system. Large-scale deposition leads to the development of characteristic landforms, including floodplains, alluvial fans and deltas. Within channels, bars represent smaller-scale depositional features, which are commonly found on the inside of meander bends, along the edges of channels, and where tributaries join the main channel. Braided channels are characterised by numerous mid-channel bars.

**The floodplain**

The floodplain is the lateral extent of the river at high flow. A floodplain is the flat land immediately surrounding a stream channel and submerged at times of high flow and is formed from a mixture of in-channel and overbank deposits. Their development and evolution is governed by a number of factors, including the supply of sediment (volume and calibre or diameter), the energy environment of the
channel, and the valley setting. Sediment is laid down by rivers as they migrate across the floodplain, being deposited on the inside of meander bends or when braid bars are abandoned. These channel deposits are relatively coarse in comparison with the much finer sediment that is laid down by overbank flows, further away from the channel. Processes of erosion can also be significant in reworking sediment or in removing part, or all, of the floodplain surface.

![Figure 2.42: Floodplain construction by bedload deposition](image)

Point bar deposit grows laterally through time, and it forms a floodplain in this process: deposition develops a floodplain just as erosion makes valleys. **Flood plains are built up as flat areas adjacent to main channel is subjected to periodic flooding and suspended sediment is deposited**, but they can also be formed by deposition of bedload as the channel migrates across its valley.

**Floodplains are** major landforms caused by river deposition. Large sized materials are deposited first when a stream channel breaks into a gentle slope. Thus, normally, fine sized materials like sand, silt and clay are carried by relatively slow moving waters in gentler channels usually found in the plains and deposited over the bed and when the waters spill over the banks during flooding above the bed. A river bed made of river deposits is the active floodplain. The floodplain above the bank is inactive floodplain. Inactive floodplain above the banks basically contain two types of deposits — flood deposits and channel deposits. In plains, channels shift laterally and change their courses occasionally leaving cut-off courses which get filled up gradually. Such areas over flood plains built up by abandoned or cut-off channels contain coarse deposits. The flood deposits of spilled waters carry relatively finer materials like silt and clay. The flood plains in a delta are called *delta plains*.

![Figure 2.43: The effect of lateral channel migration with increasing meander sinuosity in forming or carving out a floodplain](image)

**Alluvial fans**

**Alluvial fans** are typically found in situations where an upland drainage basin flows out onto a wide plain. They are fan-shaped deposits of water-transported material (alluvium) and they typically form at the base of any topographic feature where there is a marked break in slope. Consequently, alluvial fans tend to be coarse-grained, especially at their mouths, while they can be relatively fine-grained at their edges.
The sudden change from confined to unconfined conditions leads to flow divergence, while mean flow velocity is decreased by the reduction in slope. The resultant deposition leads to the formation of a conical feature with a convex cross-profile. Most fans have a radius of less than 8 km, but can be more than 100 km wide in some cases. Fans are commonly found in dry mountain regions, where an abundant sediment supply is associated with extreme discharges and frequent mass movements. Alluvial fans in humid areas show normally low cones with gentle slope from head to toe and they appear as high cones with steep slope in arid and semi-arid climates.

Figure 2.44: (a) An alluvial fan deposited by a hill stream on the way to Amarnath, Jammu and Kashmir. (b) Alluvial fan in Death Valley, California

Bajada

Where a number of individual fans develop along a mountain front, they may grow laterally and coalesce to form a sloping apron of sediment called a bajada.

Figure 2.45: Bajada formed from coalescing alluvial fans in Death Valley, California

Deltas

Deltas are found where sediment-charged water flows into a body of still water, dumping and spreading its load into the water body. They extend outwards from shorelines where rivers enter lakes, inland seas and oceans. In coastal areas deltas form where the supply of sediment is greater than the rate of marine erosion, although sediment is redistributed by coastal processes. The influence of fluvial processes tends to dominate in the case of lake deltas.

Unlike in alluvial fans, the deposits making up deltas are very well sorted with clear stratification. The coarsest materials settle out first and the finer fractions like silts and clays are carried out into the sea. As the delta grows, the river distributaries continue to increase in length (figure 2.46) and the delta continues to build up into the water body.
FLOODPLAIN GEOMORPHIC UNITS

Levees

Levees are found along the banks of large rivers and form when debris-laden floodwater overflows the channel and slows down as it moves onto the floodplain. They are elongated, raised linear ridges of relatively coarse deposits that run parallel to the stream channel and which form at the channel-floodplain boundary during overbank flow events (figure 2.47). During flooding as the water spills over the bank, the velocity of the water comes down and large sized and high specific gravity materials get dumped in the immediate vicinity of the bank as ridges. They are high nearer the banks and slope gently away from the river. The levee deposits are coarser than the deposits spread by flood waters away from the river. When rivers shift laterally, a series of natural levees can form. Moving across the boundary from channel to floodplain, there is a sudden loss of momentum because of the interaction between fast channel flow and slow floodplain flow, resulting in the preferential deposition of material along the edges of the channel. The photograph left shows a meandering river in flood.

The boundary between channel and floodplain may be the site of a natural levee (a broad, low ridge of alluvium built along the side of a channel by debris-laden floodwater). Levees are clearly visible as the raised strips of land running along the channel margins. The height of levees is scaled to the size of the channel and their presence implies a relatively stable channel location (Brierley and Fryirs, 2005). These natural levees should not be confused with the artificial levees that are constructed along river banks for purposes of flood control.
Point bars

Point bars are also known as meander bars. They are found on the convex side of meanders of large rivers and are sediments deposited in a linear fashion by flowing waters along the bank. They are almost uniform in profile and in width and contain mixed sizes of sediments. If there more than one ridge, narrow and elongated depressions are found in between the point bars.

Rivers build a series of them depending upon the water flow and supply of sediment. As the rivers build the point bars on the convex side, the bank on the concave side will erode actively.

Figure 2.48 : Natural levee and point bars

Specific landforms associated with the floodplain of a meandering stream

Oxbow lakes

As meanders grow into deep loops, the same may get cut-off due to erosion at the inflection points and are left as ox-bow lakes. Oxbow lakes are therefore crescent-shaped lakes formed in an abandoned river bend which has become separated from the main stream by a change in the course of the river. Old channels abandoned as a river meanders across its floodplain form oxbows.

Figure 2.49 : The formation of oxbow lakes through the cut-off of mature meanders

Splays or Crevasse splays

Another landform associated with meandering streams is a splay, which is a fan-shaped lobe of sediment deposited when sediment-charged water breaks the bank of the levee and flows beyond the levee. A splay is therefore a deposit of coarse material resulting from a levee breach during a flood. If flow is sufficiently concentrated, a new channel may be cut and deepened by scour.
**Backswamps**

A low area of swampy ground beyond a river’s natural levees. The build-up of sediment in the channel may mean that the channel is at a higher elevation than the surrounding floodplain. When levees are overtopped, water can enter the lower-lying area on the other side of the levee. This may be a depression or a swamp area characterised by wetland vegetation (Figure 8.9b). Colour Plate 9 shows some good examples of backswamps. These are not exclusively associated with anabranching rivers and can also form at the valley margins of other channel types.

**Flood channels**

Flood channels are relatively straight channels that bypass the main channel. They have a lesser depth than the main channel and are dry for much of the time, only becoming filled with water as the flow approaches bankfull.

**Floodouts**

Floodouts are associated with dryland channels. They occur where floodwaters leave the main channel and branch out onto the floodplain in a number of distributory channels. This happens where low gradients, downstream transmission losses and high rates of evaporation lead to a downstream reduction in channel capacity. Channels may re-form downstream from the floodout if flow concentration is sufficient, forming a discontinuous channel. Alternatively the floodout may mark the channel terminus. Floodouts can also form where the channel is blocked by bedrock outcrops, fluvial, or aeolian deposits such as sand dunes (Tooth, 1999).

**Meander scroll bars**

A meander scroll consists of long, curving, parallel ridges (scrolls) that during stages of high water have been aggraded against the inner bank of the meandering channel, while the opposite bank experienced erosion. In some cases, former point bar deposits can be seen in the surface topography of the floodplain as scroll bars, with each scroll representing a former location of the point bar (Figure 8.9a). The undulating ridge and swale topography that results consists of higher ridges separated by topographic lows called swales. Meander scroll bars can be seen as a series of vegetated ridges on the point-bar deposits in the foreground of Colour Plate 10. Migrating meanders do not always form scroll bars and the surface topography of these deposits may be relatively featureless.

![Figure 2.50: Meander scroll bars and other meander floodplain landforms](image)

**Cut-offs**

These are abandoned meander bends that have been short-circuited by the flow. Cut-offs become infilled over time by a process of abandoned channel accretion.
**Palaeochannels**

Palaeochannels are longer sections of abandoned channel (Colour Plate 18). Like active channels, palaeochannels exhibit a wide range of different planforms. As time goes by, they gradually become infilled by abandoned channel accretion, the degree of infilling reflecting the age of the channel. The rate at which infilling occurs is dependent on factors such as the geometry of the palaeochannel and its position on the floodplain in relation to overbank events.

**Bedrock channels**

Bedrock channels also show a wide diversity of form. In comparison with alluvial channels, bedrock and mixed bedrock–alluvial rivers have received relatively little attention until recently. These channels often behave in a different way to alluvial channels, being strongly influenced by the resistant nature of their substrate. Structural controls, such as joints, bedding planes and the underlying geological strata can all have a significant effect on flow processes and river morphology. As with alluvial channels, the flow may follow single or multiple channels. Straight reaches are often associated with structural controls, for example where the channel follows the line of a fault or joint. However, flow characteristics also have an influence in shaping the channel. Colour Plate 13 shows the regularly undulating walls of a slot canyon, which have been shaped by flash floods. Meanders can also form in bedrock-influenced channels, as can be seen from the spectacular incised meanders of the Colorado (Colour Plate 5). Because of the resistant substrate, bedrock meanders tend to be scaled to higher flows than their alluvial counterparts.

![Bedrock channels](image)

**Figure 2.51 Bedrock channels**

**Channels floored by bedrock and lacking an alluvial bed cover.**

An example of a multi-channel bedrock river is shown in Colour Plate 2. The individual channels have cut their course to flow around bedrock bars. In some mixed bedrock–alluvial channels, bedrock bars may form a core that becomes covered in alluvial deposits, giving the appearance of an alluvial channel.

Indicates transport capacity >> sediment supply.

**Bedrock channels**

- Fixed channel boundaries (bedrock banks and bed)
- High transport capacity
- Low Storage
- Input = Output
**Bedrock vs. Alluvial Channels**

| Bedrock: | sediment supply < transport capacity |
| Alluvial: | sediment supply ≥ transport capacity |

**Long time** (>10³ yr):
- mountain channels = bedrock
- floodplain channels = alluvial.

**Shorter time** (<10³ yr): material on bed surface defines bedrock vs. alluvial.

**Steps and pools**

Steps and pools often characterise steep, upland channels in a wide range of humid and arid environments. The steps are formed from coarser material and form vertical drops over which the flow plunges into the deeper, comparatively still water of the pool immediately downstream. Steps are relatively permanent features and consist of a framework of larger particles that is tightly packed with finer material. In forested catchments, woody debris forms part of the structure of steps, while steps and pools can also form in bedrock channels. Like riffles and pools, step–pool sequences are most apparent during low-flow conditions as they tend to be drowned out at higher flows. It is also during low-flow conditions that step–pool systems offer the most flow.

**PROCESSES OF EROSION IN BEDROCK CHANNELS**

The morphology of bedrock channels is mainly influenced by processes of erosion because the supply of sediment is often limited. Three types of erosion are significant: block quarrying, abrasion and corrosion.

**Block quarrying** is the dominant process (Hancock et al., 1998) and involves the removal of blocks of rock from the bed of the channel by drag and lift forces. The size of the quarried blocks can be considerable. Tinkler (1993) reports blocks of sandstone 1.2 m × 1.45 m × 0.11 m and 1.0 m × 0.5 m × 0.05 m being removed from the bed of Twenty Mile Creek, Niagara Peninsula, Ontario, during normal winter flows, when the flow depth was less than 0.4 m.

Before blocks can be entrained by the flow, a certain amount of ‘preparation’ is required to loosen them. Subaerial weathering and other weakening processes play an important role in this. Weakening processes described by Hancock et al. (1998) include the bashing of exposed slabs by particles carried in the load and a previously undocumented process termed ‘wedging’, which leads to the enlargement of cracks in the bedrock substrate. This is thought to occur when small bedload particles are able to enter cracks that are momentarily widened by fluid forces. The particles then become very firmly lodged and prevent the crack from narrowing again. As time progresses, further widening of the crack can be sustained as larger particles fall into it, and may ultimately lead to block detachment. Under conditions of very high flow velocity, sudden changes in pressure can generate shock waves that weaken the bed by the process of cavitation. This effect is caused by the sudden collapse of vapour pockets within the flow (Knighton, 1998).

**Abrasion** is the process by which the channel boundary is scratched, ground and polished by particles carried in the flow. Erosion is often concentrated where there are weaknesses and irregularities in the rock bed, which allow abrasion to take place at an accelerated rate. This can lead to the development of potholes, deep circular scour features that often form in bedrock reaches. Once a pothole starts to develop, the flow is affected, focusing further erosion. Any coarse material that collects in the pothole is swirled around by the flow, deepening and enlarging it, and literally drills down into the channel bed. Over time potholes may coalesce, leading to a lowering of the bed elevation. Plate 7.1 shows how potholes have contributed to bed lowering near the site of a waterfall.
Scouring by finer material carried by the flow, such as sand, leads to the development of sculpted forms. These include flutes and ripple-like features, which reflect structures within the flow (Plate 7.2). These are commonly observed on the crests of large boulders and other protrusions into the flow, where flow separation takes place and fine sediment is decoupled from the flow (Hancock et al., 1998). The rock boundary may also be polished by fine material carried in suspension.

Bedrock channels formed in soluble rock are also susceptible to erosion by corrosion, especially where the presence of joints and bedding planes allows solutional enlargement. Solutional features such as scallops may also be seen. These spoon-shaped hollows often cover the walls of cave streamways. Their length is related to the formative flow velocity, ranging from a few millimetres (relatively fast flow) to several metres (relatively slow). Although the actual processes of erosion operate at a small scale, their effects can be seen over scales ranging from millimetres to kilometres. There are several controls on rates of erosion, which influence the processes described above. These include micro-scale (millimetres to centimetres) variations in the rock structure, the larger scale effects of bedding, joints and fractures, and basin-scale influences such as regional geology and base level history (Wohl, 1998).

**EROSIONAL LANDFORMS**

**Valleys**

Valleys start as small and narrow rills; the rills will gradually develop into long and wide gullies; the gullies will further deepen, widen and lengthen to give rise to valleys. Depending upon dimensions and shape, many types of valleys like V-shaped valley, gorge, canyon, etc. can be recognised.

A **gorge** is a deep valley with very steep to straight sides (figure 2.52) and a **canyon** is characterised by steep step-like side slopes (Figure 2.53) and may be as deep as a gorge. A **gorge** is almost equal in width at its top and its base.

In contrast, a **canyon** is **wider at its top compared to its base** (figure 2.53). In fact, a canyon is a variant of gorge. Valley types depend upon the type and structure of rocks in which they form. For example, canyons commonly form in horizontal bedded sedimentary rocks and gorges form in hard rocks.

![The Valley of Kaveri river near Hogenekal, Dharmapuri district, Tamilnadu in the form of a gorge](image1)

![An entrenched meander loop of river Colorado in USA showing step-like side slopes of its valley typical of a canyon](image2)

**Potholes and Plunge Pools**

Over the rocky beds of hill-streams more or less circular depressions called potholes form because of stream erosion aided by the abrasion of rock fragments. Once a small and shallow depression forms, pebbles and boulders get collected in those depressions and get rotated by flowing water and
consequently the depressions grow in dimensions. A series of such depressions eventually join and the stream valley gets deepened. At the foot of waterfalls also, large potholes, quite deep and wide, form because of the shear impact of water and rotation of boulders. Such large and deep holes at the base of waterfalls are called plunge pools. These pools also help in the deepening of valleys. Waterfalls are also transitory like any other landform and will recede gradually and bring the floor of the valley above waterfalls to the level below.

**Incised or Entrenched Meanders**

In streams that flow rapidly over steep gradients, normally erosion is concentrated on the bottom of the stream channel. Also, in the case of steep gradient streams, lateral erosion on the sides of the valleys is not much when compared to the streams flowing on low and gentle slopes. Because of active lateral erosion, streams flowing over gentle slopes, develop sinuous or meandering courses. It is common to find meandering courses over floodplains and delta plains where stream gradients are very gentle. But very deep and wide meanders can also be found cut in hard rocks. Such meanders are called incised or entrenched meanders. Meander loops develop over original gentle surfaces in the initial stages of development of streams and the same loops get entrenched into the rocks normally due to erosion or slow, continued uplift of the land over which they start. They widen and deepen over time and can be found as deep gorges and canyons in hard rock areas. They give an indication on the status of original land surfaces over which streams have developed.

**River Terraces**

River terraces are surfaces marking old valley floor or floodplain levels. They may be bedrock surfaces without any alluvial cover or alluvial terraces consisting of stream deposits. River terraces are basically products of erosion as they result due to vertical erosion by the stream into its own depositional floodplain. There can be a number of such terraces at different heights indicating former river bed levels. The river terraces may occur at the same elevation on either side of the rivers in which case they are called paired terraces (figure 2.54).

![Figure 2.54: Paired and unpaired river terraces](image)
When a terrace is present only on one side of the stream and with none on the other side or one at quite a different elevation on the other side, the terraces are called unpaired terraces. Unpaired terraces are typical in areas of slow uplift of land or where the water column changes are not uniform along both the banks. The terraces may result due to (i) receding water after a peak flow; (ii) change in hydrological regime due to climatic changes; (iii) tectonic uplift of land; (iv) sea level changes in case of rivers closer to the sea.

Many stream valleys contain one or more relatively flat alluvial terraces that lie above the floodplain. A terrace is a remnant of an abandoned floodplain. Streams may create depositional landforms (especially floodplains) and then start to down-cut in response to uplift.

**Anabranching bedrock channels**

Multiple bedrock channels can also be found. Preferential erosion along lines of weakness, such as joints and fractures, can lead to the development of anabranching reaches. Tooth and McCarthy (2004) report examples from arid and humid regions including South and North America, India and South Africa. (A small-scale South African example is shown in Colour Plate 2.) This type of anabranching is also referred to in the literature as anastomosing or erosional braiding. The aerial photograph in Plate 8.14 shows an anabranching bedrock reach of the semi-arid Sabie River, Mpumalanga Province, South Africa. Extensive bedrock outcrops are found along the Sabie, which has incised a wide macro-channel in which all but the most extreme floods are contained. Significant downstream variations are seen in channel morphology in response to changes in the distribution and thickness of sediment deposits. The channel changes several times from a single to a multiple-channel form and various different bedrock, alluvial and mixed-reach types have been identified (Heritage et al., 1999). Some of the anabranching reaches are characterised by extensive bedrock pavements, whereas along other reaches, deposition has created alluvial islands with bedrock core bars. Vegetation plays an important part in stabilising these deposits (Plate 8.15). The aerial photograph was taken seven months after a major flood event, which took place in February 2000. This had an estimated return period of 200 years (Heritage et al., 2004). Given the extreme flood distribution associated with semi-arid regions, this was a huge event which resulted in major modifications to parts of the channel. Patterns of change were complex, with some deposits being largely unaffected by the flood. However, many of the mixed anastomosing reaches experienced widespread sediment stripping. The bedrock core bars and individual anabranches can be seen clearly in Plate 8.14.

Preferential erosion along lines of weakness (joints and fractures) can lead to the development of anabranching reaches in bedrock channels.

![Figure 2.55: An anabranching bedrock reach of the Sabie River, Mpumalanga. (SanParks & CWE Wits.)](image1)

![Figure 2.56: Anabranching bedrock channel with rock bars, Mpumalanga (Chariton)](image2)