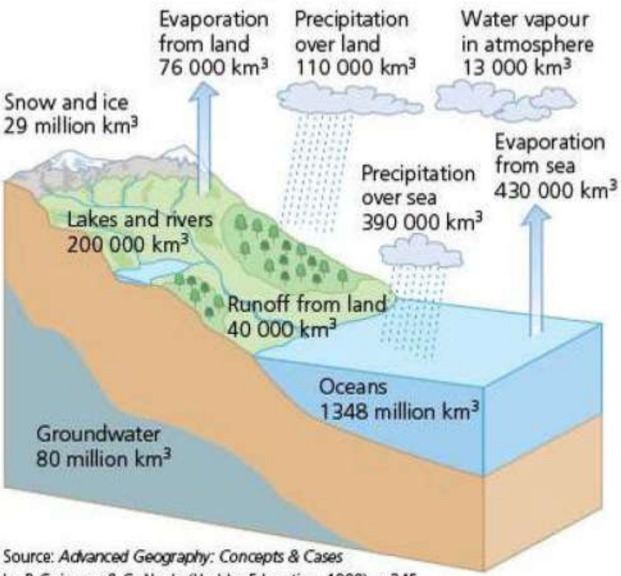
1 Hydrology and fluvial geomorphology

1.1 The drainage basin system

The hydrological cycle refers to the cycle of water between atmosphere, lithosphere and biosphere (Figure 1.1). At a local scale – the drainage basin (Figure 1.2) – the cycle has a single input, precipitation (PPT), and two major losses (outputs): evapotranspiration (EVT) and runoff. A third output, leakage, may also occur from the deeper subsurface to other basins. The drainage basin system is an open system as it allows the movement of energy and matter across its boundaries.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.245

Figure 1.1 The global hydrological cycle

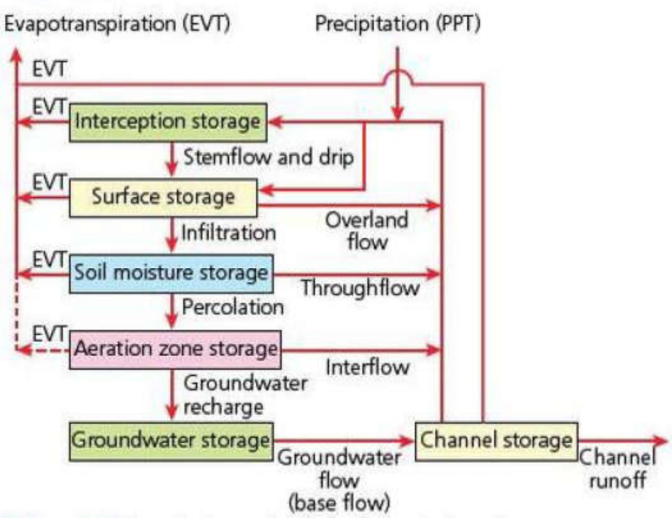


Figure 1.2 The drainage basin hydrological cycle

Water can be stored at a number of stages or levels within the cycle. These stores include vegetation, surface, soil moisture, groundwater and water channels.

Human modifications are made at every scale. Relevant examples include large-scale changes of channel flow and storage, irrigation and land drainage, and large-scale abstraction of groundwater and surface water for domestic and industrial use.

Outputs

Evaporation

Evaporation is the process by which a liquid is changed into a gas. The process by which a solid is changed into a gas is sublimation. These terms refer to the conversion of solid and liquid precipitation (snow, ice and water) to water vapour in the atmosphere. Evaporation is most important from oceans and seas. It increases under warm, dry conditions and decreases under cold, calm conditions. Evaporation losses are greater in arid and semi-arid climates than in polar regions.

Factors affecting evaporation include meteorological factors such as temperature, humidity and wind speed. Of these, temperature is the most important factor. Other factors include the amount of water available, vegetation cover and colour of the surface (albedo or reflectivity of the surface).

Evapotranspiration

Transpiration is the process by which water vapour escapes from a living plant, principally the leaves, and enters the atmosphere. The combined effects of evaporation and transpiration are normally referred to as evapotranspiration (EVT). EVT represents the most important aspect of water loss, accounting for the loss of nearly 100 per cent of the annual precipitation in arid areas and 75 per cent in humid areas. Only over ice and snow fields, bare rock slopes, desert areas, water surfaces and bare soil will purely evaporative losses occur.

Potential evapotranspiration (P.EVT)

The distinction between actual EVT and P.EVT lies in the concept of moisture availability. Potential evapotranspiration is the water loss that would occur if there were an unlimited supply of water in the soil for use by the vegetation. For example, the actual evapotranspiration rate in Egypt is less than 250 mm, because there is less than 250mm of rain annually. However, given the high temperatures experienced in Egypt, if the rainfall were as high as 2000mm, there would be sufficient heat to evaporate that water. Hence the potential evapotranspiration rate there is 2000mm. The factors affecting evapotranspiration include all those that affect evaporation. In addition, some plants, such as cacti, have adaptations to help them reduce moisture loss.

River discharge

River discharge refers to the movement of water in channels such as streams and rivers. The water may enter the river as direct channel precipitation (it falls on the channel) or it may reach the channel by surface runoff, groundwater flow (baseflow), or throughflow (water flowing through the soil).

Stores

Interception

Interception refers to water that is caught and stored by vegetation. There are three main components:

- interception loss – water that is retained by plant surfaces and that is later evaporated away or absorbed by the plant
- throughfall – water that either falls through gaps in the vegetation or that drops from leaves or twigs
- stemflow – water that trickles along twigs and branches and finally down the main trunk.

Interception loss varies with different types of vegetation (Figure 1.3). Interception is less from grasses than from deciduous woodland owing to the smaller surface area of the grass shoots. From agricultural crops, and from cereals in particular, interception increases with crop density. Coniferous trees intercept more than deciduous trees in winter, but this is reversed in summer.

Soil water

Soil water (soil moisture) is the subsurface water in soil and subsurface layers above the water table. From here water may be:

- absorbed
- held
- transmitted downwards towards the water table, or
- transmitted upwards towards the soil surface and the atmosphere.

In coarse-textured soils much of the water is held in fairly large pores at fairly low suctions, while very little is held in small pores. In the finer-textured clay soils the range of pore sizes is much greater and, in particular, there is a higher proportion of small pores in which the water is held at very high suctions.

Field capacity refers to the amount of water held in the soil after excess water drains away; that is, saturation or near saturation. Wilting point refers to the range of moisture content in which permanent wilting of plants occurs.

There are a number of important seasonal variations in soil moisture budgets (Figure 1.4):

- Soil moisture deficit is the degree to which soil moisture falls below field capacity. In temperate areas, during late winter and early spring, soil moisture deficit is very low, due to high levels of precipitation and limited evapotranspiration.
- Soil moisture recharge occurs when precipitation exceeds potential evapotranspiration – there is some refilling of water in the dried-up pores of the soil.
- Soil moisture surplus is the period when soil is saturated and water cannot enter, and so flows over the surface.
- Soil moisture utilisation is the process by which water is drawn to the surface through capillary action.

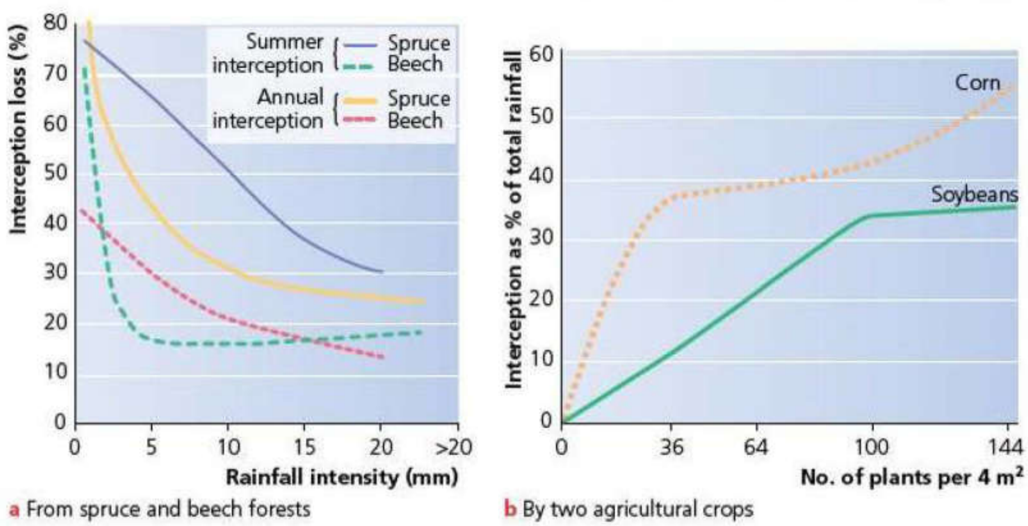


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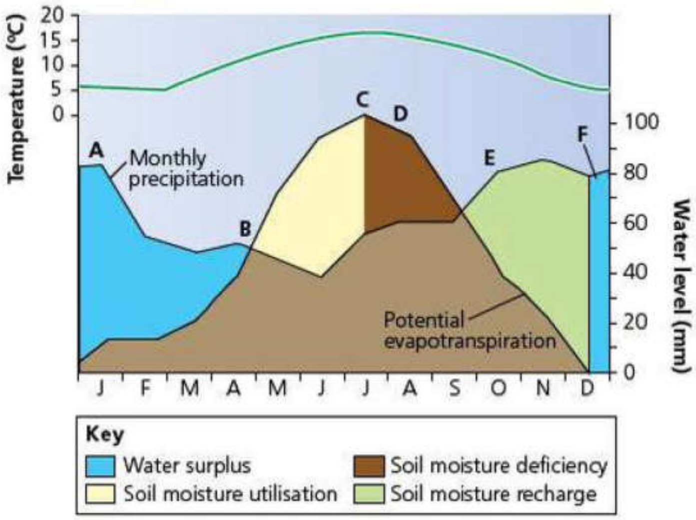
Figure 1.3 Interception losses for different types of vegetation



A Precipitation > potential evapotranspiration. Soil water store is full and there is a soil moisture surplus for plant use, runoff and groundwater recharge.

B Potential evapotranspiration > precipitation. Water store is being used up by plants or lost by evaporation (soil moisture utilisation).

C Soil moisture store is now used up. Any precipitation is likely to be absorbed by the soil rather than produce runoff. River levels will fall or dry up completely.

D There is a deficiency of soil water as the store is used up and potential evapotranspiration > precipitation. Plants must adapt to survive; crops must be irrigated.

E Precipitation > potential evapotranspiration. Soil water store will start to fill again (soil moisture recharge).

F Soil water store is full. Field capacity has been reached. Additional rainfall will percolate down to the water table and groundwater stores will be recharged.

Figure 1.4 Soil moisture status

Surface water

There are a number of types of surface water, some of which are temporary and some are permanent. Temporary sources include small puddles following a rainstorm and turloughs (seasonal lakes in limestone in the west of Ireland), while permanent stores include lakes, wetlands, swamps, peat bogs and marshes.

Groundwater

Groundwater refers to subsurface water that is stored under the surface in rocks. Groundwater accounts for 96.5 per cent of all freshwater on the Earth (Table 1.1). However, while some soil moisture may be recycled by evaporation into atmospheric moisture within a matter of days or weeks, groundwater may not be recycled for as long as 20 000 years. Recharge refers to the refilling of water in pores where the water has dried up or been extracted by human activity. Hence, in some places where recharge is not taking place, groundwater is considered a non-renewable resource.

Table 1.1 Global water reservoirs

Reservoir		Value ($km^{-3} \times 10^{-3}$)	% of total
Ocean		1 350 000.0	97.403
Atmosphere		13.0	0.00094
Land		35 977.8	2.596
Of which	Rivers	1.7	0.00012
	Freshwater lakes	100.0	0.0072
	Inland seas	105.0	0.0076
	Soil water	70.0	0.0051
	Groundwater	8 200.0	0.592
	Ice caps/glaciers	27 500.0	1.984
	Biota	1.1	0.00088

Channel storage

Channel storage refers to all water that is stored in rivers, streams and other drainage channels. Some rivers are seasonal, and some may disappear underground either naturally, such as in areas of Carboniferous limestone, or in urban areas, where they may be covered (culverted).

Flows

Above ground

Throughfall refers to water that either falls through gaps in vegetation or that drops from leaves or twigs. Stemflow refers to water that trickles along twigs and branches and finally down the main trunk.

Overland flow (surface runoff) is water that flows over the land's surface. Surface runoff (or overland flow) occurs in two main ways:

- when precipitation exceeds the infiltration rate
- when the soil is saturated (all the pore spaces are filled with water).

In areas of high precipitation intensity and low infiltration capacity, overland runoff is common. This is clearly seen in semi-arid areas and in cultivated fields. By contrast, where precipitation intensity is low and infiltration is high, most overland flow occurs close to streams and river channels.

Channel flow or stream flow refers to the movement of water in channels such as streams and rivers. The water may have entered the stream as a result of direct precipitation, overland flow, groundwater flow (baseflow) or throughflow (water flowing through the soil).

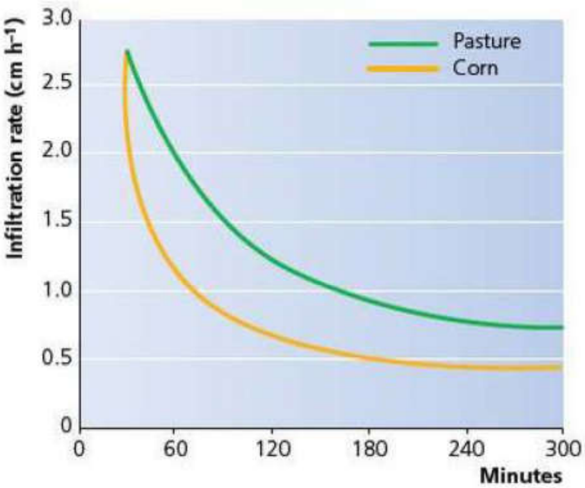
Below ground

Porosity is the capacity of a rock to hold water, for example sandstone has a porosity (pore space) of 5–15 per cent, whereas clay may be up to 50 per cent. Permeability is the ability to transmit water through a rock via joints and fissures.

Infiltration

Infiltration is the process by which water soaks into or is absorbed by the soil. The infiltration capacity is the maximum rate at which rain can be absorbed by a soil in a given condition.

Infiltration capacity decreases with time through a period of rainfall until a more or less constant value is reached (Figure 1.5). Infiltration rates of 0–4 mm/hour are common on clays, whereas 3–12 mm/hour are common on sands. Vegetation also increases infiltration. This is because it intercepts some rainfall and slows down the speed at which it arrives at the surface. For example, on bare soils where rainsplash impact occurs, infiltration rates may reach 10 mm/hour. On similar soils covered by vegetation, rates of between 50 and 100 mm/hour have been recorded. Infiltrated water is chemically rich as it picks up minerals and organic acids from vegetation and soil.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.247

Figure 1.5 Infiltration rates under vegetation

Infiltration is inversely related to overland runoff and is influenced by a variety of factors, such as duration of rainfall, antecedent soil moisture (pre-existing levels of soil moisture), soil porosity, vegetation cover (Table 1.2), raindrop size and slope angle (Figure 1.6). In contrast, overland flow is water that flows over the land's surface.

Table 1.2 Influence of ground cover on infiltration rates

Ground cover	Infiltration rate (mm/hour)
Old permanent pasture	57
Permanent pasture: moderately grazed	19
Permanent pasture: heavily grazed	13
Strip-cropped	10
Weeds or grain	9
Clean tilled	7
Bare, crusted ground	6

Percolation

Water moves slowly downwards from the soil into the bedrock – this is known as percolation. Depending on the permeability of the rock, this may be very slow or in some rocks, such as Carboniferous limestone and chalk, it may be quite fast, locally.

Throughflow

Throughflow refers to water flowing through the soil in natural pipes and percolines (lines of concentrated water flow between soil horizons).

Groundwater and baseflow

Most groundwater is found within a few hundred metres of the surface but has been found at depths of up to 4 kilometres beneath the surface. Baseflow refers to the part of a river's discharge that is provided by groundwater seeping into the bed of a river. It is a relatively constant flow although it increases slightly following a wet period.

Underground water

The permanently saturated zone within solid rocks and sediments is known as the phreatic zone. The upper layer of this is known as the water table. The water table varies seasonally. In temperate zones it is higher in winter following increased levels of precipitation. The zone that is seasonally wetted and seasonally dries out is known as the aeration zone.

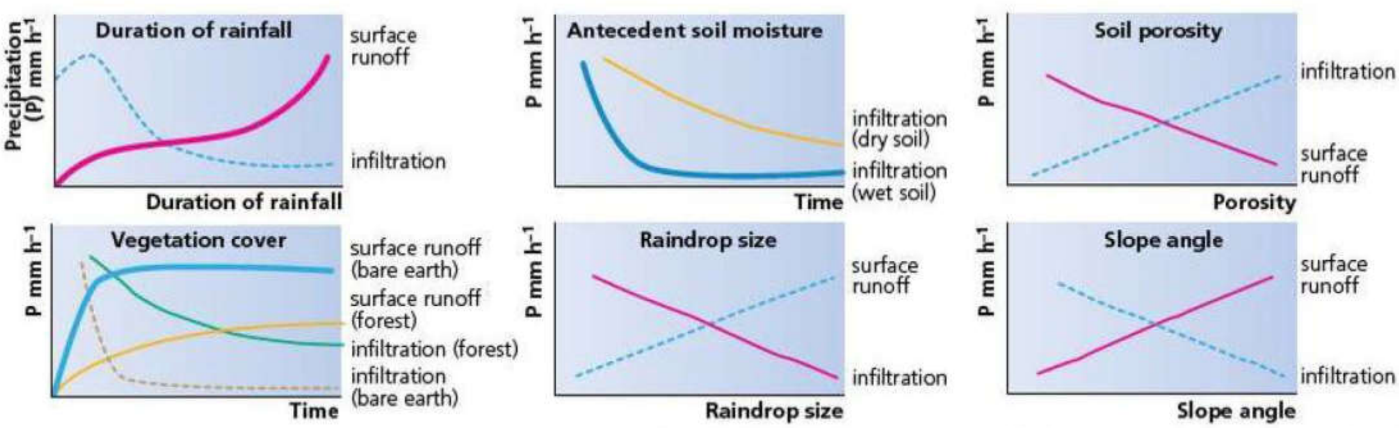


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Figure 1.6 Factors affecting infiltration and surface runoff

Aquifers (rocks that contain significant quantities of water) provide a great reservoir of water. Aquifers are permeable rocks such as sandstones and limestones. The water in aquifers moves very slowly and acts as a natural regulator in the hydrological cycle by absorbing rainfall that otherwise would reach streams rapidly. In addition, aquifers maintain stream flow during long dry periods. Where water flow reaches the surface (as shown by the discharge areas in Figure 1.7), springs may be found. These may be substantial enough to become the source of a stream or river.

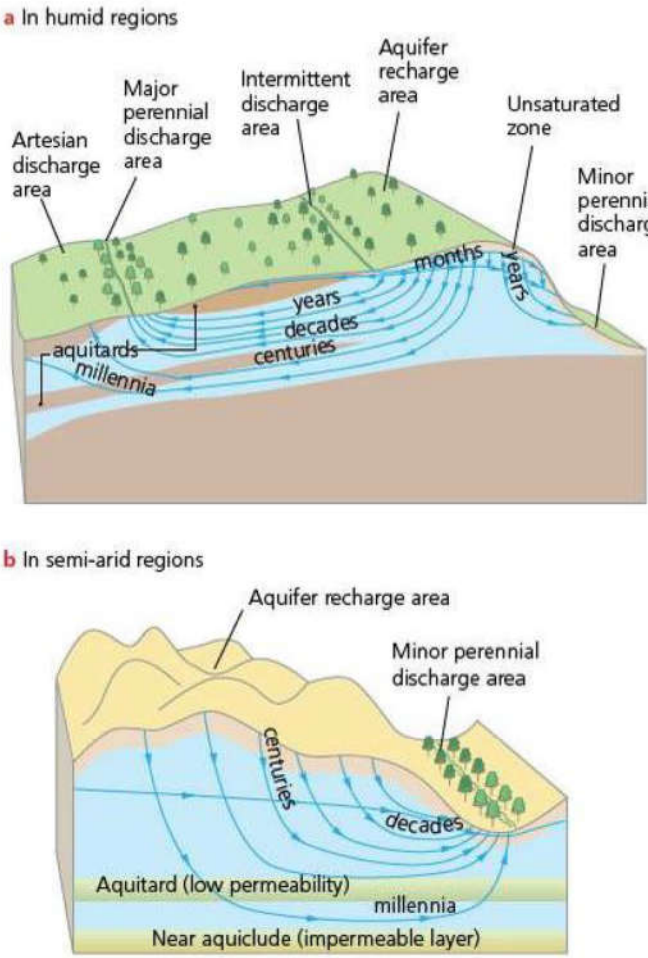

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Figure 1.7 Groundwater and aquifer characteristics

Groundwater recharge occurs as a result of:

- **infiltration** of part of the total precipitation at the ground surface
- **seepage** through the banks and bed of surface water bodies such as ditches, rivers, lakes and oceans
- **groundwater leakage and inflow** from adjacent rocks and aquifers
- **artificial recharge** from irrigation, reservoirs, and so on.

Losses of groundwater result from:

- **evapotranspiration**, particularly in low-lying areas where the water table is close to the ground surface
- **natural discharge**, by means of spring flow and seepage into surface water bodies
- **groundwater leakage and outflow**, along aquicludes and into adjacent aquifers
- **artificial abstraction**, for example the water table near Lubbock on the High Plains of Texas (USA) has declined by 30–50m in just 50years, and in Saudi Arabia the groundwater reserve in 2010 was 42per cent less than in 1985.

Section 1.1 Activities

1 Define the following hydrological characteristics:
   a interception   b evaporation   c infiltration.
2 Study Figure 1.2.
   a Define the terms *overland flow* and *throughflow*.
   b Compare the nature of water movement in these two flows.
   c Suggest reasons for the differences you have noted.
3 Figure 1.3 shows interception losses from spruce and beech forests and from three agricultural crops. Describe and comment on the relationship between the number of plants and interception, and the type of plants and interception.
4 Figure 1.6 shows the relationship between infiltration, overland flow (surface runoff) and six factors. Write a paragraph on each of the factors, describing and explaining the effect it has on infiltration and overland runoff.
5 Comment on the relationship between ground cover and infiltration, as shown in Table 1.2.
6 Define the terms *groundwater* and *baseflow*.
7 Outline the ways in which human activities have affected groundwater.

1.2 Discharge relationships within drainage basins

Hydrographs

A storm hydrograph shows how the discharge of a river varies over a short time (Figure 1.8). Normally it refers to an individual storm or group of storms of not more than a few days in length. Before the storm starts, the main supply of water to the stream is through groundwater flow or baseflow. This is the main supplier of water to rivers. During the storm, some water infiltrates into the soil while some flows over the surface as overland flow or runoff. This reaches the river quickly as quickflow, which causes a rapid rise in the level of the river. The rising limb shows us how quickly the flood waters begin to rise, whereas the recessional limb is the speed with which the water level in the river declines after the peak. The peak flow is the maximum discharge of the river as a result of the storm, and the time lag is the time between the height of the storm (not the start or the end) and the maximum flow in the river.

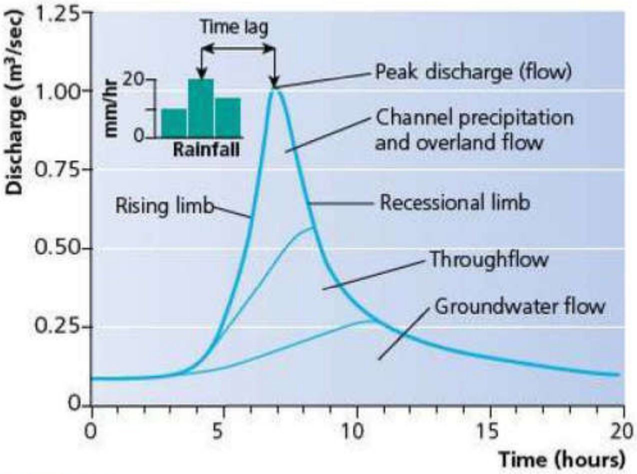


Figure 1.8 A simple hydrograph

In contrast, a **river regime** is the annual variation in the discharge of a river. Stream discharge occurs as a result of overland runoff and groundwater springs, and from lakes and meltwater in mountainous or sub-polar environments. The character or **regime** of the resulting stream or river is influenced by several variable factors:

- the amount and nature of precipitation
- the local rocks, especially porosity and permeability
- the shape or morphology of the drainage basin, its area and slope
- the amount and type of vegetation cover
- the amount and type of soil cover.

On an annual basis, the most important factor determining stream regime is climate. Figure 1.9 shows generalised regimes for Europe. Notice how the regime for the Shannon at Killaloe (Ireland) has a typical temperate regime, with a clear winter maximum. By contrast, Arctic areas such as the Gloma in Norway and the Kemi in Finland have a peak in spring associated with snowmelt. Others, such as the Po near Venice, have two main maxima – autumn and winter rains (Mediterranean climate) and spring snowmelt from Alpine tributaries.

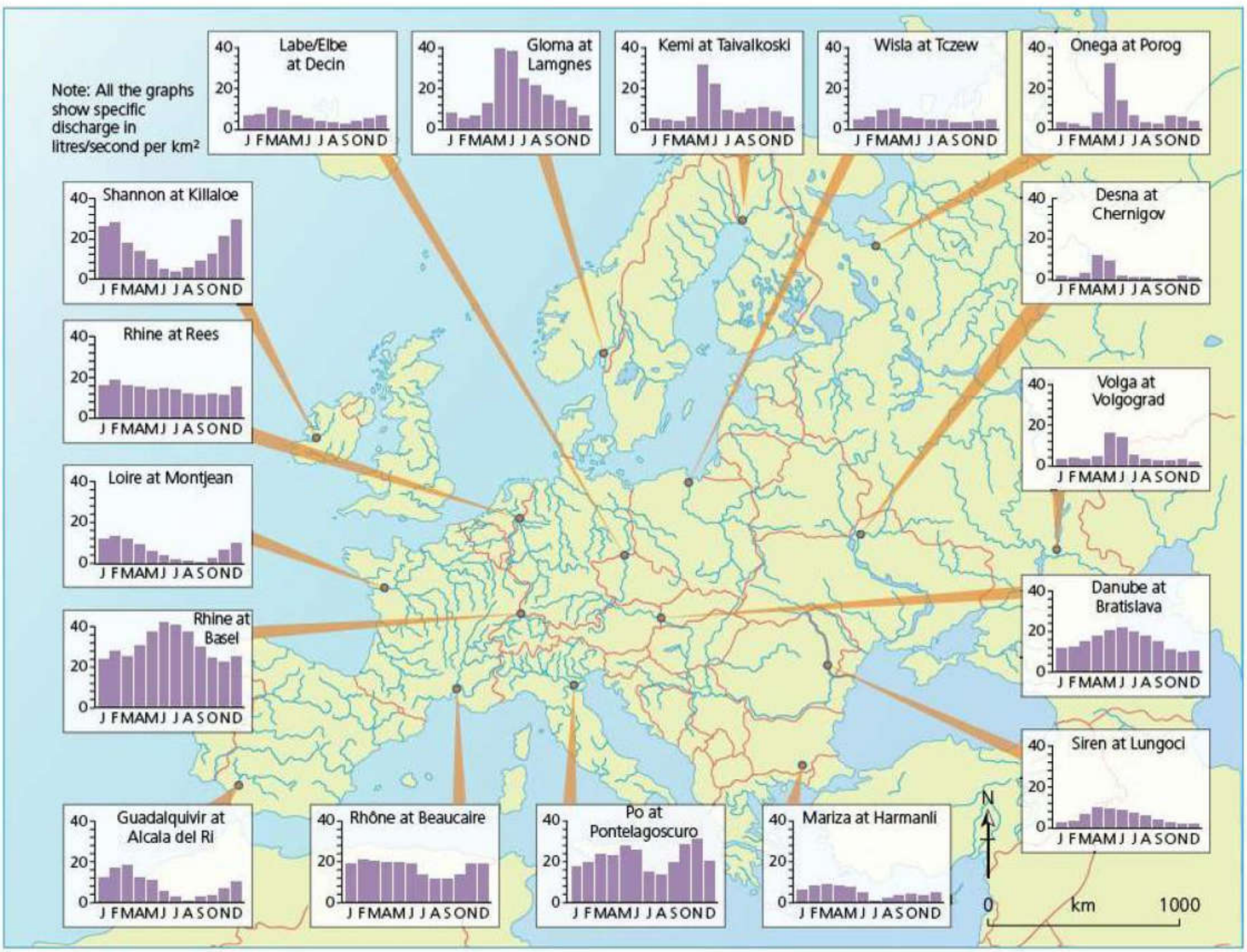
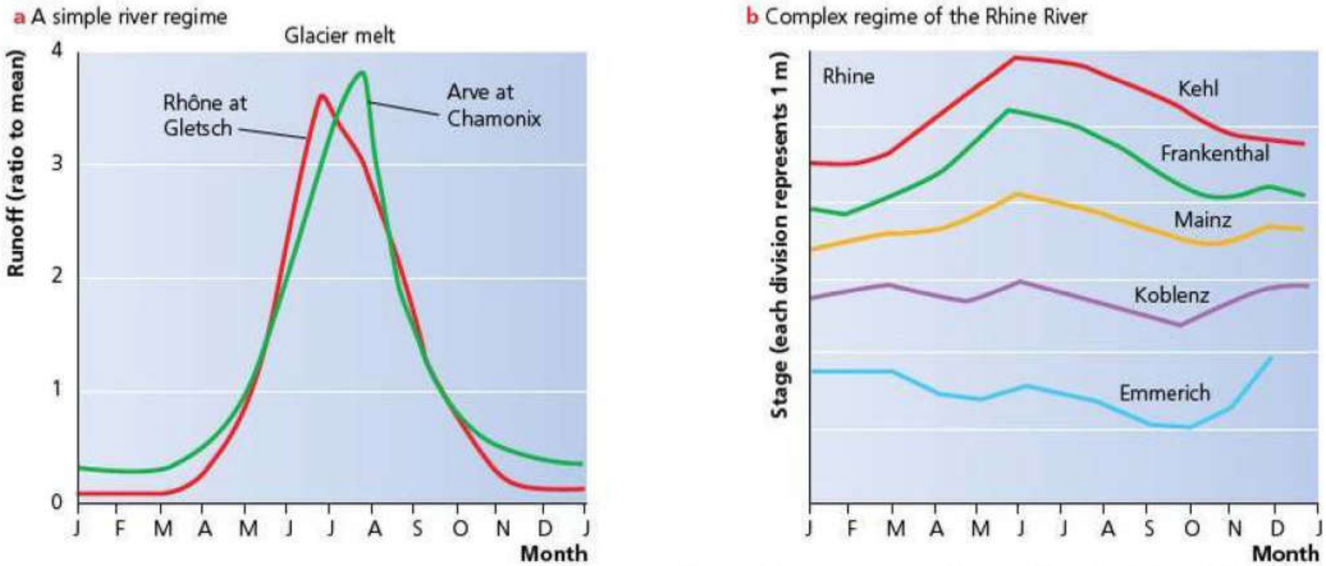


Figure 1.9 River regimes in Europe



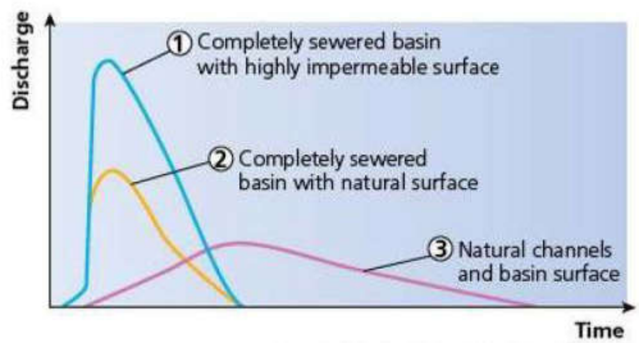
Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.262

Figure 1.10 Simple and complex river regimes

Figure 1.10a shows a simple regime, based upon a single river with one major peak flow. By contrast, Figure 1.10b shows a complex regime for the River Rhine. It has a number of large tributaries that flow in a variety of environments, including alpine, Mediterranean and temperate. By the time the Rhine has travelled downstream, it is influenced by many, at times contrasting, regimes.

Influences on hydrographs

The effect of urban development on hydrographs is to increase peak flow and decrease time lag (Figure 1.11). This is due to an increase in the proportion of impermeable ground in a drainage basin, as well as an increase in the drainage density. Storm hydrographs also vary, with a number of other factors (Table 1.3) such as basin shape, drainage density and gradient.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.255

Figure 1.11 The effects of urban development on storm hydrographs

Table 1.3 Factors affecting storm hydrographs

Factor	Influence on storm hydrograph
Climate	
Precipitation type and intensity	Highly intensive rainfall is likely to produce overland flow, a steep rising limb and high peak flow. Low-intensity rainfall is likely to infiltrate into the soil and percolate slowly into the rock, thereby increasing the time lag and reducing the peak flow. Precipitation that falls as snow sits on the ground until it melts. Sudden, rapid melting can cause flooding and lead to high rates of overland flow, and high peak flows.
Temperature, evaporation, transpiration and evapotranspiration	Not only does temperature affect the type of precipitation, it also affects the evaporation rate (higher temperatures lead to more evaporation and so less water getting into rivers). On the other hand, warm air can hold more water so the potential for high peak flows in hot areas is raised. Increased vegetation cover intercepts more rainfall and may return a proportion of it through transpiration, thereby reducing the amount of water reaching stream channels. The greater the return through evapotranspiration, the less water is able to reach stream channels, and therefore the peak of the hydrograph is reduced.
Antecedent moisture	If it has been raining previously and the ground is saturated or nearly saturated, rainfall will quickly produce overland flow, a high peak flow and short time lag.

⇨

Factor	Influence on storm hydrograph
Drainage basin characteristics	
Drainage basin size and shape	Smaller drainage basins respond more quickly to rainfall conditions. For example, the Boscastle (UK) floods of 2004 drained an area of less than 15 km². This meant that the peak of the flood occurred soon after the peak of the storm. In contrast, the Mississippi River is over 3700 km long – it takes much longer for the lower part of the river to respond to an event that might occur in the upper course of the river. Circular basins respond more quickly than linear basins, where the response is more drawn out.
Drainage density	Basins with a high drainage density, such as urban basins with a network of sewers and drains, respond very quickly. Networks with a low drainage density have a very long time lag.
Porosity and impermeability of rocks and soils	Impermeable surfaces cause more water to flow overland. This causes greater peak flows. Urban areas contain large areas of impermeable surfaces. In contrast, rocks such as chalk and gravel are permeable and allow water to infiltrate and percolate. This reduces the peak flow and increases the time lag. Sandy soils allow water to infiltrate, whereas clay is much more impermeable and causes water to pass overland.
Rock type	Impermeable rocks such as granite and clay produce greater peak flows with a more flashy response. In contrast, more permeable rocks such as chalk and limestone produce storm hydrographs with a much lower peak flow (if at all) and with a much delayed/less flashy response (greater time lag).
Slopes	Steeper slopes create more overland flow, shorter time lags and higher peak flows.
Vegetation type	Forest vegetation intercepts more rainfall, especially in summer, and so reduces the amount of overland flow and peak flow and increases time lag. In winter, deciduous trees lose their leaves and so intercept less.
Land use	Land uses that create impermeable surfaces, or reduce vegetation cover, reduce interception and increase overland flow. If more drainage channels are built (sewers, ditches, drains), the water is carried to rivers very quickly. This means that peak flows are increased and time lags reduced.

Section 1.2 Activities

1. Compare the river regimes of the Gloma (Norway), Shannon (Ireland) and Rhine (Switzerland). Suggest reasons for their differences.
2. Table 1.4 shows precipitation and runoff data for a storm on the Delaware River, New York. Using this data, plot the storm hydrograph for this storm. Describe the main characteristics of the hydrograph you have drawn.
3. Define the terms *river regime* and *storm hydrograph*.
4. Study Figure 1.11, which shows the impact of urbanisation on storm hydrographs. Describe and explain the differences in the relationship between discharge and time.

Table 1.4 Precipitation and runoff data for a storm on the Delaware River, New York

Date	Time	Duration of rainfall	Total (cm)
29 September	6 a.m.	12 hours	0.1
29 September	6 p.m.	12 hours	0.9
30 September	6 p.m.	24 hours	3.7
30 September	12 p.m.	6 hours	0.1
		Total	**4.8**

Date	Stream runoff (m³/s)
28 September	28.3 (baseflow)
29 September	28.3 (baseflow)
30 September	339.2
1 October	2094.2
2 October	1330.1
3 October	594.3
4 October	367.9
5 October	254.2
6 October	198.1
7 October	176.0
8 October	170.0
9 October	165.2 (baseflow)

1.3 River channel processes and landforms

Erosion

Abrasion (corrasion) is the wearing away of the bed and bank by the load carried by a river. It is the mechanical impact produced by the debris eroding the river's bed and banks. In most rivers it is the principal means of erosion. The effectiveness of abrasion depends on the concentration, hardness and energy of the impacting particles and the resistance of the bedrock. Abrasion increases as velocity increases (kinetic energy is proportional to the square of velocity).

Attrition is the wearing away of the load carried by a river. It creates smaller, rounder particles.

Hydraulic action is the force of air and water on the sides of rivers and in cracks. It includes the direct force of flowing water, and cavitation – the force of air exploding. As fluids accelerate, pressure drops and may cause air bubbles to form. Cavitation occurs as bubbles implode and evict tiny jets of water with velocities of up to 130 m/s. These can damage solid rock. Cavitation is an important process in rapids and waterfalls, and is generally accompanied by abrasion.

Corrosion or solution is the removal of chemical ions, especially calcium. The key factors controlling the rate of corrosion are bedrock, solute concentration of the stream water, discharge and velocity. Maximum rates of corrosion occur where fast-flowing, undersaturated streams pass over soluble rocks – humid zone streams flowing over mountain limestone.

There are a number of factors affecting rates of erosion. These include:

- load – the heavier and sharper the load the greater the potential for erosion
- velocity – the greater the velocity the greater the potential for erosion (see Figure 1.13)
- gradient – increased gradient increases the rate of erosion
- geology – soft, unconsolidated rocks such as sand and gravel are easily eroded
- pH – rates of solution are increased when the water is more acidic
- human impact – deforestation, dams and bridges interfere with the natural flow of a river and frequently end up increasing the rate of erosion.

Erosion by the river will provide loose material. This eroded material (plus other weathered material that has moved downslope from the upper valley sides) is carried by the river as its load.

Global sediment yield

It is possible to convert a value of mean annual sediment and solute load to an estimate of the rate of land surface lowering by fluvial denudation. This gives a combined sediment and solute load of 250 tonnes/km^2 per year – that is, an annual rate of lowering of the order of 0.1 mm per year. There is a great deal of variation in sediment yields. These range from 10 tonnes/km^2 per year in such areas as northern Europe and parts of Australia to in excess of 10 000 tonnes/km^2 per year in certain areas where conditions are especially conducive to high rates of erosion (Figure 1.12). These include Taiwan, New Zealand's South Island and the Middle Yellow River basin in China. In the first two cases, steep slopes, high rainfall and tectonic instability are major influences, while in the last case the deep loess deposits and the almost complete lack of natural vegetation cover are important. Rates of land surface lowering vary from less than 0.004 mm per year to over 4 mm per year. The broad pattern of global suspended sediment is shown on the map and it reflects the influence of a wide range of factors, including climate, relief, geology, vegetation cover and land use.

Load transport

Load is transported downstream in a number of ways:

- The smallest particles (silts and clays) are carried in suspension as the suspended load.
- Larger particles (sands, gravels, very small stones) are transported in a series of 'hops' as the saltated load.
- Pebbles are shunted along the bed as the bed or tracted load.
- In areas of calcareous rock, material is carried in solution as the dissolved load.

The load of a river varies with discharge and velocity. The capacity of a stream refers to the largest amount of debris that a stream can carry, while the competence refers to the diameter of the largest particle that can be carried.

Deposition and sedimentation

There are a number of causes of deposition, such as:

- a shallowing of gradient, which decreases velocity and energy
- a decrease in the volume of water in the channel
- an increase in the friction between water and channel.

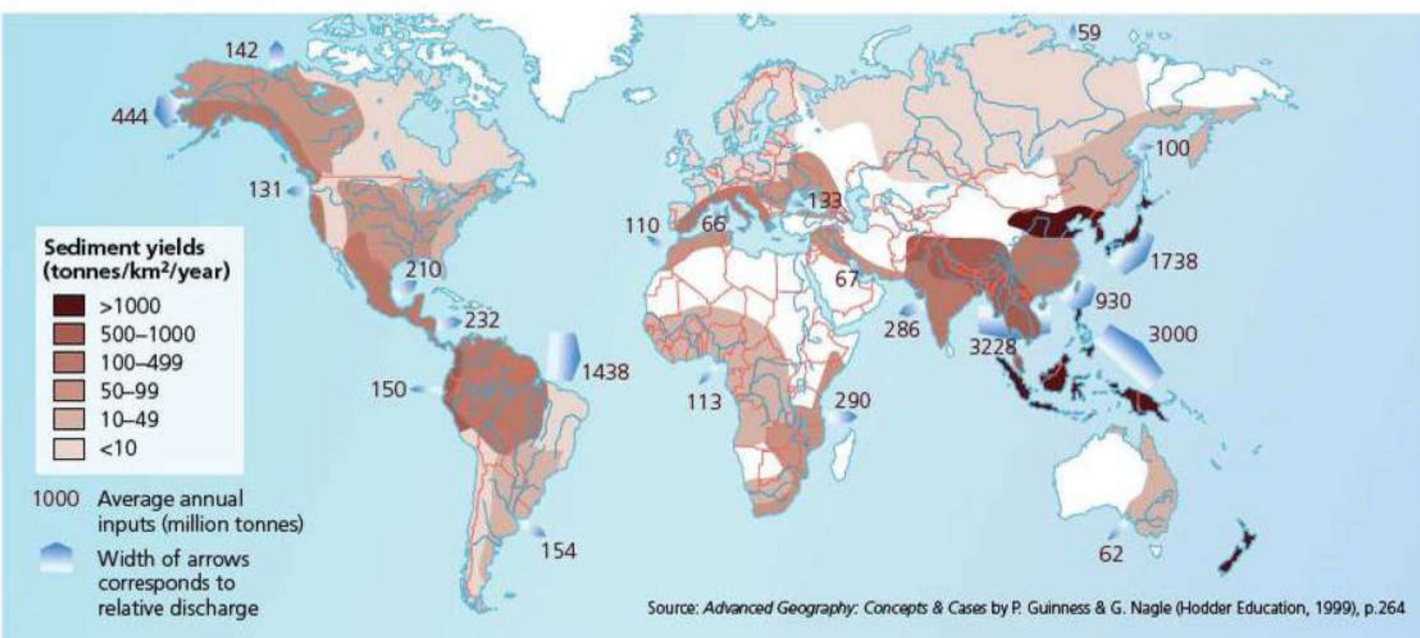
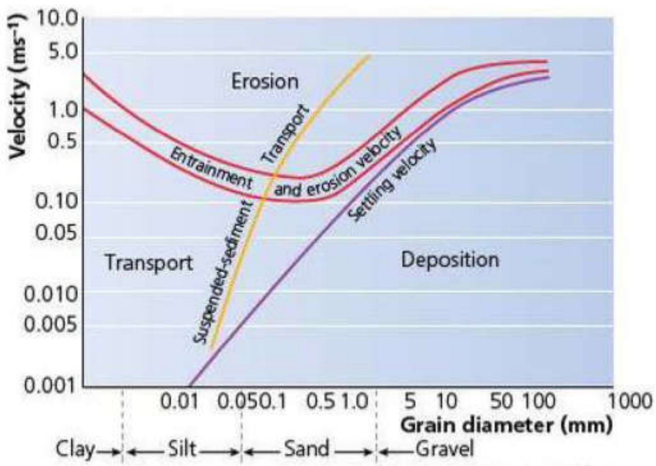


Figure 1.12 Global sediment yield

The Hjülstrom curve

The critical erosion velocity is the lowest velocity at which grains of a given size can be moved. The relationship between these variables is shown by means of a Hjülstrom curve (Figure 1.13). For example, sand can be moved more easily than silt or clay, as fine-grained particles tend to be more cohesive. High velocities are required to move gravel and cobbles because of their large size. The critical velocities tend to be an area rather than a straight line on the graph.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.263

Figure 1.13 Hjülstrom curve

There are three important features on Hjülstrom curves:

- The smallest and largest particles require high velocities to lift them. For example, particles between 0.1 mm and 1 mm require velocities of around 100 mm/s to be entrained, compared with values of over 500 mm/s to lift clay (0.01 mm) and gravel (over 2 mm). Clay resists entrainment due to its cohesion; gravel due to its weight.
- Higher velocities are required for entrainment than for transport.
- When velocity falls below a certain level (settling or fall velocity), those particles are deposited.

Section 1.3 Activities

Study Figure 1.13.

1. Describe the work of the river when sediment size is 1 mm.
2. Comment on the relationship between velocity, sediment size and river process when the river is moving at $0.5 m/s^{-1}$.

River flow

Velocity and discharge

River flow and associated features of erosion are complex. The velocity and energy of a stream are controlled by:

- the gradient of the channel bed
- the volume of water within the channel, which is controlled largely by precipitation in the drainage basin (for example bankfull gives rapid flow, whereas low levels give lower flows)
- the shape of the channel
- channel roughness, including friction.

Manning's Equation

$Q = (AR^{2/3} S^{1/2})/n$

where Q = discharge, A = cross-sectional area, R = hydraulic radius, S = channel slope (as a fraction), n = coefficient of bed roughness (the rougher the bed the higher the value).

As water flows over riffles, for example, there are changes in cross-sectional area, slope and hydraulic radius. Slope and velocity increase but depth decreases. Discharge remains the same.

Manning's 'n'

Mountain stream, rocky bed	0.04–0.05
Alluvial channel (large dunes)	0.02–0.035
Alluvial channel (small ripples)	0.014–0.024

Patterns of flow

There are three main types of flow: laminar, turbulent and helicoidal. For laminar flow, a smooth, straight channel with a low velocity is required. This allows water to flow in sheets, or laminae, parallel to the channel bed. It is rare in reality and most commonly occurs in the lower reaches. However, it is more common in groundwater, and in glaciers when one layer of ice moves over another.

Turbulent flow occurs where there are higher velocities and complex channel morphology such as a meandering channel with alternating pools and riffles. Bed roughness also increases turbulence, for example mountain streams with rocky beds create more turbulence than alluvial channels. Turbulence causes marked variations in pressure within the water. As the turbulent water swirls (eddies) against the bed or bank of the river, air is trapped in pores, cracks and crevices and put momentarily under great pressure. As the eddy swirls away, pressure is released; the air expands suddenly, creating a small explosion that weakens the bed or bank material. Thus turbulence is associated with hydraulic action.

Vertical turbulence creates hollows in the channel bed. Hollows may trap pebbles that are then swirled by eddying, grinding at the bed. This is a form of vertical corrasion or abrasion and given time may create potholes (Figure 1.14). Cavitation and vertical abrasion may help to deepen the channel, allowing the river to down-cut its valley. If the down-cutting is dominant over the other forms of erosion (vertical erosion exceeds lateral erosion), then a gulley or gorge will develop.

Figure 1.14 Potholes as seen by the areas occupied by water (dark patches)

Horizontal turbulence often takes the form of helicoidal flow, a 'corkscrewing' motion. This is associated with the presence of alternating pools and riffles in the channel bed, and where the river is carrying large amounts of material. The erosion and deposition by helicoidal flow creates meanders (Figure 1.15). The thalweg is the line of maximum velocity and it travels from outside bank to outside bank of the meanders. The main current strikes the outer bank and creates a return flow to the inner bank, close to the channel bend. The movement transports sediment from the outer bank to the inner bank where it is deposited as a sand bar.

Channel types

Sinuosity is the length of a stream channel expressed as a ratio of the valley length. A low sinuosity has a value of 1.0 (that is, it is straight) whereas a high sinuosity is above 4.4. The main groupings are straight channels (<1.5) and meandering (>1.5). Straight channels are rare. Even when they do occur the thalweg (line of maximum velocity) moves from side to side. These channels generally have a central ridge of deposited material, due to the water flow pattern.

Braiding occurs when the channel is divided by islands or bars (Figure 1.16). Islands are vegetated and long-lived, whereas bars are unvegetated, less stable and often short-term features. Braided channels are formed by various factors, for example:

- a steep channel gradient
- a large proportion of coarse material
- easily erodable bank material
- highly variable discharge.

Braiding tends to occur when a stream does not have the capacity to transport its load in a single channel, whether it is straight or meandering. It occurs when river discharge is very variable and banks are easily erodable. This gives abundant sediment. It is especially common in periglacial and semi-arid areas.

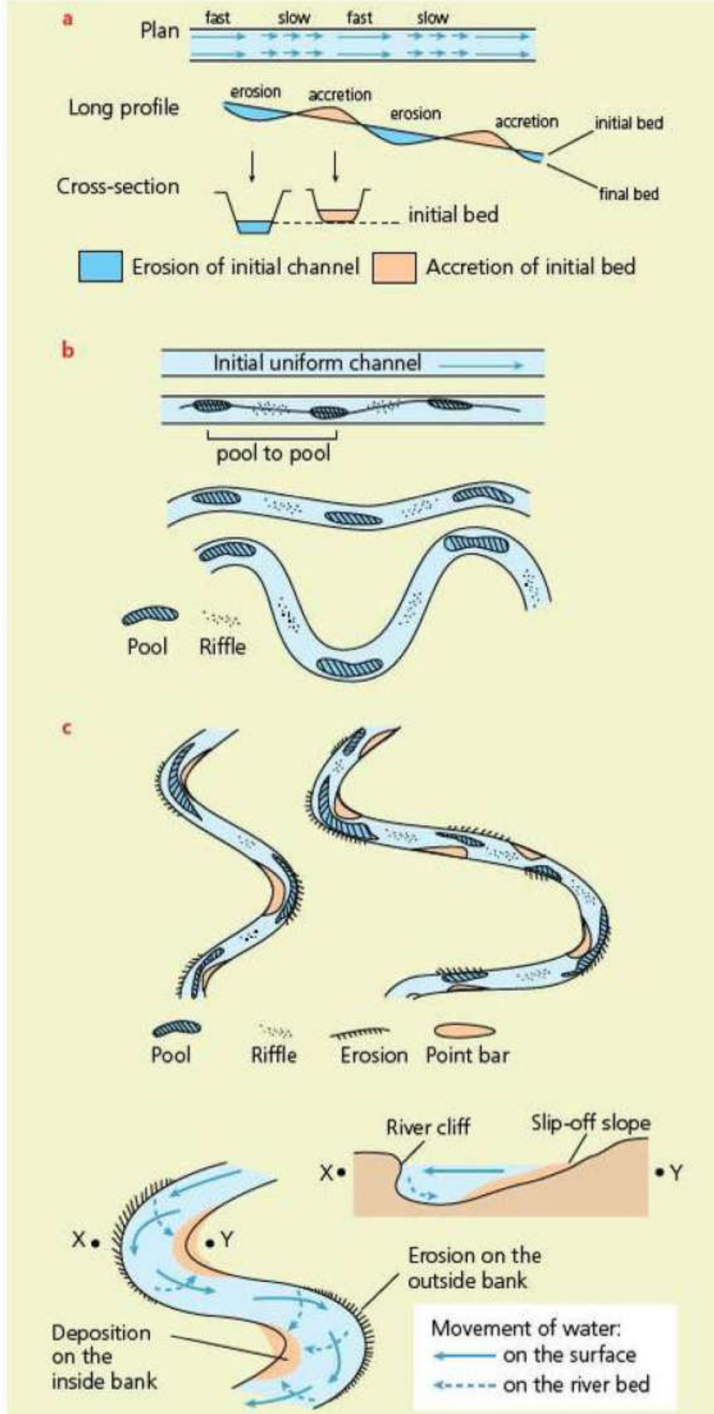


Figure 1.15 Meander formation

Braiding begins with a mid-channel bar that grows downstream. As the discharge decreases following a flood, the coarse bed load is first to be deposited. This forms the basis of bars that grow downstream and, as the flood is reduced, finer sediment is deposited. The upstream end becomes stabilised with vegetation. This island localises and narrows the channel in an attempt to increase the velocity to a point where it can transport its load. Frequently, subdivision sets in.

Figure 1.16 A braided river, Mýrdalsjökull, Iceland

Meanders

Meanders are complex (Figure 1.15). There are a number of relationships, although the reasons are not always very clear. However, they are *not* the result of obstructions in the floodplain. Meandering is the normal behaviour of fluids and gases in motion. Meanders can occur on a variety of materials, from ice to solid rock. Meander development occurs in conditions where channel slope, discharge and load combine to create a situation where meandering is the only way that the stream can use up the energy it possesses equally throughout the channel reach. The wavelength of the meander is dependent upon three main factors: channel width, discharge and the nature of the bed and banks.

Meanders and channel characteristics

- Meander wavelengths are generally 6–10 times channel width and discharge.
- Meander wavelengths are generally 5 times the radius of curvature.
- The meander belt (peak-to-peak amplitude) is generally 14–20 times the channel width.
- Riffles occur at about 6 times the channel width.
- Sinuosity increases as depth of channel increases in relation to width.
- Meandering is more pronounced when the bed load is varied.
- Meander wavelength increases in streams that carry coarse debris.
- Meandering is more likely on shallow slopes.
- Meandering best develops at or near bankfull state.

Natural meanders are rarely 'standard'. This is due, in part, to variations in bed load; where the bed load is coarse, meanders are often very irregular.

Causes of meanders

There is no simple explanation for the creation of meanders, and a number of factors are likely to be important.

- **Friction** with the channel bed and bank causes turbulence, which makes stream flow unstable. This produces bars along the channel, and a helicoidal flow (corkscrew motion), with water being raised on the outer surfaces of pools, and the return flow occurring at depth.
- **Sand bars** in the channel may cause meandering.
- **Sinuosity** is best developed on moderate angles. There is a critical minimum gradient below which straight channels occur. At very low energy (low gradient), helicoidal flow is insufficient to produce alternating pools and riffles. In addition, high-velocity flows in steep gradient channels are too strong to allow cross-channel meandering and the development of alternating pools and riffles. In such circumstances, braided channels are formed.
- **Helicoidal flow** (corkscrewing) causes the line of fastest flow to move from side to side within the channel. This increases the amplitude of the meander.

Change over time

There are a number of possibilities:

- Meanders may migrate downstream and erode river cliffs.
- They may migrate laterally (sideways) and erode the floodplain.
- They may become exaggerated and become cut-offs (ox-bow lakes).
- Under special conditions, they may become intrenched or ingrown.

Intrenched and ingrown meanders

The term incised meanders describes meanders that are especially well developed on horizontally bedded rocks, and form when a river cuts through alluvium and into underlying bedrock. Two main types occur – intrenched and ingrown meanders. Intrenched meanders are symmetrical, and occur when down-cutting is fast enough to offset the lateral migration of meanders. This frequently occurs when there is a significant fall in base level (generally sea level). The Goosenecks of the San Juan in the USA are classic examples of intrenched meanders. Ingrown meanders are the result of lateral meander migration. They are asymmetric in cross-section – examples can be seen in the lower Seine in France.

Landforms

Meanders

Meanders have an asymmetric cross-section (Figure 1.15b). They are deeper on the outside bank and shallower on the inside bank. In between meanders they are more symmetrical. They begin with the development of pools and riffles in a straight channel and the thalweg begins to flow from side to side. Helicoidal flow occurs, whereby surface water flows towards the outer banks, while the bottom flow is towards the inner bank. This causes the variations in the cross-section and variations in erosion and deposition. These variations give rise to river cliffs on the outer bank and point bars on the inner bank.

Pools and riffles

Pools and riffles are formed by turbulence. Eddies cause the deposition of coarse sediment (riffles) at high velocity points and fine sediment (pools) at low velocity. Riffles have a steeper gradient than pools, which leads to variations in subcritical and supercritical flow, and therefore erosion and deposition.

Riffles are small ridges of material deposited where the river velocity is reduced midstream, in between pools (the deep parts of a meander).

Braided rivers

A braided river channel consists of a number of interconnected shallow channels separated by alluvial and shingle bars (islands). These may be exposed during low flow conditions. They are formed in rivers that are heavily laden with sediment and have a pronounced seasonal flow. There are excellent examples on the Eyjafjörður in northern Iceland.

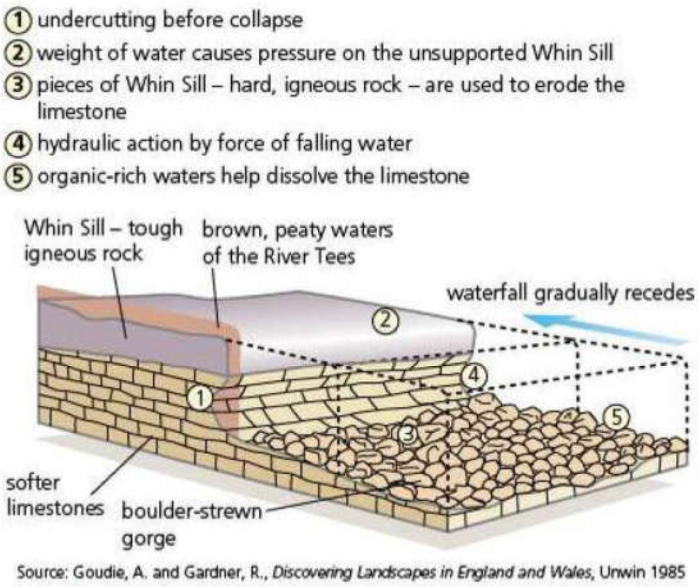
Section 1.3 Activities

Study Figure 1.15.

1 Compare the main characteristics of river cliffs with those of point bars.
2 Briefly explain the meaning of the term *helicoidal flow*.
3 Describe and explain the role of pools and riffles in the development of meanders in a river channel.

Waterfalls and gorges

Waterfalls occur where the river spills over a sudden change in gradient, undercutting rocks by hydraulic impact and abrasion, thereby creating a waterfall (Figures 1.17 and 1.18). There are many reasons for this sudden change in gradient along the river:



Source: Goudie, A. and Gardner, R., *Discovering Landscapes in England and Wales*, Unwin 1985

Figure 1.17 Waterfall formation

- a band of resistant strata such as the resistant limestones at Niagara Falls
- a plateau edge such as Victoria Falls on the Zimbabwe–Zambia border
- a fault scarp such as at Gordale, Yorkshire (UK)
- a hanging valley such as at Glencoyne, Cumbria in the UK
- coastal cliffs.

The undercutting at the base of a waterfall creates a precarious overhang, which will ultimately collapse. Thus a waterfall may appear to migrate upstream, leaving a gorge of recession downstream. The Niagara Gorge is 11 kilometres long due to the retreat of Niagara Falls.

Gorge development is common, for example where the local rocks are very resistant to weathering but susceptible to the more powerful river erosion. Similarly, in arid areas where the water necessary for weathering is scarce, gorges are formed by periods of river erosion. A rapid acceleration in down-cutting is also associated when a river is rejuvenated, again creating a gorge-like landscape. Gorges may also be formed as a result of:

- antecedent drainage (Rhine Gorge)
- glacial overflow channelling (Newtondale, UK)
- the collapse of underground caverns in Carboniferous limestone areas
- surface runoff over limestone during a periglacial period
- the retreat of waterfalls (Niagara Falls)
- superimposed drainage (Avon Gorge, UK).

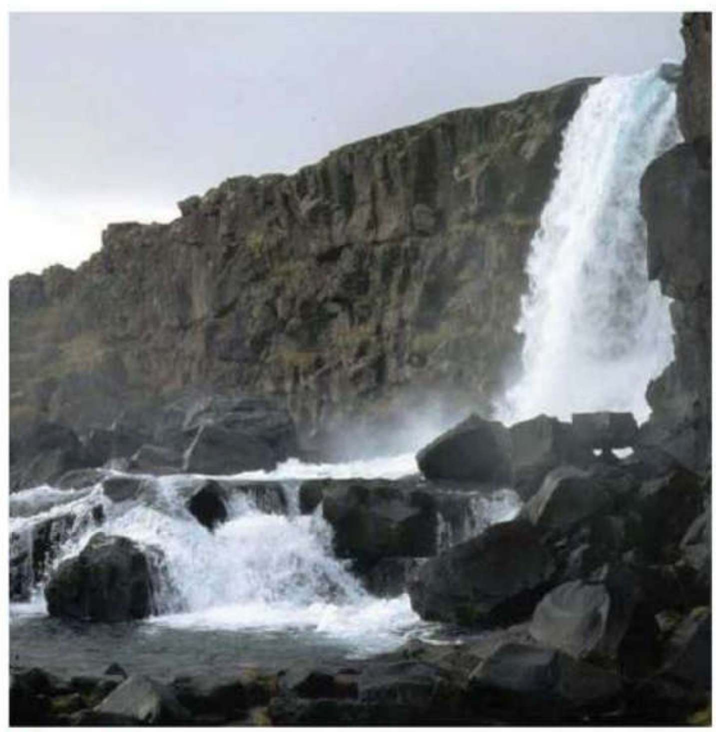


Figure 1.18 Axara waterfall, Iceland

Case Study: Niagara Falls

Most of the world's great waterfalls are the result of the undercutting of resistant cap rocks, and the retreat or recession that follows. The Niagara River flows for about 50 kilometres between Lake Erie and Lake Ontario. In that distance it falls just 108 metres, giving an average gradient of 1:500. However, most of the descent occurs in the 1.5 kilometres above the Niagara Falls (13 metres) and at the Falls themselves (55 metres). The Niagara River flows in a 2 kilometre-wide channel just 1 kilometre above the Falls, and then into a narrow 400 metre-wide gorge, 75 metres deep and 11 kilometres long. Within the gorge the river falls a further 30 metres.

The course of the Niagara River was established about 12 000 years ago when water from Lake Erie began to spill northwards into Lake Ontario. In doing so, it passed over the highly resistant dolomitic (limestone) escarpment. Over the last 12 000 years the Falls have retreated 11 kilometres, giving an average rate of retreat of about 1 metre per year. Water velocity accelerates over the Falls, and decreases at the base of the Falls. Hydraulic action and abrasion have caused the development of a large plunge pool at the base, while the fine spray and eddies in the river help to remove some of the softer rock underneath the resistant dolomite. As the softer rocks are removed, the dolomite is left unsupported and the weight of the water causes the dolomite to collapse. Hence the waterfall retreats, forming a gorge of recession.

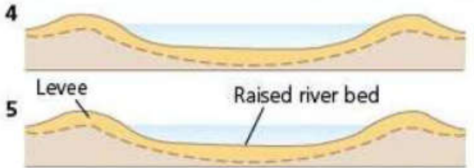
In the nineteenth century, rates of recession were recorded at 1.2 metres per year. However, now that the amount of water flowing over the Falls is controlled (due to the construction of hydro-electric power stations), rates of recession have been reduced. In addition, engineering works in the 1960s reinforced parts of the dolomite that were believed to be at risk of collapse. The Falls remains an important tourist attraction and local residents and business personnel did not want to lose their prized asset!

Section 1.3 Activities

Draw a labelled diagram to show the formation of a waterfall.

Levees, floodplains and bluffs

Levees and floodplain deposits are formed when a river bursts its banks over a long period of time. Water quickly loses velocity, leading to the rapid deposition of coarse material (heavy and difficult to move a great distance) near the channel edge. These coarse deposits build up to form embankments called **levees** (Figure 1.19). The finer material is carried further away to be dropped on the **floodplain** (Figure 1.20), sometimes creating **backswamps**. Repeated annual flooding slowly builds up the floodplain. Old floodplains may be eroded – the remnants are known as terraces. At the edge of the terrace is a line of relatively steep slopes known as **river bluffs**.



1 When the river floods, it bursts its banks. It deposits its coarsest load (gravel and sand) closest to the bank and the finer load (silt and clay) further away.
2, 3, 4 This continues over a long time, for centuries.
5 The river has built up raised banks, called levees, consisting of coarse material, and a floodplain of fine material.

Figure 1.19 The formation of levees

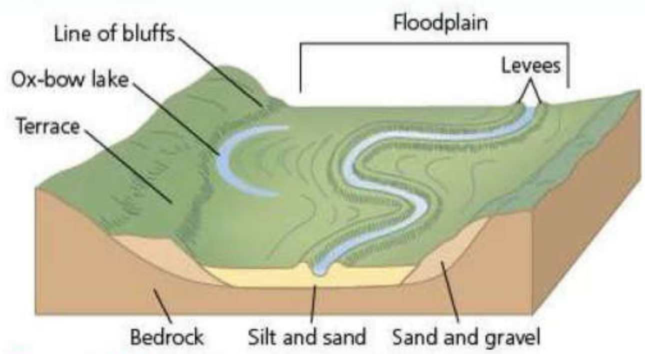
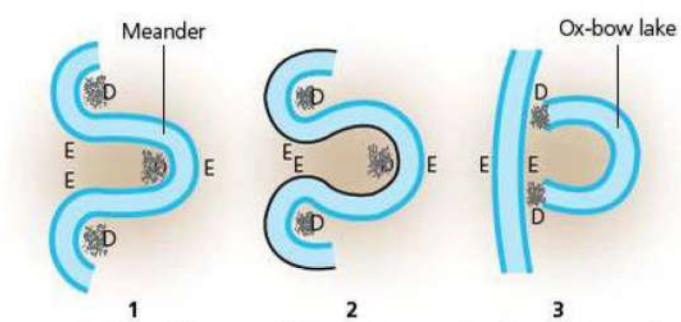


Figure 1.20 Floodplains, levees and bluffs

Ox-bow lakes

Ox-bow lakes are the result of both erosion and deposition. Lateral erosion, caused by helicoidal flow, is concentrated on the outer, deeper bank of a meander. During times of flooding, erosion increases. The river breaks through and creates a new steeper channel. In time, the old meander is closed off by deposition to form an ox-bow lake.

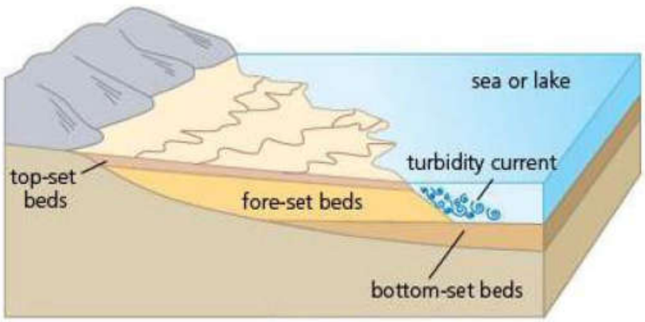


1 Erosion (E) and deposition (D) around a meander (a bend in a river).
2 Increased erosion during flood conditions. The meander becomes exaggerated.
3 The river breaks through during a flood. Further deposition causes the old meander to become an ox-bow lake.

Figure 1.21 Formation of an ox-bow lake

Deltas

Deltas are river sediments deposited when a river enters a standing body of water such as a lake, a lagoon, a sea or an ocean (Figure 1.22). They are the result of the interaction of fluvial and marine processes. For a delta to form there must be a heavily laden river, such as the Nile or the Mississippi, and a standing body of water with negligible currents, such as the Mediterranean or the Gulf of Mexico. Deposition is enhanced if the water is saline, because salty water causes small clay particles to flocculate or adhere together. Other factors include the type of sediment, local geology, sea-level changes, plant growth and human impact.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.268

Figure 1.22 Model of a simple delta

The material deposited as a delta can be divided into three types:

- Bottomset beds – the lower parts of the delta are built outwards along the sea floor by turbidity currents (currents of water loaded with material). These beds are composed of very fine material.
- Foreset beds – over the bottomset beds, inclined/sloping layers of coarse material are deposited. Each bed is deposited above and in front of the previous one, the material moving by rolling and saltation. Thus the delta is built seaward.
- Topset beds – composed of fine material, they are really part of the continuation of the river's floodplain. These topset beds are extended and built up by the work of numerous distributaries (where the main river has split into several smaller channels).

The character of any delta is influenced by the complex interaction of several variables (Figure 1.23):

- the rate of river deposition
- the rate of stabilisation by vegetation growth
- tidal currents
- the presence (or absence) of longshore drift
- human activity (deltas often form prime farmland when drained).

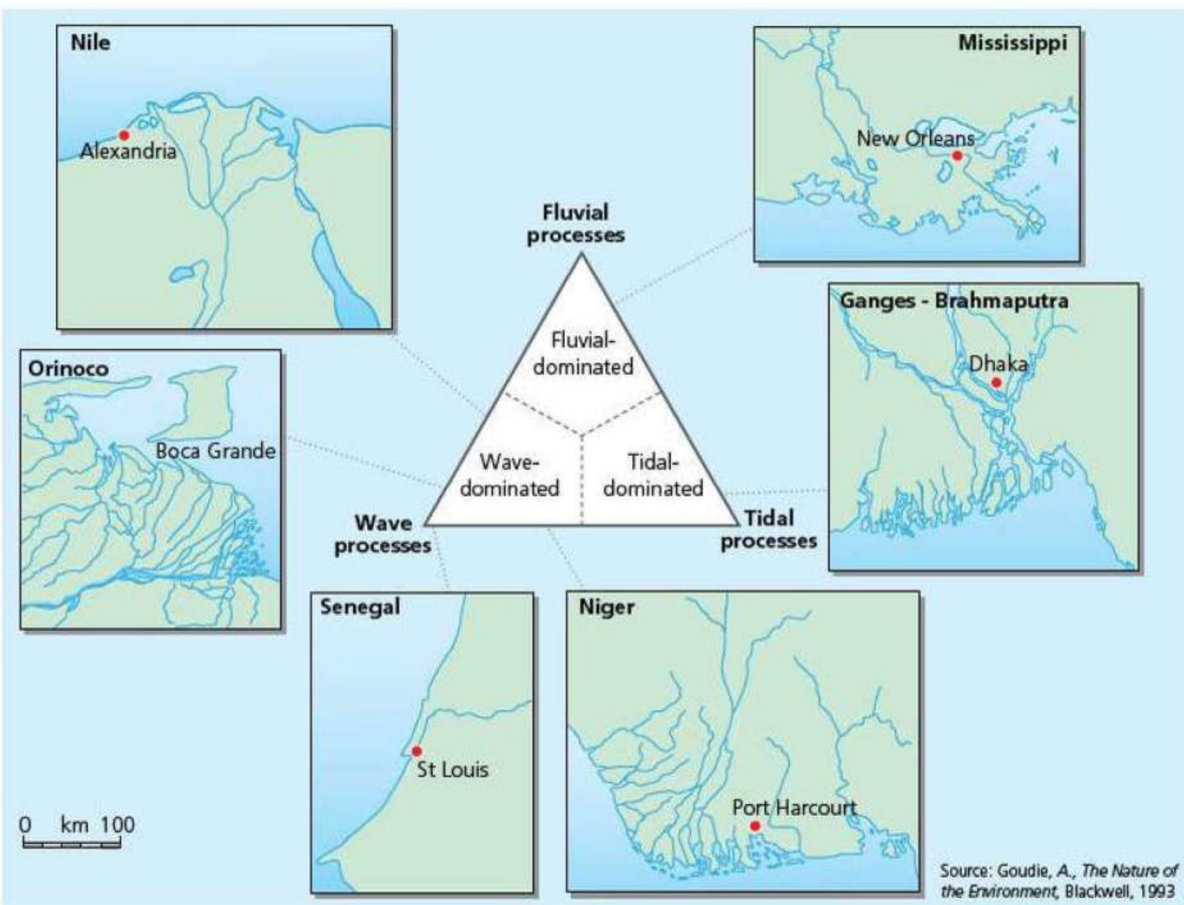


Figure 1.23 River delta shapes related to river, wave and tidal processes

There are many types of delta, but the three 'classic' ones are:

- Arcuate delta, or fan-shaped – these are found in areas where regular longshore drift or other currents keep the seaward edge of the delta trimmed and relatively smooth in shape, such as the Nile and Rhône deltas.
- Cuspate delta – pointed like a tooth or cusp, for example the Ebro and Tiber deltas, shaped by regular but opposing gentle water movement.
- Bird's-foot delta – where the river brings down enormous amounts of fine silt, deposition can occur in a still sea area, along the edges of the distributaries for a very long distance offshore, such as the Mississippi delta.

Deltas can also be formed inland. When a river enters a lake it will deposit some or all of its load, so forming a lacustrine delta. As the delta builds up and out, it may ultimately fill the lake basin. The largest lacustrine deltas are those that are being built out into the Caspian Sea by the Volga, Ural, Kura and other rivers.

Case Study: The future of the Nile delta

The Nile delta is under threat from rising sea levels. Without the food it produces, Egypt faces much hardship. The delta is one of the most fertile tracts of land in the world. However, coastal erosion is steadily eroding it in some places at a rate of almost 100 metres a year. This is partly because the annual deposits from the Nile floods – which balanced coastal erosion – no longer reach the delta, instead being trapped behind the Aswan High Dam. However, erosion of the delta continues, and may be increasing, partly as a result of global warming and rising sea levels. The delta is home to about 50 million people, living at densities of up to 4000 people per km^2.

The Intergovernmental Panel on Climate Change has declared Egypt's Nile delta to be among the top three areas most vulnerable to a rise in sea level. Even a small temperature increase will displace millions of Egyptians from one of the most densely populated regions on Earth.

The delta stretches out from the northern reaches of Cairo into 25 000 km^2 of farmland fed by the Nile's branches. It is home to two-thirds of the country's rapidly growing population, and responsible for more than 60 per cent of its food supply. About 270 kilometres of the delta's coastline is at a dangerously low level and a 1 metre rise in the sea level would drown 20 per cent of the delta.

The delta is also suffering from a number of environmental crises, including flooding, coastal erosion, salinisation, industrial/agricultural pollution and urban encroachment. Egypt's population of 83 million is set to increase to more than 110 million in the next two decades. More people in the delta means more cars, more pollution and less land to feed them all on, just at a time when increased crop production is needed most.

Saltwater intrusion is destroying crops. Coastal farmland has always been threatened by salt water, but salinity has traditionally been kept at bay by plentiful supplies of fresh water flushing out the salt. It used to happen naturally with the Nile's seasonal floods; after the construction of Egypt's High Dam, these seasonal floods came to an end, but a vast network of irrigation canals continued to bring enough fresh water to ensure salinity levels remained low.

Today, however, Nile water barely reaches the end of the delta. A growing population has extracted water supplies upstream, and what water does make it downriver is increasingly polluted with toxins and other impurities.

The impact of climate change is likely to be a 70 per cent drop in the amount of Nile water reaching the delta over the next 50 years, due to increased evaporation and heavier demands on water use upstream. The consequences for food production are ominous: wheat and maize yields could be down 40 per cent and 50 per cent respectively, and farmers could lose around $1000 per hectare for each degree rise in the average temperature.

While politicians, scientists and community workers are trying to educate Egyptians about the dangers of climate change, there is confusion over whether the focus should be on promoting ways to combat climate change, or on accepting climate change as inevitable and instead encouraging new forms of adaptation to the nation's uncertain future.

Egypt's contribution to global carbon emissions is just 0.5 per cent – nine times less per person than for the USA. However, the consequences of climate change are disproportionate and potentially disastrous.

The scale of the crisis – more people, less land, less water, less food – is overwhelming. As a result, many now believe that Egypt's future lies far away from the delta, in land newly reclaimed from the desert. Since the time of the pharaohs, when the delta was first farmed, Egypt's political leaders have tried to harness the Nile. The Egyptian government is creating an array of canals and pumping stations that draw water from the Nile into sandy valleys to the east and west, where the desert is slowly being turned green. The Nile delta may well become history – as a landform and for the people who live and work there.

Section 1.3 Activities

1 Outline the main conditions needed for delta formation.
2 Suggest reasons for the variety of deltas, as shown in Figure 1.23.
3 a Outline the natural and human processes that are operating on the Nile delta.
  b Comment on the advantages and disadvantages for people living in the delta.

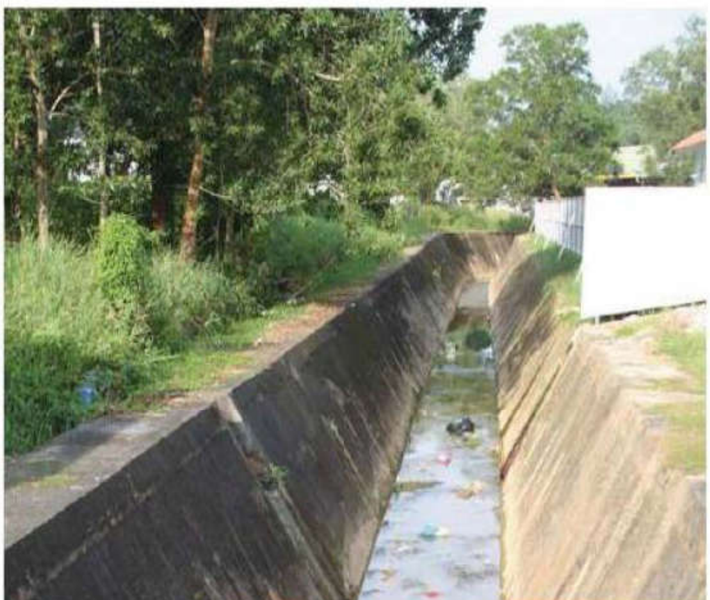
1.4 The human impact

Modifications to catchment stores and flows, and to channel flows

Evaporation and evapotranspiration

The human impact on evaporation and evapotranspiration is relatively small in relation to the rest of the hydrological cycle but is nevertheless important. There are a number of impacts:

- Dams – there has been an increase in evaporation due to the construction of large dams. For example, Lake Nasser behind the Aswan Dam loses up to a third of its water due to evaporation. Water loss can be reduced by using chemical sprays on the water, by building sand-fill dams and by covering the dams with some form of plastic.
- Urbanisation leads to a huge reduction in evapotranspiration due to the lack of vegetation. There may also be a slight increase in evaporation because of higher temperatures and increased surface storage (see Figure 1.24).



Urbanising influence	Potential hydrological response
Removal of trees and vegetation	Decreased evapotranspiration and interception; increased stream sedimentation
Initial construction of houses, streets and culverts	Decreased infiltration and lowered groundwater table; increased storm flows and decreased base flows during dry periods
Complete development of residential, commercial and industrial areas	Decreased porosity, reducing time of runoff concentration, thereby increasing peak discharges and compressing the time distribution of the flow; greatly increased volume of runoff and flood damage potential
Construction of storm drains and channel improvements	Local relief from flooding; concentration of floodwaters may aggravate flood problems downstream

Figure 1.24 Potential hydrological effects of urbanisation

Interception

Interception is determined by vegetation, density and type. Most vegetation is not natural but represents some disturbance by human activity. In farmland areas, for example, cereals intercept less than broad leaves. Row crops, such as wheat or corn, leave a lot of soil bare. For example, in the Mississippi basin, while sediment yields in woodland areas are just 1 unit, sediment from soil covered by pasture produces 30 units and areas under corn produce 350 units of sediment. Deforestation leads to:

- a reduction in evapotranspiration
- an increase in surface runoff
- a decline of surface storage
- a decline in time lag.

Afforestation is believed to have the opposite effect, although the evidence does not necessarily support it. For example, in parts of the Severn catchment, sediment loads increased four times after afforestation. Why was this? The result is explained by a combination of an increase in overland runoff, little ground vegetation, young trees, access routes for tractors, and fire- and wind-breaks. All of these allowed a lot of bare ground. However, after only five years the amount of erosion declined.

Infiltration and soil water

Human activity has a great impact on infiltration and soil water. Land-use changes are important. Urbanisation creates an impermeable surface with compacted soil. This reduces infiltration and increases overland runoff and flood peaks (Figure 1.25).

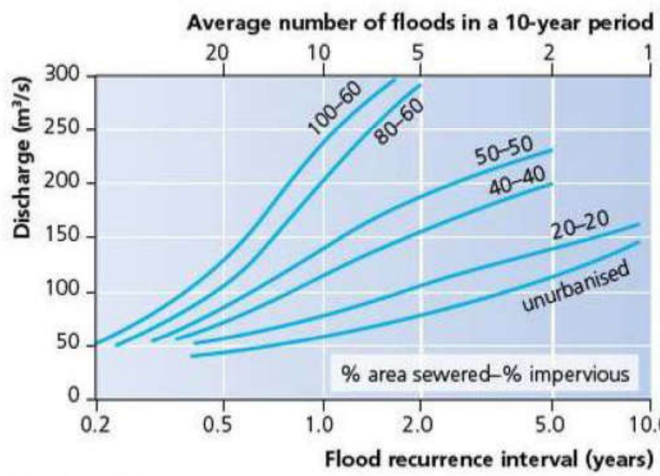


Figure 1.25 Flood frequency and urbanisation

Infiltration is up to five times greater under forest compared with grassland. This is because the forest trees channel water down their roots and stems. With deforestation there is reduced interception, increased soil compaction and more overland flow. Land-use practices are also important. Grazing leads to a decline in infiltration due to compaction and ponding of the soil. By contrast, ploughing increases infiltration because it loosens soils.

Waterlogging and salinisation are common if there is poor drainage. When the water table is close to the surface, evaporation of water leaves salts behind and may form an impermeable crust. Human activity also has an increasing impact on surface storage. There is increased surface storage due to the building of large-scale dams. These dams are being built in increasing numbers, and they are also larger in terms of general size and volume. This leads to:

- increased storage of water
- decreased flood peaks
- low flows in rivers
- decreased sediment yields (clear-water erosion)
- increased losses due to evaporation and seepage, leading to changes in temperature and salinity of the water
- decreased flooding of the land
- triggering of earthquakes
- salinisation, for example in the Indus Valley in Pakistan, 1.9 million hectares are severely saline and up to 0.4 million hectares are lost per annum to salinity
- large dams can cause local changes in climate.

In other areas there is a decline in the surface storage, for example in urban areas water is channelled away very rapidly over impermeable surfaces into drains and gutters.

Section 1.4 Activities

Study Figure 1.25. Describe and explain the changes in flood frequency and flood magnitude that occur as urbanisation increases.

Abstraction

Water availability problems occur when the demand for water exceeds the amount available during a certain period. This happens in areas with low rainfall and high population density, and in areas where there is intensive agricultural or industrial activity. Over-abstraction may lead to the drying up of rivers, falling water tables and saltwater intrusion in coastal areas.

In many parts of Europe, groundwater is the main source of fresh water. However, in many places water is being taken from the ground faster than it is being replenished.

Saline intrusion is widespread along the Mediterranean coastlines of Italy, Spain and Turkey (Figure 1.26), where the demands of tourist resorts are the major cause of over-abstraction. In Malta, most groundwater can no longer be used for domestic consumption or irrigation because it has been contaminated by saline intrusion. Consequently, Malta now has to use desalinated water. Intrusion of saline water due to excessive extraction of water is also a problem in northern countries, notably Denmark.

Irrigation is the main cause of groundwater overexploitation in agricultural areas. In Italy, overexploitation of the Po River in the region of the Milan aquifer has led to a 25 metre decrease in groundwater levels over the last 80 years.

Changing groundwater

Human activity has seriously reduced the long-term viability of irrigated agriculture in the High Plains of Texas. Before irrigation development started in the 1930s, the High Plains groundwater system was stable, in a state of dynamic equilibrium with long-term recharge equal to long-term discharge. However, groundwater is now being used at a rapid rate to supply centre-pivot irrigation schemes. In under 50 years, the water level has declined by 30–50 metres in a large area to the north of Lubbock, Texas. The aquifer has narrowed by more than 50 per cent

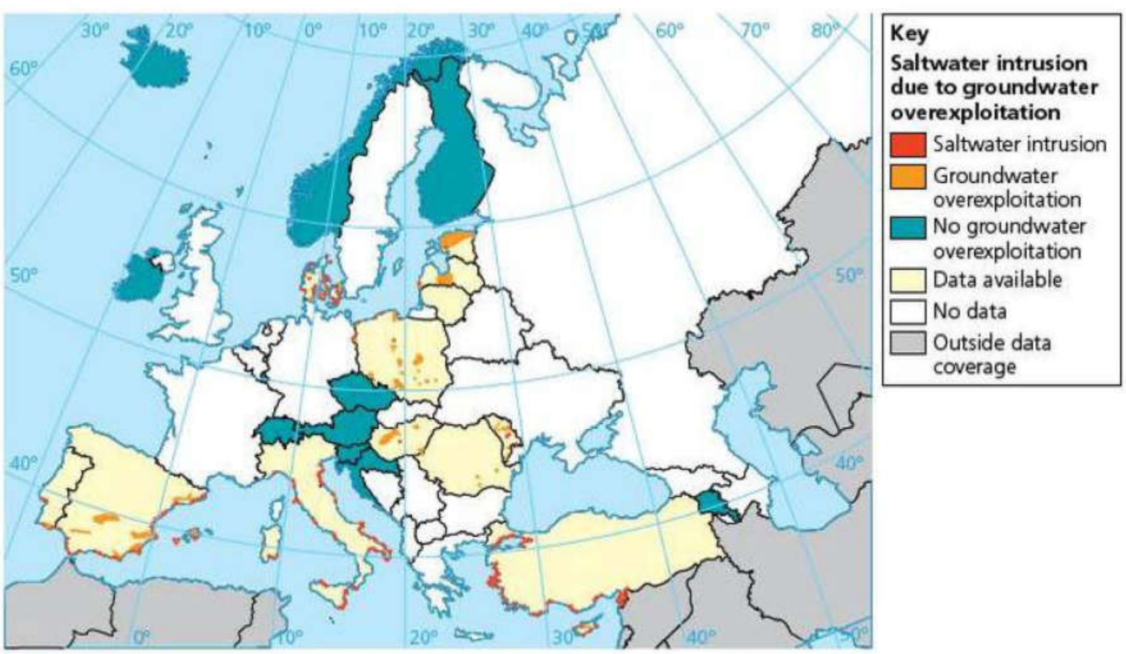


Figure 1.26 Groundwater abstraction and saline intrusion in Western Europe

in large parts of certain counties, and the area irrigated by each well is contracting as well as yields falling.

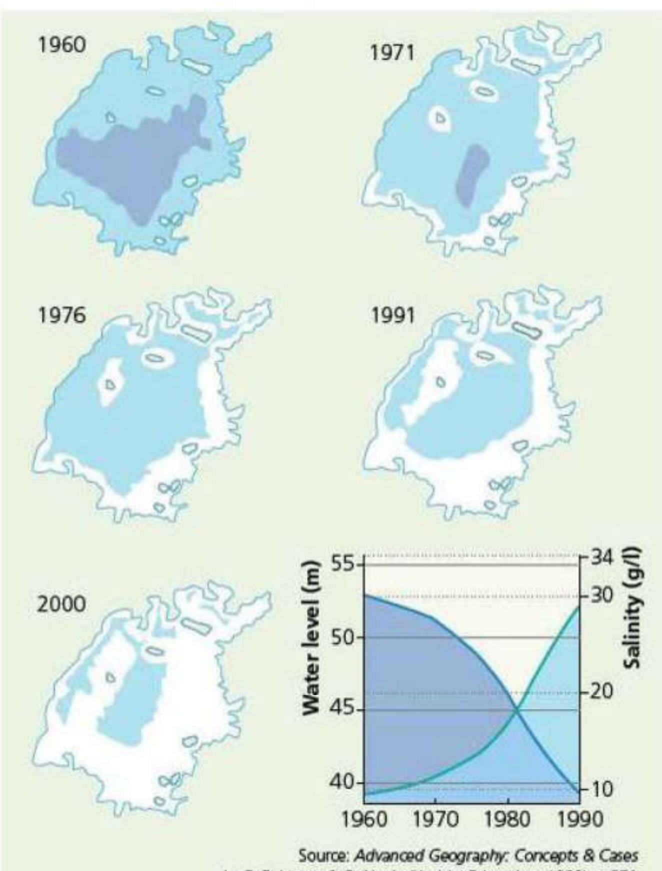
By contrast, in some industrial areas, recent reductions in industrial activity have led to less groundwater being taken out of the ground. As a result, groundwater levels in such areas have begun to rise, adding to the problem caused by leakage from ancient, deteriorating pipe and sewerage systems. Such a rise has numerous implications, including:

- increase in spring and river flows
- re-emergence of flow from 'dry springs'
- surface water flooding
- pollution of surface waters and the spread of underground pollution
- flooding of basements
- increased leakage into tunnels
- reduction in stability of slopes and retaining walls
- reduction in bearing capacity of foundations and piles
- swelling of clays as they absorb water
- chemical attack on building foundations.

There are various methods of recharging groundwater resources, provided that sufficient surface water is available. Where the materials containing the aquifer are permeable (as in some alluvial fans, coastal sand dunes or glacial deposits), water-spreading (a form of infiltration and seepage) is used. By contrast, in sediments with impermeable layers, such water-spreading techniques are not effective, and the appropriate method may then be to pump water into deep pits or into wells. This method is used extensively on the heavily settled coastal plain of Israel, both to replenish the groundwater reservoirs when surplus irrigation water is available, and in an attempt to diminish the problems associated with saltwater intrusions from the Mediterranean.

Case Study: Changing hydrology of the Aral Sea

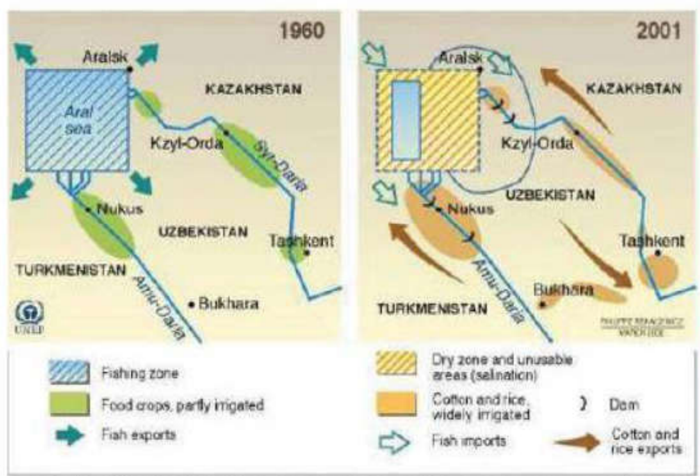
The Aral Sea began shrinking in the 1960s when Soviet irrigation schemes took water from the Syr Darya and the Amu Darya rivers. This greatly reduced the amount of water reaching the Aral Sea. By 1994, the shorelines had fallen by 16 metres, the surface area had declined by 50 per cent and the volume had been reduced by 75 per cent (Figure 1.27). By contrast, salinity levels had increased by 300 per cent.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.251

Figure 1.27 The changing hydrology of the Aral Sea

Increased salinity levels killed off the fishing industry. Moreover, ports such as Muynak are now tens of kilometres from the shore. Salt from the dry seabed has reduced soil fertility and frequent dust storms are ruining the region's cotton production. Drinking water has been polluted by pesticides and fertilisers and the air has been affected by dust and salt. There has been a noticeable rise in respiratory and stomach disorders and the region has one of the highest infant mortality rates in the former Soviet Union.



Source: Philippe Rekacewicz, *An Assassinated Sea*, in Histoire-Géographie, initiation économique, page 333, Classe de Troisième, Hatier, Paris, 1993 (data updated in 2002); *L'état du Monde*, 1992 and 2001 editions, La Découverte, Paris

Source: quoted at www.columbia.edu/~tmt2120/impacts%20to%20life%20in%20the%20region.htm

Figure 1.28 The economic impacts of the shrinking sea

Section 1.4 Activities

Study Figures 1.27 and 1.28.

1 Why do you think the Former Soviet Union (FSU) embarked on such a programme of large-scale irrigation? Use an atlas to produce detailed information.
2 Why have salinity levels increased so much?
3 What problems does the shrinking of the Aral Sea cause for towns such as Aralsk and Muynak?
4 What is the likely effect of the irrigation scheme on the two rivers in terms of velocity, erosion, sediment transport and deposition?

Water storage – dams

The number of large dams (more than 15 metres high) that are being built is increasing rapidly and is reaching a level of almost two completions every day (Figure 1.29).

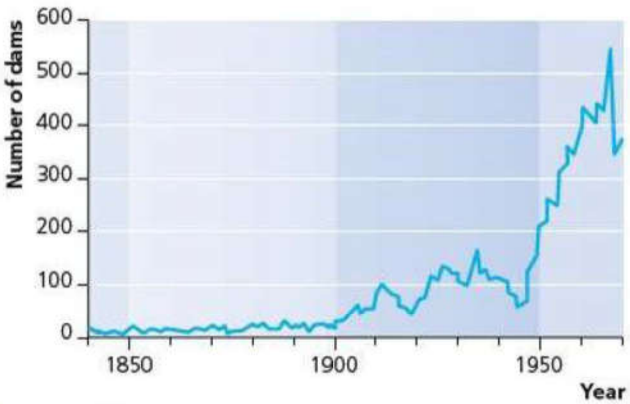


Figure 1.29 The trend in building large dams

The advantages of dams are numerous, as the following examples from the Aswan High Dam on the River Nile, Egypt, show:

- **flood and drought control** – dams allow good crops in dry years as, for example, in Egypt in 1972 and 1973
- **irrigation** – 60 per cent of water from the Aswan Dam is used for irrigation and up to 4000 km of the desert are irrigated
- **hydro-electric power** – this accounts for 7000 million kW hours each year
- **improved navigation**
- **recreation and tourism**.

It is estimated that the value of the Aswan High Dam is about $500 million to the Egyptian economy each year.

On the other hand, there are numerous disadvantages. For example:

- **water losses** – the dam provides less than half the amount of water expected
- **salinisation** – crop yields have been reduced on up to one-third of the area irrigated by water from the Aswan Dam, due to salinisation
- **groundwater changes** – seepage leads to increased groundwater levels and may cause secondary salinisation
- **displacement of population** – up to 100 000 Nubian people have been removed from their ancestral homes
- **drowning of archaeological sites** – the tombs of Ramases II and Nefertari at Abu Simbel had to be removed to safer locations – however, the increase in the humidity of the area has led to an increase in the weathering of ancient monuments
- **seismic stress** – the earthquake of November 1981 is believed to have been caused by the Aswan Dam; as water levels in the Dam increase so too does seismic activity
- **deposition within the lake** – infilling is taking place at about 100 million tonnes each year
- **channel erosion (clear-water erosion) on the channel bed** – lowering the channel by 25 mm over 18 years, a modest amount
- **erosion of the Nile delta** – this is taking place at a rate of about 2.5 cm each year
- **loss of nutrients** – it is estimated that it costs $100 million to buy commercial fertilisers to make up for the lack of nutrients each year
- **decreased fish catches** – sardine yields are down 95 per cent and 3000 jobs in Egyptian fisheries have been lost
- **diseases have spread** – such as schistosomiasis (bilharzia).

Figure 1.30 Paphos dam, Cyprus

Section 1.4 Activities

1 Study Figure 1.29. Describe the pattern shown and suggest reasons to explain the trend.
2 Evaluate the effectiveness of large dams.

Flood risk

Floods are one of the most common of all environmental hazards. This is because so many people live in fertile river valleys and in low-lying coastal areas. For much of the time, rivers act as a resource. However, extremes of too much water – or too little – can be considered a hazard (Figure 1.31).

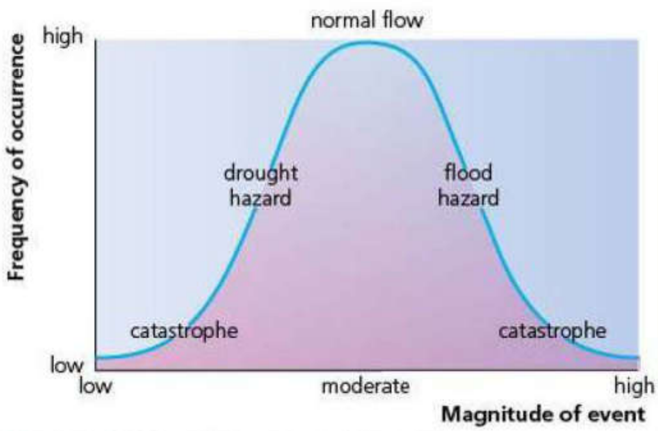


Figure 1.31 River discharge and frequency

In addition, extreme events occur infrequently. Many urban areas are designed to cope with floods that occur on a regular basis, perhaps annually or once in a decade. Most are ill-equipped to deal with the low-frequency/ high-magnitude event that may occur once every 100 years or every 500 years (Figure 1.32). The **recurrence interval** refers to the regularity of a flood of a given size. Small floods may be expected to occur regularly. Larger floods occur less often. A 100-year flood is the flood that is expected to occur, *on average*, once every 100 years. Increasingly, larger floods are less common, but more damaging.

The nature and scale of flooding varies greatly. For example, less than 2 per cent of the population of England and Wales and in Australia live in areas exposed to flooding, compared with 10 per cent of the US population. The worst problems occur in Asia where floods damage about 4 million hectares of land each year and affect the lives of over 17 million people. Worst of all is China, where over 5 million people have been killed in floods since 1860.

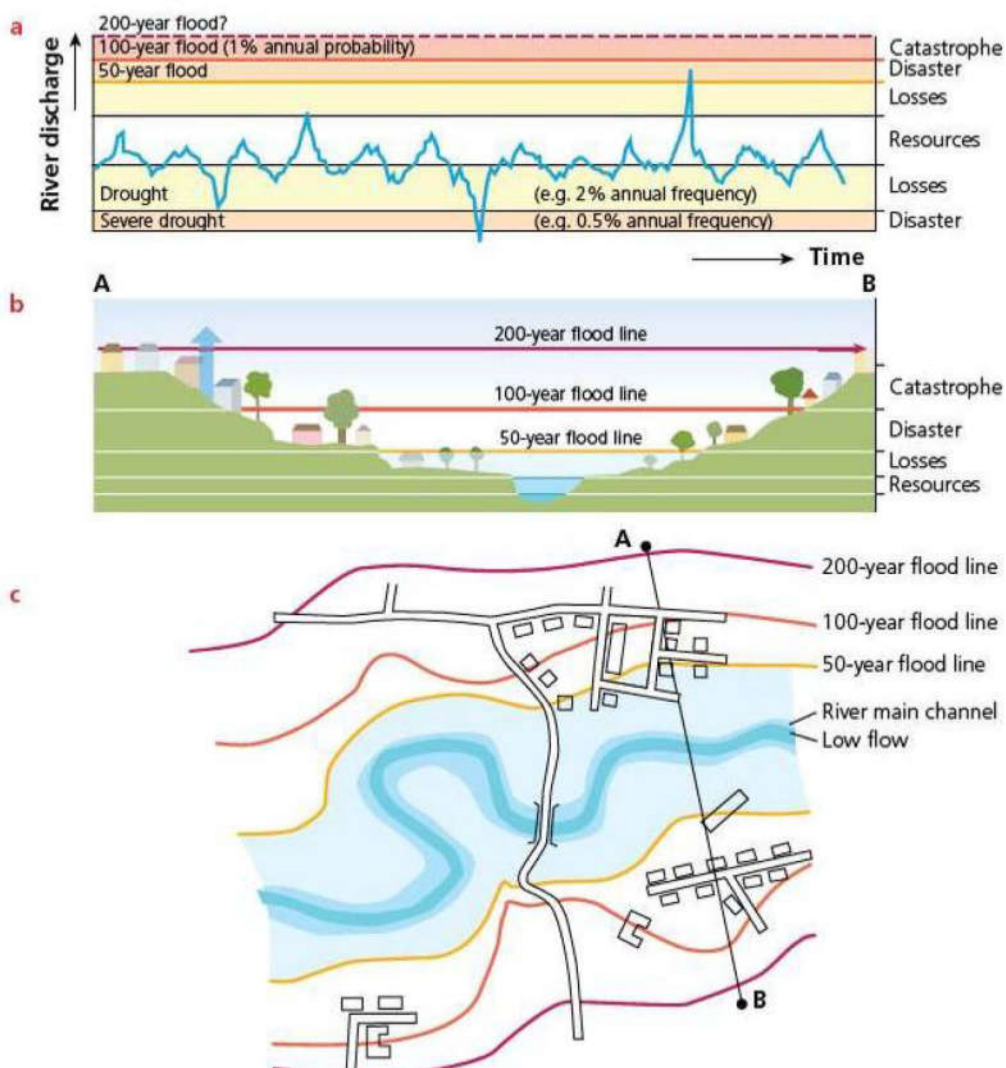


Figure 1.32 Urban land use and flood risk

Some environments are more at risk than others. The most vulnerable include the following:

- Low-lying parts of active floodplains and river estuaries. For example, in Bangladesh 110 million people living on the floodplain of the Ganges and Brahmaputra rivers are relatively unprotected. Floods caused by the monsoon regularly cover 20–30 per cent of the flat delta. In very high floods, up to half of the country may be flooded. In 1988, 46 per cent of the land was flooded and more than 1500 people were killed.
- Small basins subject to flash floods. These are especially common in arid and semi-arid areas. In tropical areas, some 90 per cent of lives lost through drowning are the result of intense rainfall on steep slopes.
- Areas below unsafe dams. In the USA, there are about 30 000 large dams and 2000 communities are at risk from dams. Following the 2008 Sichuan earthquake in China, some 35 quake dams were created by landslides blocking river routes. These were eventually made safe by engineers and the Chinese military.
- Low-lying inland shorelines such as along the Great Lakes and the Great Salt Lake in the USA.

In most high-income countries (HICs), the number of deaths from floods is declining, while in contrast the economic cost of flood damage has been increasing. In low-income countries (LICs), on the other hand, the death rate due to flooding is much greater, although the economic cost is not as great. It is likely that the hazard in LICs will increase over time as more people migrate and settle in low-lying areas and river basins. Often newer migrants are forced into the more hazardous zones.

Since the Second World War (1939–45), there has been a change in the understanding of the flood hazard, in the attitude towards floods and in the policy towards reducing the flood hazard. The response to hazards has moved away from physical control (engineering structures) towards reducing vulnerability through non-structural approaches.

Causes of flooding

A flood is a high flow of water that overtops the bank of a river. The main causes of floods are climatic forces, whereas the flood-intensifying conditions tend to be drainage basin specific (Figure 1.33). Most floods in the UK, for example, are associated with deep depressions (low pressure systems) that are both long-lasting and cover a wide area. By contrast, in India up to 70 per cent of the annual rainfall occurs in three months during the summer monsoon. In Alpine and Arctic areas, melting snow is responsible for widespread flooding.

Flood-intensifying conditions cover a range of factors, which alter the drainage basin response to a given storm (Figure 1.34). The factors that influence the storm hydrograph determine the response of the basin to the storm. These factors include topography, vegetation, soil type, rock type and characteristics of the drainage basin.

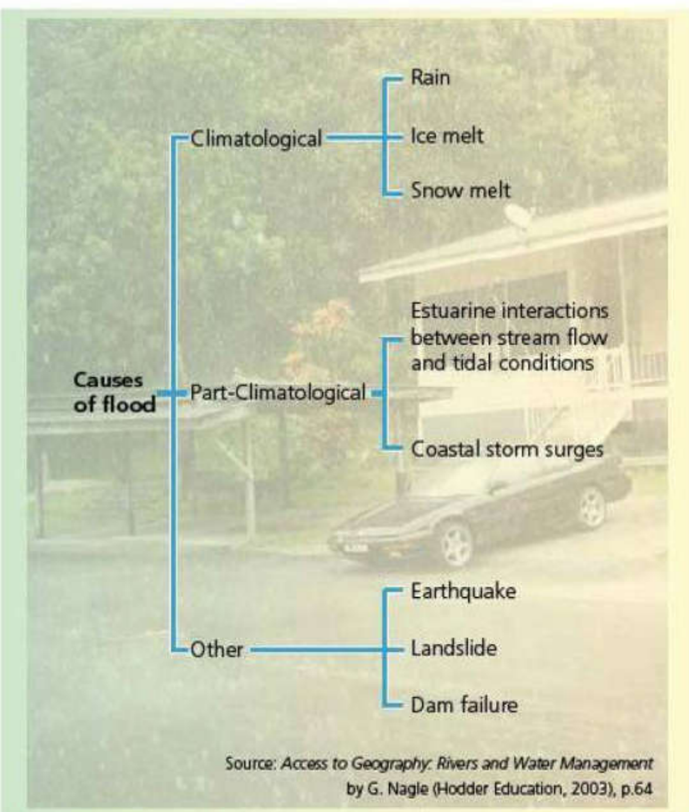


Figure 1.33 The causes of floods

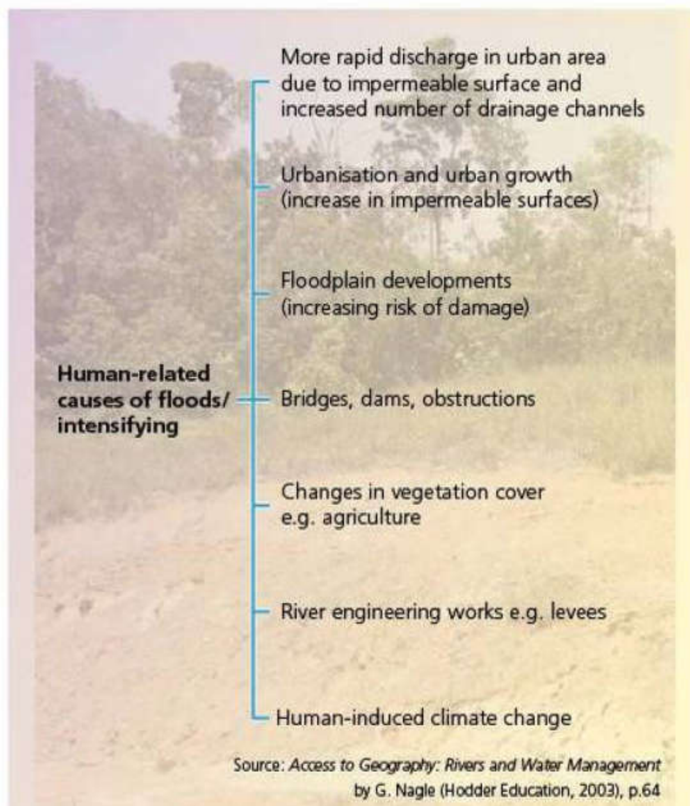


Figure 1.34 Flood-intensifying conditions

The potential for damage by floodwaters increases exponentially with velocity. The physical stresses on buildings are increased even more when rough, rapidly flowing water contains debris such as rocks, sediment and trees.

Other conditions that intensify floods include changes in land use. Urbanisation, for example, increases the magnitude and frequency of floods in at least three ways:

- creation of highly impermeable surfaces, such as roads, roofs, pavements
- smooth surfaces served with a dense network of drains, gutters and underground sewers increase drainage density
- natural river channels are often constricted by bridge supports or riverside facilities, reducing their carrying capacity.

Deforestation is also a cause of increased flood runoff and a decrease in channel capacity. This occurs due to an increase in deposition within the channel. However, the evidence is not always conclusive. In the Himalayas, for example, changes in flooding and increased deposition of silt in parts of the lower Ganges–Brahmaputra are due to the combination of high monsoon rains, steep slopes and the seismically unstable terrain. These ensure that runoff is rapid and sedimentation is high, irrespective of the vegetation cover.

The prevention and amelioration of floods

Forecasting and warning

During the 1980s and 1990s, flood forecasting and warning had become more accurate and these are now among the most widely used measures to reduce the problems caused by flooding. Despite advances in weather satellites and the use of radar for forecasting, over 50 per cent of all unprotected dwellings in England and Wales have less than six hours of flood warning time. In most LICs there is much less effective flood forecasting. An exception is Bangladesh. Most floods in Bangladesh originate in the Himalayas, so authorities have about 72 hours' warning.

According to the United Nations Environment Programme's publication *Early Warning and Assessment*, there are a number of things that could be done to improve flood warnings. These include:

- improved rainfall and snow pack estimates, and better and longer forecasts of rainfall
- better gauging of rivers, collection of meteorological information and mapping of channels
- better and current information about human populations and infrastructure; elevation and stream channels need to be incorporated into flood-risk assessment models
- better sharing of information is needed between forecasters, national agencies, relief organisations and the general public
- more complete and timely sharing of information of meteorological and hydrological information is needed among countries within international drainage basins
- technology should be shared among all agencies involved in flood forecasting and risk assessment, both in the basins and throughout the world.

Loss sharing

Economic growth and population movements throughout the twentieth century have caused many floodplains to be built on. However, for people to live on floodplains there needs to be flood protection. This can take many forms, such as loss-sharing adjustments and event modifications.

Loss-sharing adjustments include disaster aid and insurance. Disaster aid refers to any aid, such as money, equipment, staff and technical assistance, that is given to a community following a disaster. In HICs, insurance is an important loss-sharing strategy. However, not all flood-prone households have insurance and many of those that are insured may be underinsured.

Hard engineering

Traditionally, floods have been managed by methods of 'hard engineering'. This largely means dams, levees, wing dykes and straightened channels that are wider and deeper than the ones they replace. In some cases, new diversion spillways (flood-relief channels and intercepting channels) may be built (Figure 1.35). Although hard engineering may reduce floods in some locations, it may cause unexpected effects elsewhere in the drainage basin, for example decreased water quality, increased sedimentation, bed and bank erosion and loss of habitats.

Levees are the most common form of river engineering. They can also be used to divert and restrict water to low-value land on the floodplain. Over 4500 kilometres of the Mississippi River have levees. Channel improvements such as channel enlargement will increase the carrying capacity of the river. Reservoirs store excess rainwater in the upper drainage basin. However, this may only be appropriate in small drainage networks. It has been estimated that some 66 billion m^3 of storage is needed to make any significant impact on major floods in Bangladesh!

Hazard-resistant design

Flood-proofing includes any adjustments to buildings and their contents that help reduce losses. Some are temporary, such as:

- blocking up entrances
- sealing doors and windows
- removal of damageable goods to higher levels
- use of sandbags.

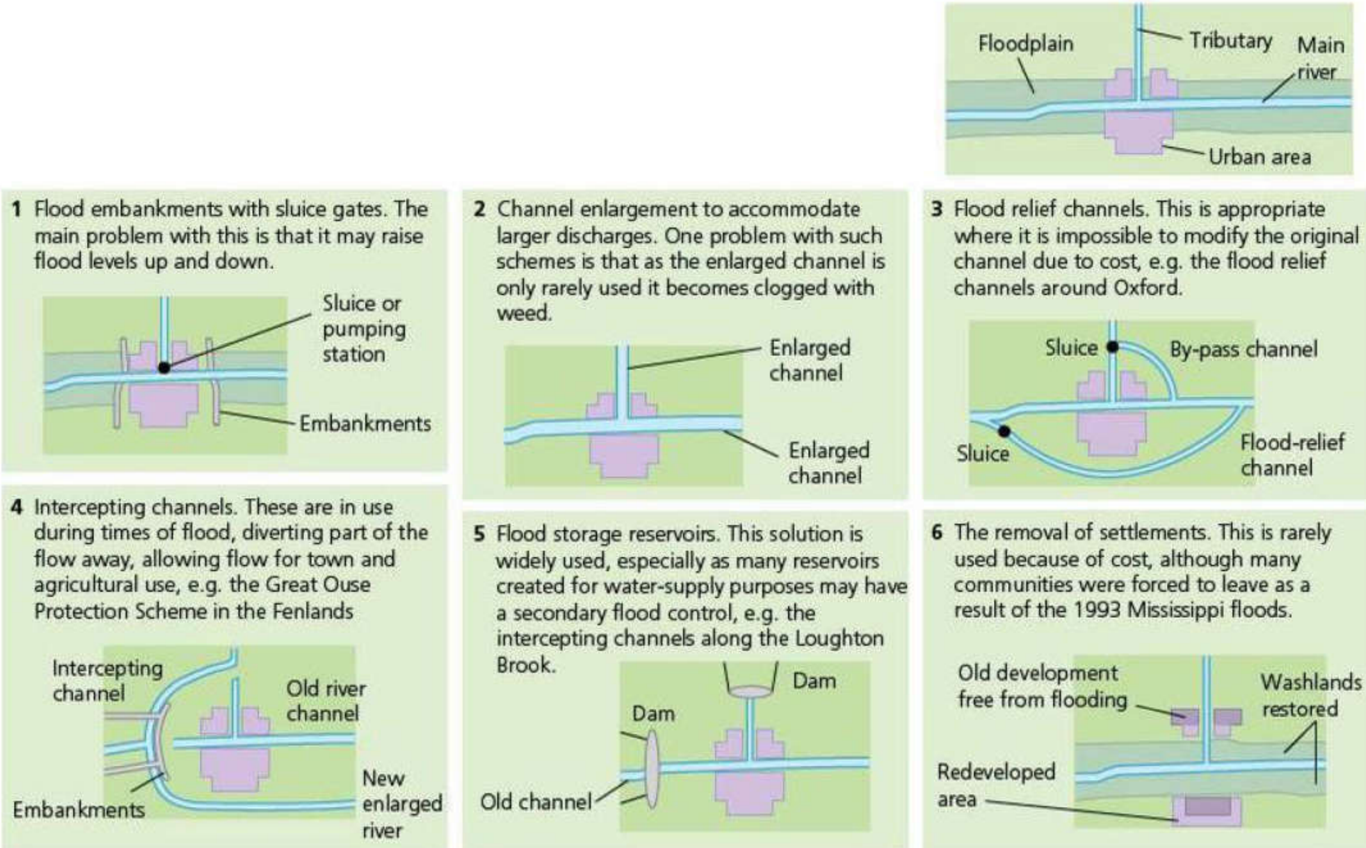


Figure 1.35 Channel diversions

Source: *Access to Geography: Rivers and Water Management* by G. Nagle (Hodder Education, 2003), p.65

Figure 1.36 Flood-relief channel, Zermatt, Switzerland

By contrast, long-term measures include moving the living spaces above the likely level of the floodplain. This normally means building above the flood level, but could also include building homes on stilts.

Land-use zoning

Most land-use zoning and land-use planning has been introduced since the Second World War. In the USA, land-use management has been effective in protecting new housing developments from 1 in 100-year floods (that is, the size of flood that we would expect to occur once every century).

One example where partial urban relocation has occurred is at Soldier's Grove on the Kickapoo River in south-western Wisconsin, USA. The town experienced a series of floods in the 1970s, and the Army Corps of Engineers proposed building two levees and moving part of the urban area. Following floods in 1978, they decided that relocation of the entire business district would be better than just flood-damage reduction. Although levees would have protected the village from most floods, they would not have provided other opportunities. Relocation allowed energy conservation and an increase in commercial activity in the area.

Soft engineering

Soft engineering generally refers to working with natural processes and features rather than attempts to control them. They include the management of whole catchments (catchment management plans), wetland conservation and river restoration.

Event modification adjustments include environmental control and hazard-resistant design. Physical control of floods depends on two measures: flood abatement and flood diversion. **Flood abatement** involves decreasing the amount of runoff, thereby reducing the flood peak in a drainage basin. There are a number of ways of reducing flood peaks. These include:

- reforestation
- reseeding of sparsely vegetated areas to increase evaporative losses
- treatment of slopes such as by contour ploughing or terracing to reduce runoff
- comprehensive protection of vegetation from wildfires, overgrazing and clear-cutting of forests
- clearance of sediment and other debris from headwater streams
- construction of small water- and sediment-holding areas
- preservation of natural water-storage zones, such as lakes.

Flood diversion refers to the practice of allowing certain areas, such as wetlands and floodplains, to be flooded to a greater extent. Natural flooding may be increased through the use of flood-relief channels (diversion spillways) to direct more water into these areas during times of flood.

River restoration

Case Study: Costs and benefits of the Kissimmee River restoration scheme

Figure 1.37 Part of the restored Kissimmee Restoration Scheme, Florida, USA

The 165 kilometre Kissimmee River once meandered through central Florida. Its floodplain, reaching up to 5 kilometres wide, was inundated for long periods by heavy seasonal rains. Wetland plants, wading birds and fish thrived there, but the frequent, prolonged flooding caused a severe impact on people.

Between 1962 and 1971, engineering changes were made to deepen, straighten and widen the river, which was transformed into a 90 kilometre, 10 metre-deep drainage canal. The river was channelised to provide an outlet canal for draining floodwaters from the developing upper Kissimmee lakes basin, and to provide flood protection for land adjacent to the river.

Impacts of channelisation

The channelisation of the Kissimee River had several unintended impacts:

- the loss of 2000 to 14 000 hectares of wetlands
- a 90 per cent reduction in wading bird and waterfowl usage
- a continuing long-term decline in game fish populations.

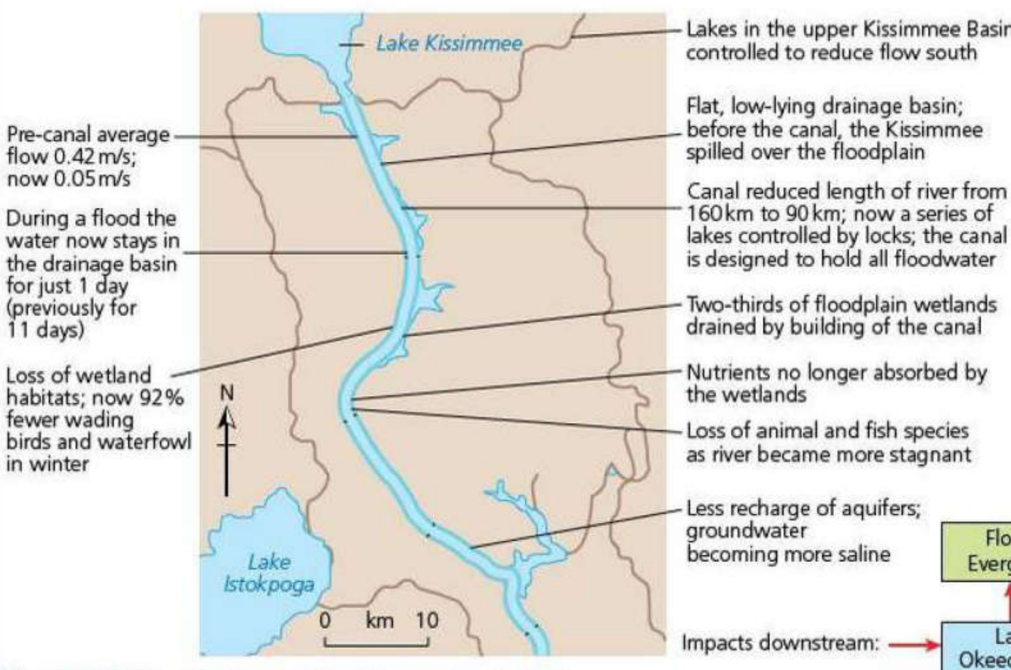


Figure 1.38 The Kissimmee River Restoration Project

Concerns about the sustainability of existing ecosystems led to a state and federally supported restoration study. The result was a massive restoration project, on a scale unmatched elsewhere.

The project restored over 100 km² of river and associated floodplain wetlands. It was started in 1999 and completed in 2015. It benefits over 320 fish and wildlife species, including the endangered bald eagle, wood stork and snail kite. It has created over 11 000 hectares of wetlands. Seasonal rains and flows now inundate the floodplain in the restored areas.

Restoration of the river and its associated natural resources required **dechannelisation**. This entailed backfilling approximately half of the flood-control channel and re-establishing the flow of water through the natural river channel. In residential areas, the flood-control channel will remain in place.

The costs of restoration

It is estimated that the project cost over $400 million (initial channelisation cost $20 million), a bill being shared by the state of Florida and the federal government.

Restoration of the river's floodplain could result in higher losses of water due to evapotranspiration during wet periods. In extremely dry spells, navigation may be impeded in some sections of the restored river. It is, however, expected that navigable depths will be maintained at least 90 per cent of the time.

Benefits of restoration

- Higher water levels should ultimately support a natural river ecosystem again.
- Re-establishment of floodplain wetlands and the associated nutrient filtration function is expected to result in decreased nutrient loads to Lake Okeechobee.
- Populations of key avian species, such as wading birds and waterfowl, have returned to the restored area, and in some cases numbers have more than tripled.
- Dissolved oxygen levels have doubled, which is critical for the survival of fish and other aquatic species.
- Potential revenue associated with increased recreational usage (such as hunting and fishing) and ecotourism on the restored river could significantly enhance local and regional economies.

Section 1.4 Activities

1 Outline the natural and human causes of floods.
2 Compare and contrast methods of flood management.
3 To what extent can flood frequency and magnitude be predicted?
4 Outline the disadvantages of channelisation as shown in Figure 1.36.
5 Outline the benefits of wetlands.
6 What is meant by *river restoration*? What are the benefits of river restoration?

Case Study: Flooding in Bangladesh

Figure 1.39 Satellite image of the 1998 floods

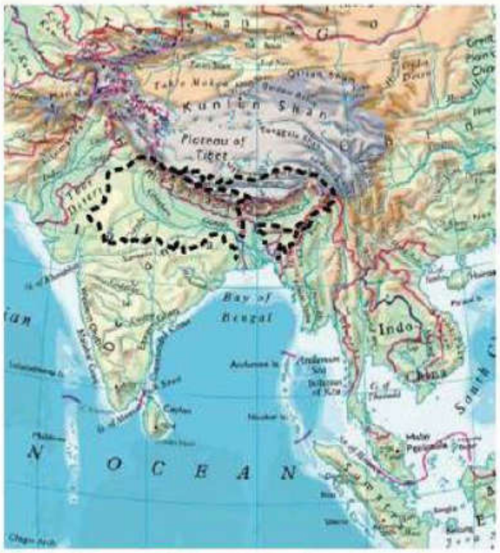
Bangladesh is a small, flat and low-lying country: 60 per cent is less than 6 metres above sea level. For this reason, tides affect one-third of land area. Banglasdesh is located where the Ganga, Brahmaputra (called *Jamuna* in Bangladesh) and Meghna rivers meet. The average gradient of the rivers is 6 cm/km. The country drains an area 12 times its own size. It has a high frequency of floods and cyclones.

Table 1.5 Bangladesh factfile

Area	143 998 km²
Population	166 million (2014)
Age structure	51 % under 25 years of age
Population density	1161/km²
Annual growth rate	0.6 %
Literacy	58.8 %
PPP	$3400
Life expectancy	70.65 years
Employment	Agriculture: 47 % Industry: 13 % Services: 40 %

Source: CIA World Factbook

Bangladesh has a high population density, low human development index (HDI) and a majority of the population is dependent on agriculture. An area of about 150 000 km² is shared by 123 million people.



Source: Philip's Interactive Modern School Atlas by G. Nagle (Hodder Education, 2006) © Philip's

Figure 1.40 The Ganges drainage basin

Several regions affect conditions within Bangladesh:

- **high plateau of Tibet** – the source of the Brahmaputra, where most of the river flow derives from snow melt and glacier melt
- **Himalayas** – source of the Ganga and many of the springs that feed into the Brahmaputra
- **Ganga Plain** – one of the largest lowland areas in the world, and a region of intense cultivation
- **Meghalaya Hills** – located between the floodplain of north-east Bangladesh and the Indian lowlands of Assam; rise to a height of 2500 m and act as a barrier to the monsoon winds from the Indian Ocean; Cherrapungee has an annual rainfall of over 11 000 mm.

Table 1.6 Watershed characteristics of the Ganga and the Brahmaputra/Meghna (Br/M) rivers and a comparison with the Nile, the Amazon and the Mississippi

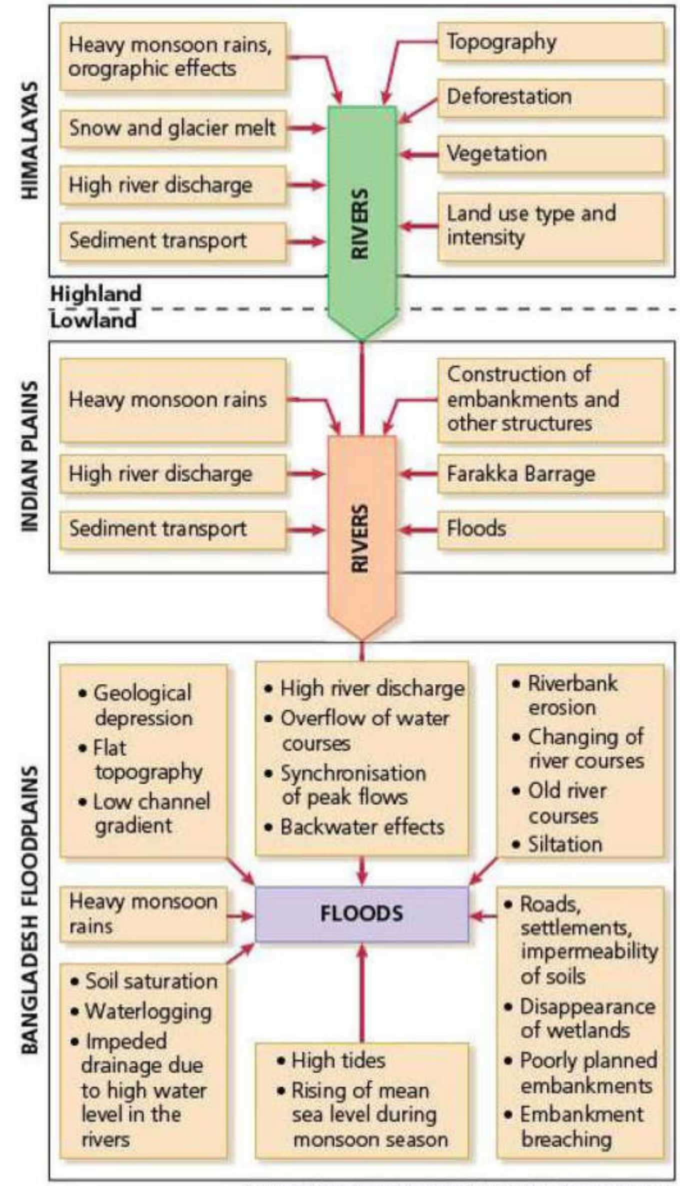
Characteristics	Ganga	Br/M	Nile	Amazon	Mississippi
Basin area (km²)	1016104	651334	3254555	6144727	3202230
Length (km)	2296	2772	5964	4406	4240
Average annual discharge (m³/s)	11365	19772	2760	176177	17600
Forest (%)	4	19	2	73	22
Cropland (%)	7	29	10	15	35
Cropland irrigated (%)	15	47	5	0	4
Grassland (%)	7	29	52	8	22
Large dams	6	0	7	2	2091

Source: Hofer, T. and Messerli, B, 2006, Floods in Bangladesh, *United Nations University Press, Table 2.2*

The Ganges and the Brahmaputra are two of the world's largest rivers by catchment size, length, amount of flow, sediment discharge (the Brahmaputra carries 540 million tons of sediment per year, the Ganges 520 million tons) and lateral shifting.

Causes of flooding

There are many causes of flooding in Bangladesh (Figure 1.41), which originate in three areas – the highlands (Himalayas); the Indian Plains of the Ganges and the Brahmaputra; and the floodplains of Bangladesh.



Source: Hofer, T and Messerli, B, 2006, *Floods in Bangladesh*, United Nations University Press

Figure 1.41 The causes of floods in the Ganges

Flooding in Bangladesh alternates between periods of high flood frequency and low flood frequency.

- Floods in the western part of Bangladesh were more intensive in the eighteenth and nineteenth centuries than in the twentieth or twenty-first centuries.
- Massive floods occurred regularly long before human impact on the watershed began; there is no evidence that flood frequency is increasing.
- The variation in the extent of flooding year by year has been increasing since the 1950s.

⇨

- There is increasing monsoon rain, particularly in the Brahmaputra–Meghna system.
- There is a worsening impact on the Bangladeshi people, but human influence in the Himalayas is not thought to be increasing flooding in Bangladesh.

Flooding is viewed very differently by rural people and by politicians and engineers. For many rural people, flooding is a short-term necessity for their crops; engineers and politicians see the damage it causes to infrastructure and the economy.

The 1998 floods

These were the longest lasting and most devastating floods in 100 years; 1998 was a La Niña year, in which normal circulatory patterns are intensified. The most-affected areas of Bangladesh included the capital Dhaka and other areas close to the main rivers; 53 of the 64 districts of the country – that is, about 50 per cent – were affected, by up to 3 metres of water for up to 67 days. The flooding on 7 September was probably the worst of the twentieth century.

The main causes were:

- the high peaks on all three main rivers occurring at the same time
- high tides causing the river floods to back up
- a strong monsoon that caused excessive flooding, and obstructions by man-made infrastructure.

Table 1.7 Major impacts of the 1998 floods

Number of people affected	c.30 million
Number of deaths	c.780–1500
Number facing malnutrition	25 million
Rice production loss	2.2 million tons
Damage to cultivated area	1.5 million ha
Loss of livestock sector	$500 million
Roads damaged	15 000 km
Embankments damaged	c.4500 km
Bridges/culverts damaged	>20 000
Villages damaged	30 000
Houses damaged	550 000–900 000

Source: Hofer, T. and Messerli, B, 2006, Floods in Bangladesh, *United Nations University Press, Table 2.2*

Coping with flooding in Bangladesh

- Many houses, and also many roads, are built on raised platforms, above the level of the average flood. People who live on islands mainly use bamboo and reeds for their houses, which can be dismantled in about an hour in an emergency.
- Rural people cultivate different varieties of rice, some of which can grow in floodwaters of 1 metre and grow up to 20 centimetres a day to keep up with the rising water level; jute and sugar cane can also withstand submergence.
- It takes up to three days for floodwaters to rise, giving people some time to prepare, such as raising platforms in their homes so that they can sleep on dry ground.
- Levees can prevent overflow but may cause deposition in the channel, which raises the river bed and reduces the capacity of the river.
- Levees can give a false sense of security – they protect against minor floods but not against major ones.
- The Flood Action Plan 1989–95 led to the development of the Bangladesh Water and Flood Management Strategy Report, which stated that there are three main water-resource development options:
  Minimum intervention – improve forecasting and improve existing flood schemes but do not create new ones
  Selective intervention – protect densely populated areas, key infrastructure and water supplies
  Major intervention – build large-scale engineering works on all main rivers.
- In terms of existing measures, there are currently over 10 000 kilometres of levees and a number of raised flood and cyclone shelters.
- Groynes in rivers protect important townships.
- Non-structural measures include flood forecasting, preparation and relief. The Flood Forecasting Warning Centre issues five-day forecasts during the monsoon season.
- Up to 20 per cent of the population is at risk from lateral erosion, which is more predictable on the Ganga than on the braided Brahmaputra. Many families may be forced to move 10 to 15 times during their lifetime.

Social problems

- **Loss of land**, leading to loss of social status and poverty, which can prevent a family's children from being able to marry.
- **Food shortages**, leading to reliance on relatives and neighbours.

Section 1.4 Activities

1 Study Table 1.6. Outline the main differences in watershed characteristics of the rivers. Suggest how these differences may affect the flood hazard.
2 Study Figure 1.41. Outline the main physical and human causes of flooding in Bangladesh.
3 Describe the main impacts of the 1998 floods in Bangladesh. Why were the impacts so great?
4 Evaluate the opportunities for flood control in Bangladesh.