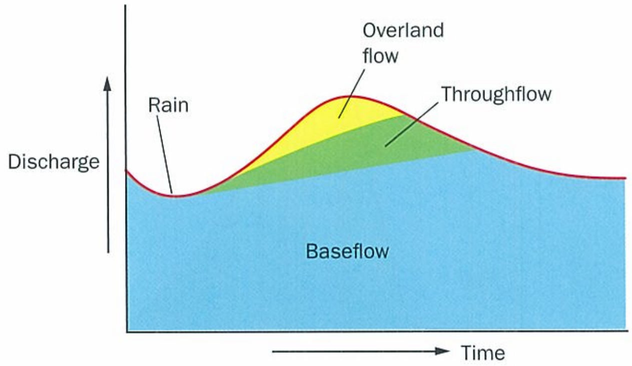


Fig. 1.15 The storm hydrograph of a drainage basin with very little overland flow but a great deal of throughflow and baseflow

Fig. 1.15 is typical of a well-forested drainage basin or a drainage basin with permeable soil and bedrock. The lag time is long and peak discharge is low. Baseflow is controlling the discharge of this river.

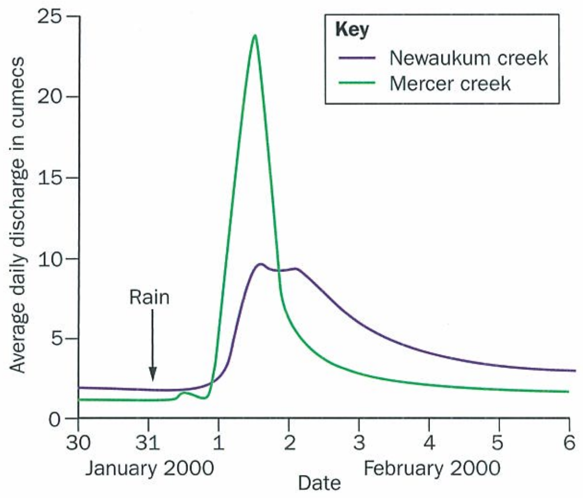


Fig. 1.16 The impact of urbanisation on the storm hydrograph

Fig. 1.16 shows the storm hydrographs for two, very similar and neighbouring drainage basins in western Washington, USA. Both drainage basins received equal inputs of rainfall from the same storm on 31 January 2000. Discharge in Mercer Creek, an urbanised drainage basin, increased more quickly and reached a higher peak than discharge in Newaukum Creek, a neighbouring rural drainage basin of equivalent size.

9. Study Fig. 1.16. Suggest reasons for the differences in the two storm hydrographs.

River channel processes and landforms

Channel processes

The **river channel** is the 'trench' in which the river flows. It is defined by the river bed and the river banks.

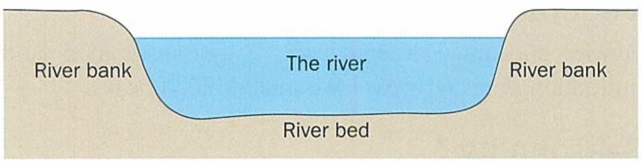


Fig. 1.17 A cross-section of a river channel

Water flows downhill through the river channel. Because the flowing water has mass and velocity, it also has energy and it uses this energy to do work, changing the shape and nature of the river channel. Considerable changes to the river channel occur as the river flows from its source to its mouth. These

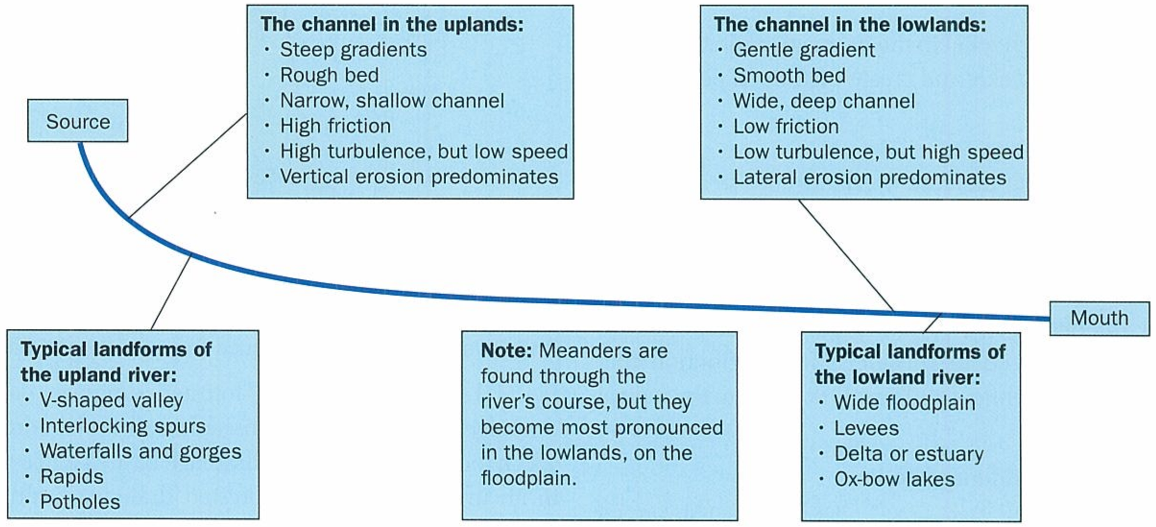


Fig. 1.18 The long profile of a river channel

changes are illustrated by the **long profile** of a river channel. The long profile of a river channel is a line drawn from the source of the river (where it starts) to the mouth of the river (where it meets the sea). It shows how the gradient of the river channel changes as it flows downhill. The typical long profile is concave - steeper in the hills and gentler in the lowlands.

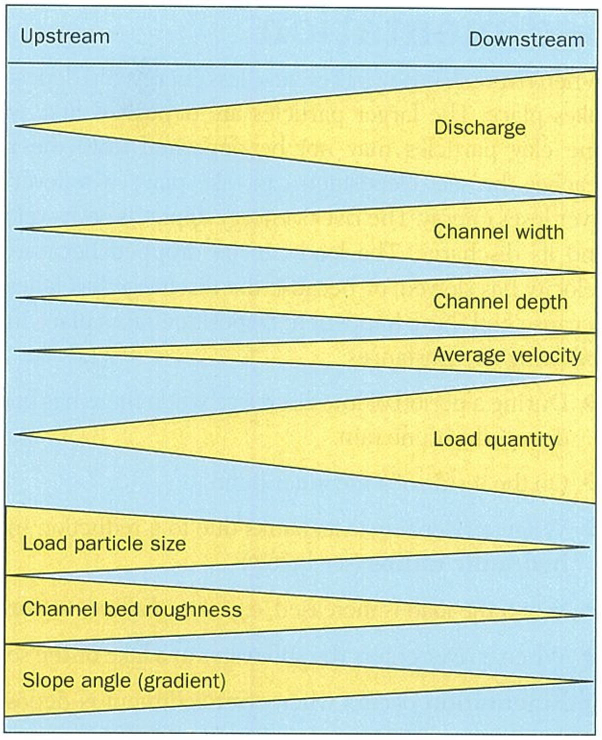


Fig. 1.19 Bradshaw's model of downstream changes on a river

This diagram summarises many of the changes that take place in the river channel as you move downstream, from the source to the mouth. The river is an open, dynamic natural system and Bradshaw's model is important because it shows that the river can respond to changes in its inputs of discharge and **sediment** by changing any one of the variables shown.

10. (a) What is 'discharge'? Describe and attempt to explain how it changes as the river flows downstream.

(b) What is 'load quantity'? Describe and attempt to explain how it changes as the river flows downstream.

(c) What is 'load particle size'? Describe and attempt to explain how it changes as the river flows downstream.

River channel processes – erosion

Erosion is the *wearing away* of the surface of the Earth. It is an active process, involving movement. Rivers erode their channels as they flow downhill towards the sea. Rivers have energy because the river water has mass and velocity and some of this energy is used to erode the river channel in four main ways.

Abrasion - sometimes called corrasion. A river uses its load of sediment to wear away its bed and banks. In the uplands, pebbles get caught in hollows in the river bed. As they swirl around, the process of abrasion produces a pothole.

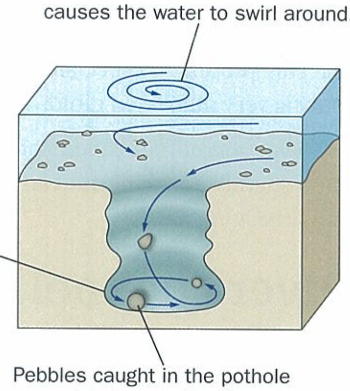


Fig. 1.20 The effect of abrasion on a rocky river bed

Attrition - particles of sediment in the load of the river (especially the **bedload**) bump into each other and wear each other away. As a result, river sediment becomes smaller and more rounded as it is carried downstream.

Upstream, the bedload is mostly angular

Further downstream, attrition has made the bedload much rounder, smaller and smoother

Fig. 1.21 The effect of attrition on a river's bedload

Hydraulic action – the direct force of the flowing river water can break material from the bed and banks. Even more powerful is the related process of **cavitation**, the force of exploding air. Powerful **eddies** in the flowing river water compress and decompress water in cracks in the river bank. This can lead to the formation of air bubbles in the water, which explode outwards, weakening the crack and leading to pieces breaking off. This process is especially important where the water is moving very quickly, in rapids and waterfalls.

Solution – sometimes called corrosion. Natural river water is often slightly acidic and it can dissolve rocks such as chalk and limestone.

River channel processes – transportation

Rivers transport the load that is supplied to them in four main ways. The sediment is produced by river erosion and by other landscape processes such as weathering and mass movement on the valley sides.

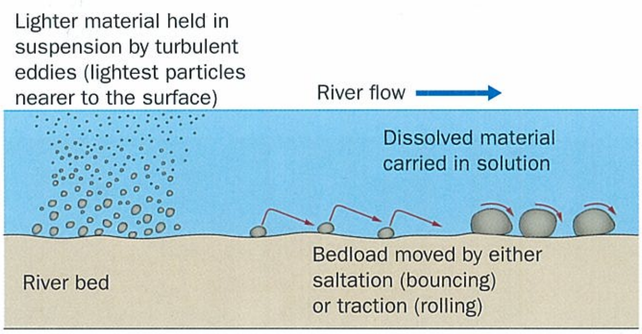


Fig. 1.22 How the river transports its load of sediment

Traction – the larger particles of the bedload are rolled along by the force of the flowing water. (The bedload is the load that spends all or some of its time on the river bed.)

Saltation – the smaller particles of bedload tend to hop along the bed of the river. A faster eddy picks them up and they move along in the body of the water until the current slows and they fall back to the river bed.

Suspension – this accounts for most of the load, especially in a lowland river. Lowland rivers nearly always look muddy and brown because of the large amounts of sand, silt and clay suspended in the water.

Solution – the dissolved load is derived from soluble rock such as limestone and chalk. Chalk streams are often clear because the dissolved load is not visible.

The load of the river varies as the energy of the river (discharge and velocity) changes. At times of high discharge, the river can carry a large amount of sediment – even small streams look muddy at times of flood. The load of a river is usually calculated at the **bankfull** stage, at the point when the river is flowing most efficiently, just before it spills out onto its floodplain. The **capacity** of the river is the total amount of load that it is carrying. The **competence** of the river is the maximum size of particle that the river is capable of transporting at the bankfull stage.

River channel processes – deposition and sedimentation

When rivers slow down they have less energy and deposition takes place. The larger particles are deposited first, while fine clay particles may not be deposited until the river reaches the sea. Deposition can take place whenever the river loses energy. The river's energy depends on its velocity and its discharge. The load can be dropped because the velocity has slowed, or because the discharge has fallen, or because both have happened. Deposition takes place in the following circumstances:

→ During a period of low discharge when there has been a dry spell with no rain.

→ On the inside of a meander bend.

→ When a river bursts its banks due to a reduction in the **hydraulic radius** (see below).

→ When the load is increased, e.g. after **deforestation**.

→ When a river enters the still water of a lake or the sea.

Sedimentation occurs when river sediment is deposited from still water. This process is common on floodplains and on the sea bed. On the sea bed it is aided by the process of **flocculation**, the way that charged ions in sea water allow clay particles to coagulate together and settle out of suspension. The bottomset, foreset and topset beds in a **delta** (Fig. 1.36 on page 20) are produced by sedimentation. Material deposited as sediments may become sedimentary rock, linking river processes with the rock cycle.

River channel processes – the Hjulström curves

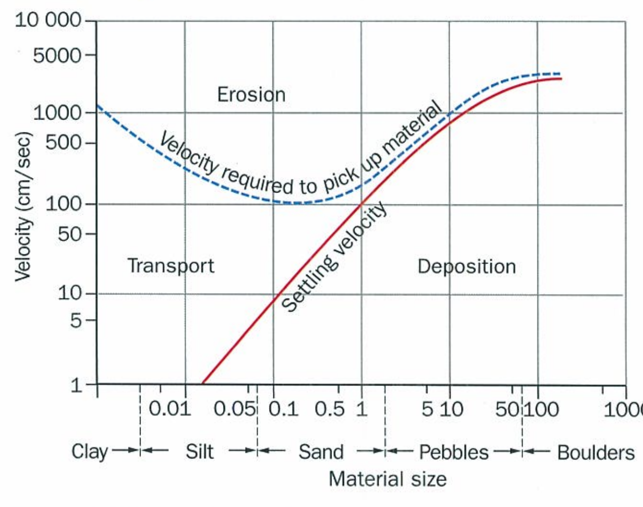


Fig. 1.23 The Hjulström curves

This diagram is a complex graph which uses logarithmic scales on both the horizontal and vertical axes. This is known as a **log/log graph**. This technique allows a wide range of data to be shown on a relatively small graph. The diagram shows the relationship between particle size and velocity. The top curve is sometimes known as the *critical erosion velocity curve* and shows the river velocity required to pick up sediment particles of different sizes. The lower curve is the *mean settling velocity curve* and shows the speed that the river has to slow to, before particles of different sizes will be dropped (deposited). The main points to note are:

- The velocity needed to keep particles moving is always lower than the velocity needed to start them moving. This means that if a swift eddy starts to move a particle, the river water will have to slow down significantly before the particle is dropped.
- Sand is the easiest material to erode. Sand can be picked up at lower velocities than either smaller or larger particles. Clay is cohesive (sticky) and pebbles are heavy - both need more energy to be eroded than sand particles do.
- Fine clays, once picked up, will stay in suspension even if the water stops moving. This is another reason why lowland rivers always look muddy.
- When a river slows down, the coarse material is dropped first, the finest last. This why **levées** form close to the river during a flood.

11. Study Fig. 1.23.

(a) How fast has the river to be moving before an average-sized pebble (10 mm) is picked up?

(b) At what velocity will a sand particle of 1 mm be dropped by the river?

(c) The velocity of water in the river channel increases after heavy rain. As the velocity reaches 1000 cm/sec, what is the status of: a tiny clay particle on the river bed, a sand grain and a boulder on the river bed?

River flow – factors affecting the energy of a river

Rivers have *kinetic* energy because they have mass (discharge) and velocity.

Discharge is affected by precipitation and the characteristics of the drainage basin system. Discharge generally increases as a river flows downstream because more and more tributaries bring their water to the main river.

Velocity is affected by a range of factors but friction and gradient are the most important. Although we would expect rivers with a steep gradient to flow very quickly, research has shown that friction is more important than gradient. This is why rivers in the lowlands with a gentle gradient, but a very smooth bed, flow faster than rivers in the uplands with a steep gradient, but a very rough bed. Upland rivers look as if they are flowing quickly but the extreme **turbulence** caused by the very rough river bed means that the downstream velocity is quite low. Friction is measured in two ways: bed roughness and hydraulic radius.

Bed roughness

A rough channel produces more friction and provides more resistance to river flow than a smooth channel. Roughness is measured by *Manning's N*. There are different ways of calculating Manning's N, but the simplest formula is as follows:

$$N = \frac{R^{0.67} \times S^{0.5}}{V}$$

where:

N = Manning's N - the roughness coefficient

R = hydraulic radius (see below)

S = channel gradient (as a fraction)

V = mean velocity of flow

The gradient, hydraulic radius and the velocity can all be measured using fieldwork instruments, but the calculation of Manning's N is usually carried out using a computer. The higher the value of N, the rougher the bed. Small mountain streams typically have values of around 0.05, while lowland rivers have values closer to 0.015.

Hydraulic radius

This is a measure of the *efficiency* of the river. It compares the friction caused by the bed and banks with the amount of discharge flowing down the river. In an efficient river, the water moves relatively easily, with minimum resistance to flow from friction. The formula for hydraulic radius is as follows:

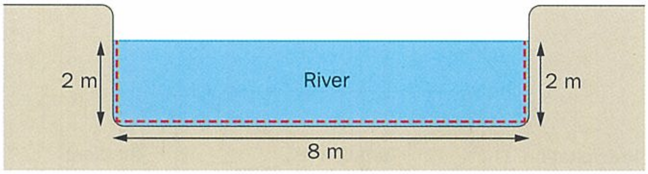
$$\text{Hydraulic radius} = \frac{\text{channel cross-sectional area (CSA)}}{\textbf{wetted perimeter (WP)}}$$

where:

CSA = channel depth × channel width

WP = length of the bed and banks in direct contact with the water in the river channel.

This is best shown in a diagram:



cross-sectional area (CSA)	$= 2\,m \times 8\,m = 16\,m^2$
wetted perimeter (WP)	$= 2\,m + 8\,m + 2\,m = 12\,m$
hydraulic radius = CSA/WP	$= \frac{16\,m^2}{12\,m} = 1.34\,m$

Fig. 1.24 How to calculate the hydraulic radius

Hydraulic radius increases downstream. The hydraulic radius also changes as the discharge changes at any one point along a river.

12. Study Fig. 1.25. Calculate the hydraulic radius for:

(a) low water

(b) normal flow

(c) the bankfull stage

(d) the overbank flood.

When is the river at its most efficient? Explain your answer.

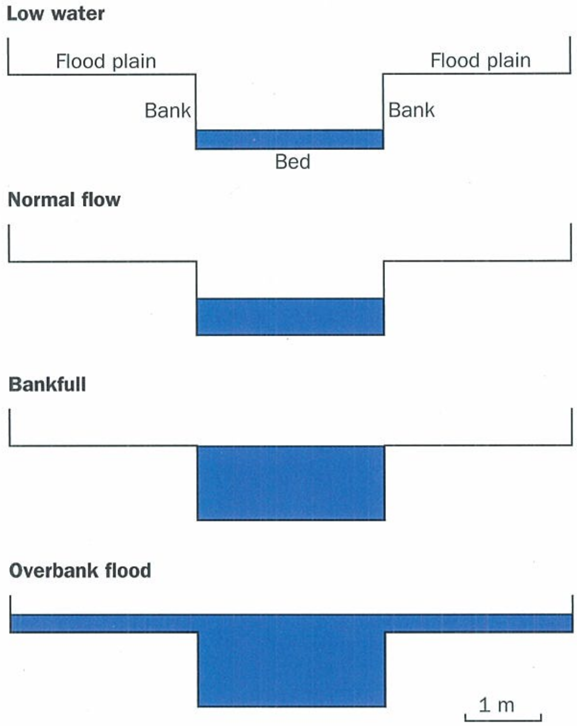


Fig. 1.25 Changing hydraulic radius

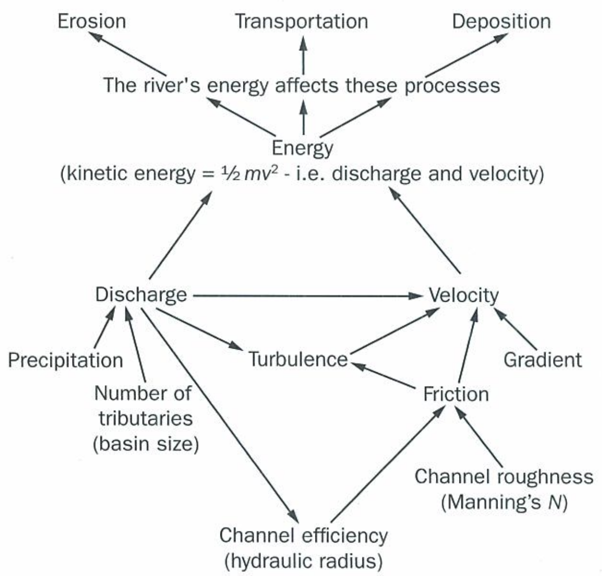


Fig. 1.26 River channel processes – a summary diagram

13. Bradshaw's model (Fig. 1.19 on page 13) does not consider all the river variables. How would you expect the following factors to change as you move downstream:

(a) channel efficiency (hydraulic radius)

(b) friction

(c) turbulence

(d) channel cross-sectional area?

Figure 1.26 summarises the complex relationships between the various processes that operate within the river channel. Don't forget that the processes change with time, often depending on changes in the river's discharge.

Patterns of flow

Water flows downhill in three main ways:

- → **laminar flow**
- → **turbulent flow**
- → **helicoidal flow**.

Laminar flow

Water flowing downwards over a smooth surface can flow in a simple sheet, with no eddies or meanders. This is known as laminar flow. Laminar flow can be observed on a smooth road surface or paved area during heavy rainfall, but it is very rare in nature because most surfaces exert enough friction for turbulence to disrupt the flowing sheet.

Turbulent flow

Water flowing in a river channel is subject to friction, both with the river bed and the banks. This friction slows the water closest to the bed and banks and the water nearer the centre of the river overtakes the slow water. Because water is a liquid, this results in turbulence. Water at the sides of the river begins to eddy towards the banks and water close to the bed of the river begins to eddy downwards. Both types of eddy operate at the same time and this leads to chaotic, turbulent flow.

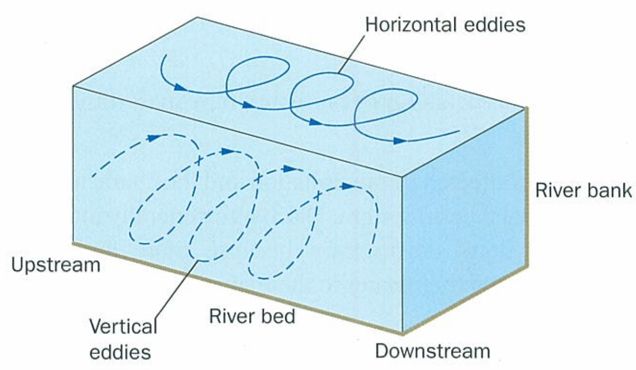


Fig. 1.27 Turbulent flow

Helicoidal flow

Water flowing down a plughole often starts to spiral as it flows downwards. This spiralling motion is typical of fluids moving at or close to the surface of a rotating planet. It is no surprise that water flowing down a river channel is subject to the same forces. The line of fastest flow (**thalweg**) follows a corkscrew or spiralling path as the river moves downstream. This is closely related to the development of meanders but even in a straight, artificial channel, helicoidal flow can be observed.

The spiralling movement of the thalweg is constrained by the river channel. Not only does the thalweg spiral from the surface to the river bed and back to the surface, but it also moves from one bank to another in a downstream direction. The vertical movement of the thalweg produces pools and riffles while the bank-to-bank motion concentrates erosion first on one bank and then on the other. This contributes greatly to the formation of regularly spaced meanders along the river's course (see Fig. 1.38 on page 21).

Channel types

There are three main types of river channel:

- straight channels
- meandering channels
- braided channels.

The **sinuosity** of a river channel is a measure of how 'bendy' it is. It is calculated by dividing the length of the river channel by the length of the valley in which it flows. This can be done for a whole river but more usually it is done for sections of a river. A perfectly straight river will have a sinuosity of 1.0 but natural river channels are rarely perfectly straight. Any river with a sinuosity less than 1.5 is considered 'straight', while a river with a sinuosity of over 1.5 is considered to be 'meandering'.

Straight river channels

These are quite rare because helicoidal flow dominates in most rivers and makes them meander. Even on a straight river, the thalweg (line of maximum flow velocity) moves from side to side because of helicoidal flow.

Fig. 1.28 A straight river channel. This is the river in Glen Tilt, Scotland, UK. The reason it is so straight is that it is guided by a straight fault (weakness) in the rocks

Meandering river channels

Most rivers meander to some extent. Upland streams meander but the most pronounced meanders are found on floodplains where **lateral erosion** is facilitated by the soft nature of the river banks. Meanders are so common because spiralling is the normal behaviour of moving fluids on the surface of a rotating planet. Rivers are confined to their channels so the tendency to spiral downwards produces helicoidal flow. This is the main reason why rivers meander (see Fig. 1.29). Meanders are *not* produced by large obstacles in the river's course.

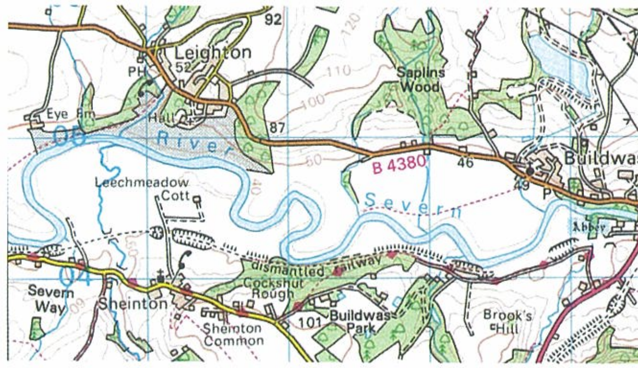


Fig. 1.29 A meandering river channel. This map extract shows the River Severn near Ironbridge in Shropshire, UK

Braided river channels

These are river channels that contain a large number of islands and bars made of sediment. They are found in areas where discharge varies a lot during the year and where a large amount of fairly coarse sediment is being carried by the river, for example glacial **outwash** streams and seasonal rivers in semi-arid areas. The braiding results from the deposition of sediment on the riverbed during a time of falling discharge. The river then splits as it flows around these deposits. A braided river channel can be extremely wide and constantly changing.

Fig. 1.30 A braided river channel. This is a river on the Skeidararsandur glacial outwash plain in southern Iceland

River landforms

Flowing water has energy which allows rivers to do work through the processes of erosion, transportation and deposition. These processes produce a whole range of distinctive *landforms* such as waterfalls, floodplains and deltas. Together, these river landforms make up what we recognise as a river *landscape*.

Landforms of the upper course

Potholes

Fig. 1.31 Potholes on a rocky river bed in South Africa

Potholes are formed by turbulence which swirls pebbles around in a depression on the river bed. The swirling pebbles enlarge the pothole by the process of abrasion. The process is explained in more detail in Fig. 1.20 on page 13. They are usually quite small features and they are evidence that vertical erosion predominates in upland rivers.

Rapids

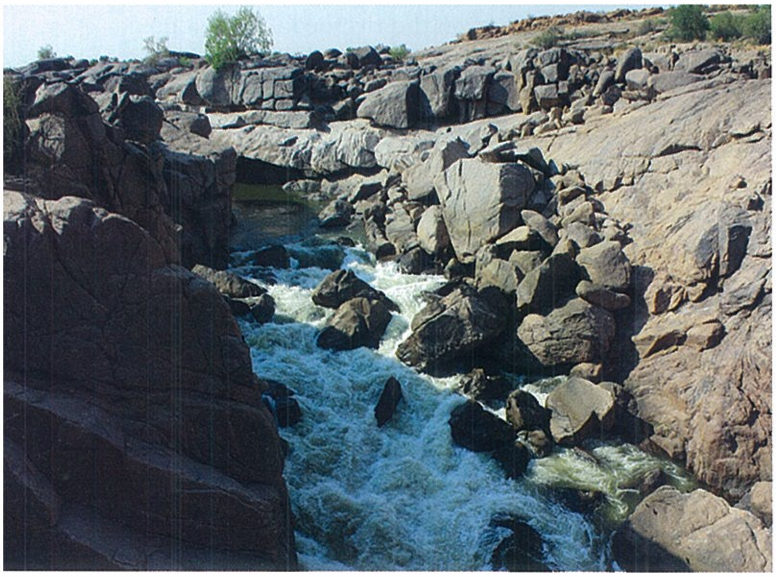


Fig. 1.32 Rapids on the Orange River in South Africa

Rapids are common in the upper course of a river. They form at places where the gradient is steep and the river bed is rocky, resistant to erosion, and irregular. They are usually caused by a band, or bands, of hard rock in the river bed.

Waterfalls and gorges

Waterfalls form where a horizontal layer of hard rock lies on top of a layer of softer rock in a river valley. The soft rock underneath is eroded more quickly by the river and gradually a **plunge pool** develops. The splashing water and eddy currents in the plunge pool undercut the hard rock layer above. This eventually creates an unsupported overhang of hard rock. The overhang then collapses into the plunge pool. If the processes of undercutting and collapse are repeated over a long period of time, the waterfall will retreat upstream - forming a deep, steep-sided valley called a **gorge**.

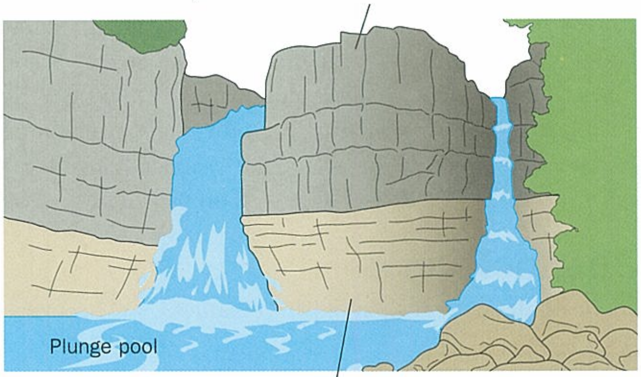


Fig. 1.33 The High Force waterfall on the River Tees is one of the largest waterfalls in England

14. (a) Make a copy of diagram A in Fig. 1.34. Add labels to the diagram to identify the main features. Write a short paragraph to explain what the diagram shows. Try to use subject specific vocabulary e.g. the names of the different types of erosion that are operating.

(b) Repeat the exercise for the other three diagrams: B, C and D.

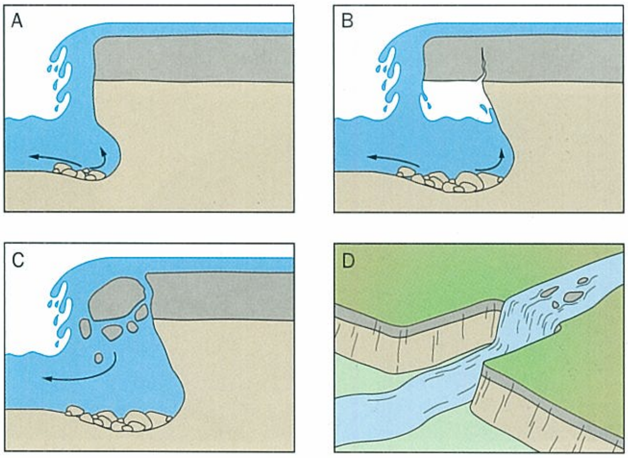


Fig. 1.34 Four diagrams showing the development of a waterfall and a gorge over time

Gorges form best when the hard rock is especially resistant to weathering but succumbs to river erosion. As well as being formed by the retreat of a waterfall, gorges can form in other circumstances:

- In semi-arid areas, where there is a short wet season leading to vertical erosion of the river bed when the river is flowing, but no water for weathering at other times of the year.
- Where a mountain range has been formed across the path of a river, but the vertical erosion of the river has been able to keep up with the growth of the mountain range. The gorge of the Brahmaputra River where it flows from Tibet, through the Himalayas, is an excellent example. This is known as **antecedent drainage**.

Landforms of the lower course

Floodplains, levées and bluffs

A floodplain is the flat land next to the river which is liable to flood when the river rises after heavy rainfall. Floodplains are often badly drained, with marshes and **ox-bow lakes**. In their natural state they are unhealthy areas to live on because diseases are common. Sometimes the river actually flows above the level of the surrounding floodplain, but it is enclosed by natural embankments called levées.

Lateral erosion predominates on a floodplain. The river is close to sea level (**base level**) so it can't cut down much further. However, the floodplain is made of soft alluvium so lateral erosion is facilitated and the **meander belt** migrates constantly across the floodplain. Where a meander reaches the edge of the floodplain, it may erode back the low valley side, helping to maintain the low **bluffs** found at the side of most large floodplains.

The floodplain is made of alluvium (river silt) because it is formed by deposition of material from the river. There are three main forms of deposition which contribute to the formation of the floodplain:

- The deposition of fine silt and mud (part of the suspended load) on the floodplain itself, during times of flood. As the floodwater spreads across the floodplain, the hydraulic radius decreases, friction becomes more important, the river slows, and deposition takes place. Most deposition takes place closest to the river. This means that areas further from the river receive thinner layers of sediment and don't grow upwards quite so fast. This leads to lower areas, further from the river channel, known as backswamps.
- The deposition of **point bars** in the slow water on the inside of meanders. These deposits spread across the floodplain as the meanders migrate.
- The deposition of sediment on the river bed at times of low water when the velocity of the river slows. This is why big rivers often raise themselves above the level of the floodplain.

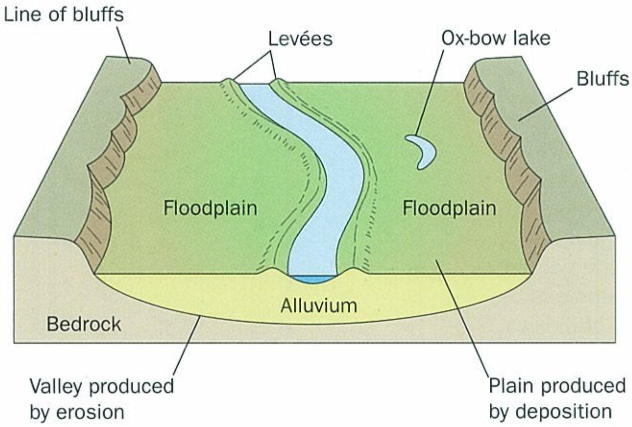


Fig. 1.35 Block diagram showing the main features of a floodplain

Like the floodplain, levées are depositional features. When rivers reach bankfull stage and then burst their banks, the current slows and deposition takes place. The biggest particles are deposited first and when the river level falls after a flood, these coarse deposits form embankments at each side of the river. They are natural features but people often raise them and strengthen them to prevent flooding. Sometimes completely artificial embankments are built for the same purpose, and in the USA these embankments are also called levées.

Landforms produced by sedimentation

Deltas

These are depositional features which form when the river meets the sea or runs into a lake. When a river meets the still water of the sea or lake, the loss of velocity leads to a loss of energy and the river's load of sediment is deposited. Sea water contains charged ions of the salts dissolved in it and these charged ions lead to the flocculation of clay particles - tiny particles cluster together, becoming bigger and so are more able to settle to the bottom. Deposition of sediment blocks the river's main channel which splits into smaller channels called **distributaries**. Continued deposition over time means that the delta grows outwards into the sea, forming a flat, marshy extension of the land. There are often lakes and **lagoons** within the delta. Because deltas are formed of fertile alluvium they are attractive areas for human settlement. They are dangerous places to live, however, because they are susceptible to flooding, both by the river and by the sea. An example of a densely populated delta is the Ganges delta in India and Bangladesh.

In lakes, this three-layer pattern is clear, but at the coast, erosion by waves and movement by tides makes the picture more complex.

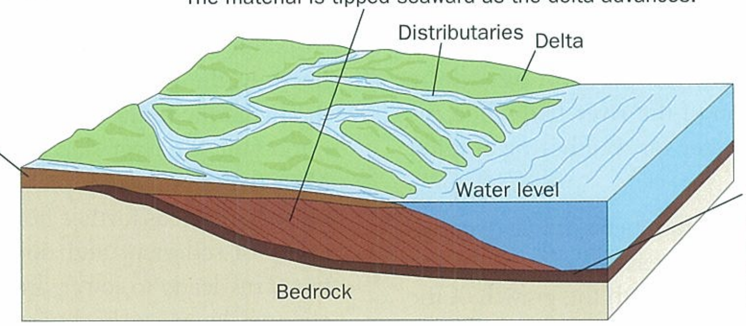


Fig. 1.36 The formation of a delta. The structure produced by the deposition of bottomset, foreset and topset beds

There are many types of delta but there are three classic types.

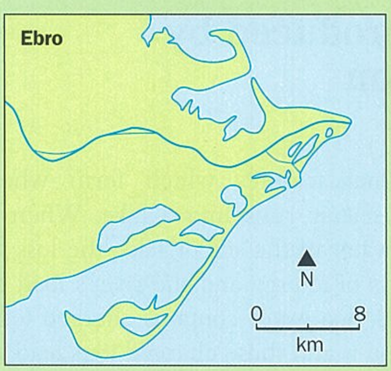
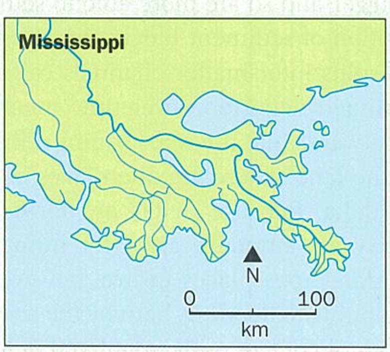
Map of delta	Description
The Niger delta 	**Arcuate deltas** are fan-shaped and they form when the **tidal range** is quite low and there is a strong movement of sediment in one direction along the coast, e.g. by longshore drift or an offshore current. This keeps the seaward edge of the delta smooth in shape. A good example is the Niger delta in West Africa.
The Ebro delta 	**Cuspate deltas** are shaped like an arrowhead or a worn tooth. There is a low tidal range and two offshore currents shape this sort of delta, operating in opposite directions at different times of the year. A good example is the Ebro delta to the south of Barcelona in Spain.
The Mississippi delta 	**Bird's foot deltas** are formed where the tidal range is low and where the river currents are strong. There is no clear offshore current to shape the delta so each distributary builds the land out into the sea, acting like a series of thin conveyor belts. The best example is the Mississippi delta in the Gulf of Mexico.

Fig. 1.37 Types of delta

Meanders and ox-bow lakes – river landforms produced both by erosion and deposition

Meanders are the most typical of all river landforms. They can be found at any point along a river's course and their associated landforms are relatively easily explained. However, the reasons why meanders form in the first place are complex and difficult to understand.

It used to be thought that meanders were caused by an obstacle along the course of the river, causing it to deflect from a straight course. Once initiated, the different rates of erosion and deposition in the inside and outside of meander bends ensured that meanders remained and developed. However this idea was thrown into doubt in the mid-20th century when it was noticed that there were certain regularities and relationships that applied to meanders wherever they were found. The most obvious was that whatever the size of the river, the wavelength of its meanders was roughly 8-10 times the width of the river. This sort of regular mathematical relationship implied that meandering was a fundamental part of a river's nature and that a universal principle was involved in their formation. This led geomorphologists to look at the way in which water flowed in rivers and to look for other regular relationships in the form of river channels.

Pools and riffles

Straight rivers develop deeper sections where erosion predominates (pools) and shallower sections where sediment has been deposited (riffles). The process that causes this is complex and not fully understood but the regular spacing of pools and riffles (the distance from pool to pool is 4-5 times the width of the river) suggests it is related to helicoidal flow. Close study of the thalweg showed that the thalweg did indeed move in a corkscrew fashion (helicoidal) and that the rising and falling of the zone of maximum velocity within the river channel corresponded to the position of pools and riffles.

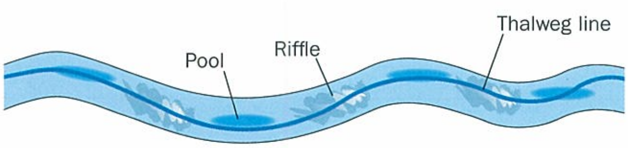


Fig. 1.38 Pools and riffles on a relatively straight river channel

Meanders

Meanders are related to pools and riffles because the meander wavelength is usually 8-10 times the river width, with a pool on the outside of each bend. In other words the distance pool to pool to pool equates to a meander wavelength.

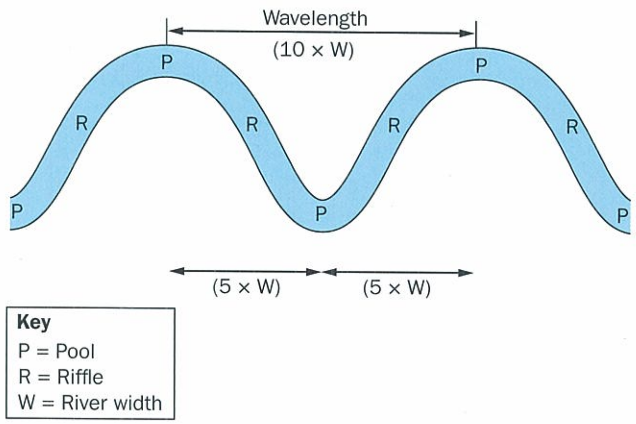


Fig. 1.39 Pools and riffles on a meandering river channel

Meanders have an asymmetric cross section and the flow of water in three dimensions is complex.

The form of a meander is the same wherever it is found. Deep water and a **river cliff** are found on the outside of the bend while shallow water and depositional features (slip-off slope or point bar) are found on the inside of the bend. This is related to the nature of the river flow, especially the different amounts of energy that the river has on the outside and inside of the bend.

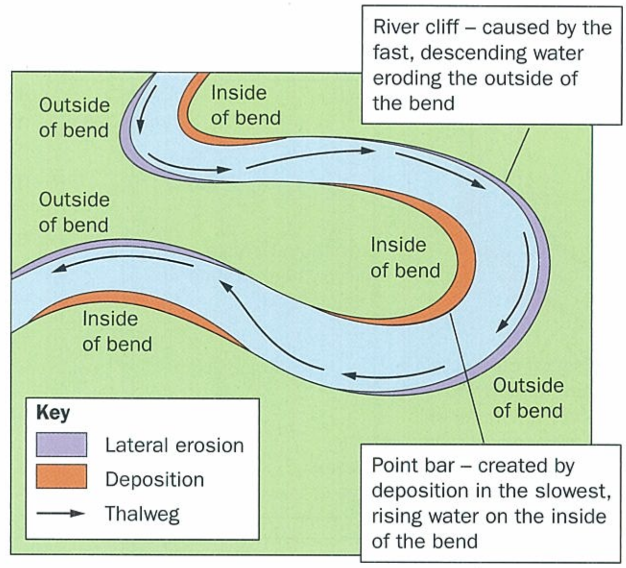
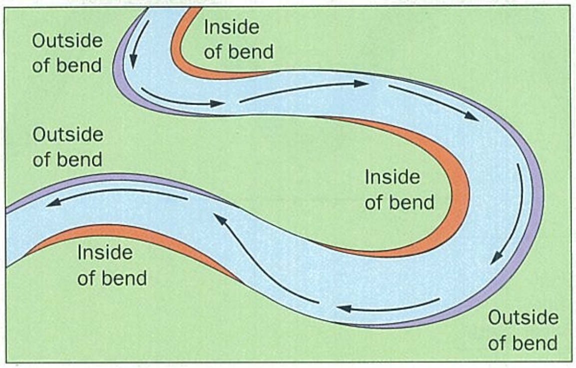
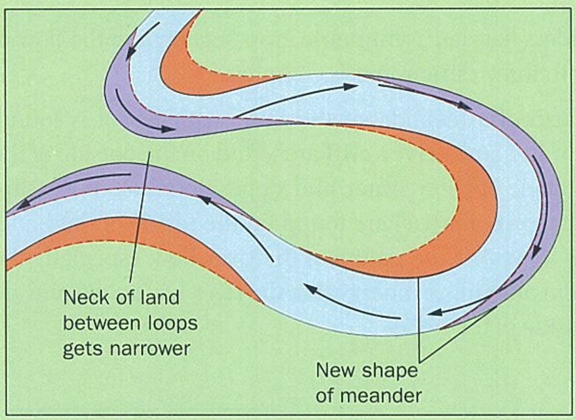
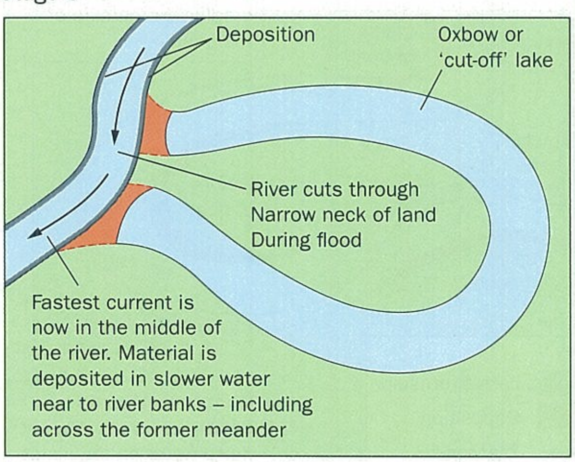


Fig. 1.40 A map of a typical meander

Ox-bow lakes

Meanders become more sinuous (bendy) over time as erosion and deposition continue to change their shape. In the soft alluvium of a floodplain, lateral erosion can be so effective that the neck of the meander becomes narrower and narrower. Eventually (usually during the high energy conditions of a flood) the neck is breached and the meander cuts itself off. An ox-bow lake is the result.

Map	Description
Stage 1  	*A meander on a floodplain.* Because the alluvium of the floodplain is soft and because the river is close to sea level (base level), lateral erosion predominates. Erosion is focused on the outside of the meander bend and deposition on the inside of the bend.
Stage 2  	*The meander becomes more sinuous.* Continued erosion on the outside of the bend undercuts the river cliff, which retreats. Deposition of material on the point bar on the inside of the bend continues. Together, these processes move the whole meander sideways. The neck of the meander becomes narrower as the two river cliffs move closer together.
Stage 3  	*An ox-bow lake is formed.* During a large flood, when the water is moving rapidly, erosion of the two river cliffs finally removes the neck of land between them. The river adopts a more direct line of flow because this increases the gradient of the river bed and makes the river flow more efficient. Deposition in the still water of the old meander cuts the meander off from the new course of the river. The ox-bow lake is a temporary feature because the growth of vegetation eventually fills it up and turns it into an area of marshy ground – very much like the rest of the natural floodplain.

Key

- Land lost to the river (eroded)
- Land gained from the river (deposited)
- Fastest current
- Earlier course of the river

Fig. 1.41 The stages in the formation of an ox-bow lake

RESEARCH Use old maps to see how much the meanders on a river near you have changed over time.