3

Drainage basins and rivers

'All the rivers run into the sea; yet the sea is not full; unto the place from whence the rivers come, thither they return again.'

The Bible, Ecclesiastes 1:7

A **drainage basin** is an area of land drained by a river and its tributaries. Its boundary is marked by a ridge of high land beyond which any precipitation will drain into adjacent basins. This boundary is called a **watershed**.

A drainage basin may be described as an **open system** and it forms part of the hydrological or water cycle. If a drainage basin is viewed as a system (Framework 3, page 45) then its characteristics are:

- **inputs** in the form of precipitation (rain and snow)
- **outputs** where the water is lost from the system either by the river carrying it to the sea or through **evapotranspiration** (the loss of water directly from the ground, water surfaces and vegetation).

Within this system, some of the water:

- is **stored** in lakes and/or in the soil, or
- passes through a series of **transfers** or flows, e.g. infiltration, percolation, throughflow.

Elements of the drainage basin system

Figure 3.1 shows the drainage basin system as it is likely to operate in a temperate humid region such as the British Isles.

Precipitation

This forms the major input into the system, though amounts vary over time and space. As a rule, the greater the intensity of a storm, the shorter its duration. Convectional thunderstorms are short, heavy and may be confined to small areas, whereas the passing of a warm front of a depression (page 231) will give a longer period of more steady rainfall extending over the entire basin.

Evapotranspiration

The two components of evapotranspiration are outputs from the system. **Evaporation** is the physical process by which moisture is lost directly into the atmosphere from water surfaces, including vegetation and the soil, due to the effects of air movement and the sun's heat. **Transpiration** is a biological process by which water is lost from a plant through the minute pores (stomata) in its leaves. Evaporation rates are affected by temperature, wind speed, humidity, hours of sunshine and other climatic factors. Transpiration rates depend on the time of year, the type and amount of vegetation, the availability of moisture and the length of the growing season. It is also possible to distinguish between the potential and the actual evapotranspiration of an area. For example, in deserts there is a high **potential evapotranspiration** because the amount of moisture that could be lost is greater than the amount of water actually available. On the other hand, in Britain the amount

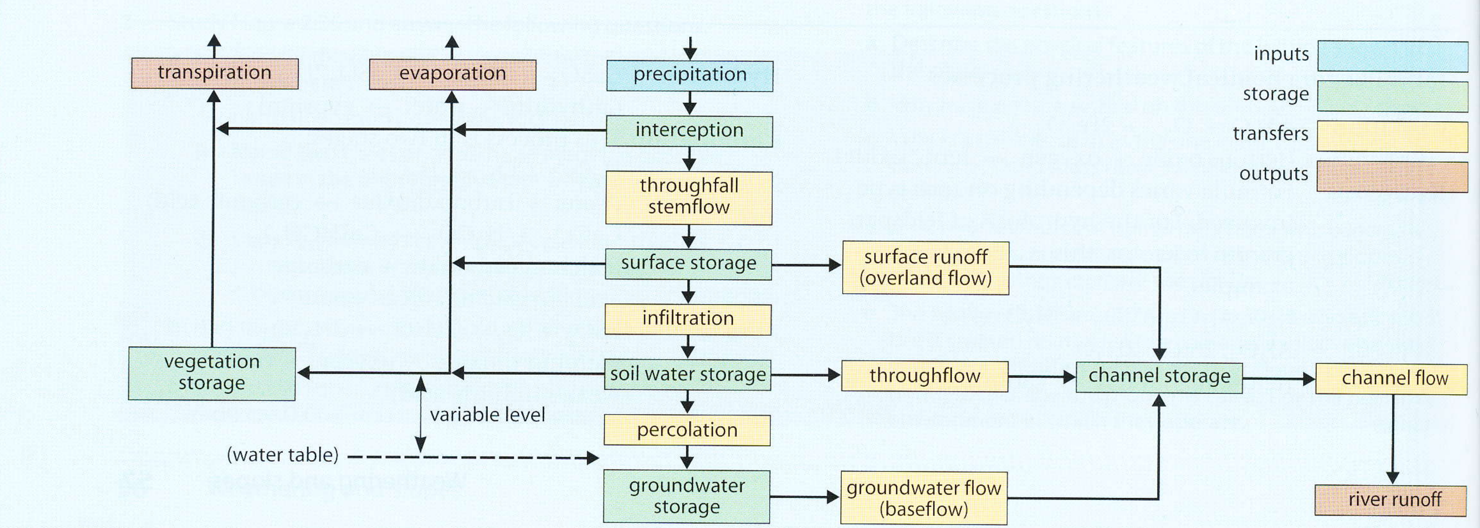


Figure 3.1
The drainage basin as an open system

of water available for evapotranspiration nearly always exceeds the amount which actually takes place, hence the term **actual evapotranspiration**. In other words, transpiration is limited by the availability of water in the soil.

Interception

The first raindrops of a rainfall event will fall on vegetation which shelters the underlying ground. This is called **interception storage**. It is greater in a woodland area or where tree crops are grown than on grass or arable land. If the precipitation is light and of short duration, much of the water may never reach the ground and it may be quickly lost from the system through evaporation. Estimates suggest that in a woodland area up to 30 per cent of the precipitation may be lost through interception, which helps to explain why soil erosion is limited in forests. According to Newson (1975), 'Interception is a dynamic process of filling and emptying a shallow store (about 2 mm in most UK trees). The emptying occurs because evaporation is very efficient for small raindrops held on tree surfaces.' In an area of deciduous trees, both interception and evapotranspiration rates will be higher in summer, although the two processes do not occur simultaneously.

If a rainfall event persists, then water begins to reach the ground by three possible routes: dropping off the leaves, or **throughfall**; flowing down the trunk, or **stemflow**; and by undergoing **secondary interception** by undergrowth. Following a warm, dry spell in summer, the ground may be hard; at the start of a rainfall event water will then lie on the surface (**surface storage**) until the upper layers become sufficiently moistened to allow it to soak slowly downwards. If precipitation is very heavy initially, or if the soil becomes saturated, then excess water will flow over the surface, a transfer known as **surface runoff** (or, in Horton's term, **overland flow**) (Figure 3.2).

Figure 3.2

Surface runoff (overland flow), Blyford, Suffolk

Infiltration

In most environments, overland flow is relatively rare except in urban areas – which have impermeable coverings of tarmac and concrete – or during exceptionally heavy storms. Soil will gradually admit water from the surface, if the supply rate is moderate, allowing it slowly to infiltrate vertically through the pores in the soil. The maximum rate at which water can pass through the soil is called its **infiltration capacity** and is expressed in mm/hr. The rate of infiltration depends upon the amount of water already in the soil (**antecedent precipitation**), the **porosity** (Figure 8.2) and structure of the soil, the nature of the soil surface (e.g. crusted, cracked, ploughed), and the type, amount and seasonal changes in vegetation cover. Some of the water will flow laterally as **throughflow**. During drier periods, some water may be drawn up towards the surface by **capillary action**.

Percolation

As water reaches the underlying soil or rock layers, which tend to be more compact, its progress is slowed. This constant movement, called percolation, creates **groundwater storage**. Water eventually collects above an impermeable rock layer, or it may fill all pore spaces, creating a **zone of saturation**. The upper boundary of the saturated material, i.e. the upper surface of the groundwater layer, is known as the **water table**. Water may then be slowly transferred laterally as **groundwater flow** or **baseflow**. Except in areas of Carboniferous limestone, groundwater levels usually respond slowly to surface storms or short periods of drought (Figure 3.5). During a lengthy dry period, some of the groundwater store will be utilised as river levels fall. In a subsequent wetter period, groundwater must be replaced before the level of the river can rise appreciably (Figure 3.3). If the water table reaches the surface, it means that the ground is saturated; excess water will then form a marsh where the land is flat, or will become surface runoff if the ground is sloping.

Channel flow

Although some rain does fall directly into the channel of a river (**channel precipitation**), most water reaches it by a combination of three transfer processes: surface runoff (overland flow), throughflow, or groundwater flow (baseflow). Once in the river, as **channel storage**, water flows towards the sea and is lost from the drainage basin system.

The water balance

This shows the state of equilibrium in the drainage basin between the inputs and outputs. It can be expressed as:

$P = Q + E \pm$ change in storage

where:

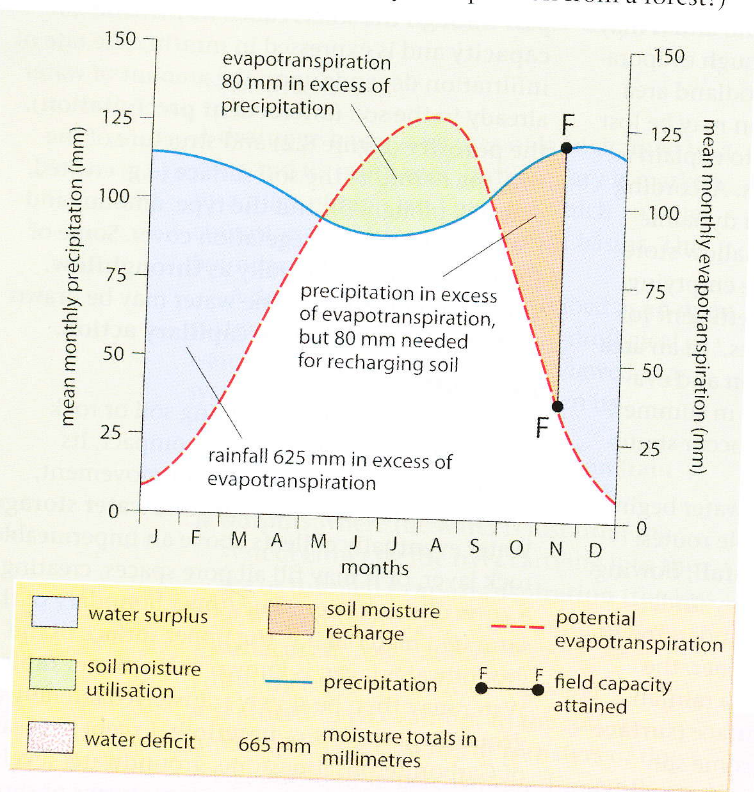
$P =$ precipitation (measured using rain gauges)

$Q =$ runoff (measured by discharge flumes in the river channel), and

$E =$ evapotranspiration. (This is far more difficult to measure – how can you measure accurately transpiration from a forest?)

Figure 3.3

A model illustrating soil moisture budget

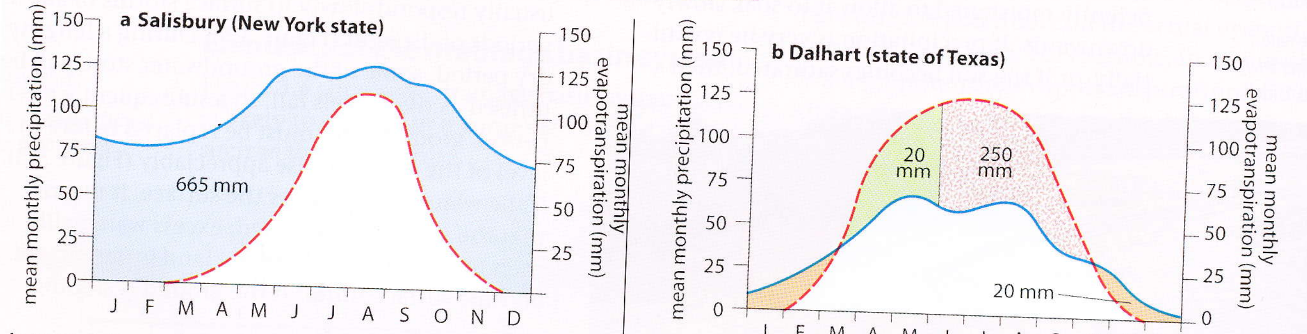


In Britain, the annual precipitation nearly always, in most years and in most places, exceeds evapotranspiration. As, therefore, precipitation input exceeds evapotranspiration loss, then there is **positive water balance** (or water budget). However in some years, e.g 1974 and 1975, and 1995 and 1996, the long, dry summers, especially in the south and east of the country, resulted in evapotranspiration exceeding precipitation to give a temporary **negative water balance.** Changes in **storage** in the water balance reflect the amount of moisture in the soil. The **soil moisture budget** is, according to Newson, a sub-system of the catchment water balance.

Figure 3.3 is a graph showing the soil moisture balance for an area in south-east England. During winter, precipitation exceeds evapotranspiration creating a **soil moisture surplus** which results in considerable surface runoff and a rise in river levels. In summer, evapotranspiration exceeds precipitation and so plants and humans have to **utilise** water from the soil store leaving it depleted and causing river levels to fall. By autumn, when precipitation again exceeds evapotranspiration, the first of the surplus water has to be used to **recharge** the soil until it reaches its **field capacity** (page 267). At no time in Figure 3.3 was the utilisation of water sufficient to create a **soil moisture deficit** (as in Figure 3.4b).

Figure 3.4

Soil moisture budget for two towns in the USA

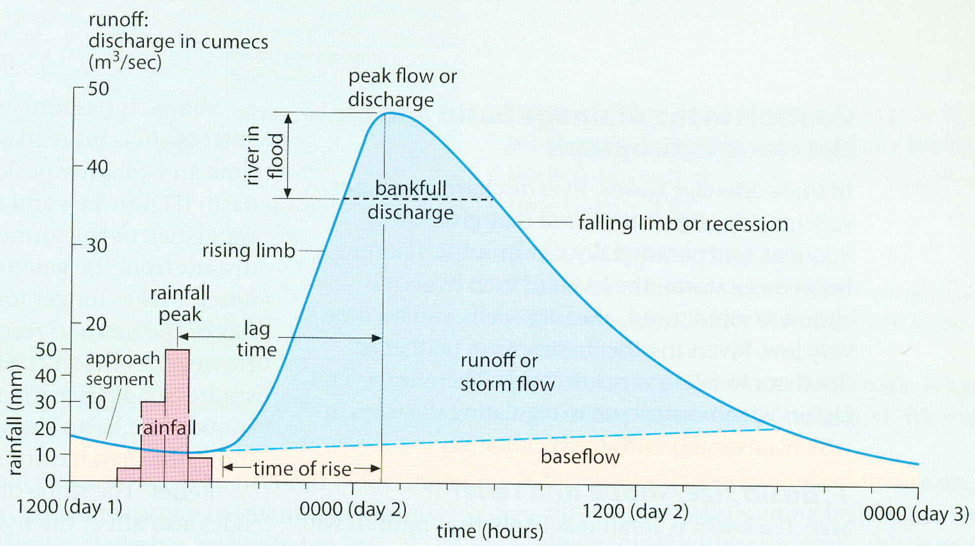


As precipitation is above potential evapotranspiration throughout the year then there is, in an average year, neither a water shortage nor a need to utilise moisture from the soil.

By spring, potential evapotranspiration is greater than precipitation. As there is no water surplus, then plants have to utilise moisture from the soil. By midsummer, water in the soil has been used up and there is a water deficit – meaning that plants can only survive if they are either drought-resistant or if they can obtain water through irrigation. When precipitation does exceed potential evapotranspiration, in winter, the rain is needed to replace (recharge) that taken from the soil earlier in the year, and amounts are insufficient to give a water surplus.

Figure 3.5

The storm hydrograph



The storm hydrograph

An important aspect of **hydrology** (the study of water, **precipitation**, **runoff** and **evaporation/transpiration processes**) is how a drainage basin reacts to a period of rain. This is important because it can be used in predicting the flood risk and in making the necessary precautions to avoid damage to property and loss of life. The response of a river can be studied by using the **storm** or **flood hydrograph**. The hydrograph is a means of showing the discharge of a river at a given point over a short period of time. **Discharge** is the amount of water originating as precipitation which reaches the channel by surface runoff, throughflow and baseflow. Discharge is therefore the water *not* stored in the drainage basin by interception, as surface storage, soil moisture storage or groundwater storage or lost through evapotranspiration (Figure 3.1). The model of a storm hydrograph, Figure 3.5, shows how the discharge of a river responds to an individual rainfall event.

Measuring discharge

Discharge is the velocity (speed) of the river, measured in metres (m) per second, multiplied by the cross-sectional area of the river, measured in m^2. This gives the volume in m^3/sec or **cumecs**. It can be expressed as:

$Q = A \times V$

where:

Q = discharge

A = cross-sectional area

V = velocity.

Interpreting the hydrograph

Refer to the hydrograph in Figure 3.5. The graph includes the **approach segment** which shows the discharge of the river before the storm (the antecedent flow rate). When the storm begins, the river's response is negligible for although some of the rain does fall directly into the channel, most falls elsewhere in the basin and takes time to reach the channel. However, when the initial surface runoff and, later, the throughflow eventually reach the river there is a rapid increase in discharge as indicated by the **rising limb**. The steeper the rising limb, the faster the response to rainfall – i.e. water reaches the channel more quickly. The **peak discharge** (peak flow) occurs when the river reaches its highest level. The period between maximum precipitation and peak discharge is referred to as the **lag time**. The lag time varies according to conditions within the drainage basin, e.g. soil and rock type, slope and size of the basin, drainage density, type and amount of vegetation and water already in storage. Rivers with a short lag time tend to experience a higher peak discharge and are more prone to flooding than rivers with a long lag time. The **falling** or **recession limb** is the segment of the graph where discharge is decreasing and river levels are falling. This segment is usually less steep than the rising limb because throughflow is being released relatively slowly into the channel. By the time all the water from the storm has passed through the channel at a given location, the river will have returned to its baseflow level – unless there has been another storm within the basin. **Stormflow** is the discharge, both surface and subsurface flow, attributed to a single storm. **Baseflow** is very slow to respond to a storm, but by continually releasing groundwater it maintains the river's flow during periods of low precipitation. Indeed, baseflow is more significant over a longer period of time than an individual storm and reflects seasonal changes in precipitation, snowmelt, vegetation and evapotranspiration. Finally, on the graph, **bankfull discharge** occurs when a river's water level reaches the top of its channel; any further increase in discharge will result in flooding of the surrounding land. This happens, on average, once every year or two.

Controls in the drainage basin and on the storm hydrograph

In some drainage basins, river discharge increases very quickly after a storm and may give rise to frequent, and occasionally catastrophic, flooding. Following a storm, the levels of such rivers fall almost as rapidly and, after dry spells, can become very low. Rivers in other basins seem neither to flood nor to fall to very low levels. There are several factors which contribute to regulating the ways in which a river responds to precipitation.

1 Basin size, shape and relief

Size If a basin is small it is likely that rainfall will reach the main channel more rapidly than in a larger basin where the water has much further to travel. Lag time will therefore be shorter in the smaller basin.

Shape It has long been accepted that a circular basin is more likely to have a shorter lag time and a higher peak flow than an elongated basin (Figure 3.6a and b). All the points on the watershed of the former are approximately equidistant from the gauging station, whereas in the latter it takes longer for water from the extremities of the basin to reach the gauging station. However, Newson (1994) has pointed out that studies made in many regions of the world have shown that basin shape is less reliable as a flood indicator than basin size and slope.

Relief The slope of the basin and its valley sides also affect the hydrograph. In steep-sided upland valleys, water is likely to reach the river more quickly than in gently sloping lowland areas (Figure 3.6c).

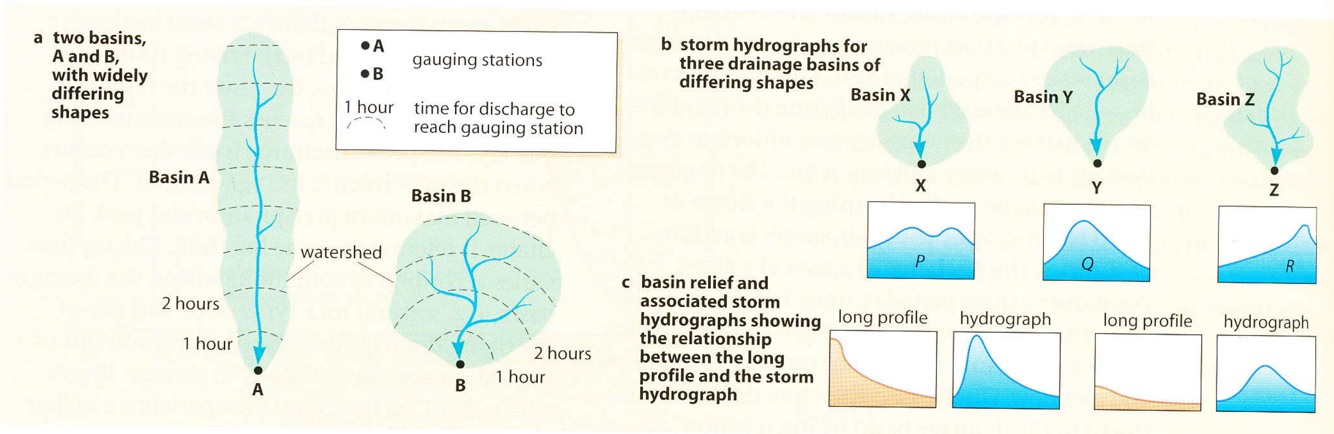


Figure 3.6

Drainage basin shape

2 Types of precipitation

Prolonged rainfall Flooding most frequently occurs following a long period of heavy rainfall when the ground has become saturated and infiltration has been replaced by surface runoff (overland flow).

Intense storms (e.g. convectional thunderstorms) When heavy rain occurs, the rainfall intensity may be greater than the infiltration capacity of the soil (e.g. in summer in Britain, when the ground may be harder). The resulting surface runoff is likely to produce a rapid rise in river levels (flash floods) – Boscastle, Cornwall, Places 12, page 80.

Snowfall Heavy snowfall means that water is held in surface storage and river levels drop. When temperatures rise rapidly (in Britain, this may be with the passage of a warm front and its associated rainfall, page 231), meltwater soon reaches the main river. It is possible that the ground will remain frozen for some time, in which case infiltration will be impeded.

3 Temperature

Extremes of temperature can restrict infiltration (very cold in winter, very hot and dry in summer) and so increase surface runoff. If evapotranspiration rates are high, then there will be less water available to flow into the main river.

4 Land use

Vegetation Vegetation may help to prevent flooding by intercepting rainfall (storing moisture on its leaves before it evaporates back into the atmosphere – page 59). Estimates suggest that tropical rainforests intercept up to 80 per cent of rainfall (30 per cent of which may later evaporate) whereas arable land may intercept only 10 per cent. Interception is less during the winter in Britain when deciduous trees have shed their leaves and crops have been harvested to expose bare earth. Plant roots, especially those of trees, reduce throughflow by taking up water from the soil.

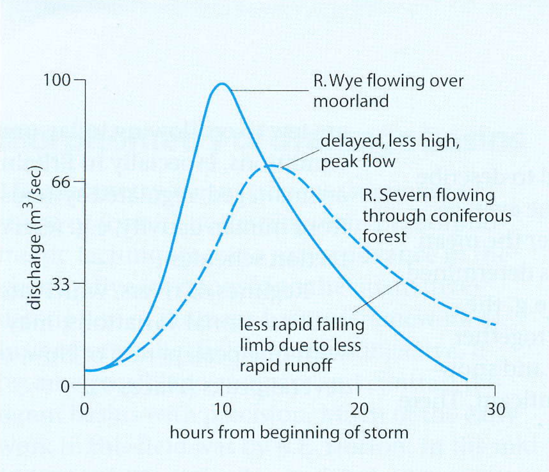


Figure 3.7

The effect of vegetation on the storm hydrographs of the Rivers Wye and Severn (geology and precipitation are the same in both basins)

Flooding is more likely to occur in deforested areas, e.g. the increasingly frequent and serious flooding in Bangladesh is attributed to the removal of trees in Nepal and other Himalayan areas. In areas of afforestation, flooding may initially increase as the land is cleared of old vegetation and drained, but later decrease as the planted trees mature. Newson (1994) points out that, after 20 years of data collecting, the evidence suggests that the canopy has more effect on medium flows than on high flows, as the main ditches remain active.

Figure 3.7 contrasts the storm hydrographs of two rivers. Although they rise very close together, the River Wye flows over moors and grassland, whereas the River Severn flows through an area of coniferous forest.

Urbanisation Urbanisation has increased flood risk. Water cannot infiltrate through tarmac and concrete, and gutters and drains carry water more quickly to the nearest river. Small streams may be either canalised so that (with friction reduced) the water flows away more quickly, or culverted, which allows only a limited amount of water to pass through at one time (Figure 3.8).

Figure 3.8

An urban river

5 Rock type (geology)

Rocks that allow water to pass through them are said to be **permeable**. There are two types of permeable rock:

- **Porous**, e.g. sandstone and chalk, which contain numerous pores able to fill with and store water (Figure 8.2).
- **Pervious**, e.g. Carboniferous limestone, which allow water to flow along bedding planes and down joints within the rock, although the rock itself is impervious (Figure 8.1).

As both types permit rapid infiltration, there is little surface runoff and only a limited number of surface streams. In contrast **impermeable rocks**, such as granite, do not allow water to pass through them and so they are characterised by more surface runoff and a greater number of streams.

6 Soil type

This controls the rate and volume of infiltration, the amount of soil moisture storage and the rate of throughflow (page 265). Sandy soils, with large pore spaces, allow rapid infiltration and do not encourage flooding. Clays have much smaller pore spaces and they are less well connected; this reduces infiltration and throughflow, but encourages surface runoff and increases the risk of flooding.

7 Drainage density

This refers to the number of surface streams in a given area (page 67). The density is higher on impermeable rocks and clays, and lower on permeable rocks and sands. The higher the density, the greater is the probability of flash floods. A **flash flood** is a sudden rise of water in a river, shown on the hydrograph as a shorter lag time and a higher peak flow in relation to normal discharge.

8 Tides and storm surges

High spring tides tend to prevent river floodwater from escaping into the sea. Floodwater therefore builds up in the lower part of the valley. If high tides coincide with gale-force winds blowing onshore and a narrowing estuary, the result may be a **storm surge** (Places 19, page 148). This happened in south-east England and in the Netherlands in 1953 and prompted the construction of the Thames Barrier and the implementation of the Dutch Delta Plan.

River regimes

The regime of a river is the term used to describe the annual variation in discharge. The average regime, which can be shown by either the mean daily or the mean monthly figures, is determined primarily by the climate of the area, e.g. the amount and distribution of rainfall, together with the rates of evapotranspiration and snow-melt. Local geology may also be significant. There are few rivers flowing today under wholly natural conditions, especially in Britain. Most are managed, regulated systems which result from human activity, e.g. reservoirs and flood protection schemes.

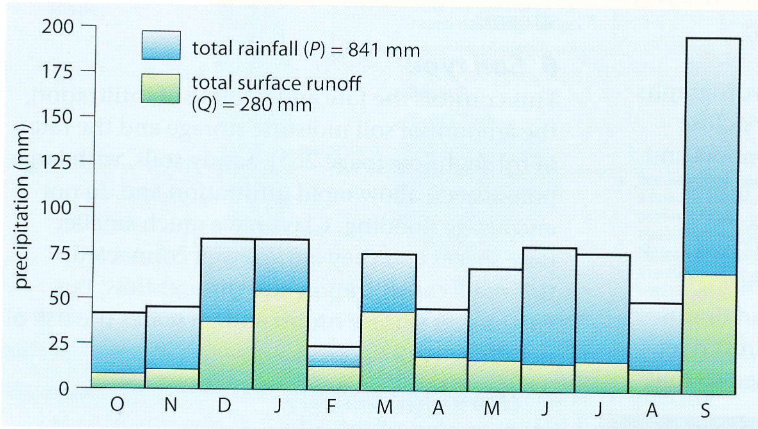
Regimes of rivers, which are used to demonstrate seasonal variations, may be either simple, with one peak period of flow, or complex with several peaks (Places 9).

Places 9 River Don, Yorkshire and River Torridge, Devon: river discharge

Figure 3.9 shows the rainfall and runoff figures for the River Don (South Yorkshire) for one year. Discharge is usually at its highest in winter when Britain receives most of its depressions and when evapotranspiration is limited due to the low temperatures. Early spring may also show a peak if the source of the river is in an upland area liable to heavy winter snowfalls – in this case, the Pennines. It is possible for runoff to exceed precipitation, e.g. when heavy snowfall at the end of a month melts during a milder, drier period at the beginning of the next month. In contrast, river levels are lowest in summer when most of Britain receives less rainfall and when evapotranspiration rates are at their highest. There is often a correlation, or relationship, between the two variables of rainfall and runoff. This relationship can be shown by means of a scattergraph (Framework 19, page 612). Rainfall is plotted along the base (the *x* axis) because it is the independent variable, i.e. it does not depend on the amount of runoff. Runoff is plotted on the vertical or *y* axis because it is the dependent variable, i.e. runoff does depend upon the amount of rainfall.

Figure 3.9

Rainfall and runoff for the River Don, Yorkshire



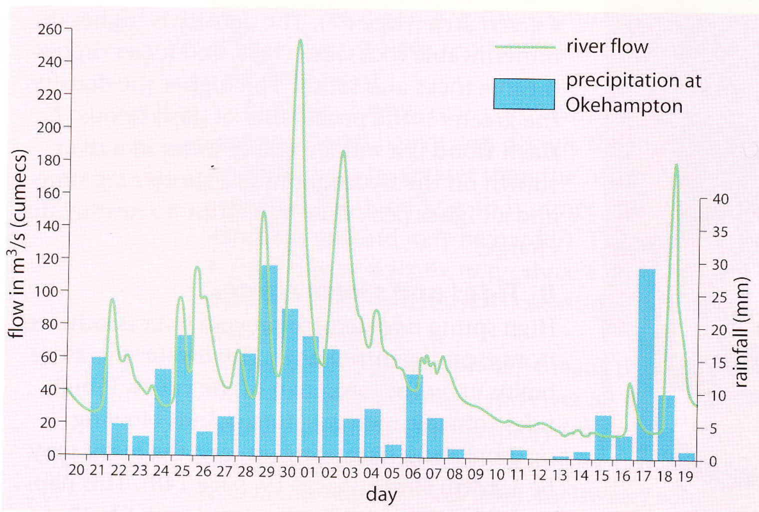


Figure 3.10

Hydrograph for the River Torridge at Torrington, Devon, late 1992

The Environment Agency (EA) also produces hydrographs covering longer periods of time than for a single storm (Figure 3.5) but with far greater, and more useful, data than that given for the annual regime of a river (Figure 3.9).

Figure 3.10 gives rainfall and discharge for a wet month in late 1992 for the River Torridge in Devon. It shows that:

a as most of the peak discharges occur within a day of peak rainfall then the river must respond quickly to rainfall and, therefore, is likely to pose a flood risk

b the highest discharge (on the 30th) came after several very wet days during which river levels had no time to drop, rather than after a very wet day (the 17th) which followed a relatively dry spell of weather.

Morphometry of drainage basins

Morphometry means 'the measurement of shape or form'. The development of morphometric techniques was a major advance in the quantitative (as opposed to the qualitative) description of drainage basins (Framework 4). Instead of studies being purely subjective, it became possible to compare and contrast different basins with precision. Much of the early work in this field was by R.E. Horton. In the mid-1940s he devised the 'Laws of drainage composition' which established a hierarchy of streams ranked according to 'order'. One of these laws, the **law of stream number**, states that within a drainage basin a constant geometric relationship exists between stream order and stream number (Figure 3.12a).

Figure 3.11 shows how one of Horton's successors, A.N. Strahler, defined streams of different order. All the initial, unbranched source tributaries he called **first order** streams. When two first order streams join they form a **second order**; when two second order streams merge they form a **third order**; and so on. Notice that it needs two stream segments of equal order to join to produce a segment of a higher order, while the order remains unchanged if a lower order segment joins a higher order segment. For example, a second order plus a second order gives a third order but if a second order stream joins a third order, the resultant stream remains as a third order. A basin may therefore be described in terms of the highest order stream within it, e.g. a 'third order basin' or a 'fourth order basin'.

If the number of segments in a stream order is plotted on a semi-log graph against the stream order, then the resultant best-fit line will be straight (Figure 3.12a). On a semi-log graph, the vertical scale, showing the dependent variable (Framework 19, page 612), is divided into cycles, each of which begins and ends ten times greater than the previous cycle, e.g. a range of 1 to 10, 10 to 100, 100 to 1000, and so on. (If the horizontal scale, showing the independent variable, had also been divided into cycles instead of having an arithmetic scale, then Figure 3.12 would have been referred to as a log-log graph (Figure 18.25).) Logarithmic graphs are valuable when:

- the rate of change is of more interest than the amount of change: the steeper the line the greater the rate of change
- there is a greater range in the data than there is space to express on an arithmetic scale (a log scale compresses values)
- there are considerably more data at one end of the range than the other.

Figure 3.12a shows a perfect negative correlation (Figure 21.14): as the independent variable (in this case the stream order) increases, then the dependent variable (the number of streams) decreases. Studies of stream ordering for most rivers in the world produce a similar straight-line relationship. For any exceptions to Horton's law of stream ordering, further studies can be made to determine which local factors alter the relationship. Relationships also exist between stream order and the mean length of streams (Figure 3.12b), and stream order and mean drainage basin area (Figure 3.12c).

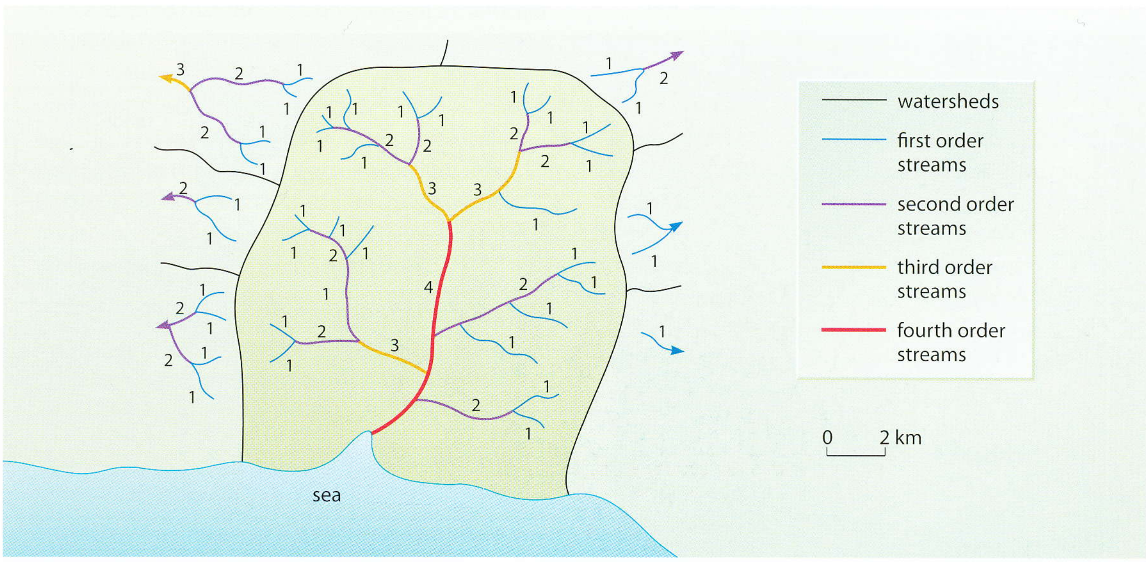
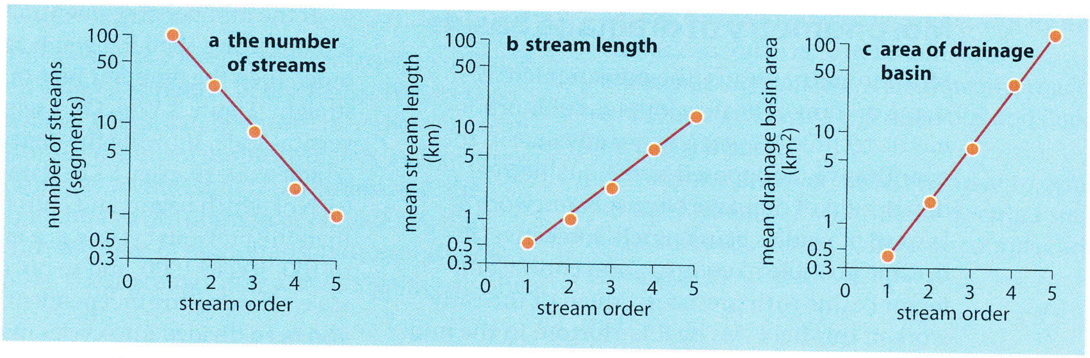


Figure 3.11

Strahler's method of stream ordering

Figure 3.12

Relationships between stream order and other variables



Comparing drainage basins

Horton's work has made it possible to compare different drainage basins scientifically (quantitatively) rather than relying on subjective (qualitative) descriptions by individuals. It also allows studies of drainage basin morphometry in different parts of the world to use the same standards, measurements and 'language'.

Figure 3.13 shows two imaginary and adjacent basins. These can be compared in several different ways, including:

- the bifurcation ratio, and
- drainage density.

The bifurcation ratio

This is the relationship between the number of streams of one order and those of the next highest order. It is obtained by dividing the number of streams in one order by the number in the next highest order, e.g. for basin A in Figure 3.13:

$$\frac{N1}{N2} = \frac{\text{(number of first order streams)}}{\text{(number of second order streams)}} = \frac{26}{6} = 4.33$$

$$\frac{N2}{N3} = \frac{\text{(number of second order streams)}}{\text{(number of third order streams)}} = \frac{6}{2} = 3.00$$

$$\frac{N3}{N4} = \frac{\text{(number of third order streams)}}{\text{(number of fourth order streams)}} = \frac{2}{1} = 2.00$$

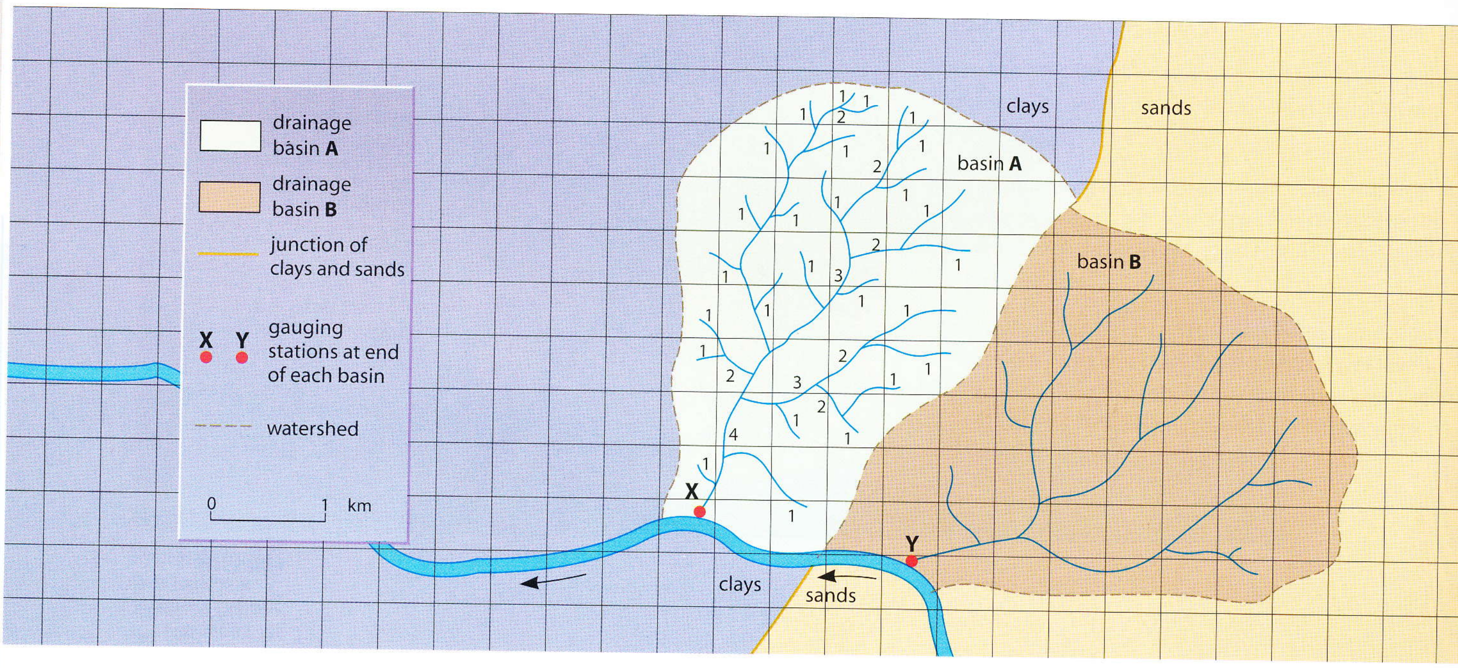
and then finding the mean of all the ratios in basin being studied, i.e.

$$\frac{4.33 + 3.00 + 2.00}{3} = 3.11 = \text{bifurcation ratio for basin A}$$

The human significance of the bifurcation ratio is that as the ratio is reduced so the risk o flooding within the basin increases. It also indicates the flood risk for parts, rather than all, of the basin. Most British rivers have a bifurcatio ratio of between 3 and 5.

Figure 3.13

A comparison between two adjacent drainage basins on clays and sands



Drainage density

This is calculated by measuring the total length of all the streams within the basin (L) and dividing by the area of the whole basin (A). It is therefore the average length of stream within each unit area. For basin **A** in Figure 3.13, this will be:

$$\frac{L}{A} = \frac{22.65}{12.50} = 1.81 \text{ km per km}^2$$

In Britain most drainage densities lie between 2 and 4 km per km^2 but this varies considerably according to local conditions. A number of factors influence drainage density. It tends to be highest in areas where the land surface is impermeable, where slopes are steep, where rainfall is heavy and prolonged, and where vegetation cover is lacking.

a **Geology and soils** On very permeable rocks or soils (e.g. chalk, sands) drainage densities may be under 1 km per km^2, whereas this increases to over 5 km per km^2 on highly impermeable surfaces (e.g. granite, clays). In Figure 3.13 with two adjacent drainage basins of approximately equal size, shape and probably rainfall, the difference in drainage density is likely to be due to basin **A** being on clays and basin **B** on sands.

b **Land use** The drainage density, especially of first order streams, is much greater in areas with little vegetation cover. The density decreases, as does the number of first order streams, if the area becomes afforested. Deserts tend to have the highest densities of first order channels, even if the channels are dry for most of the time.

c **Time** As a river pattern develops over a period of time, the number of tributaries will decrease, as will the drainage density.

d **Precipitation** Densities are usually highest in areas where rainfall totals and intensity are also high.

e **Relief** Density is usually greater on steeper slopes than on more gentle slopes.

Framework 4 Quantitative techniques and statistical methods of data interpretation

As geography adjusted to a more scientific approach in the 1960s, a series of statistical techniques were adopted which could be used to quantify field data and add objectivity to the testing of hypotheses and theories. This period is often referred to as the 'Quantitative Revolution'.

At first it seemed to many, the author included, that mathematics had taken over the subject, but it is now accepted that these techniques are a useful aid provided they are not seen as an end in themselves. They provide a tool which, if carefully handled and understood, gives greater precision to arguments, helps in the identification of patterns and may contribute to the discovery of relationships and possible cause–effect links. In short, by providing greater accuracy in handling data they reduce the reliance upon subjective conclusions.

It is essential to select the most appropriate techniques for the data and for the job in hand. Therefore some understanding of the statistical methods involved is important.

Statistical methods may be profitably employed in these areas.

1 **Sampling** (Framework 6, page 159) Rapid collection of the data is made possible.

2 **Correlation and regression** (Framework 19, page 612) This not only shows possible relationships between two variables but quantifies or measures the strength of those relationships.

3 **Spatial distributions** (Framework 19, page 612) Not only may this approach be used to identify patterns, but it may also demonstrate how likely it is that the resultant distributions occurred by chance.

When these new techniques first appeared in schools in the 1970s, they appeared extremely daunting until it was realised that often the difficulty of the worked examples detracted from the usefulness of the technique itself. Where such techniques appear in this book, the mathematics have been simplified to show more clearly how methods may be used and to what effect. With the wider availability of calculators and computers it has become easier to take advantage of more complex calculations to test geographical hypotheses (Framework 10, page 299). Much of the 'number crunching' has now been removed by the increasing availability of statistical packages for computers.

Figure 3.14

Turbulence in a river: the confluence of the Rio Amazon (red with silt from the Andes) and the Rio Negro (black with plant acids)

River form and velocity

A river will try to adopt a channel shape that best fulfils its two main functions: transporting water and sediment. It is important to understand the significance of channel shape in order to identify the controls on the flow of a river.

Types of flow

As water flows downhill under gravity, it seeks the path of least resistance – i.e. a river possesses potential energy and follows a route that will maximise the rate of flow (velocity) and minimise the loss of this energy caused by friction. Most friction occurs along the banks and bed of the river, but the internal friction of the water and air resistance on the surface are also significant.

There are two patterns of flow, **laminar** and **turbulent**. Laminar flow (Figure 3.15a) is a horizontal movement of water so rarely experienced in rivers that it is usually discounted. Such a form of flow, if it existed, would travel over sediment on the river bed without disturbing it. Turbulent flow, the dominant mechanism, consists of a series of erratic eddies, both vertical and horizontal, in a downstream direction (Figures 3.14 and 3.15b). Turbulence varies with the velocity of the river which, in turn, depends upon the amount of energy available after friction has been overcome. It is estimated that under 'normal' conditions about 95 per cent of a river's energy is expended in order to overcome friction.

Influence of velocity on turbulence

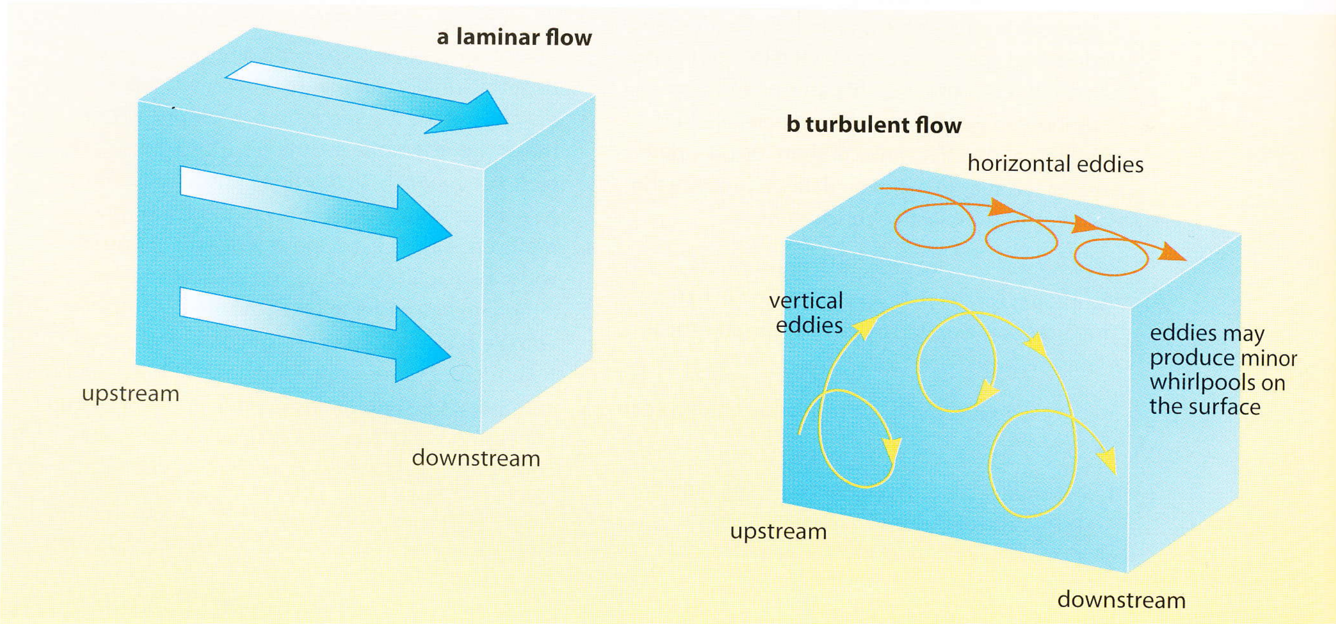
- If the velocity is high, the amount of energy still available after friction has been overcome will be greater and so turbulence increases. This results in sediment on the bed being disturbed and carried downstream. The faster the flow of the river, the larger the quantity and size of particles which can be transported. The transported material is referred to as the river's **load**.
- When the velocity is low, there is less energy to overcome friction. Turbulence decreases and may not be visible to the human eye. Sediment on the river bed remains undisturbed. Indeed, as turbulence maintains the transport of the load, a reduction in turbulence may lead to deposition of sediment.

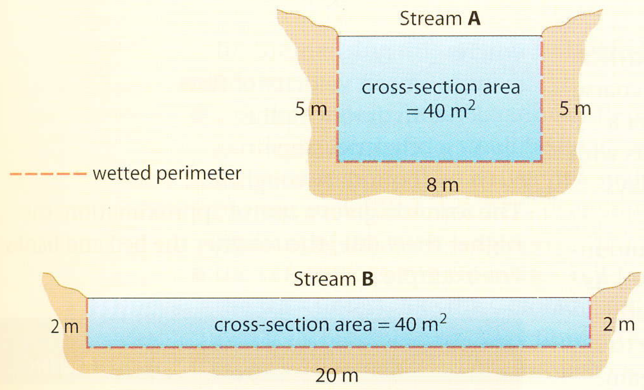
The velocity of a river is influenced by three main factors:

1 channel shape in cross-section
2 roughness of the channel's bed and banks, and
3 channel slope.

Figure 3.15

Types of flow in a river





Wetted perimeter	Hydraulic radius
Stream **A**: 5 + 5 + 8 = 18 m	Stream **A**: $\frac{40}{18}$ = 2.22 m
Stream **B**: 2 + 2 + 20 = 24 m	Stream **B**: $\frac{40}{24}$ = 1.66 m

Figure 3.16

The wetted perimeter, hydraulic radius and efficiency of two different-shaped channels with equal area

1 Channel shape

This is best described by the term **hydraulic radius**, i.e. the ratio between the area of the cross-section of a river channel and the length of its wetted perimeter. The cross-section area is obtained by measuring the width and the mean depth of the channel. The **wetted perimeter** is the total length of the bed and bank sides in contact with the water in the channel. Figure 3.16 shows two channels with the same cross-section area but with different shapes and hydraulic radii.

Stream A has a larger hydraulic radius, meaning that it has a smaller amount of water in its cross-section in contact with the wetted perimeter. This creates less friction which in turn reduces energy loss and allows greater velocity. Stream A is said to be the more efficient of the two rivers.

Stream B has a smaller hydraulic radius, meaning that a larger amount of water is in contact with the wetted perimeter. This results in greater friction, more energy loss and reduced velocity. Stream B is less efficient than stream A.

The shape of the cross-section controls the point of maximum velocity in a river's channel. The point of maximum velocity is different in a river with a straight course where the channel is likely to be approximately symmetrical (Figure 3.17a) compared with a meandering channel where the shape is asymmetrical (Figure 3.17b).

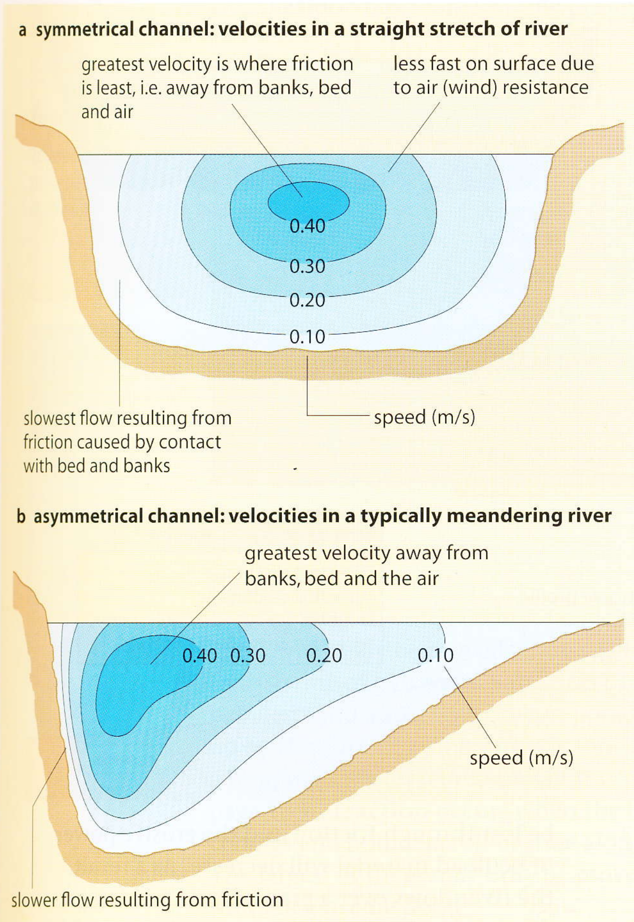


Figure 3.17

Cross-sections of a symmetrical and an asymmetrical stream channel

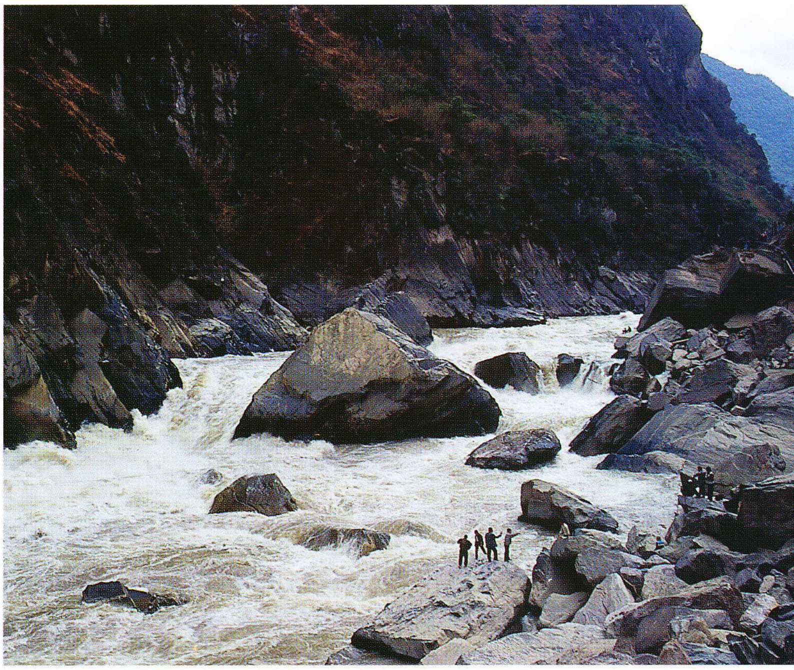


Figure 3.18

Tiger Leaping Gorge on the River Yangtze, China. This gorge has been suggested as a site for a future hydro-electric power station. It is nearly 1500 km upstream from the Three Gorges Dam

2 Roughness of channel bed and banks

A river flowing between banks composed of coarse material with numerous protrusions and over a bed of large, angular rocks (Figure 3.18) meets with more resistance than a river with cohesive clays and silts forming its bed and banks.

Figure 3.19 shows why the velocity of a mountain stream is less than that of a lowland river. As bank and bed roughness increase, so does turbulence. Therefore a mountain stream is likely to pick up loose material and carry it downstream.

Roughness is difficult to measure, but Manning, an engineer, calculated a **roughness coefficient** by which he interrelated the three factors affecting the velocity of a river. In his formula, known as 'Manning's N':

$$v = \frac{R^{0.67}\ S^{0.5}}{n}$$

where:

v = mean velocity of flow
R = hydraulic radius
S = channel slope
n = boundary roughness.

The formula gives a useful approximation: the higher the value, the rougher the bed and banks. For example:

Bed profile	Sand and gravel	Coarse gravel	Boulders
Uniform	0.02	0.03	0.05
Undulating	0.05	0.06	0.07
Highly irregular	0.08	0.09	0.10

Figure 3.19

Why a river increases in velocity towards its mouth

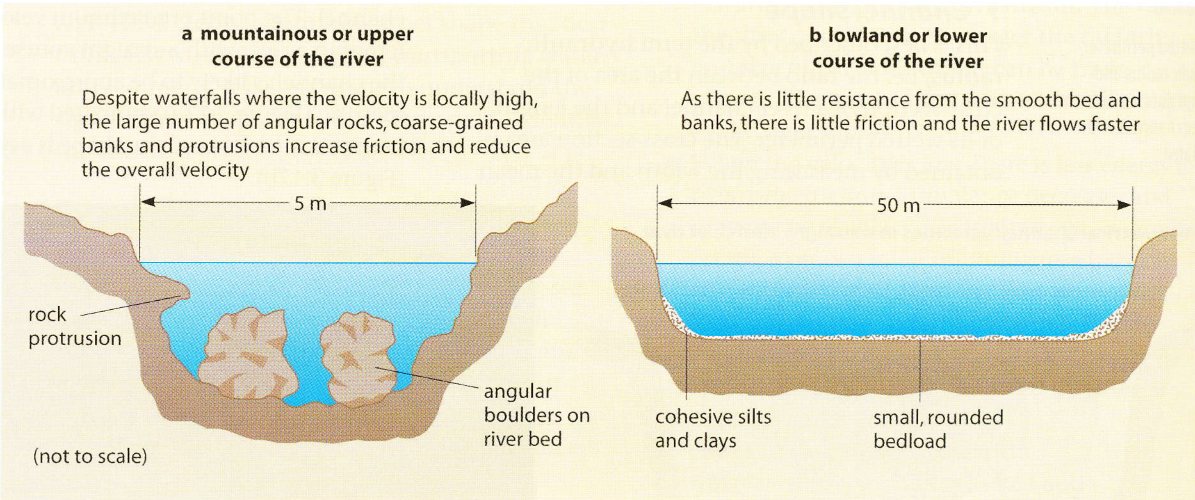
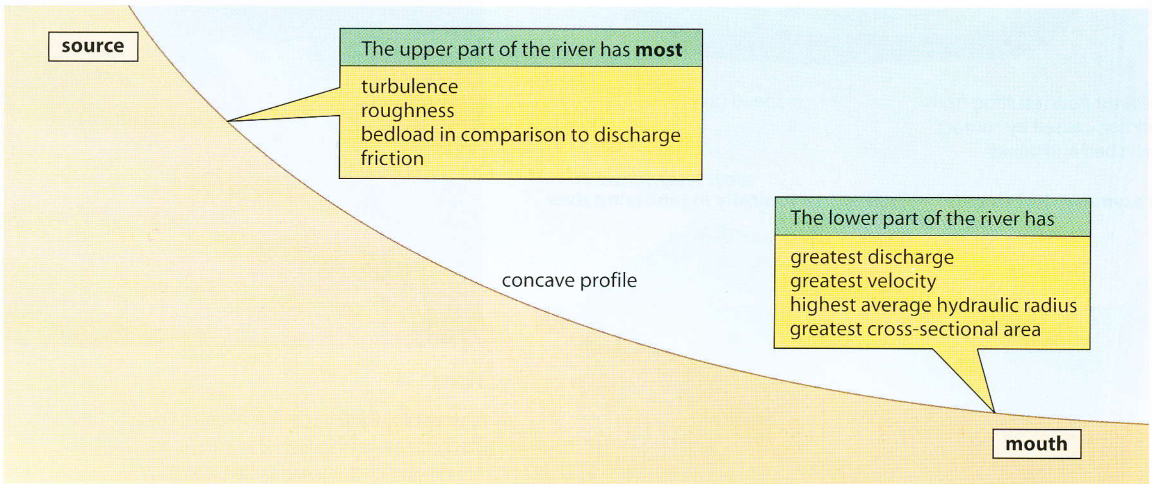


Figure 3.20

The characteristic long profile of a river



3 Channel slope

As more tributaries and water from surface runoff, throughflow and groundwater flow join the main river, the discharge, the channel cross-section area and the hydraulic radius will all increase. At the same time, less energy will be lost through friction and the erosive power of bedload material will decrease. As a result, the river flows over a gradually decreasing gradient – the characteristic concave **long profile (thalweg)** as shown in Figure 3.20.

In summarising this section it should be noted that:

- a river in a deep, broad channel, often with a gentle gradient and a small bedload, will have a greater velocity than a river in a shallow, narrow, rock-filled channel – even if the gradient of the latter is steeper
- the velocity of a river increases as it nears the sea – unless, like the Colorado and the Nile (Places 73, page 490), it flows through deserts where water is lost through evaporation or by human extraction for water supply
- the velocity increases as the depth, width and discharge of a river all increase
- as roughness increases, so too does turbulence and the ability of the river to pick up and transport sediment.

Transportation

Any energy remaining after the river has overcome friction can be used to transport sediment. The amount of energy available increases rapidly as the discharge, velocity and turbulence increase, until the river reaches flood levels. A river in flood has a large wetted perimeter and the extra friction is likely to cause deposition on the floodplain. A river at bankfull stage can move large quantities of soil and rock – its load – along its channel. In Britain, most material carried by a river is either sediment being redistributed from its banks, or material reaching the river from mass movement on its valley sides.

The load is transported by three main processes: **suspension**, **solution** and as **bedload** (Figure 3.21 and Places 10, page 73).

Suspended load

Very fine particles of clay and silt are dislodged and carried by turbulence in a fast-flowing river. The greater the turbulence and velocity, the larger the quantity and size of particles which can be picked up. The material held in suspension usually forms the greatest part of the total load; it increases in amount towards the river's mouth, giving the water its brown or black colour.

Dissolved or solution load

If the bedrock of a river is readily soluble, like limestone, it is constantly dissolved in flowing water and removed in solution. Except in limestone areas, the material in solution forms only a relatively small proportion of the total load.

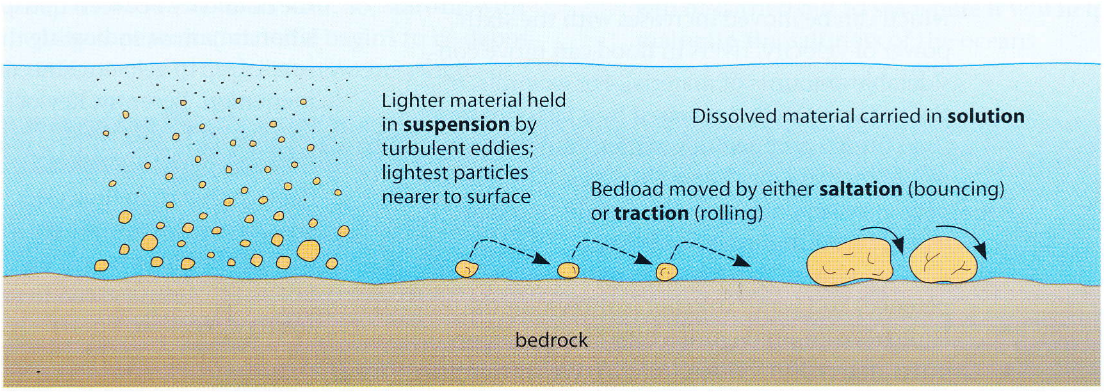


Figure 3.21

Transportation processes in a river or stream

Bedload

Larger particles which cannot be picked up by the current may be moved along the bed of the river in one of two ways. **Saltation** occurs when pebbles, sand and gravel are temporarily lifted up by the current and bounced along the bed in a hopping motion (compare saltation in deserts, page 183). **Traction** occurs when the largest cobbles and boulders roll or slide along the bed. The largest of these may only be moved during times of extreme flood.

It is much more difficult to measure the bedload than the suspended or dissolved load. Its contribution to the total load may be small unless the river is in flood. It has been suggested that the proportion of material carried in one year by the River Tyne is 57 per cent in suspension, 35 per cent in solution and 8 per cent as bedload. This is the equivalent of a 10-tonne lorry tipping its load into the river every 20 minutes throughout the year. In comparison, the Amazon's load is equivalent to four such lorries tipping every minute of the year!

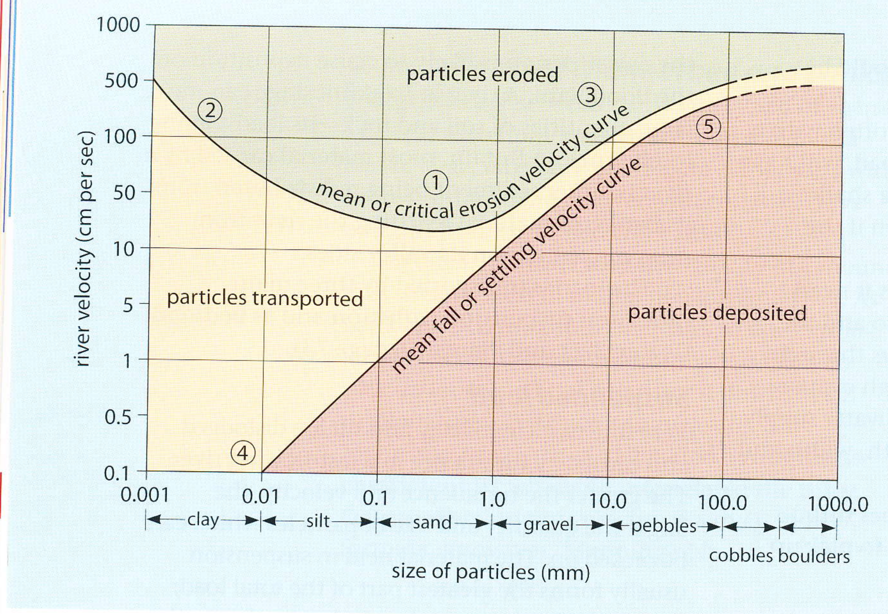


Figure 3.22

The Hjulström graph, showing the relationship between velocity and particle size. It shows the velocities necessary ('critical') for the initiation of movement (erosion); for deposition (sedimentation); and the area where transportation will continue to occur once movement has been initiated

Competence and capacity

Two further terms should be noted at this point: the competence and capacity of a river. **Competence** is the maximum size of material which a river is capable of transporting. **Capacity** is the total load actually transported. When the velocity is low, only small particles such as clay, silt and fine sand can be picked up (Figure 3.22). As the velocity increases, larger material can be moved. Because the maximum particle mass which can be moved increases with the sixth power of velocity, rivers in flood can move considerable amounts of material. For example, if the stream velocity increased by a factor of four, then the mass of boulders which could be moved would increase by 4^6 or 4096 times; if by a factor of five, the maximum mass it could transport would be multiplied 15 625 times.

The relationship between particle size (competence) and water velocity is shown on the Hjulström graph (Figure 3.22). The **mean**, or **critical, erosion velocity** curve gives the approximate velocity needed to pick up and transport, in suspension, particles of various sizes. The material carried by the river (capacity) is responsible for most of the subsequent erosion. The **mean fall** or **settling velocity** curve shows the velocities at which particles of a given size become too heavy to be transported and so will fall out of suspension and be deposited.

The graph shows two important points:

1 Sand can be transported at lower velocities than either finer or coarser particles. Particles of about 0.2 mm diameter can be picked up by a velocity of 20 cm per second (labelled 1 on the graph) whereas finer clay particles (2), because of their cohesive properties, need a velocity similar to that of pebbles (3) to be dislodged. During times of high discharge and velocity, the size and amount of the river's load will increase considerably, causing increased erosion within the channel.

2 The velocity required to maintain particles in suspension is less than the velocity needed to pick them up. For very fine clays (4) the velocity required to maintain them is virtually nil – at which point the river must almost have stopped flowing! This means that material picked up by turbulent tributaries and lower order streams can be kept in suspension by a less turbulent, higher order main river. For coarser particles (5), the boundary between transportation and deposition is narrow, indicating that only a relatively small drop in velocity is needed to cause sedimentation. Recently, Keylock has argued that an alternative method to that of Hjulström for measuring transport of river sediment is by flow depth rather than flow velocity. He suggests that shear stress – a measure of the force per unit area that the flow exerts on a particle on the river bed – can cause particles to roll out of their riverbed location.

Erosion

The material carried by a river can contribute to the wearing away of its banks and, to a lesser extent and mainly in the upper course, its bed. There are four main processes of erosion.

Corrasion

Corrasion occurs when the river picks up material and rubs it along its bed and banks, wearing them away by **abrasion**, rather like sandpaper. This process is most effective during times of flood and is the major method by which the river erodes both vertically and horizontally. If there are hollows in the river bed, pebbles are likely to become trapped. Turbulent eddies in the current can swirl pebbles around to form **potholes** (Figure 3.23).

Figure 3.23

Potholes in the bed of the Afon Glaslyn, Snowdonia

Attrition

As the bedload is moved downstream, boulders collide with other material and the impact may break the rock into smaller pieces. In time, angular rocks become increasingly rounded in appearance.

Hydraulic action

The sheer force of the water as the turbulent current hits river banks (on the outside of a meander), pushes water into cracks. The air in the cracks is compressed, pressure is increased and, in time, the bank will collapse. **Cavitation** is a form of hydraulic action caused by bubbles of air collapsing. The resultant shock waves hit and slowly weaken the banks. This is the slowest and least effective erosion process.

Solution, or corrosion

This occurs continuously and is independent of river discharge or velocity. It is related to the chemical composition of the water, e.g. the concentration of carbonic acid and humic acid.

Deposition

When the velocity of a river begins to fall, it has less energy and so no longer has the competence or capacity to carry all its load. So, starting with the largest particles, material begins to be deposited (Figure 3.22). Deposition occurs when:

- discharge is reduced following a period of low precipitation
- velocity is lessened on entering the sea or a lake (resulting in a delta)
- shallower water occurs on the inside of a meander (Figure 3.25)
- the load is suddenly increased (caused by debris from a landslide)
- the river overflows its banks so that the velocity outside the channel is reduced (resulting in a floodplain).

As the river loses energy, the following changes are likely:

- The heaviest or bedload material is deposited first. It is for this reason that the channels of mountain streams are often filled with large boulders (Figures 3.18 and 3.27). Large boulders increase the size of the wetted perimeter.
- Gravel, sand and silt – transported either as bedload or in suspension – will be carried further, to be deposited over the floodplain (Figure 3.31) or in the channel of the river as it nears its mouth (Figure 3.32).
- The finest particles of silt and clay, which are carried in suspension, may be deposited where the river meets the sea – either to infill an estuary or to form a delta (Figure 3.33).
- The dissolved load will not be deposited, but will be carried out to sea where it will help to maintain the saltiness of the oceans.

Places 10 Afon Glaslyn, North Wales: river processes

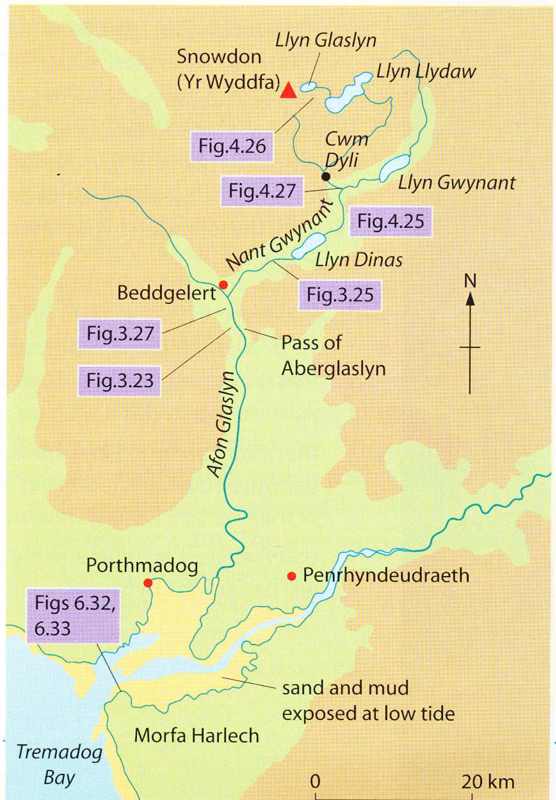


Figure 3.24
The Glaslyn Valley, North Wales

The Afon Glaslyn rises near the centre of the Snowdon massif and flows in a general southerly direction towards Tremadog Bay (Figure 3.24).

Figure 3.25
Erosion and deposition in the middle Afon Glaslyn

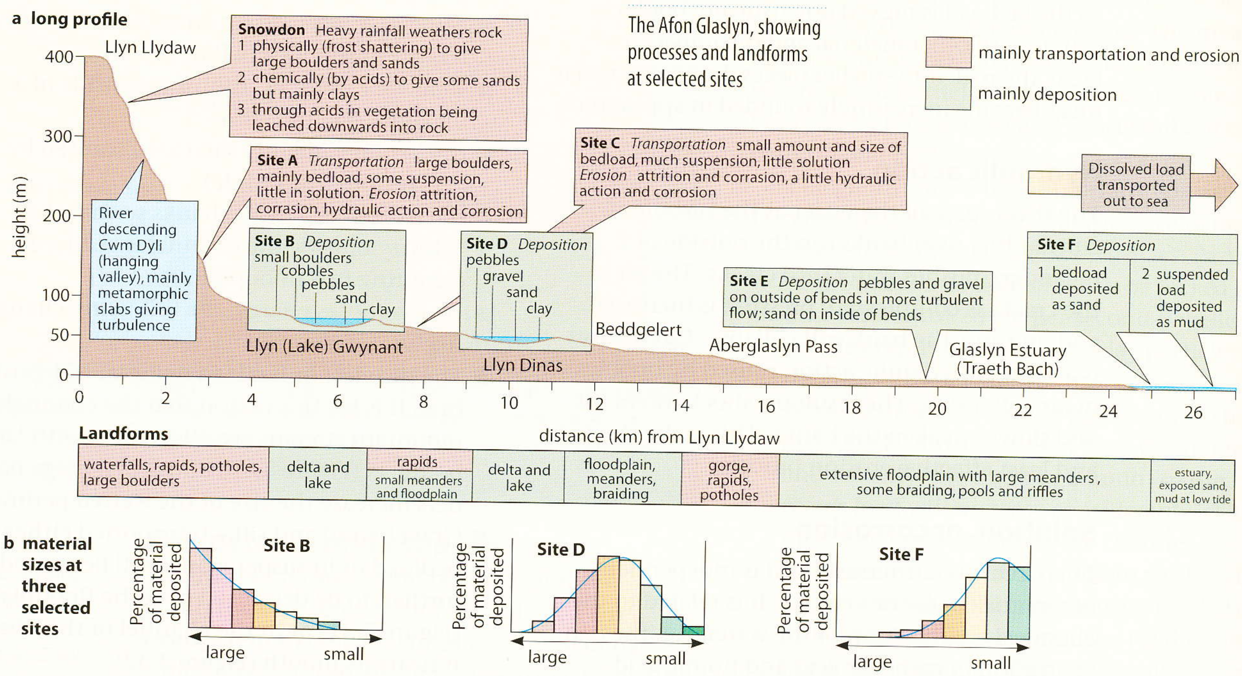


Figure 3.26

The Afon Glaslyn, showing processes and landforms at selected sites

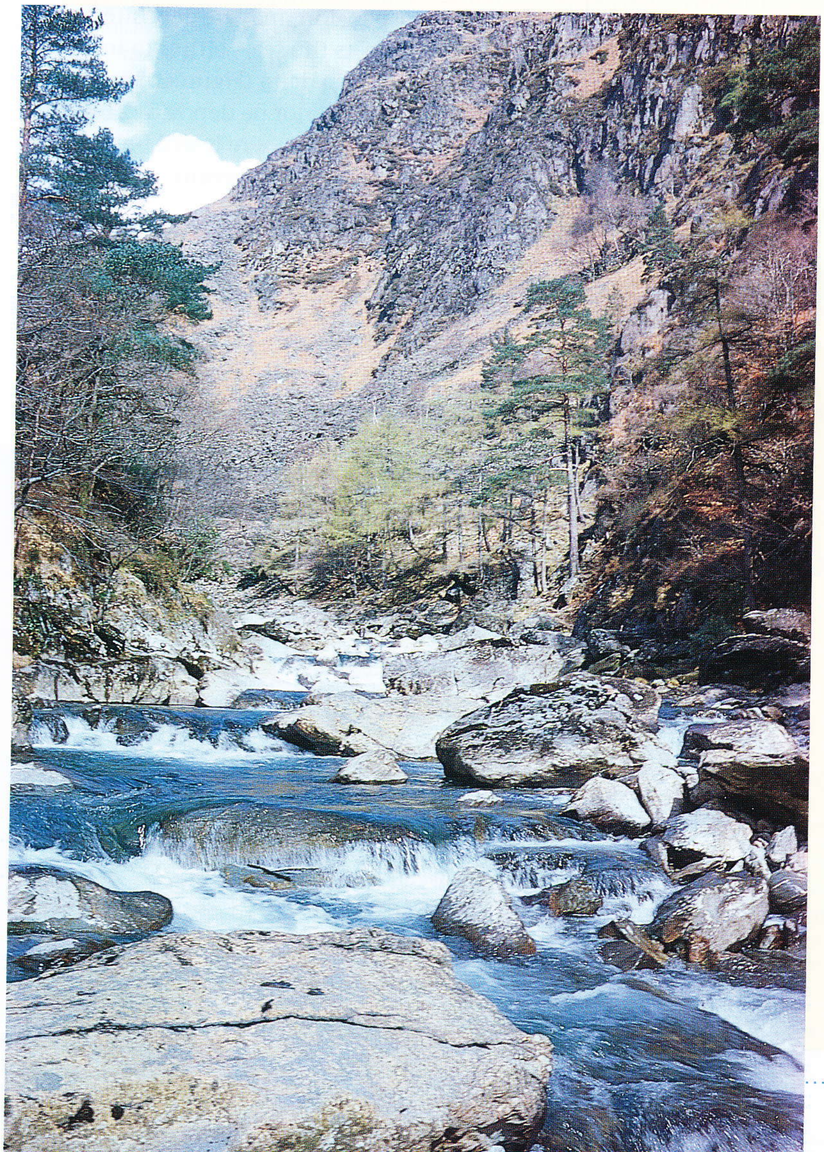


Figure 3.27

The boulder-strewn river bed of the upper Afon Glaslyn

The long profile of the Glaslyn, as shown in Figure 3.26, does not, however, match the smooth curve of the model shown in Figure 3.20. This is partly because of:

- the effect of glaciation in the upper course (Figure 4.25) and
- differences in rock structure in the middle course (the Aberglaslyn Pass in Figure 3.27).

Figure 3.26 (a summary of an Open University programme) shows the relationships between the processes of fluvial transportation, erosion and deposition. By studying this diagram, how likely are the following hypotheses (Framework 10, page 299):

- that as the competence of the river decreases, material is likely to be carried greater distances
- that the largest material, carried as the bedload, will be deposited first
- that material carried in suspension will be deposited over the floodplain or in the channel of the river as it nears its mouth
- that the finest material and the dissolved load will be carried out to sea?

Figure 3.28

V-shaped valley with interlocking spurs, small rapids and no floodplain: Peak District National Park

Fluvial landforms

As the velocity of a river increases, surplus energy becomes available which may be harnessed to transport material and cause erosion. Where the velocity decreases, an energy deficit is likely to result in depositional features.

Effects of fluvial erosion

V-shaped valleys and interlocking spurs

As shown in Figure 3.27, the channel of a river in its upper course is often choked with large, angular boulders. This bedload produces a large wetted perimeter which uses up much of the river's energy. Erosion is minimal because little energy is left to pick up and transport material. However, following periods of heavy rainfall or after rapid snowmelt, the discharge of a river may rise rapidly. As the water flows between boulders, turbulence increases and may result either in the bedload being taken up into suspension or, as is more usual because of its size, in its being rolled or bounced along the river bed. The result is intensive **vertical erosion** which enables the river to create a steep-sided valley with a characteristic V shape (Figure 3.28). The steepness of the valley sides depends upon several factors.

- **Climate** Valleys are steeper where there is sufficient rainfall:
  - **a** to instigate mass movement on the valley sides and
  - **b** to create sufficient discharge to allow the river to create enough energy to move its bedload and, therefore, to erode vertically, or
  - **c** for rivers to cross desert areas which have little rain to wash down the valley sides, e.g. the Grand Canyon (Figure 7.19).
- **Rock structure** Resistant, permeable rocks like Carboniferous limestone (Figure 8.5) often produce almost vertical sides in contrast to less resistant, impermeable rocks such as clay which are likely to produce more gentle slopes.
- **Vegetation** Vegetation may help to bind the soil together and thus keep the hillslope more stable.

Interlocking spurs form because the river is forced to follow a winding course around the protrusions of the surrounding highland. As the resultant spurs interlock, the view up or down the valley is restricted (Figure 3.28).

A process characteristic at the source of a river is **headward erosion**, or **spring sapping**. Here, where throughflow reaches the surface, the river may erode back towards its watershed as it undercuts the rock, soil and vegetation. Given time this can lead to river capture or piracy (page 85).

Waterfalls

A waterfall forms when a river, after flowing over relatively hard rock, meets a band of less resistant rock or, as is common in South America and Africa, where it flows over the edge of a plateau. As the water approaches the brink of the falls, velocity increases because the water in front of it loses contact with its bed and so is unhampered by friction (Figure 3.29). The underlying softer rock is worn away as water falls onto it. In time, the harder rock may become undercut and unstable and may eventually collapse. Some of this collapsed rock may be swirled around at the foot of the falls by turbulence, usually at times of high discharge, to create a deep **plunge pool**. As this process is repeated, the waterfall retreats upstream leaving a deep, steep-sided **gorge** (Places 11). At Niagara, where a hard band of limestone overlies softer shales and sandstone, the Niagara River plunges 50 m causing the falls to retreat by 1 m a year and so creating the Niagara Gorge.

Rapids

Rapids develop where the gradient of the river bed increases without a sudden break of slope (as in a waterfall) or where the stream flows over a series of gently dipping bands of harder rock. Rapids increase the turbulence of a river and hence its erosive power (Figure 3.27).

Places 11 Iguaçu Falls, Brazil: a waterfall

The Iguaçu River, a tributary of the Parana, forms part of the border between Brazil and Argentina. At one point along its course, the Iguaçu plunges 80 m over a 3 km wide, crescent-shaped precipice (Figure 3.30). The Iguaçu Falls occur where the river leaves the resistant basaltic lava which forms the southern edge of the Brazilian plateau and flows onto less resistant rock, while their crescent shape results from the retreat of the falls upstream (Figure 3.29).

By the end of the rainy season (January/February) up to 4 million litres of water a day can pour over the individual cascades – numbering up to 275 – which combine to form the falls. The main attraction is the Devil's Throat where 14 separate falls unite to create a deafening noise, volumes of spray, foaming water and a large rainbow. In contrast, by the end of the dry season (June/July), river levels may be very low – indeed, for one month in 1978 it actually dried up.

Figure 3.29 Fieldsketch of the Iguaçu Falls

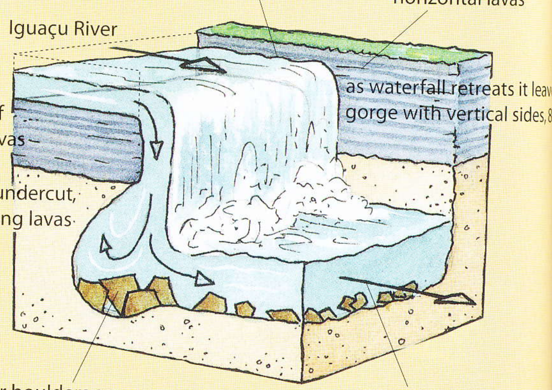


Figure 3.30 The Iguaçu Falls

Effects of fluvial deposition

Deposition of sediment takes place when there is a decrease in energy or an increase in capacity which makes the river less competent to transport its load. This can occur anywhere from the upper course, where large boulders may be left, to the mouth, where fine clays may be deposited.

Floodplains

Rivers have most energy when at their bankfull stage. Should the river continue to rise, then the water will cover any adjacent flat land. The land susceptible to flooding in this way is known as the **floodplain** (Figure 3.31 and Places 10, page 74). As the river spreads over its floodplain, there will be a sudden increase in both the wetted perimeter and the hydraulic radius. This results in an increase in friction, a corresponding decrease in velocity and the deposition of material previously held in suspension. The thin veneer of silt, deposited by each flood, increases the fertility of the land, while the successive flooding causes the floodplain to build up in height (as yet it has proved impossible to bore down to bedrock in the lower Nile valley). The floodplain may also be made up of material deposited as point bars on the inside of meanders (Figure 3.38) and can be widened by the **lateral erosion** of the meanders. The edge of the floodplain is often marked by a prominent slope known as the **bluff line** (Figure 3.31).

Levées

When a river overflows its banks, the increase in friction produced by the contact with the floodplain causes material to be deposited. The coarsest material is dropped first to form a small, natural embankment (or levée) alongside the channel (Figure 3.31). During subsequent periods of low discharge, further deposition will occur within the main channel causing the bed of the river to rise and the risk of flooding to increase. To try to contain the river, the embankments are sometimes artificially strengthened and heightened (the levée protecting St Louis from the Mississippi is 15.8 m higher than the floodplain which it is meant to protect). Some rivers, such as the Mississippi and Yangtze, flow above the level of their floodplains which means that if the levées collapse there can be serious damage to property, and loss of life (Case Study 3A).

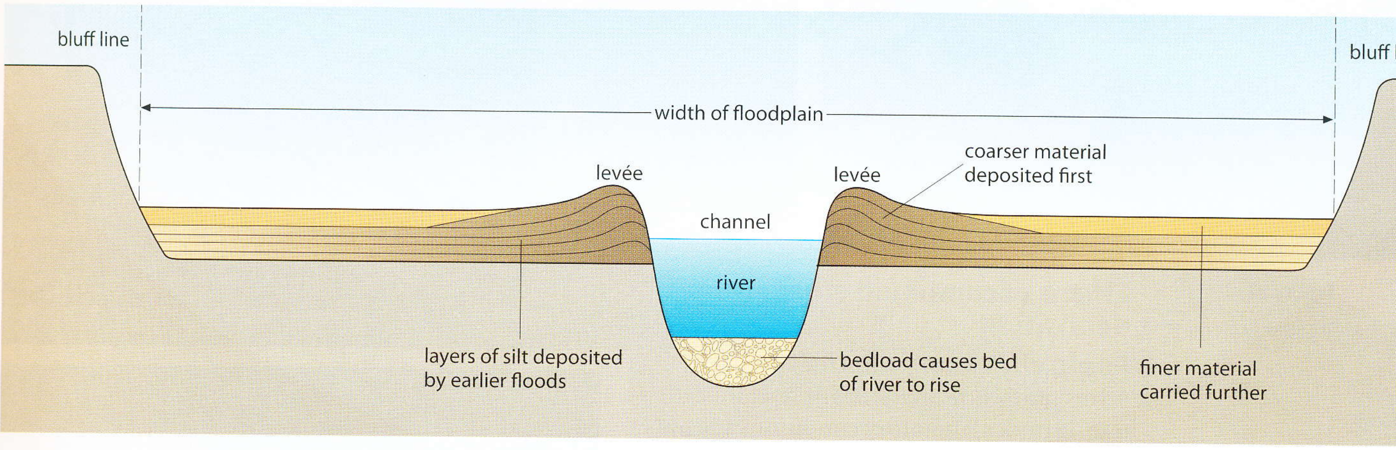


Figure 3.31

Cross-section of a floodplain showing levées and bluffs

Braiding

For short periods of the year, some rivers carry a very high load in relation to their velocity, e.g. during snowmelt periods in Alpine or Arctic areas. When a river's level falls rapidly, competence and capacity are reduced, and the channel may become choked with material, causing the river to braid – that is, to divide into a series of diverging and converging segments (Figures 3.32 and 5.16).

Figure 3.32

A braided river, South Island, New Zealand

Deltas

A delta is usually composed of fine sediment which is deposited when a river loses energy and competence as it flows into an area of slow-moving water such as a lake (Figure 4.22) or the sea. When rivers like the Mississippi or the Nile reach the sea, the meeting of fresh and salt water produces an electric charge which causes clay particles to coagulate and to settle on the seabed, a process called **flocculation**.

Deltas are so called because it was thought that their shape resembled that of delta, the fourth letter of the Greek alphabet (Δ). In fact, deltas vary greatly in shape but geomorphologists have grouped them into three basic forms:

- **arcuate:** having a rounded, convex outer margin, e.g. the Nile
- **cuspate:** where the material brought down by a river is spread out evenly on either side of its channel, e.g. the Tiber
- **bird's foot:** where the river has many distributaries bounded by sediment and which extend out to sea like the claws of a bird's foot, e.g. the Mississippi (Figure 3.33).

Although deltas provide some of the world's most fertile land, their flatness makes them high flood-risk areas, while the shallow and frequently changing river channels hinder navigation.

Figure 3.33

The Mississippi delta

Figure 3.35

A pool and riffles in the River Gelt, Cumbria

Effects of combined erosion and deposition

Pools, riffles and meanders

Rivers rarely flow in a straight line. Indeed, testing under laboratory conditions suggests that a straight course is abnormal and unstable. How meanders begin to form is uncertain, but they appear to have their origins during times of flood and in relatively straight sections where pools and riffles develop (Figure 3.34). The usual spacing between **pools**, areas of deeper water, and **riffles**, areas of shallower water, is usually very regular, being five to six times that of the bed width. The pool is an area of greater erosion where the available energy in the river builds up due to a reduction in friction. Energy is dissipated across the riffle area. As a higher proportion of the total energy is then needed to overcome friction, the erosive capacity is decreased and, except at times of high discharge, material is deposited (Figure 3.35). The regular spacings of pools and riffles, spacings which are almost perfect in an alluvial stretch of river, are believed to result from a series of secondary flows which exist within the main flow. Secondary flows include **helicoidal flow**, a corkscrew movement, as shown in Figure 3.15b, and a series of converging and diverging lateral rotations. Helicoidal flow is believed to be responsible for moving material from the outside of one meander bend and then depositing much of it on the inside of the next bend. It is thought, therefore, that it is the secondary flows that increase the sinuosity (the curving nature) of the meander (Figure 3.36), producing a regular meander wavelength which is about ten times that of the bed width. Sinuosity is described as:

$$\frac{\text{actual channel length}}{\text{straight-line distance}}$$

Figure 3.34

A possible sequence in the development of a meander

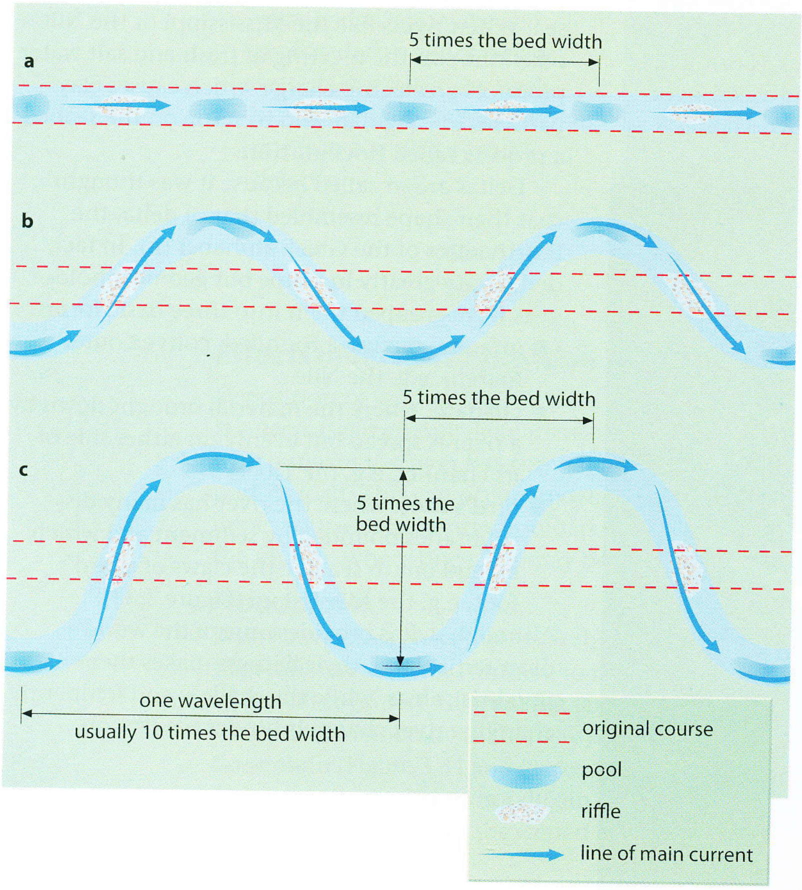


Figure 3.36

Meanders on the River Cuckmere, East Sussex

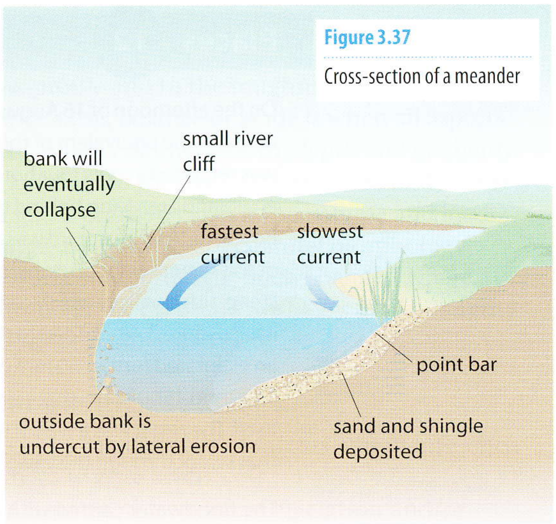


Figure 3.37

Cross-section of a meander

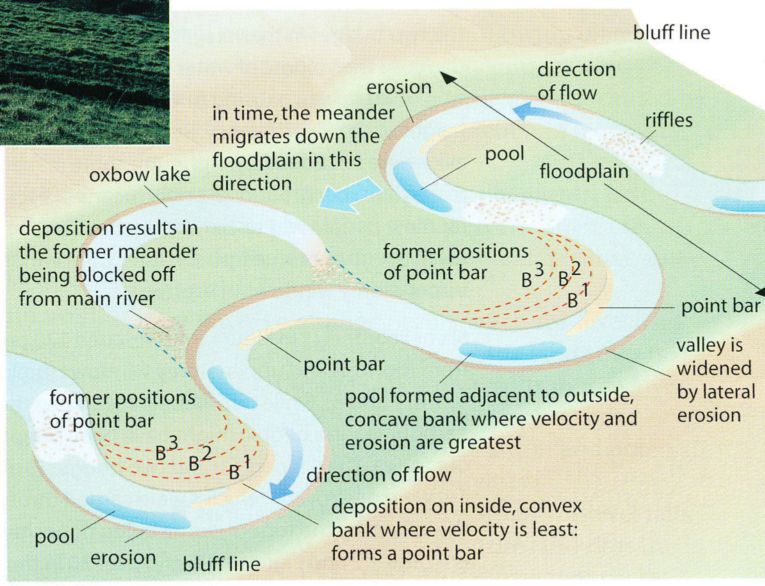


Figure 3.38

Meanders, point bars and oxbow lakes, showing migration of meanders and changing positions of point bars over time

Figure 3.39

Meanders and oxbow lakes, Alaska, USA

Meanders, point bars and oxbow lakes

A meander has an asymmetrical cross-section (Figure 3.37) formed by erosion on the outside bend, where discharge and velocity are greatest and friction is at a minimum, and deposition on the inside, where discharge and velocity are at a minimum and friction is at its greatest (Figure 3.25). Material deposited on the convex inside of the bend may take the form of a curving **point bar** (Figure 3.38). The particles are usually graded in size, with the largest material being found on the upstream side of the feature (there is rarely any gradation up the slope itself). As erosion continues on the outer bend, the whole meander tends to migrate slowly downstream. Material forming the point bar becomes a contributory factor in the formation of the floodplain. Over time, the sinuosity of the meander may become so pronounced that, during a flood, the river cuts through the narrow neck of land in order to shorten its course. Having achieved a temporary straightening of its channel, the main current will then flow in mid-channel. Deposition can now take place next to the banks and so, eventually, the old curve of the river will be abandoned, leaving a crescent-shaped feature known as an **oxbow lake** or **cutoff** (Figures 3.38 and 3.39).

Places 12 Boscastle, Cornwall: a flash flood

On the afternoon of 16 August 2004, 200.2 mm of rainfall – the equivalent of three normal months – was recorded in only four hours on Bodmin Moor, an upland area lying behind the Cornish village of Boscastle. As the ground was already saturated, most of this water swept downhill and through two narrow, steep-sided valleys which converged on the village itself (Figure 3.40). Added to this volume of water was an estimated further 50 mm of rain that fell between 1300 and 1500 hours that same afternoon on Boscastle itself. The result was a wall of water over 3 m in height that swept through the village (Figure 3.41).

The floodwater carried with it cars, tree branches and other debris which became trapped behind the two bridges in the village, which then acted as dams. As the volume of water increased the bridges were swept away, causing further surges in the height of the River Valency. Residents and tourists alike were forced to flee. Although some managed to reach higher ground, the only means of escape for most people was to clamber upstairs and to await eventual rescue by helicopter from either upper-storey windows or rooftops.

Six helicopters (1 in Figure 3.42) rescued 120 people from rooftops and upper-storey windows (buildings 4, 5, 6, 7 and 8), while two lifeboats searched the harbour fearing people might have been swept out to sea. The car park (2) and two bridges (9 and 16) were destroyed. Vehicles were carried through the village by the torrent, some being deposited en route (12 and Figure 3.41) and over 30 in the harbour. Two shops (10 and 17) and four houses were destroyed while other buildings were badly damaged including the Visitor Centre (3) and two tourist shops (11 and 15). Among buildings flooded was a restaurant (13) and the village store (4), museum (14) and Youth Hostel (18). Power had to be switched off to protect rescuers and survivors from electrocution. When the floodwater receded, the village was left under a carpet of thick brown mud.

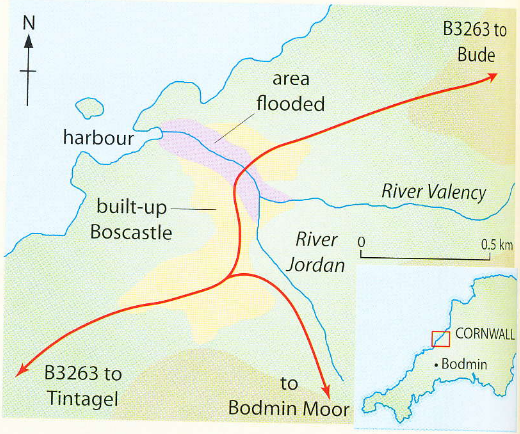


Figure 3.40

The flood at Boscastle

Figure 3.42

Annotated photo from the *Daily Telegraph*, Tuesday 17 August 2004

Figure 3.41

Water rages through the village of Boscastle carrying cars with it

Base level and the graded river

Base level

This is the lowest level to which erosion by running water can take place. In the case of rivers, this theoretical limit is sea-level. Exceptions occur when a river flows into an inland sea (e.g. the River Jordan into the Dead Sea) and if there happens to be a temporary **local base level**, such as where a river flows into a lake, where a tributary joins a main river, or where there is a resistant band of rock crossing a valley.

Grade

The concept of **grade** is one of a river forming an open system (Framework 3, page 45) in a state of dynamic equilibrium where there is a balance between the rate of erosion and the rate of deposition. In its simplest interpretation, a graded river has a gently sloping long profile with the gradient decreasing towards its mouth (Figure 3.43a). This balance is always transitory as the slope (profile) has to adjust constantly to changes in discharge and sediment load. These can cause short-term increases in either the rate of erosion or deposition until the state of equilibrium has again been reached. This may be illustrated by two situations:

- The long profile of a river happens to contain a waterfall and a lake (Figure 3.43b). Erosion is likely to be greatest at the waterfall, while deposition occurs in the lake. In time, both features will be eliminated.
- There is a lengthy period of heavy rainfall within a river basin. As the volume of water rises and consequently the velocity and load of the river increase, so too will the rate of erosion. Ultimately, the extra load carried by the river leads to extra deposition further down the valley or out at sea.

In a wider interpretation, grade is a balance not only in the long profile, but also in the river's cross-profile and in the roughness of its channel. In this sense, balance or grade is when all aspects of the river's channel (width, depth and gradient) are adjusted to the discharge and load of the river at a given point in time. If the volume and load change, then the river's channel morphology must adjust accordingly. Such changes, where and when they do occur, are likely to take lengthy periods of geological time.

Changes in base level

There are three groups of factors which influence changes in base level:

- **Climatic:** the effects of glaciation and/or changes in rainfall.
- **Tectonic:** crustal uplift, following plate movement, and local volcanic activity.
- **Eustatic and isostatic adjustment:** caused by the expansion and contraction of ice sheets (page 123).

As will be seen in Chapter 6, changes in base level affect coasts as well as rivers. There are two types of base level movement: positive and negative.

- **Positive change** occurs when sea-level rises in relation to the land (or the land sinks in relation to the sea). This results in a decrease in the gradient of the river with a corresponding increase in deposition and potential flooding of coastal areas.
- **Negative change** occurs when sea-level falls in relation to the land (or the land rises in relation to the sea). This movement causes land to emerge from the sea, steepening the gradient of the river and therefore increasing the rate of fluvial erosion. This process is called **rejuvenation**.

Figure 3.43

River profiles

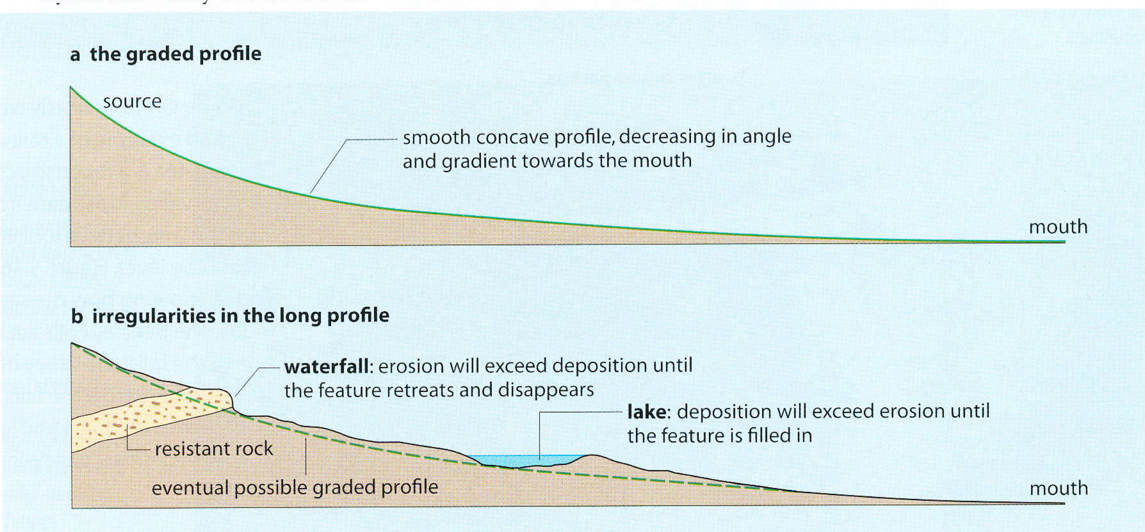


Figure 3.44

The effect of rejuvenation on the long profile

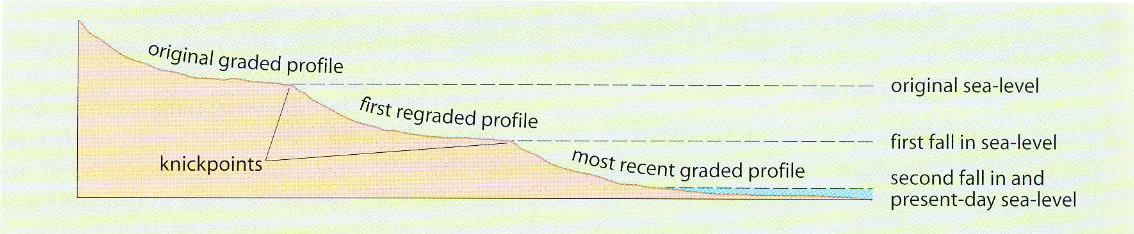


Figure 3.45

A rejuvenated river, Antalya, Turkey: the land has only recently experienced tectonic uplift and the river has had insufficient time to re-adjust to the new sea-level

Rejuvenation

A negative change in base level increases the potential energy of a river, enabling it to revive its erosive activity; in doing so, it upsets any possible graded long profile. Beginning in its lowest reaches, next to the sea, the river will try to regrade itself.

During the Pleistocene glacial period, Britain was depressed by the weight of ice. Following deglaciation, the land slowly and intermittently rose again (**isostatic uplift**, page 123). Thus rejuvenation took place on more than one occasion, with the result that many rivers today show several partly graded profiles (Figure 3.44). Where the rise in the land (or drop in sea-level) is too rapid to allow a river sufficient time to erode vertically to the new sea-level, it may have to descend as a waterfall over recently emerged sea cliffs (Figure 3.45). In time, the river will cut downwards and backwards and the waterfall will retreat upstream. The **knickpoint**, usually indicated by the presence of a waterfall, marks the maximum extent of the newly graded profile (Places 13). Should a river become completely regraded, which is unlikely because of the timescale involved, the knickpoint and all of the original graded profile will disappear.

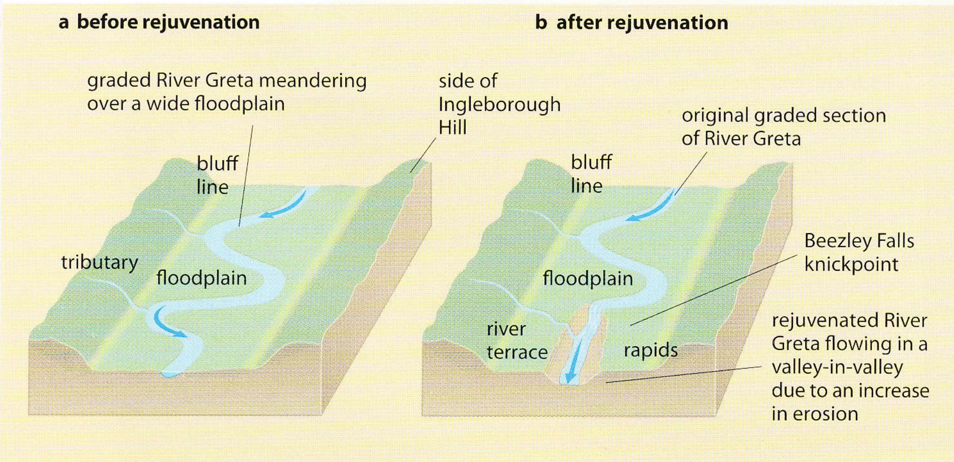
River terraces and incised meanders

River terraces are remnants of former floodplains which, following vertical erosion caused by rejuvenation, have been left high and dry above the maximum level of present-day flooding. They offer excellent sites for the location of towns (e.g. London, Figures 3.47 and 14.9). Above the present floodplain of the Thames at London are two earlier ones forming the Taplow and Boyn Hill terraces. If a river cuts rapidly into its floodplain, a pair of terraces of equal height may be seen flanking the river and creating a **valley-in-valley** feature. However, more often than not, the river cuts down relatively slowly, enabling it to meander at the same time. The result is that the terrace to one side of the river

Figure 3.46

The River Greta (*after* D.S. Walker)

Places 13 River Greta, Yorkshire Dales National Park: a rejuvenated river



The River Greta, in north-west Yorkshire, is a good example of a rejuvenated river. Figure 3.46a is a reconstruction to show what its valley (upstream from the village of Ingleton) might have looked like before the fall in base level. Figure 3.46b is a simplified sketch showing how the same area appears today. The Beezley Falls are a knickpoint. Above the falls, the valley has a wide, open appearance. Below the falls, the river flows over a series of rapids and smaller falls in a deep, steep-sided 'valley-in-valley'.

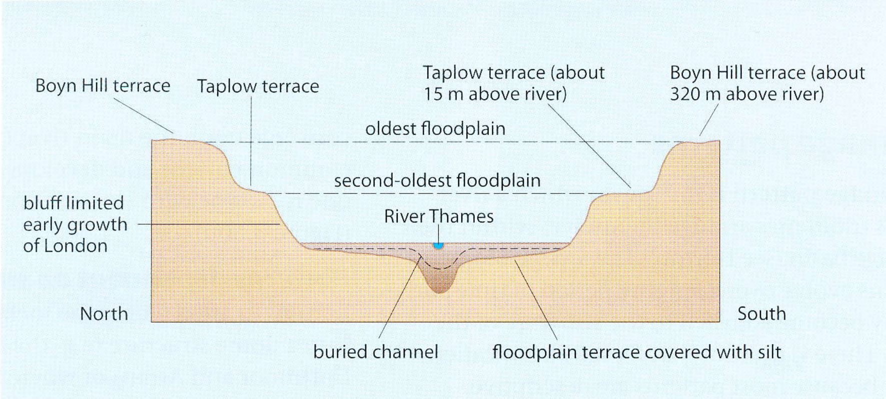


Figure 3.47

Cross-section illustrating the paired river terraces of the Thames at London

may be removed as the meanders migrate downstream. Figure 3.49 shows terraces, not paired, on a small stream crossing a beach on southern Arran. In this case, rejuvenation takes place twice daily as the tide ebbs and sea-level falls.

If the uplift of land (or fall in sea-level) continues for a lengthy period, the river may cut downwards to form incised meanders. There are two types of incised meander. **Entrenched meanders** have a symmetrical cross-section and result from either a very rapid incision by the river, or the valley sides being resistant to erosion (the River Wear at Durham, Figures 3.48a and 14.6). **Ingrown meanders** occur when the uplift of the land, or incision by the river, is less rapid, allowing the river time to shift laterally and to produce an asymmetrical cross-valley shape (the River Wye at Tintern Abbey, Figure 3.48b). As with meanders in the lower course of a normal river, incised meanders can also change their channels to leave an abandoned meander with a central **meander core** (Figure 3.48b).

Figure 3.48

Incised meanders and associated cross-valley profiles

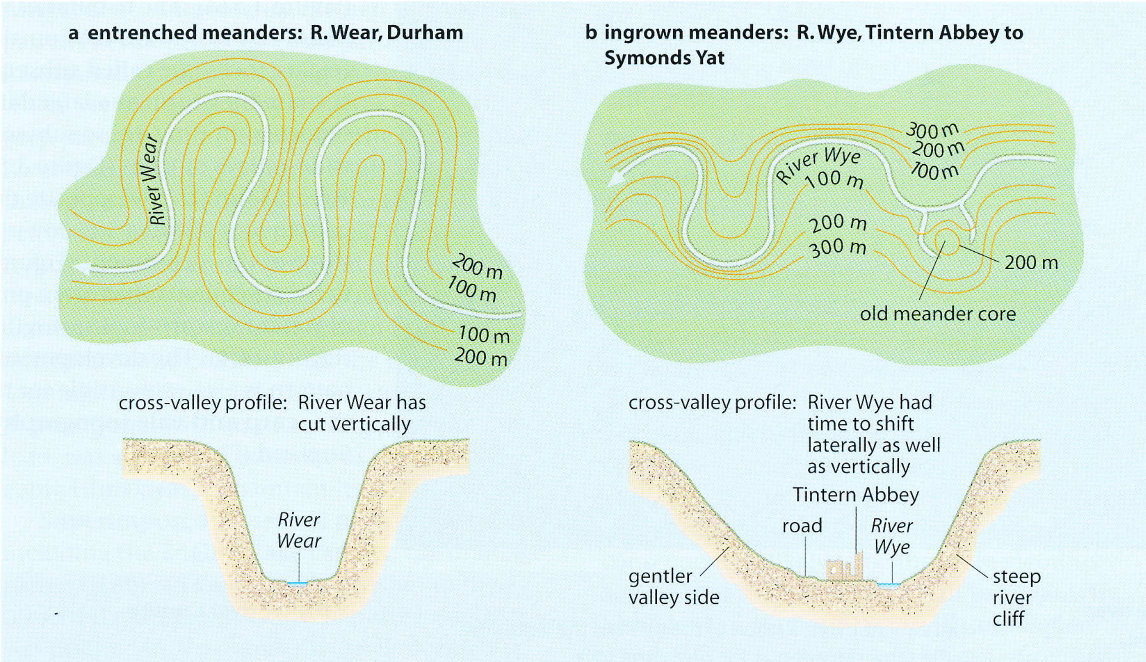


Figure 3.49

Rejuvenation on a micro scale: a small stream crossing a beach at Kildonan, Arran, has cut downwards to the level of the falling tide – note the ingrown meander, river terraces and valley-in-valley features

Drainage patterns

A **drainage pattern** is the way in which a river and its tributaries arrange themselves within their drainage basin (see Horton's Laws, page 65). Most patterns evolve over a lengthy period of time and usually become adjusted to the structure of the basin. There is no widely accepted classification, partly because most patterns are descriptive.

Patterns independent of structure

Parallel This, the simplest pattern, occurs on newly uplifted land or other uniformly sloping surfaces which allow rivers and tributaries to flow downhill more or less parallel with each other, e.g. rivers flowing south-eastwards from the Aberdare Mountains in Kenya (Figure 3.50a).

Dendritic Deriving its name from the Greek word dendron, meaning a tree, this is a tree-like pattern in which the many tributaries (branches) converge upon the main river (trunk). It is a common pattern and develops in basins having one rock type with no variations in structure (Figure 3.50b).

Patterns dependent on structure

Radial In areas where the rocks have been lifted into a dome structure (e.g. the batholiths of Dartmoor and Arran) or where a conical volcanic cone has formed (e.g. Mount Etna), rivers radiate outwards from a central point like the spokes of a wheel (Figure 3.50c).

Trellised or rectangular In areas of alternating resistant and less resistant rock, tributaries will form and join the main river at right-angles (Figure 3.50d). Sometimes each individual segment is of approximately equal length. The main river, called a **consequent river** because it is a consequence of the initial uplift or slope (compare parallel drainage), flows in the same direction as the dip of the rocks (Figure 3.51a). The tributaries which develop, mainly by headward erosion along areas of weaker rocks, are called **subsequent streams** because they form at a later date than the consequents. In time, these subsequents create wide valleys or vales (Figure 3.51b). **Obsequent streams** flow in the opposite direction from the consequent streams, i.e. down the steep scarp slope of the escarpment (Figure 3.51b). It is these obsequents that often provide the sources of water for scarp-foot springline settlements (Figure 14.4). The development of this drainage pattern is also responsible for the formation of the **scarp and vale topography** of south-east England (Figure 8.9).

Figure 3.50

Drainage patterns

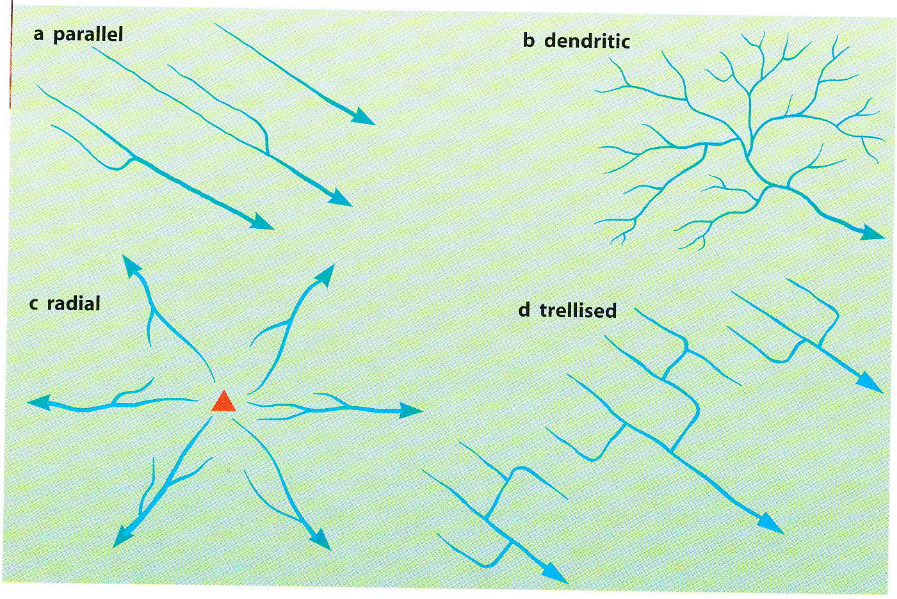
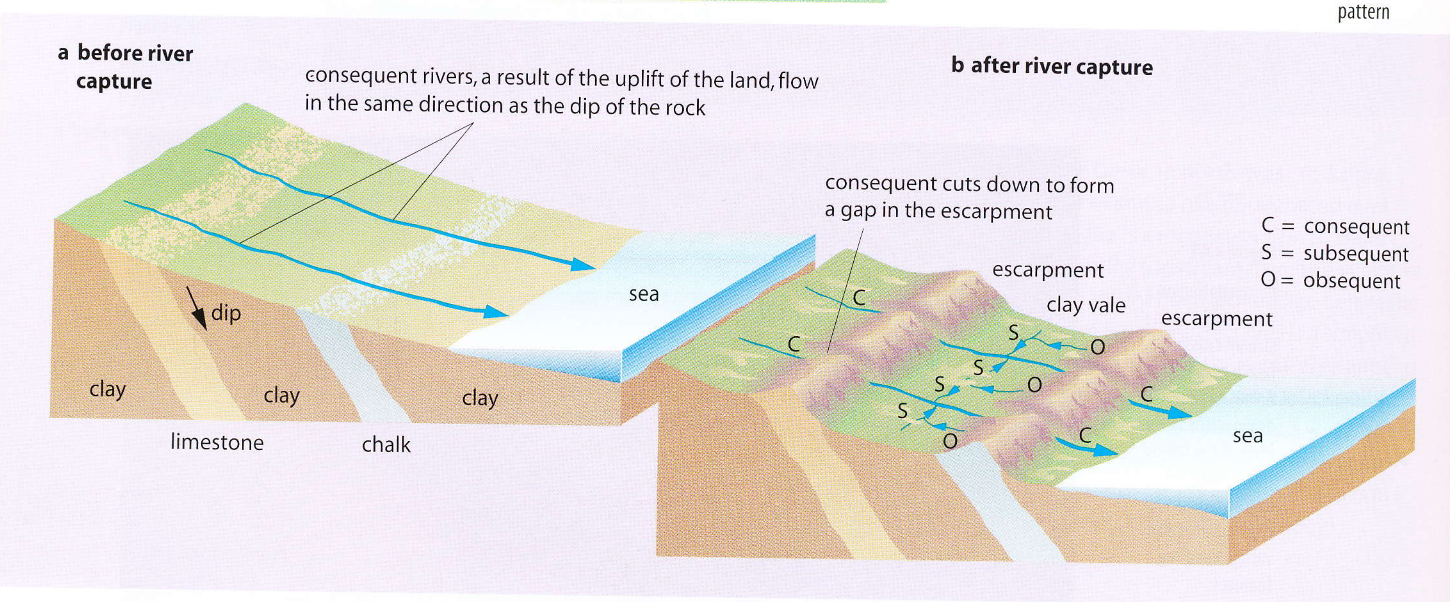


Figure 3.51

Development of a trellised drainage pattern



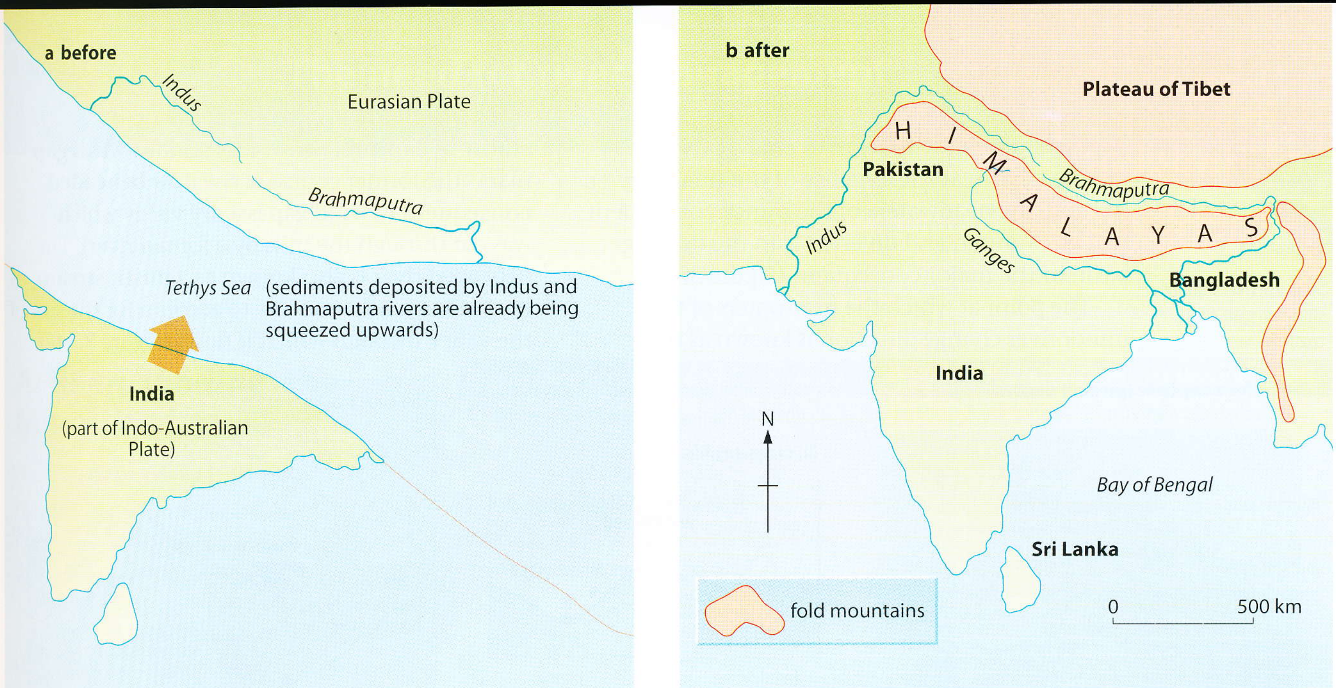


Figure 3.52

Antecedent drainage, Himalayas

Patterns apparently unrelated to structure

Antecedent Antecedence is when the drainage pattern developed before such structural movements as the uplift or folding of the land, and where vertical erosion by the river was able to keep pace with the later uplift. The Brahmaputra River rises in Tibet, but turns southwards to flow through a series of deep gorges in the Himalayas before reaching the Bay of Bengal (Figure 3.52). It must at one stage have flowed southwards into the Tethys Sea (Figure 1.4) which had existed before the Indo-Australian Plate moved northwards and collided with the Eurasian Plate forming the Himalayas (pages 19 and 20). The Brahmaputra, with an increasing gradient and load, was able to cut downwards through the rising Himalayas to maintain its original course.

Superimposed In several parts of the world, including the English Lake District, the drainage pattern seems to have no relationship to the present-day surface rocks. When the Lake District was uplifted into a dome, the newly-formed volcanic rocks were covered by sedimentary limestones and sandstones. The radial drainage pattern which developed, together with later glacial processes, cut through and ultimately removed the surface layers of sedimentary rock to superimpose itself upon the underlying volcanic rocks.

River capture

Rivers, in attempting to adjust to structure, may capture the headwaters of their neighbours. For example, most eastward-flowing English rivers between the Humber and central Northumberland have had their courses altered by **river capture** or **piracy** (Figure 3.53).

Figure 3.54a shows a case where there are two consequent rivers with one having a greater discharge and higher erosional activity than the other. Each has a tributary (subsequents X and Y) flowing along a valley of weaker rock, but subsequent X (the tributary of the master, or larger, consequent) is likely to be the more vigorous. Subsequent X will, therefore, cut backwards by headward erosion until it reaches subsequent Y (the tributary of the weaker consequent); then, by a process known as **watershed migration**

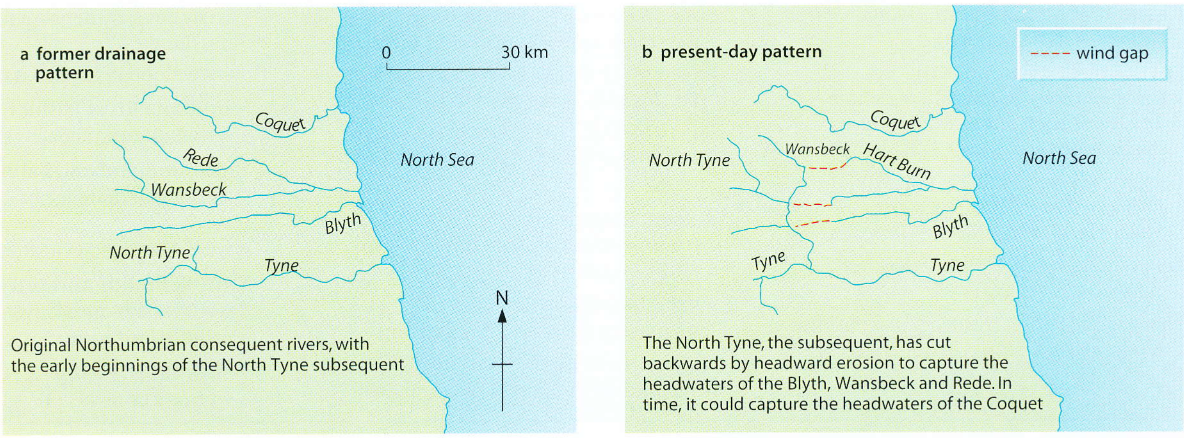


Figure 3.53

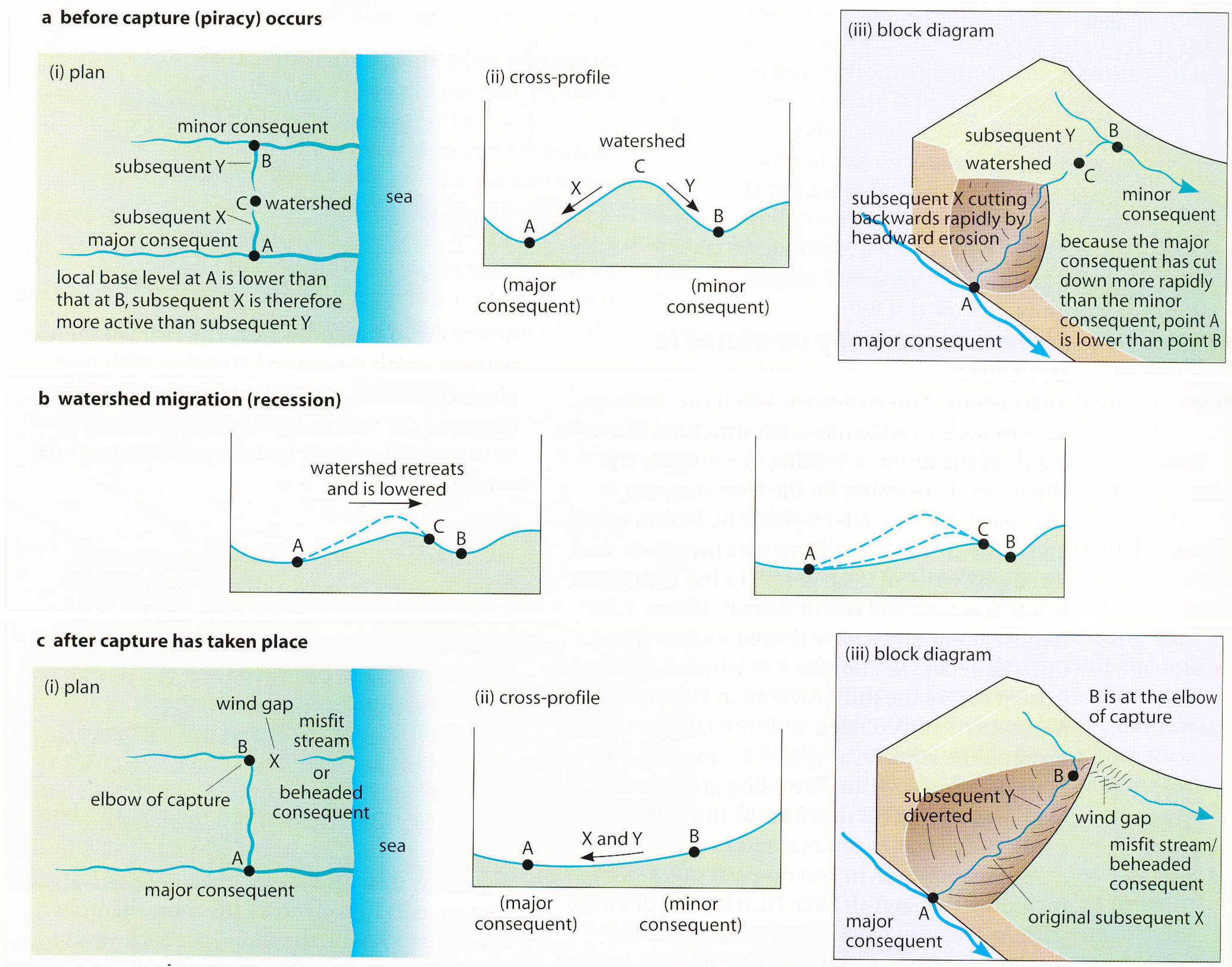
River capture, Northumberland

(Figure 3.54b), it will begin to enlarge its own drainage basin at the expense of the smaller river. In time, the headwaters of the minor consequent will be captured and diverted into the drainage basin of the major consequent (Figure 3.54c).

The point at which the headwaters of the minor river change direction is known as the **elbow of capture**. Below this point, a **wind gap** marks the former course of the now **beheaded consequent** (a wind gap is a dry valley which was cut through the hills by a former river). The beheaded river is also known as a **misfit stream**, as its discharge is far too low to account for the size of the valley through which it flows (Figure 3.54c).

Figure 3.54

Stages in river capture shown in plan and cross-profile



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www.broads-authority.gov.uk/managing/rivers-and-broads.html

Environment Agency, environmental information index (UK rivers, floods):
www.environment-agency.gov.uk/?lang=_e
www.floodarchive.co.uk

Minnesota River Basin:
www.soils.umn.edu/research/mn-river/

Newfoundland and Labrador site (examples of drainage basins and flood-risk zones):
www.heritage.nf.ca/sitemap.html

Norfolk Broads Authority:
www.broads-authority.gov.uk/broads/pages/river4.html

Yellow River, China:
www.cis.umassd.edu/~gleung/

A River flooding: the Mississippi, 1993

Flooding by rivers is a natural event which, because people often choose to live in flood-risk areas, becomes a hazard (page 31). To people living in the Mississippi valley, 'that their river should flood is as natural as sunshine in Florida or snowfall in the Rockies'. Without human intervention, the Mississippi would flood virtually every year. Indeed, it has been this frequency of flooding which has, over many centuries, allowed today's river to flow for much of its course over a wide, fertile, flat, alluvial floodplain (Figures 3.55 and 3.56).

Figure 3.55

The flood hazard and the Mississippi River

Enquiry route on river flooding	Application to a specific event: the Mississippi, 1993
1 Where is the river/drainage basin located?	The Mississippi – together with its main tributaries, the Missouri and the Ohio – drains one-third of the USA and a small part of Canada (Figure 3.56).
2 What is the frequency of flooding?	Left to its own devices, flooding would be an almost annual event with late spring being the peak period.
3 What is the magnitude of flooding?	Until recently, major floods occurred every 5–10 years (there were six in the 1880s) and a serious/extreme flood occurred approximately once every 40 years.
4 What are the natural causes of flooding?	Usually it results from heavy rainfall (January–May) in the Appalachian Mountains, especially if this coincides with snowmelt (Figure 3.56).
5 What are the consequences of flooding?	Initially, it was to develop the wide, alluvial floodplain. The 1927 flood caused 217 deaths; 700 000 people were evacuated; the river became up to 150 km wide (usual width 1 km); livestock and crops were lost; services were destroyed.
6 What attempts can be made to reduce the flood hazard?	Until the 1927 flood, the main policy was 'hold by levées' – by 1993, some levées were 15 m high (Figure 3.57). After 1927, new schemes included building dams and storage reservoirs (6 huge dams and 105 reservoirs on Missouri); afforestation to reduce/delay runoff; creating diversion spillways (e.g. Bonnet Carré floodway diverts floodwater into Lake Pontchartrain and the sea); cutting through meanders to straighten and shorten the course (Figure 3.57).
7 How successful have the attempts to reduce flooding been?	In 1883, Mark Twain claimed that 'You cannot tame that lawless stream'. By 1973, it appeared that the river had been tamed: there was no further flooding . . . until 1993. Has human intervention made the danger worse? (page 96)

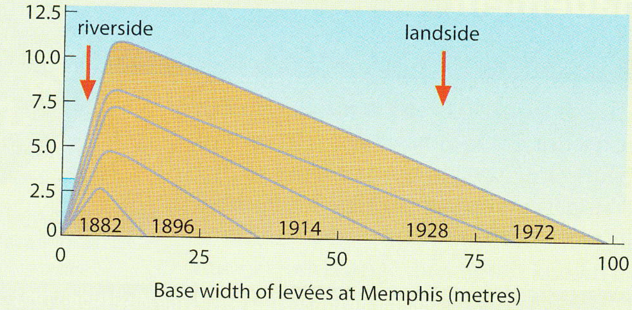
Usually, of course, the great floods occur in the lower river, in the last 1 600 km below Cairo, Illinois. This is where the plain flattens out (the river drops less than 120 m from here to its mouth) and where the Ohio and Tennessee flow into the Mississippi.

Of the water that flows past Memphis, only about 38 per cent comes from the Missouri–Mississippi network. The bulk comes from the Ohio and Tennessee, from the lush Appalachians, rather than the dry Mid-West. 'We don't mind too much about the Missouri,' says Donna Willett, speaking for the US Army Corps of Engineers (who have the responsibility of flood prevention). 'It can rain there for weeks, and we wouldn't mind. We can handle three times the water coming down in those floods. But the Ohio, well, that's another story. When that starts rising, we start watching ...'

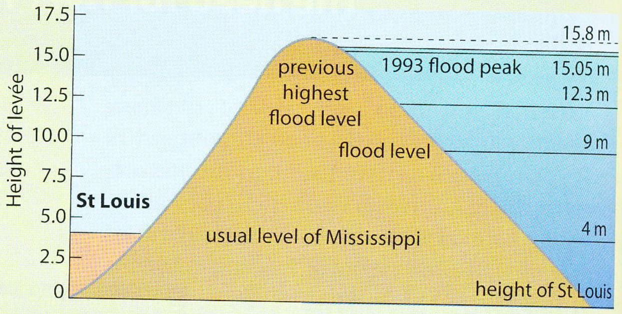
Figure 3.56

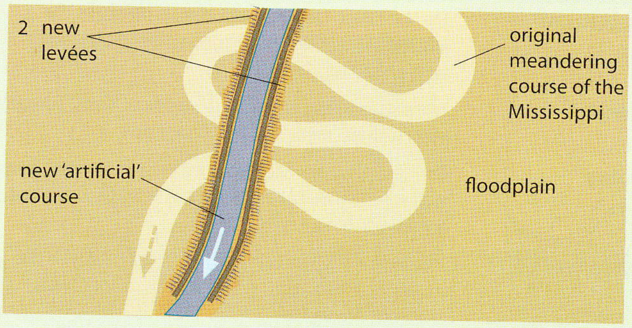
Flooding in the Mississippi Basin

1a Height (metres) of levées at Memphis



b The 1993 flood at St Louis





By making the course straighter and shorter, floodwater could be removed from the river basin as quickly as possible. It was achieved by cutting through the narrow necks of large meanders. Between 1934 and 1945 one stretch of the river alone was reduced from 530 km to almost 230 km. By shortening the distance, the gradient and therefore the velocity of the river increases. (But rivers try to create meanders rather than flow naturally in straight courses.)

Figure 3.57

Two engineering schemes to try to control flooding

Engineering/planning schemes in the Mississippi basin

Prior to the 1993 flood, it was perceived that the flow of the Mississippi had been controlled. This had been achieved through a variety of flood prevention schemes (Figure 3.57).

- Levées had been heightened, in places to over 15 m, and strengthened. There were almost 3000 km of levées along the main river and its tributaries.
- By cutting through meanders, the Mississippi had been straightened and shortened: for 1750 km, it flows in artificial channels.
- Large spillways had been built to take excess water during times of flood.
- The flow of the major tributaries (Missouri, Ohio and Tennessee) had been controlled by a series of dams.

Why did the Mississippi flood in 1993?

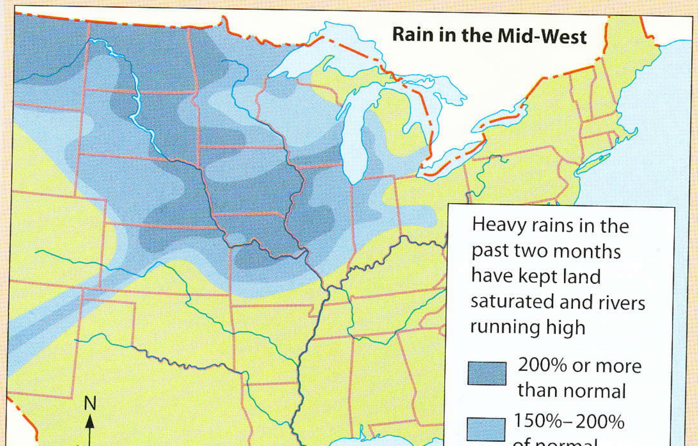
The Mid-West was already having a wet year when record-setting spring and summer rains hit. The rain ran off the soggy ground and into rapidly rising rivers. Several parts of the central USA had over 200 per cent more rain than was usual for the time of year (Figure 3.58). It was the ferocity, location and timing of the flood that took everyone by surprise. Normally, river levels are falling in midsummer, the upper Mississippi was not perceived to be the major flood-risk area, and people believed that flooding in the basin had been controlled. Floodwater at St Louis reached an all-time high (Figure 3.58). Satellite photographs showed the extent of the flooding (Figure 3.59). Figure 3.60 describes some of its effects.

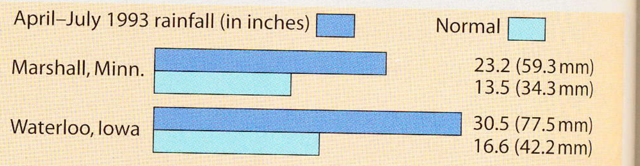
After the flood: should rivers run freer?

Since the first levée was built on the Mississippi in 1718, engineers have been channelling the river to protect farmland and towns from floodwaters. But have the levées, dams and diversion channels actually aggravated the flooding? There are two schools of thought. One advocates accepting that rivers are part of a complex ecological balance and that flooding should be allowed as a natural event (Figure 3.71). The other argues for better defences and a more effective control of rivers (Figure 3.70).

Figure 3.58

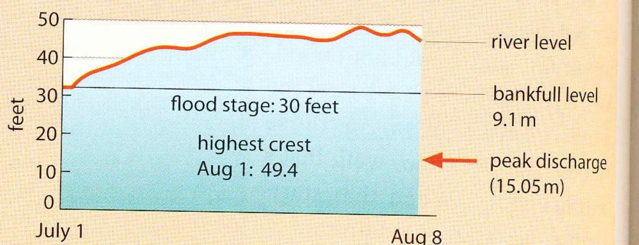
Extract from *US Today*, a daily newspaper





St Louis

Although there were some nervous moments, the city's massive 11-mile long, 52-foot floodwall protected the downtown from flooding. The river crested here August 1 at a record 49.4 feet, and the amount of water flowing past the Gateway Arch surpassed a record 1 million cubic feet per second.



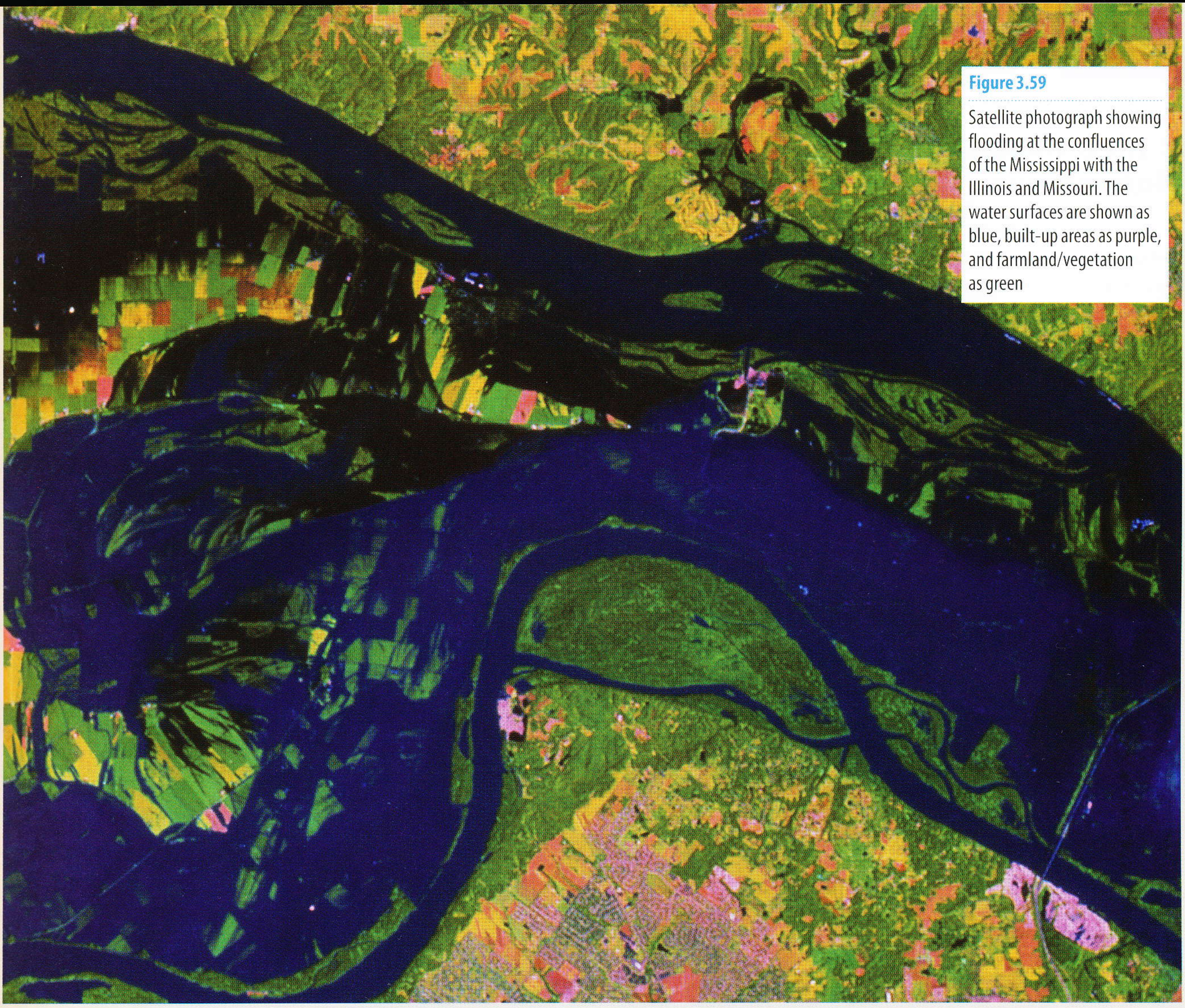


Figure 3.59

Satellite photograph showing flooding at the confluences of the Mississippi with the Illinois and Missouri. The water surfaces are shown as blue, built-up areas as purple, and farmland/vegetation as green

Figure 3.60

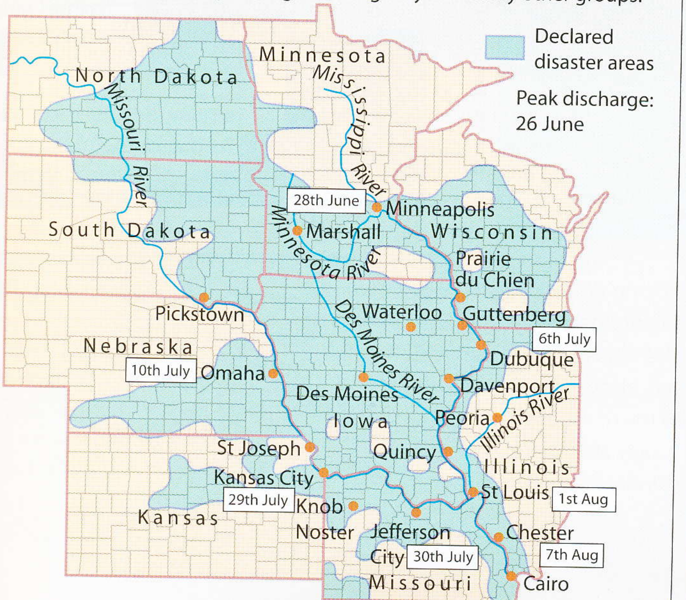
The consequences of flooding in the St Louis area

US Today, 9 August 1993

Flood of '93

Damage	Deaths	Evacuated	Houses	Crops
$10.5 billion	45	74 000	45 000	$6.5 billion

Nearly half of the counties in nine states bordering the upper reaches of the Mississippi and Missouri rivers have been declared federal disaster areas. This is the first step in becoming eligible for federal aid, including direct grants from Congress, Federal Emergency Management Agency and many other groups:



Illinois: In the fight against flooding rivers, 17 levées were breached, including one that flooded the town of Valmeyer and 70000 acres of surrounding farmland. One flood-related death was reported.

In Alton, the treatment plant was flooded Aug 1, cutting off water to the town's 33000 residents. "Our levee did not breach, but the water came in through the street, the drains, anywhere there was a hole, at such a rate that pumps couldn't keep up," says Mayor Bob Towse.

Statewide property losses may top $365 million, including damage to 140 miles of roads and eight bridges. Agricultural damage is estimated at more than $610 million. An estimated 4% of the state's cropland—900000 acres—was flooded. In addition, 15727 people were displaced, 860 businesses closed and nearly 9000 jobs lost.

Missouri: The highest death toll—25—and the greatest property damage—$1.3 billion—of all flooded states were reported here. Statewide, 13 airports have been closed, and 25000 residents evacuated. Flooding on 1.8 million acres of farmland has caused about $1.7 billion in crop losses.

Heroic efforts apparently saved historic Ste Genevieve, which has been battling rising waters since the start of July.

B River flooding: Mozambique

Mozambique has a pronounced single wet season followed by a lengthy dry season. As shown in Figure 3.61, both Maputo, the capital city, and Beira, the second city, receive almost 75 per cent of their annual rainfall during the five or six summer months when the sun is almost overhead (Figure 12.12) and when the south-east trades, blowing over the warm offshore Mozambique Current, are at their strongest (page 319). This rainfall pattern is repeated in the countries to the west and where Mozambique's three main rivers, the Zambezi, Save and Limpopo, have their headwaters.

The people of Mozambique are accustomed to the threat of seasonal flooding. In 2000 the country experienced its worst floods for over 50 years, an event that, in the following years, seemed to become an almost annual occurrence until 2008 when the government introduced its 'prevention-focused rather than response-oriented' policy.

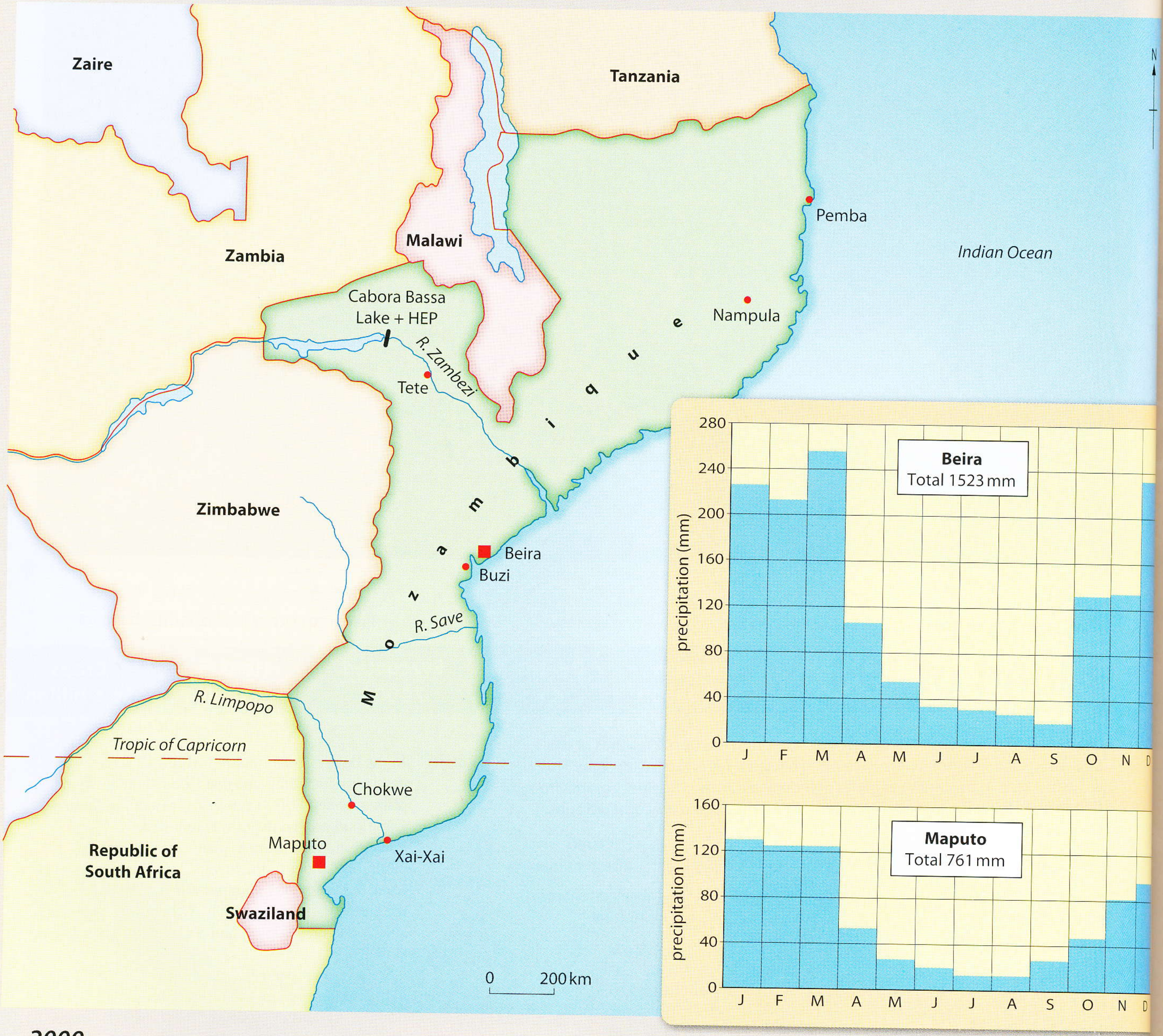


Figure 3.61

Mozambique, with rainfall graphs for Maputo and Beira

2000

Rivers, especially the Limpopo, began to overflow their banks in early February after several days of heavy rain, with the extreme south of the country the most severely affected. In Maputo, tens of thousands of people were forced to leave their homes, the worst-hit being those living in flimsy shanty settlements located on the edges of the city. Houses, roads, bridges and crops were destroyed, electricity supplies were disrupted and towns were left without a clean water supply after pumping stations were either inundated or swept away.

On 22 February the coastal region near Beira received the full impact of tropical storm Eline – a relatively rare hazard event in Mozambique. Winds of up to 260 km/hr hit a coastal area just north of the still-affected flooded regions. By 24 February, further heavy rainfall over much of southern Africa had swollen Mozambique's rivers by up to 8 m above their normal level (Figure 3.62). On 27 February, flash floods inundated more areas near to Chokwe and Xai-Xai. Estimates suggested that up to 7000 people, without food and water for several days, were surviving in the tops of trees or on small islands of high ground (Figure 3.63). International relief aid, when it eventually arrived, was to last for several months.

Final figures stated that 7000 people died, half a million were left homeless, 2 million had their lives affected, 11 per cent of farmland was ruined, 20 000 cattle were drowned and local industries in Maputo were forced to close.

2001

Over a month of heavy rain caused rivers in central areas, including the Zambezi near to Chokwe, to overflow. These floods led to 41 deaths, made 750 000 people homeless and affected half a million people in total. Roads and bridges, some only just repaired from the previous year, were swept away.

2006 and 2007

Following droughts in 2004 and 2005, heavy rainfall at the end of December 2005 and through early 2006 again affected thousands of people, although this time the death toll was down to 21. However, in 2007, several weeks of heavy rain resulted in the worst Zambezi floods since 2000. Fears that the huge Cabora Bassa dam (Figure 3.61) might overflow led to water being released from the lake behind it. This resulted in the level of the Zambezi rising even higher, and increased flooding in the lower basin. As a result 30 people died and 70 000 people were forced to leave their homes.

2008

Although an estimated 115 000 people were affected by the 2008 flood, the death toll was limited to 20. This was, according to UN aid workers, due to Mozambique's success in preparing for the flood event (Figure 3.64).

Figure 3.62
Aerial photo showing the extent of the 2000 flood

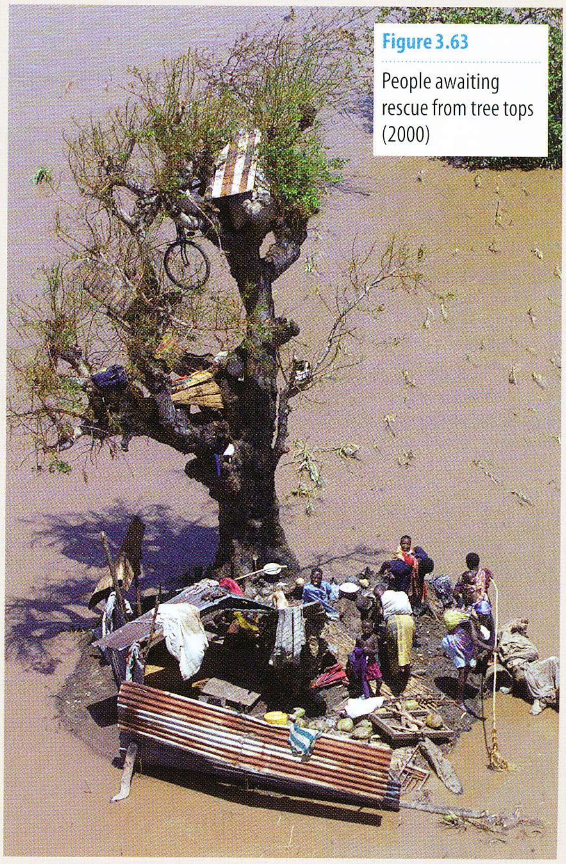


Figure 3.63
People awaiting rescue from tree tops (2000)

There has been, this year, a significant improvement in the government's disaster management. During the previous year the government had revamped its policies, making them prevention-focused rather than response-oriented. Realising that floods (and droughts) are going to happen, then the best approach is to try to minimise their impact. The Disaster Agency opened regional branches and began monitoring weather forecasts, upstream dam capacities and rainfall in neighbouring countries. It also set up an early-warning system and moved boats, together with reserves of food and medical supplies, to places with a high flood risk. Finally it drew up contingency plans aimed at evacuating low-lying villages should the need arise.

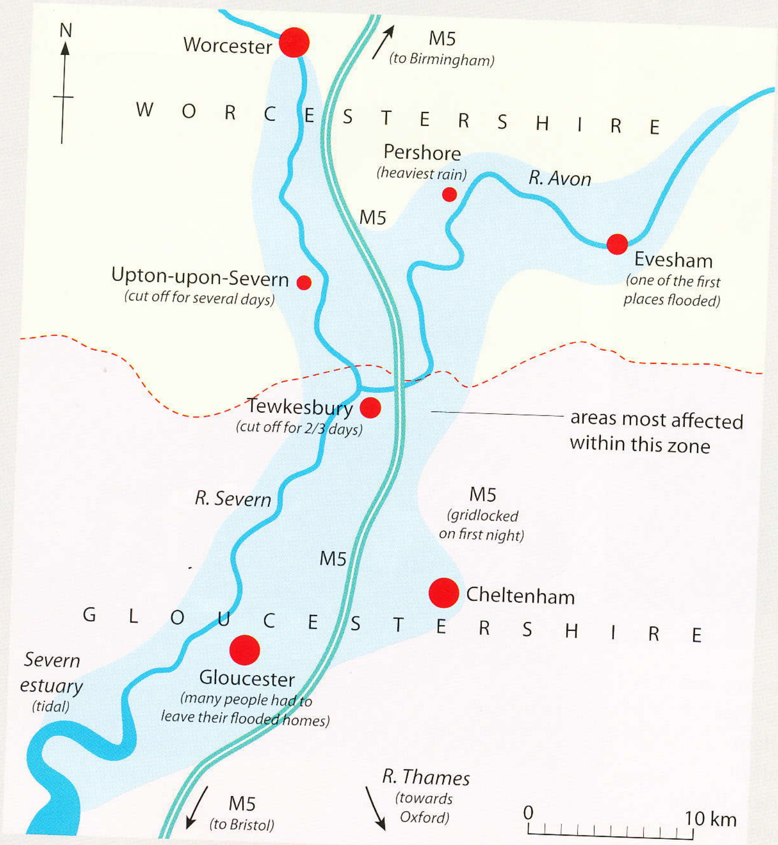
Figure 3.64
Extract from a 2008 UN report (UN/BBC News Africa)

C Flooding: the Severn in England, 2007

For many parts of England and Wales, 2007 was the wettest year, and certainly the wettest summer, ever recorded. The main reason was a failure by the polar front jet stream to move northwards as it usually does at this time of year (Figure 9.37). This meant that instead of the drier, more settled weather associated with a British summer, winds still came from the now warm Atlantic Ocean. Being warm, these winds were able to collect more moisture than was usual as they crossed the sea, resulting in heavy rainfall as they reached the British Isles. Torrential rain during June caused severe flooding in Hull, Doncaster and Sheffield that was to leave some properties uninhabitable for over a year.

Figure 3.65

Lower Severn valley



20 July

Although forecasters had warned of heavy rain for up to a week beforehand and the Met Office had issued a severe weather warning two days before, no one quite expected the downpours of 20 July. Two months of rain fell in two hours, and three times July's normal total in 24 hours in parts of the Midlands where the soil was already saturated and many rivers were close to their bankfull level. Pershore, in Worcestershire, received 145 mm in that one day. Flash flooding immediately affected several towns in the Avon and lower Severn valleys (Figure 3.65). By early evening much of Evesham and parts of Stratford-upon-Avon were under water, 1 billion litres of water was pouring through Gloucester where up to 2000 people were to spend the night in emergency shelters, and residents in Tewkesbury, at the confluence of the Severn and Avon, had begun to leave their homes. The flooding and the volume of traffic caused gridlock on major roads in the area, with an estimated 10 000 motorists left stranded for up to 10 hours on the M5 between Worcester and Gloucester (Figure 3.66). This gridlock prevented the emergency services moving equipment such as portable steel flood barriers to places like Upton-upon-Severn which were threatened by flooding, and hampered their attempts to rescue people already trapped. The result was the largest deployment of rescue helicopters and the biggest peacetime emergency ever in the United Kingdom.

Figure 3.66

Gridlocked traffic on a flooded road near Tewkesbury

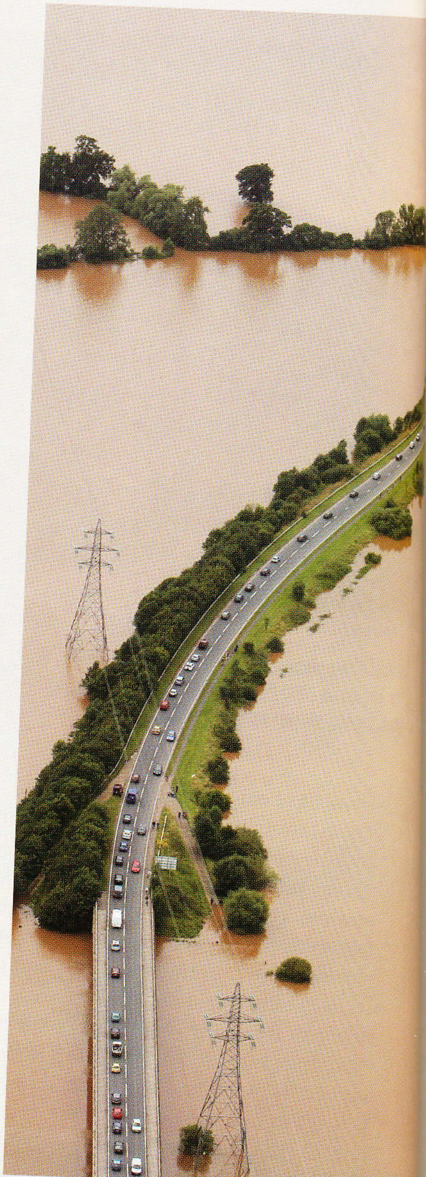


Figure 3.67 Flooded Tewkesbury, at the confluence of the Severn and Avon

22 July

More rain, together with runoff arriving from the headwaters of the River Severn, made the situation even worse. Helicopters were still rescuing people from Tewkesbury where 75 000 residents were completely cut off (Figure 3.67). Nearby, the Avon began to flood a water treatment works at the Mythe, forcing it to close down and leaving 350 000 people without water for washing, cooking or sewerage. Some 20 km to the south, a major crisis arose as floodwater began seeping into an electricity sub-power station, threatening to cut off supplies to 600 000 people. This led to the military being called in to help construct a 1 km embankment around the station to prevent further flooding and then to pump out water that was already in it. This was achieved despite having only six hours before a high tide at nearby Gloucester would cause the level of the Severn to peak at almost 8 m above its usual level. Meanwhile further heavy rain was beginning to cause major disruptions to places further east in the Thames Valley.

23 July

Half of Gloucestershire was now without water and people were told that it might be two weeks before supplies could be restored, and 50 000 homes were without electricity. Freshwater tankers and bottled water suppliers were struggling to reach places still cut off, while supermarkets were experiencing panic buying. Of the thousands of people who had had to evacuate their homes in the region, some were warned it would be over a year before they could return. While the Severn was still over its banks in several places and severe flood warnings remained in place between Tewkesbury and Gloucester, it was now people living close to the Thames in Oxfordshire who were faced with a real threat from flooding.

24 July

Floodwater had by now receded from most places in the Severn valley apart from properties adjacent to the river itself. Mopping up could begin but the real clean-up was expected to take months. Initial estimates of flood damage were put at over £2 billion.

D Flood and river management

Economically more developed countries such as the United Kingdom have the capital and technology that enable them to better predict, plan for, manage and respond to the flood risk than do less economically developed countries such as Mozambique.

Flood management in the UK is the responsibility of the Environment Agency (EA). The EA has the powers to set measures in place to reduce the risk of flooding on rivers and tidal waters. It also has the lead role in providing flood warnings and, wherever possible, to protect people and property at risk. Dynamic issues such as climate change, floodplain development and evolving technology mean that the EA has to frequently update its flood warning service and advice. The EA aims to reduce the impacts of flooding by:

- strategic and development planning
- investment in planning and managing flood defences
- mapping areas at risk of flooding and managing flooding information
- managing floods and providing the flood warning service.

Flood incidents vary in scale and impact, from low impact of unpopulated floodplains to severe flooding in large towns and cities which can disrupt key parts of the urban, and even regional, infrastructure. According to the EA, a flood incident involves planning for floods, communicating the risk of flooding, detecting and forecasting flooding, issuing flood warnings, providing information on flooding and responding to flooding (Figures 3.68 and 3.69).

Figure 3.68

How the EA prepares for and manages a flood event

	Role of the EA	Organisations involved
Planning for flooding	We constantly plan for flooding and organise how we will respond to each incident. We regularly meet with our professional partners to create multi-agency response plans and major incident plans for flooding. These detail how each organisation will respond to flooding in specific locations.	Police, ambulance, fire and rescue services. Local authorities, utility companies and community groups
Communicating flood risk	We talk to the public throughout the year about all aspects of our flood risk management work. We focus on flood awareness, our flood warning service (Figure 3.69) and providing information about what to do before, during and after the event.	Residents and property owners living or working in the area
Detecting flooding	We monitor rivers and sea conditions, 24 hours a day, 365 days a year, so we are prepared for potential flooding. We use remote detection systems to measure rainfall, wind speeds and direction, water levels and water flows in rivers and seas.	Met Office
Forecasting flooding	We use flood forecasting so that we know when and where to issue flood warnings and when to operate our flood defences. We share this with our professional partners so that they can also respond to flooding.	Met Office, emergency services, utility companies, local authorities
Issuing flood warnings	We send warnings by automated voice messages to landline and mobile phones, and by fax, pager, SMS text, email, static sirens, public address loudhailers and broadcasts by radio and television.	General public, professional partners, the media
Providing information on flooding	If the public have not received flood warnings or want confirmation of the warnings issued, they can view warnings in force by: visiting our website at www.environment-agency.gov.uk/floodline, viewing Teletext (page 154) and Ceefax (page 149), or contacting Floodline on 0845 988 1188.	Website, the media, telephone
Responding to flooding	During a flood our priority is to issue flood warnings and make sure that our flood defences are working properly.	Emergency services, local authorities

Figure 3.69

Guide to the EA's flood warning codes

Flood Watch	Flood Warning	Severe Flood Warning
Flooding of low-lying land and roads is expected. Be aware, be prepared, watch out.	**Flooding of homes and businesses is expected. Act now!**	**Severe flooding is expected. There is extreme danger to life and property. Act now!**
Triggers	**Triggers**	**Triggers**
• Recorded rainfall that will cause flooding • Recorded or forecast water levels that will cause flooding • Snowmelt forecast	• Heavy rainfall that could cause flash flooding • Snowmelt • Observed rising level – critical trigger point reached • Forecast level or flow – trigger point for Flood Warning forecast • Site observations, e.g. blockages or defence failures • Actual flooding	As for Flood Warning plus: • Site observations of severe flooding or major problems with infrastructure and services • Forecasts predict a worsening situation and severe flooding likely • Actual flooding • Professional judgement, including consultation with professional partners
Impact on the ground	**Impact on the ground**	**Impact on the ground**
• Fast-flowing rivers • Bankfull rivers • Flooding of fields and recreation land • Minor road flooding • Car park flooding • Farmland flooding • Surface water flooding (linked to river flooding) • Overland flow from rivers and streams • Localised flooding due to heavy storms	• Flooding of homes • Flooding of businesses • Flooding of cellars and basements • Underground rail stations and lines vulnerable • Flooding of major road infrastructure • Flooding of rail infrastructure • Significant floodplain inundation (high risk to caravan parks or campsites) • Flooding of major tourist/recreational attractions • Damage to flood defences	• Large numbers (at least 100) of homes/businesses expected to flood • Large numbers of people are likely to be affected by flooding • Highest risk to life • Severe adverse impact on local infrastructure anticipated, e.g. transport, hospitals, utilities • Significant impact on the capacity of professional partners, organisations and the public (e.g. vulnerable groups) to respond effectively • Flood defence failures or overtopping which could result in extreme flooding

All Clear

We also use an 'All Clear' message to indicate receding floodwaters and a settled outlook.

All Clear

Management in the future

Climate modellers are now predicting that by 2080, due to climate change, floods like those experienced in England in 2007, which have previously only happened once in every 150 years, could happen every 20 to 30 years. Insurers expect that by that time annual losses will be £21 billion – five times greater than in 2007. Since the floods, environmental risk consultants have been urging the British government to take urgent steps to deal with the increased risk of heavy rainfall events and that, instead of trying to control and contain the flow of rivers as in the past, space should be found for the excess water to go. A government report of 2004, 'Making Space for Water', came to the same conclusion, proposing the sacrificing of farmland, meadows and other areas of open space as a way of ensuring least damage to property and disruption to human activity (although this seemed at odds with government plans to build thousands of new homes in flood-risk areas – page 400).

Flood experts have begun detailed mapping of large urban areas in Britain. They hope, by using three-dimensional maps, not only to show which places are at greatest risk, but also to predict how deep the water might get and how long it might take before draining away.

Others are pointing out that by constructing hard defences and flood walls (Figure 3.70) all that is achieved is to push the problem further downstream. They suggest that there needs to be a major upgrading of the sewerage network and drainage systems to cope with more severe storm events, that houses should be built with the ground floor used for car parking and living space above it, and the use of stone and concrete for flooring would enable a flooded house to be hosed down and dried out more quickly than at present.

3 Case Study The need for river management

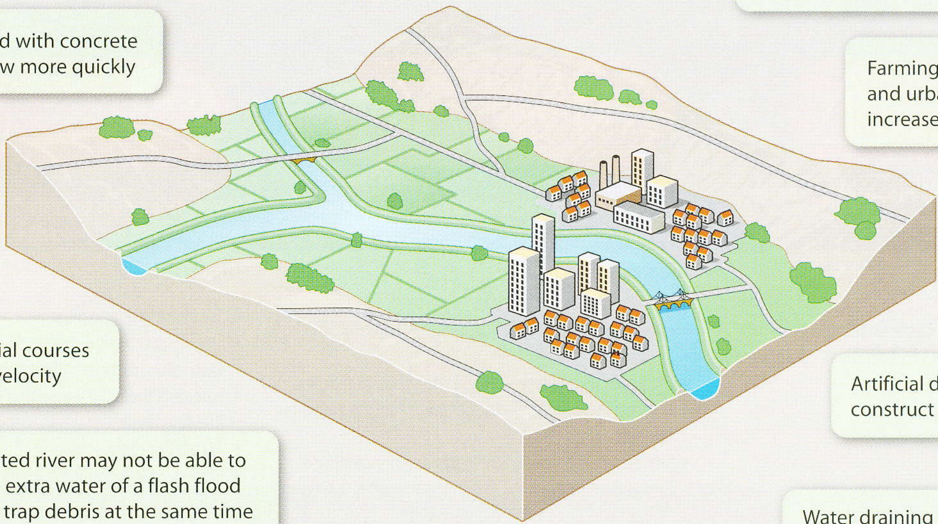


Figure 3.70
A managed river

'Much expense and environmental degradation is involved in forcing a river to flow where it is put, rather than where it wants to be, and where the designed plan is inappropriate to that reach of the river.' (Newson)

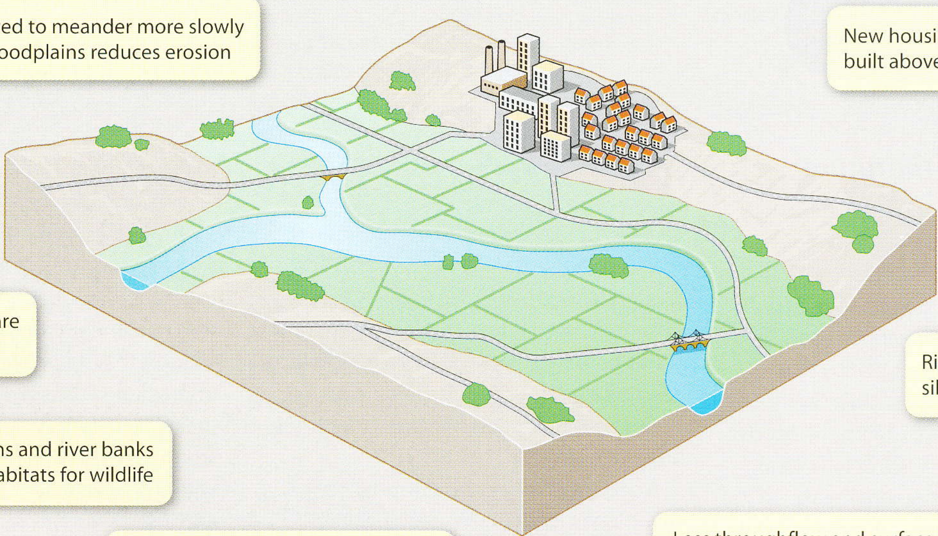


Figure 3.71
A free-flowing river

The need for river management

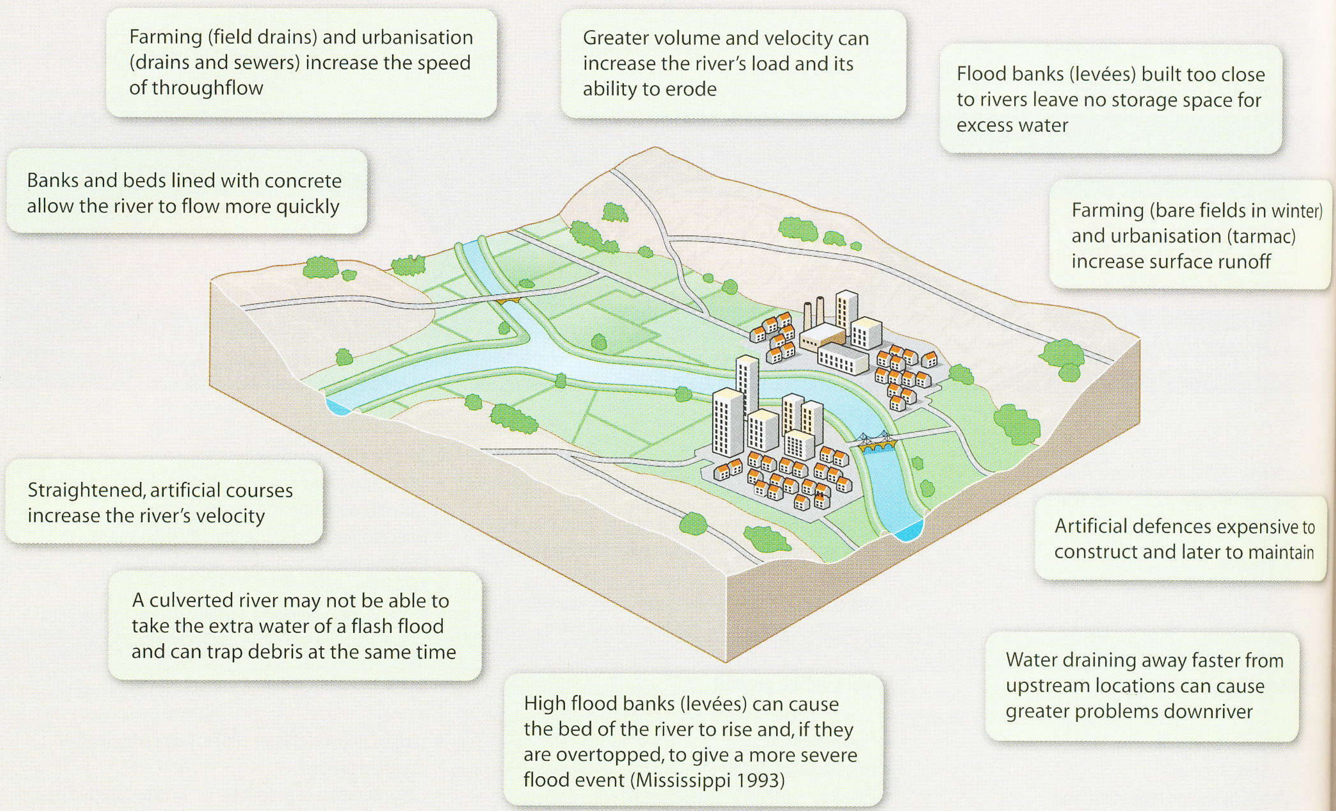


Figure 3.70

A managed river

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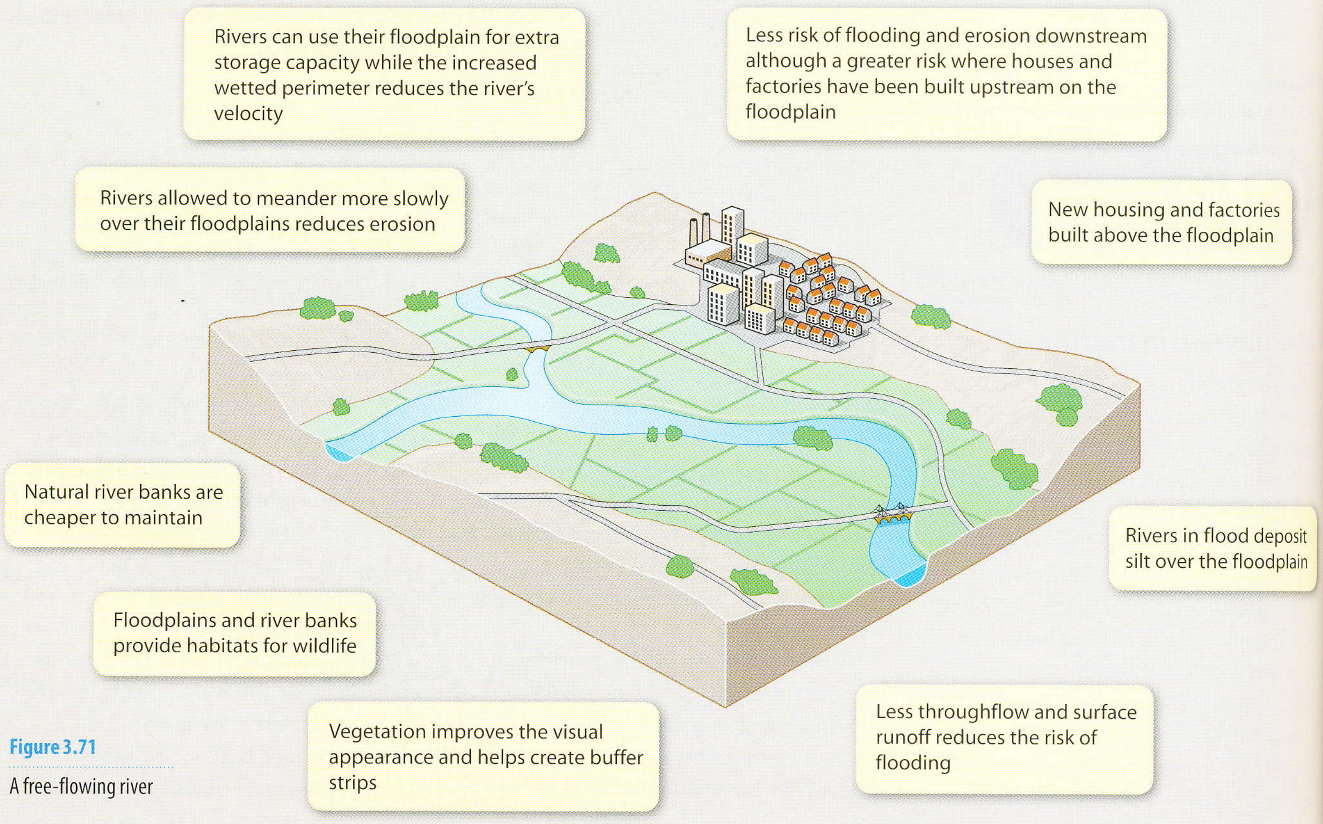

Figure 3.71

A free-flowing river

Should rivers be managed or not?

People living and working in flood-risk areas naturally want their lives, property and way of life protecting yet increasingly this can only be done at greater financial and environmental costs. Some of the problems created by trying to control rivers are shown in Figure 3.70. Yet as flood events increase in frequency and severity, there may come a time when it is impossible to finance new defences or maintain existing ones. Figure 3.71 shows some of the ways by which the EA has, in a published pack of 16 schemes, tried to rehabilitate both rivers and their floodplains in an attempt to allow people to live with, rather than trying to control, them.

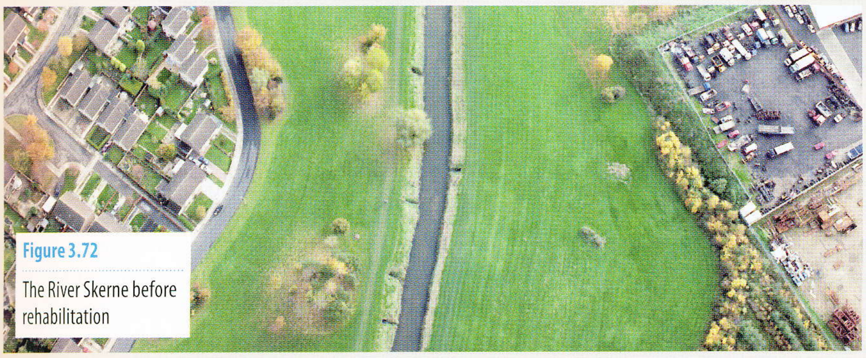

Figure 3.72
The River Skerne before rehabilitation

Figure 3.73
The River Skerne after rehabilitation

The River Skerne, near Darlington in County Durham, had, over 200 years, been progressively straightened for flood control, drainage, housing and industrial development (Figure 3.72). The floodplain had been a place for tipping contaminated waste while the river itself had become polluted, unsightly and, in places, inaccessible. Towards the end of the 20th century various organisations, including the EA, Northumbrian Water, English Nature, the Countryside Commission and Darlington Borough Council, worked together, with considerable effect, to rehabilitate the river (Figure 3.73). This has been achieved without compromising flood protection standards.

Rivers may be rehabilitated by:

- creating new habitats for wildlife (otters, birds, fish)
- reshaping river banks and channels and replacing artificial beds and banks ('hard' engineering) with natural materials
- recreating meanders and riffles
- reopening culverts.

Floodplains may be rehabilitated by:

- restoring former ponds and wetland areas or establishing new ones
- raising water tables and allowing increased flooding on floodplains
- planting trees and shrubs and creating buffer strips
- creating recreation areas.

Sources of maps

(see pages 98–99)

Textbooks
Ross, S. (2002) *Essential Mapwork Skills*, Nelson Thornes, ISBN 978-0-7487-6461-7
Ross, S. (2006) *Essential Mapwork Skills 2*, Nelson Thornes, ISBN 978-0-7487-8436-3

Shops
In the UK, Stanfords (branches in London and Bristol) carries an astonishing range of maps and is well worth a visit (website address below).

Online

British Geological Survey
www.bgs.ac.uk/enquiries/rocks_beneath.html

Caribbean Disaster Emergency Response Agency (CDERA)
www.cdera.org

Cassini Historical Maps
www.cassinimaps.co.uk

China (topographic maps)
http://cartographic.com

Environment Agency
www.enviroment-agency.gov.uk/maps

Geological Survey of India
www.gsi.gov.in

Get Mapping
www.getmapping.com

GOAD maps available through Experian at
www.business-strategies.co.uk/sitecore/content/Products%20and%20services/Goad.aspx

Google maps
www.maps.google.co.uk

Land use maps Brighton and Hove
www.sussex.ac.uk/geography/1-2-4-1-2.html

Florida
www.mapwise.com/maps/florida/land-use-zoning.html

Map Action
www.mapaction.org

Met Office
www.metoffice.gov.uk

Multimap
www.multimap.com

National Hurricane Center
www.nhc.noaa.gov

Omnimap.com
www.omnimap.com

Ordnance Survey
www.ordnancesurvey.co.uk/oswebsite
www.ordnancesurvey.co.uk/oswebsite/getamap/

Ordnance Survey of Northern Ireland
www.osni.gov.uk

Population Reference Bureau
www.prb.org/Publications/GraphicsBank/PopulationTrends.aspx

School for Disaster Geo-Information Management
www.itc.nl/unu/dgim/diag/pakistan.asp

Soil Survey Maps
www.cranfield.ac.uk/sas/nsri/index.jsp

Stanfords Maps
www.stanfords.co.uk

Streetmap
www.streetmap.co.uk

US Geological Survey
www.usgs.gov

Focusing on maps for Geography

Maps provide a rich source of information for geographical study. There are many different types, including the traditional topographic Ordnance Survey (OS) maps, and specialist ones such as soil maps, geology maps and historical maps. Detailed maps exist for many parts of the world, providing a huge amount of information on land use, tourism and communications. The Internet is a great source of maps, enabling the user to have control over scale and coverage. See page 97 for some useful sources of maps, including those described below.

Paper maps

In the UK the maps most commonly used by geography students are the topographic OS maps. These are widely available and cover England, Wales and Scotland. Maps of Northern Ireland (produced by the OS of Northern Ireland) are slightly different, although there is widespread coverage. The most commonly used OS maps are the Landranger 1:50 000 maps and the Explorer 1:25 000 maps. Now that all the cartographic details are stored digitally it is possible to obtain site-centred maps at a great variety of scales, including 1:10 000, 1:5000 and even 1:1250, which give detailed layouts of houses and gardens.

Across the world, topographic maps similar to the UK's OS maps have been produced mostly using satellite information and exploiting GIS. Recently 1:50 000 topographic maps of China have been produced and these are now widely used to support economic development.

Many specialist paper maps are available for geographical study:

- The National Soil Resources Institute at the UK's Cranfield University publishes extremely detailed soil maps.
- The British Geological Survey has produced similarly detailed geological maps identifying rock types and geological features (Figure 3.74). These have many applications, for example in studying the location of landslides or the distribution of farms.

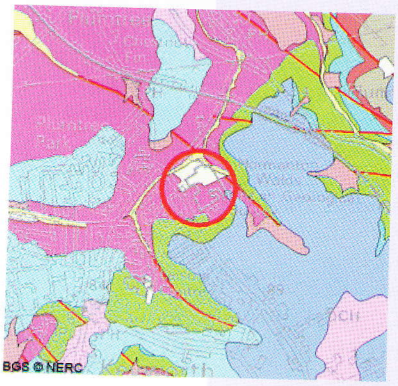

Figure 3.74

Extract from a geology map. Notice how rock types (coloured) are superimposed onto a traditional OS map
Source: www.bgs.ac.uk

- The Geological Survey of India publishes geology maps at various scales. These show details of geology as well as hazards and earth resources.
- Historical maps are now available for many parts of the UK and these are an excellent resource when investigating changes over time, for example for an inner city area such as London Docklands or on a rural–urban fringe.
- Land use maps provide a further useful historical record for geographical study. Two sets of such maps cover the UK. These were drawn up in the 1930s and 1960s. More recently in 1996, the UK Geographical Association conducted a land use survey of 1000 × 1 km^2 squares – 500 rural and 500 urban – to enable comparisons to be made with the historical land use maps. Similar maps are available for other parts of the world.
- In South Africa a large range of city maps is available from Omnimap.com, together with a selection of topographic maps at different scales and thematic maps covering land uses, resources and geology. Omnimap.com also sells a range of maps of Malaysia, including land use maps and detailed geology/mineral maps.
- International Travel Maps (printed in Canada) give an excellent coverage of South America including the Amazon rainforest. These maps can be obtained from Stanfords bookshop (see 'Sources of maps' on page 97). Similar maps published by Globetrotter give good coverage of the Middle East, and are also available from Stanfords.
- In the UK, students may come across GOAD maps at GCSE. Essentially these plot commercial land uses in towns and cities. Buildings are drawn to scale and the nature of the building use is described; individual shops and stores are named. GOAD maps provide wonderful historical records and can be used to demonstrate changing urban land use (particularly retailing). While these maps are only available for the UK, they are a useful source of information for anyone studying geography.

Maps on the Internet

Today when asked for a map, most students automatically turn to the Internet. There are several Internet map providers, including Google Maps, Multimap, Get Mapping and Streetmap. The Ordnance Survey also provides maps online, and has a service Get-a-Map by which it is possible to find a map for a named place and print it, subject to certain conditions.

The Internet gives access to maps of all kinds, quickly and cheaply (often free of charge), and usually offers interactivity, with zoom and navigation facilities. Increasingly GIS enables the user to select particular

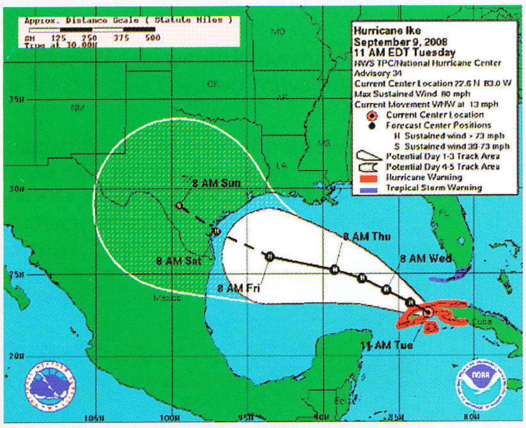

Figure 3.75

Track of Hurricane Ike, September 2008

Source: www.nhc.noaa.gov

information to include on a map. Aerial photographs and so-called 'hybrid' maps (traditional maps superimposed over aerial photos) provide a further dimension for the geography student.

Many organisations provide specialist maps. For example:

- Map Action produces maps of areas hit by natural disasters such as volcanic eruptions, earthquakes or hurricanes. These maps are produced very quickly following an event to support relief agencies in their work.
- The School for Disaster Geo-Information Management has a tremendous selection of maps relating to the 2005 Pakistan earthquake; some 40 maps have been produced at a scale of 1:50 000 to assist aid workers in the region.
- Maps plotting hurricanes can be found at the National Hurricane Center (Figure 3.75).
- A huge variety of maps to support the study of tectonics, water resources and geology can be found at the US Geological Survey.
- For disasters in the Caribbean, such as earthquakes, volcanic eruptions, hurricanes and landslides, the Caribbean Disaster Emergency Response Agency provides excellent information including maps.
- Up-to-date and archive weather maps can be found at the Met Office and a range of UK postcode-related environmental maps can be found at the Environment Agency's website.
- A great site providing population maps is the Population Reference Bureau.

Using maps in geographical research

Maps are an essential part of study at AS/A level and you should make use of them when conducting your own individual research. At the most basic level a map identifies the location of a study area. It also helps to provide context, for example where a place is in relation to other places, or important features of the landscape. Geography is about interrelationships and connections and maps are often invaluable in this respect.

Information on maps can be directly relevant to geographical study, providing an alternative source of information about an area. In physical geography, for example, maps can be used to identify features such as corries, raised beaches and sea stacks. In human geography they provide information about services, patterns of roads and settlements, and land uses.

Sketch maps

Topographic maps are wonderfully detailed but sometimes they contain too much information so that it is difficult to see the overall picture. A sketch map enables a geographer to be more focused by making a careful copy of just a few selected pieces of information. Sketch maps are invaluable when researching case studies, for example in identifying landforms along a stretch of coastline. When drawing a sketch map you must be clear about its purpose and avoid adding irrelevant detail. Ensure that your map is as accurate as possible and remember to always include a scale and a north arrow. Use labels or annotations to provide interpretation of your map.

Using maps in exams

There is a strong chance that you will be given a map extract in one or more of your exam modules; so you do need to prepare yourself thoroughly as part of your revision. Practise the essential mapwork skills such as using grid references, measuring distance, describing orientation and drawing simple sketch maps. Make sure you know most of the symbols so that you can 'read' a map without having to keep referring to the key.

Take time to learn how to interpret a map in different geographical contexts. For example, be clear what different types of housing look like in an urban area, and make sure that you can identify a high tide line when examining a stretch of coastline.

Figure 3.76

Detailed topographic map of Singapore

Source: www.omnimap.com

Activities

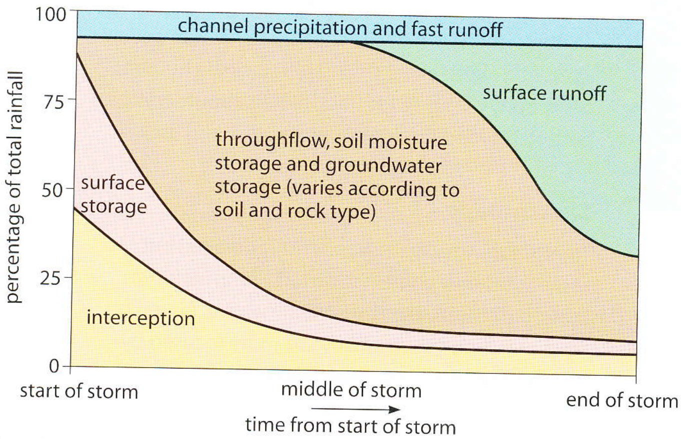

Figure 3.77

The relationship between rainfall and runoff in the course of a typical storm

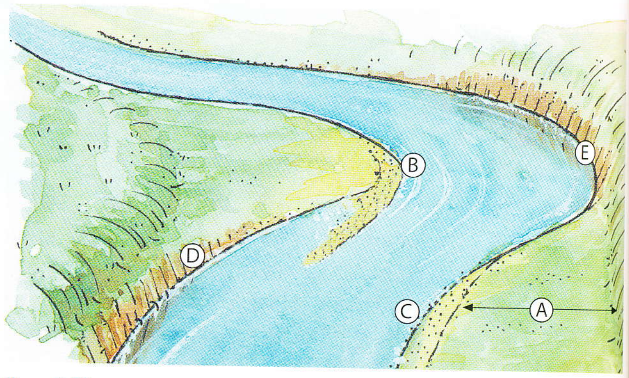

Figure 3.78

Fieldsketch of a meander

1 Study Figure 3.77.

a i What is surface storage? *(2 marks)*

ii Why does interception decrease during a storm? *(3 marks)*

iii What happens to surface runoff during the storm? *(4 marks)*

b What would happen to a river at the following stages:

i at the start of this storm

ii at the middle of the storm

iii at the end of the storm? *(8 marks)*

c The figure shows the reaction of a vegetated area to a heavy rainstorm. Describe and explain which parts of the model would change if the area were covered in concrete paving and drains. *(8 marks)*

2 **a** Study Figure 3.3 (page 60) and answer the following questions:

i What is a 'soil moisture budget'? *(2 marks)*

ii Explain each of the following terms used in the description of a soil moisture (water) budget: field capacity; water balance; soil moisture utilisation. *(7 marks)*

iii Why is there no soil moisture deficit shown in Figure 3.3? *(4 marks)*

b Why would a farmer need to understand the water balance of farmland? *(6 marks)*

c Why do water companies in Britain depend on winter rainfall to maintain reservoirs? *(6 marks)*

3 **a i** Study the diagram of a meander (Figure 3.78) and identify the location of the following landforms: inside of the bend; outside of the bend; floodplain; slip-off slope; river cliff. *(5 marks)*

ii Describe the features of the **channel cross-section** of a typical river meander. *(5 marks)*

b Choose **one** of the following features of a river: waterfall; cascade; rapids. Using one or more sketches/diagrams, describe the features of your chosen landform and explain how it is eroded by a river. *(7 marks)*

c i How does a meandering river form an oxbow lake? *(6 marks)*

ii How could the formation of an oxbow lake lead to management problems on the floodplain of a river? *(4 marks)*

Exam practice: basic structured questions

4 **a i** What is a 'storm hydrograph'? *(3 marks)*

ii What is meant by each of the following terms used in relation to a storm hydrograph: lag time; peak discharge; recession (falling) limb? *(6 marks)*

b i Identify two drainage basin characteristics that make a river react quickly to a rainstorm (have a 'flashy' regime). For **each one** explain why it has this effect. *(7 marks)*

ii With reference to specific example/s, suggest how river management strategies may be used to alleviate the problems caused by a 'flashy' regime. *(9 marks)*

5 **a i** Study Figure 3.27 (page 74). Describe the river bed shown in the photograph. *(3 marks)*

ii Suggest where the loose boulders shown beside the river have come from. *(4 marks)* iii How does a river erode a river bed such as the one in the photograph? *(6 marks)*

b Explain **two** ways in which you would know that loose rocks found on a field trip had been worn away by a river. *(6 marks)*

c With the aid of diagrams of a waterfall, show how it is being changed over time by river processes. *(6 marks)*

6 a i Describe the characteristic features of a **dendritic drainage pattern**. *(3 marks)*

ii Making good use of annotated diagrams, explain the development of a trellis drainage pattern. *(8 marks)*

b i Study Figure 3.53 (page 85). Describe the valley shape you would see if you were walking from the River Wansbeck to the Hart Burn. *(2 marks)*

ii Explain how the present drainage pattern evolved from the former drainage pattern. *(6 marks)*

c Choose and name an example of a drainage pattern other than a trellis pattern. Describe it and explain how it has been formed. *(6 marks)*

Exam practice: structured questions

7 a Using annotated diagram/s to help your answer, illustrate the components of a *storm hydrograph*. *(5 marks)*

b Explain how it is possible to measure the discharge of a stream in the field and how the results collected will be processed. *(10 marks)*

c Why do lag times differ on the same stream at different times? *(10 marks)*

8 When a housing estate is built on the rural/urban fringe, pre-existing drainage patterns are changed and river systems respond in a different way to storm events.

a Study of such changes must start before building to establish a 'baseline' for change. Briefly describe one technique you could use to measure the discharge of a stream in a rural catchment. *(5 marks)*

b Describe and account for **two** changes to discharge which may occur once the housing estate is built *(10 marks)*

c Describe **two** problems that could occur in the area due to the altered discharge pattern. *(10 marks)*

9 a Using annotated diagram/s **only**, show how the velocity of a typical river varies across its cross-section. *(5 marks)*

b i Describe the processes by which the load of a river is transported. *(8 marks)*

ii What factors affect the size of the particles eroded, transported and deposited by a river? *(12 marks)*

10 a Describe and suggest reasons for the cross-section shape of a river:

i near the source of the river

ii close to the mouth of the river. *(12 marks)*

b Identify and suggest reasons for **two** variations in the **long profile** of a river. *(13 marks)*

11 a i What is the difference between general base level and local base level? *(6 marks)*

ii Explain what happens to base level in a river system if sea-level falls. *(4 marks)*

b Choose **two** landforms formed in a river valley by a change in base level. Identify the direction of change involved and describe and explain the formation of each landform. *(15 marks)*

12 a Under what circumstances do rivers deposit material? *(12 marks)*

b i Explain how levées form as a result of natural river processes. *(5 marks)*

ii How do levées affect rivers and their tributaries? *(8 marks)*

13 Study Case Study 3B on pages 90 and 91.

a Describe the seasonal rainfall pattern in Mozambique and explain why this distribution of rainfall makes flooding common in the country's major river basins. *(7 marks)*

b Population densities are increasing in both the rural and urban areas of Mozambique. Suggest how this increases the flood hazard in the country. *(8 marks)*

c '... the government introduced its prevention-focused rather than its response-focused policy.'

Suggest what these policy changes might have meant in different parts of Mozambique. *(10 marks)*

Exam practice: essays

14 With reference to one or more river basins that you have studied, describe and evaluate river rehabilitation schemes. *(25 marks)*

15 Explain how changes in the base level of a river can affect the valley cross-section and the river's long profile. *(25 marks)*

16 'Flood hazards, resulting from a combination of physical and human influences, are increasing in many parts of the world.'

Discuss this statement with reference to rivers in countries at different stages of economic development. *(25 marks)*