Our Planet's Freshwater

PLANET GEOGRAPHY

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Stephen Codrington

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Cover photos show the Alitchur River, High Pamir Mountains, Tajikistan.

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Arizona Municipal Water Users Association: 3.27. Deva Leela: 4.31. Jassim al-Asadi: 4.59. Michael Gwyther-Jones: 4.24. NASA: 3.57. USGS: 3.24, 3.25

Preface

Our Planet's Freshwater is one of seven monographs written to support the options for the International Baccalaureate Diploma Geography (IBDP) course. These seven monographs complement three larger books that span the entire content of the IBDP Geography Program. *Our Changing Planet* covers the SL and HL Core (Paper 2), *Our Connected Planet* covers the Higher Level Core Extension (Paper 3), and *Our Dynamic Planet* includes material on all seven options in the SL and HL themes (Paper 1).

As with all the books in the *Planet Geography* series, my aspiration is that every reader of this book will acquire knowledge and wisdom to become an effective steward of our planet, committed to ensuring its healthy survival and vibrant flourishing.

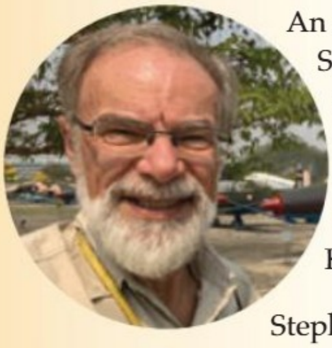
Any comments or suggestions to improve future editions of this book are always welcome. I hope you, the reader, will enjoy learning more about the geography of our fascinating planet as I have over the years.

Stephen Codrington.

The Author

Dr Stephen Codrington has a Ph.D. in Geography, and has taught the subject in several countries at both the high school and university level. He is the author or co-author of 69 books, mainly books that focus on his life-long passion for Geography.

Following his highly successful career as a teacher of Geography and Theory of Knowledge, including serving as the Head of five International Baccalaureate (IB) schools in four countries, he now works with school boards and leaders through Optimal School Governance, educates trainee teachers at Alphacrucis College, and is Chair of the Board at Djarragun College.



An Australian by birth, Stephen is a former President of both the Geographical Society of New South Wales and the Geography Teachers' Association of New South Wales (twice). He edited Geography Bulletin, the journal of the Geography Teachers' Association of New South Wales for seven years, and is now a Councillor and Treasurer of the Geographical Society of New South Wales. He has taught in schools in Australia, the United Kingdom, New Zealand, Hong Kong and the United States.

Stephen has been honoured with election as a Fellow of the Australian College of Education, the Royal Geographical Society (UK), and the Geographical Society of NSW. He was appointed to the role of IB Ambassador in 2014 and honoured with life membership of the Geographical Society of New South Wales in 2018. He is a former Chairman of HICES (Heads of Independent Co-educational Schools). Stephen's work has taken him to 161 countries, and he has been listed in Who's Who in Australia every year since 2003.

From 1996 to 2001 he served as Deputy Chief Examiner in IB Diploma Geography, setting and marking examination papers, assisting with curriculum development, and leading many teachers' workshops.

He maintains a personal website at www.stephencodrington.com that contains links to travel diaries and other items of geographical interest.

Chapter 1 Drainage basin hydrology and geomorphology

1.1 Drainage basins comprise the slopes, valley bottoms, stream channels and watersheds of the catchment areas of streams. All these elements can be seen in this view of the Saint Mary River in Montana, USA.

A systems approach to drainage basins

What is a system?

Geographers are concerned with four essential questions:

- **where** is it?
- **why** is it there?
- what is it like?, (or what are its **characteristics**?)
- and so what?, (or what are the **consequences**?).

A **systems approach** is useful because it helps us to answer the second and third questions.

The word '**system**' is used frequently in everyday speech, so the overall concept is probably already familiar to you. We speak about a transport system, a sewerage system, a political system, an educational system, and so on. In geography, the word 'system' means much the same as it means in everyday speech. Put simply, a system is a set of **interrelated parts**.

If we think about the different systems mentioned above, they all have several things in common:

- each system is made up of a number of **objects**;

- these objects are **linked** together in a **functional relationship** to achieve some **purpose**;
- the objects and the linkages between them have a **boundary**, so the limits may be determined even though there might be problems in defining the boundary precisely in some cases;
- the system doesn't exist in isolation, but it functions within a **wider environment**;
- the systems listed above are all **open systems**, which means they receive inputs from the surrounding environment, and they give outputs to the surrounding environment; and
- the **behaviour** of the system is a consequence of the system's inputs, processes, linkages and outputs — if any one of these elements changes, then the behaviour of the system is likely to change.

Question Bank 1A

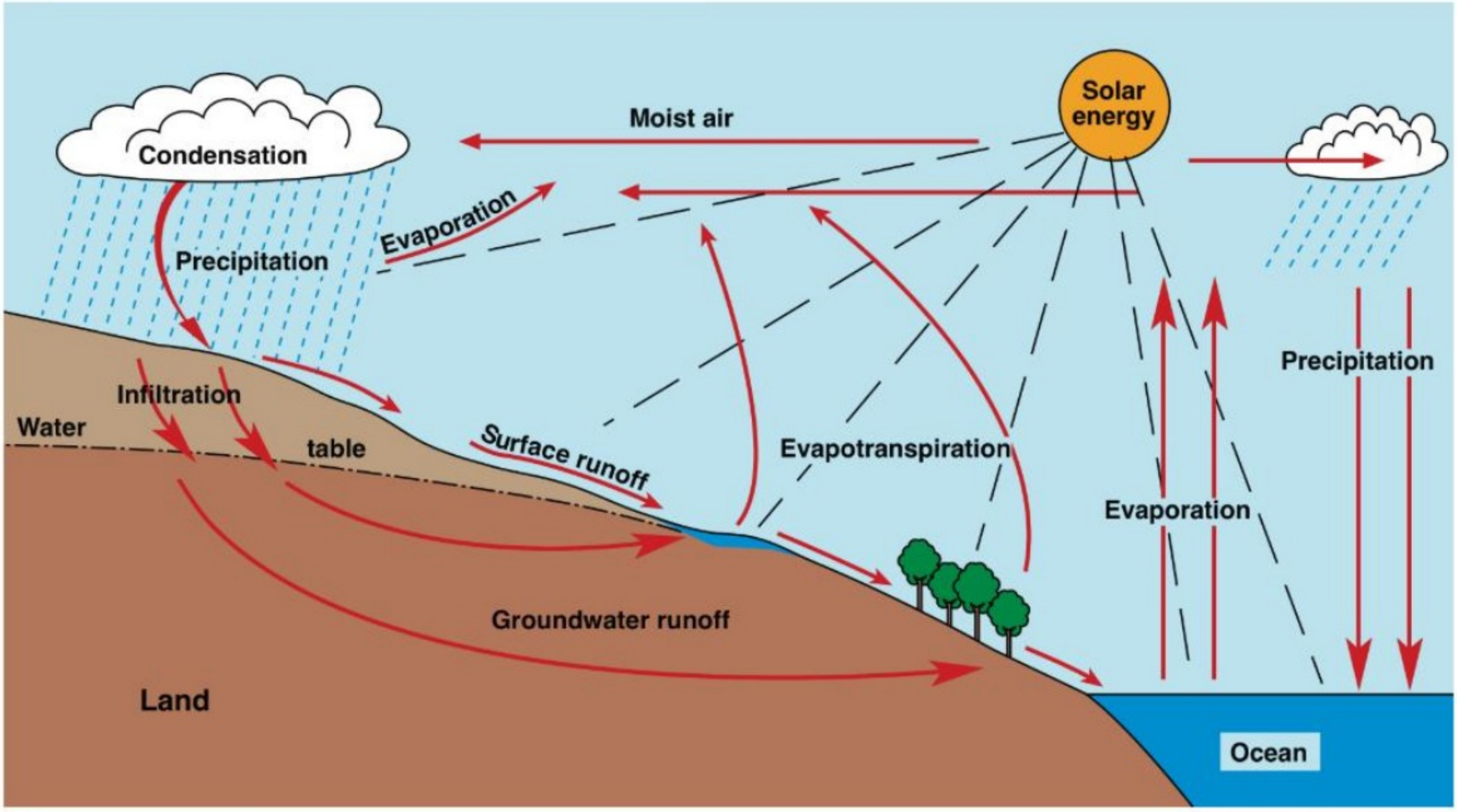
1. *Consider a hot water system and the fuel system of a car. For each of these open systems, list the details of the system under the headings: objects, purpose, surrounding environment, inputs, linkages, and outputs.*
2. *Under the same headings used in the previous question, list the details of more abstract systems such as your school system and the IB examination system.*

The water cycle

Water is being moved constantly through the environment in a never-ending process known as the **water cycle**, or **hydrological cycle**. The water cycle is a **system** of stores and flows. **Stores** are repositories where the water is held for a while, such as lakes, groundwater, puddles, ice caps, surface snow and dew. **Flows** are transfers of water from one place to another, such as rainfall, rivers, falling snow, and moving clouds. Because movements through the water cycle can be slow, some flows are also stores. Examples of slow flows that are therefore also stores include groundwater and glaciers. Although there are movements of water within the world's oceans, these movements do not shift the water to another part of the water cycle, so the oceans are regarded as stores.

As water moves through the water cycle, its **state** is changed between solid (ice and snow), liquid (water) and gas (water vapour). Water moves **downwards** by gravity, in forms such as rain and rivers, **sideways** in winds or ocean currents, or **upwards** in the atmosphere by convection.

Water in any state can be changed into any another **state** by heating or cooling. When water exists as a **solid** (as ice), rigid bonds that connect the atoms



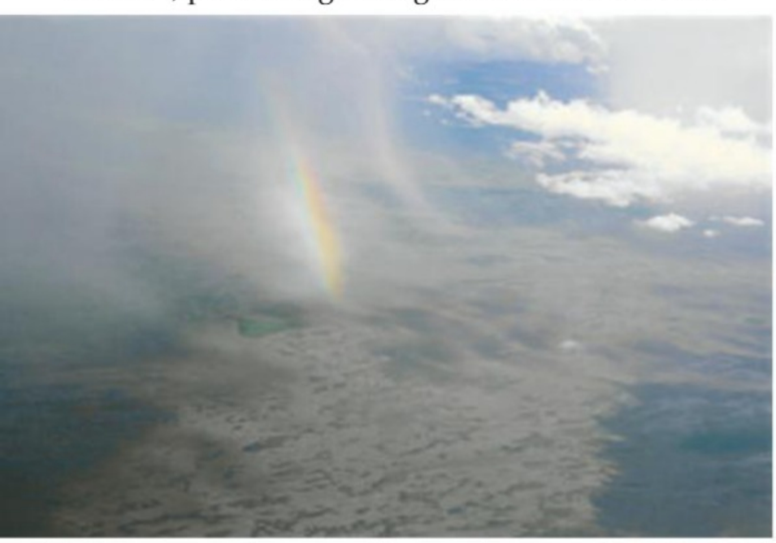
1.2 The water cycle. Flows are shown as red arrows.

hold together the molecules of water. If enough heat energy is provided, some of these bonds can be broken and the molecules become free to slide past each other as a **liquid**. This process is called **melting**. Should yet more heat break the remaining bonds, the molecules may then escape from each other and fly about freely as a gas; this is known as **evaporation**. It is also possible for ice to turn directly into a **gas** (water vapour) if enough heat energy is provided, and this process is known as **sublimation**.

The opposite processes occur when heat is removed from water. As water vapour becomes liquid water, **condensation** is said to occur – the opposite of evaporation. When water cools to become ice, **freezing** occurs. The direct change from water vapour into ice is known as **sublimation**, the same as the reverse process.

The water cycle is usually considered to be a **closed system** because, for all practical purposes, no water enters or leaves the system. Tiny quantities of 'new' water do enter the water cycle, mainly during volcanic eruptions, but these are insignificant compared with the total volume of water on the planet. Strictly speaking, the water cycle is not a completely closed system because of these small inputs. Moreover, all the **energy** for the water cycle, apart from gravity, is provided by a large input of **solar energy** (which means 'energy from the sun'). Nonetheless, the water cycle is one of the most closed systems to exist naturally on earth.

Water on the land's surface **moves** through streams and glaciers. Water also flows below the surface of the land, percolating through the soil and rock into



1.3 Precipitation takes many forms, such as snow, hail, sleet and rainfall, seen here over the Florida Everglades, USA.

rivers, lakes and ocean basins. **Precipitation**, such as rain or snow, is often **intercepted** by something before it reaches the ground.

Precipitation that has been prevented by vegetation from falling directly to the ground surface is said to be intercepted. Although animals may sometimes be the interceptor, the most common interceptor is vegetation. **Vegetation** affects the movement of water in six ways:

- by storing intercepted precipitation;
- by providing points for the re-formation of raindrops;
- by providing protection of the ground surface from the impact of raindrops;
- by providing leaf litter for debris dams;
- by removing water from the soil (that is later evaporated back into the atmosphere as a gas); and
- by disturbing the surface soil and construction of root channels.

1.4 Interception storage; snow is held on these bushes in London, UK. The snow will either melt and fall to the ground, or it will return as water vapour into the atmosphere by sublimation.

The process of **interception** impacts on the water cycle in several ways. First, interception **reduces** the amount of water reaching the ground, simply because it is stored on leaves and stems, and then some of it is evaporated. Moreover, interception **re-forms raindrops, redirects** the flow of water to the ground, and alters the **chemistry** of the rain.

In any place where the ground surface is **shielded** by vegetation, interception of precipitation occurs. The degree of interception is influenced by the type of vegetation found in an area, and its density. For example, more water is intercepted by the dense forest canopy in a tropical area than by the sparse vegetation of arid and semi-arid areas. Similarly, broad-leafed trees are more effective interceptors than trees with needle leaves, such as pines.

If more rain falls than the vegetation is able to hold in interception storage, then the water rolls off the leaves, often re-forming into drops that are much larger than the ones that originally hit the vegetation. The **increased drop size** can lead to high rates of **rainsplash erosion** around the base of the tree or shrub, especially if the distance of fall is greater than 5 metres. Water that reaches the ground either directly or after being intercepted by vegetation is called **throughfall**.

Throughfall collects on the ground surface, first filling small depressions and hollows. Almost as soon as the water begins to accumulate, however, **infiltration** begins. As water enters the soil, it becomes part of the soil water store and may, if it percolates deep enough, become part of the groundwater store. The ease with which water moves downwards through soil and rock material is called **permeability**. Where the water can move rapidly the permeability is high, but when the water moves slowly, the permeability is low.

Rainwater that has been intercepted by vegetation **reacts chemically** with the leaves and branches, and also with dust on the leaves. **Minerals** such as calcium, sodium, potassium and magnesium can be added to the throughfall water in this way, returning many chemicals from the trees back to the soil. This process can be important in **recycling nutrients** and in maintaining the fertility of forests.

Rainsplash erosion can be reduced by plant material that has fallen to the ground and accumulated. Accumulated **leaf litter** protects the surface, and can therefore reduce the quantities of soil that are moved downslope. Leaf litter can form small dams known as **debris dams**, and these provide small areas for water storage that increase the potential for infiltration.

Where **plant roots** have penetrated into the soil, and where lines of weakness in rocks open sub-surface cracks, water can move more easily from the surface into the sub-surface store. Having said this, it is usually when roots decay that the greatest access paths are provided for water to infiltrate downwards. Roots can also disturb surface

1.5 Surface roots on the floor of this rainforest in the Ngardok Nature Reserve in Palau form depression storage hollows that reduce overland surface flow, but increase the potential flows of infiltration and evaporation.

material by pushing the soil surface upwards. When large roots are very close to the surface of the soil, surface depressions are formed, and these increase the **depression storage** (**puddles**) and the potential for both infiltration and evaporation loss. Furthermore, roots that trail across the ground surface impede overland flow and provide points for small pools of water to collect.

Soil is usually **unsaturated** at the surface except during rain, flooding or in swampy areas. In this near-surface zone, water is held to the soil particles by electro-chemical bonds. This unsaturated zone is known as the **vadose zone**, and the water in the zone is known as vadose water. When vadose water moves, it is known as **throughflow**. Below the vadose zone is the **phreatic zone**, which is where soil and rock voids are full of water. The water contained in this zone is known as phreatic water, or more commonly, as **groundwater**. Groundwater is an important source of water in many parts of the world, being the second largest store of liquid water in the water cycle. Stores of groundwater are referred to as **aquifers**.

In any area where there is enough rainfall, large quantities of water will usually be held on the surface in two main areas, the **hillslopes** and the **channels**. Most of the water that flows into lakes and rivers comes from the hillslopes, as they form the largest proportion of the area of any catchment. On any hillslope there are many irregularities in the surface. These depressions trap any water that

1.6 Rivers are one of the main types of overland flow in a drainage basin, other examples being glaciers and sheet flow. This example shows the Potaro River at Kaieteur Falls in Guyana.

might enter them, forming **depression stores**. When these are filled, water begins to **flow** over the land surface as **surface flows**.

Large volumes of water may be held in these depression and surface storages. This can be seen by observing the large number of puddles on the ground following a rainstorm. Because of surface irregularities, the actual **depth** of water at particular sites may be greater (such as in swamps) or less (such as on bare rock).

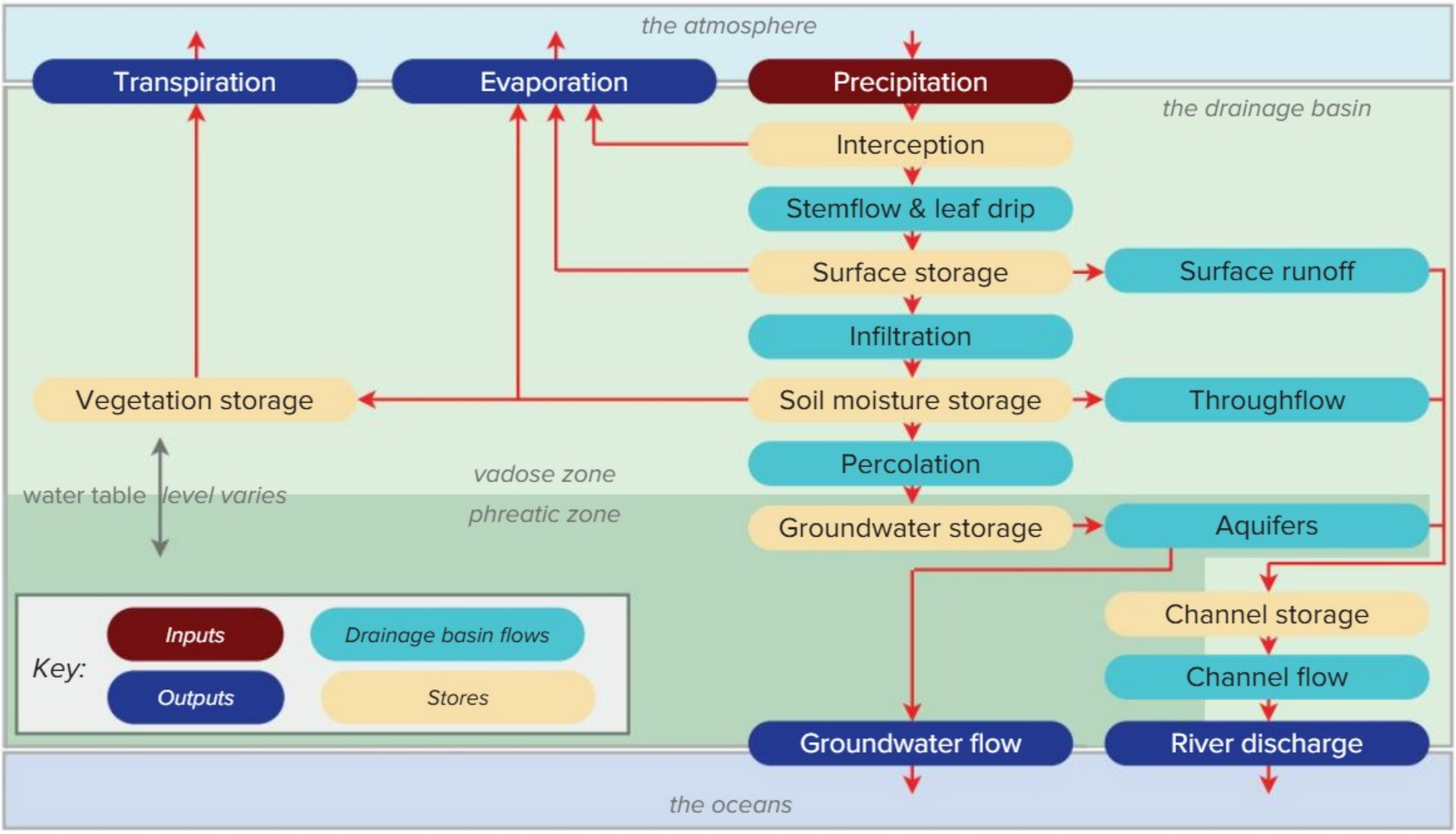
Some of the water that reaches the ground surface moves rapidly over or through shallow soil into a stream, and this water is called **quickflow**. Quickflow contributes to the rapid rise in water level in streams during and following a storm. On the other hand, the slow seepage of water from hillslopes contributes to the **base flow** of streams, which is the low flow between floods.

Question Bank 1B

1. *Explain the difference between an open system and a closed system.*
2. *Discuss the role played by vegetation in intercepting water.*
3. *List the ways in which water can move under the influence of gravity.*
4. *List the (a) stores, and (b) flows, of water in the hydrological cycle.*

The drainage basin as a system

A **drainage basin**, or **catchment**, is the area that supplies water to a stream (river or creek). The highest ridge between two valleys divides adjoining drainage basins, and these ridges are known as **watersheds**, or **interfluves**. Any ridge top therefore forms the border of a drainage basin, separating it from neighbouring drainage basins.



1.7 The drainage basin, viewed as an open system. For simplicity, the diagram refers only to water, ignoring the inputs, processes and outputs of energy and gravity.

Drainage basins may be thought of as a **system** with certain inputs, processes and outputs. The movement of water through any individual drainage basin is really a **sub-system** (a small set) of the global water cycle. Thus, the drainage basin system shown in figure 1.7 is really a more detailed diagram of one section of the planetary water cycle, viewed at a **local** or a **regional scale** rather than at the global scale.

Unlike the global water cycle, drainage basins are **open systems**. Apart from the inputs of gravity and solar energy, all the **inputs** that enter a drainage basin come from the **atmosphere** as precipitation in one form or another. The **outputs** of water leave the drainage basin for the **oceans**, either directly or indirectly.

Running water has shaped most of the earth's land surface, and therefore most of the earth's surface is part of a drainage basin. Even in coastal areas and desert landscapes, running water is the main agent of erosion and deposition that shapes the land's surface. Areas where running water is the main influence on the formation of landforms are known as **humid terrains**, because there is usually an abundance of water.

In some humid environments, temperatures are so cold for much of the year that the water remains **frozen**. Those parts of the earth's water that are frozen, such as glaciers, permafrost, ice sheets, lake ice and snow cover are known as the **cryosphere**. In these areas, the **rate of flow** through the drainage basin system decreases (slows down), while the **amount of water/ice** held in stores increases.

1.8 Snow lies in the stream valleys west of the volcano of Sopka Khodutka on the Kamchatka Peninsula of Russia, leaving the watersheds bare of snow. The pattern of snow highlights the extent of the drainage basins in the area.

1.9 After a heavy fall of snow, a thick layer of snow lies on the streets of Boston, Massachusetts, USA. This snow is part of the cryosphere, and it has increased the surface store of water while slowing the rate of flow in the drainage basin system.

Drainage basins in humid terrains include not only the streams and valleys, but also the slopes and ridges. Not surprisingly, large streams have large drainage basins, while smaller streams have smaller drainage basins. Smaller streams flow into larger streams, and so a number of smaller drainage basins will be **nested** within medium-sized drainage basins, which in turn will be nested within large drainage basins.

Water flows from high areas to low areas, usually taking the path where the least amount of energy is needed. The higher the altitude of water in a stream, the greater the amount of **potential energy** it possesses to erode the landscape. As water flows downhill, it uses up this energy by eroding (or wearing away) the land surface. A stream cannot erode below a certain **base level**. For most rivers, base level is **sea level**, although certain streams may have a local base level, such as a lake.

Like the drainage basins in which they flow, **streams** can be thought of as **systems**, with inputs, processes and outputs. Each stretch of river is an **open system** receives **inputs** of water and sediment from upstream. These inputs combine with the water and sediment in the section of river, and a quantity of water and sediment will leave the stretch of river as **outputs**.

If there is an **imbalance** between the inputs and the outputs, then **changes** will occur in the river. If more sediment enters the stream than leaves it, then **deposition** will occur. If less sediment enters the stream than leaves it, then **erosion** occurs. If the

1.10 Ultimate base level for most drainage basins is the ocean. Some drainage basins have higher local base levels, such as a lake. A few rivers flow into lakes that are below sea level, such as the Dead Sea, seen here from its east coast in Jordan where the elevation is 427 metres below sea level, the lowest point of dry land on Earth. Water from the Jordan River flows into the Dead Sea, but as there is no outlet, the water evaporates and the concentration of salt builds up. Evidence of the Dead Sea's hypersaline water is the white salt precipitate visible along the shoreline.

input of water, sediment and energy entering a section of a stream **equals** the output of water, sediment, and energy, then changes in the **shape** (or **form**) of the stream are unlikely, and the stream is said to be in **dynamic equilibrium**. This means that while individual particles of water and sediment are constantly moving (and are therefore 'dynamic'), the overall pattern is not changing (and is therefore in 'equilibrium').

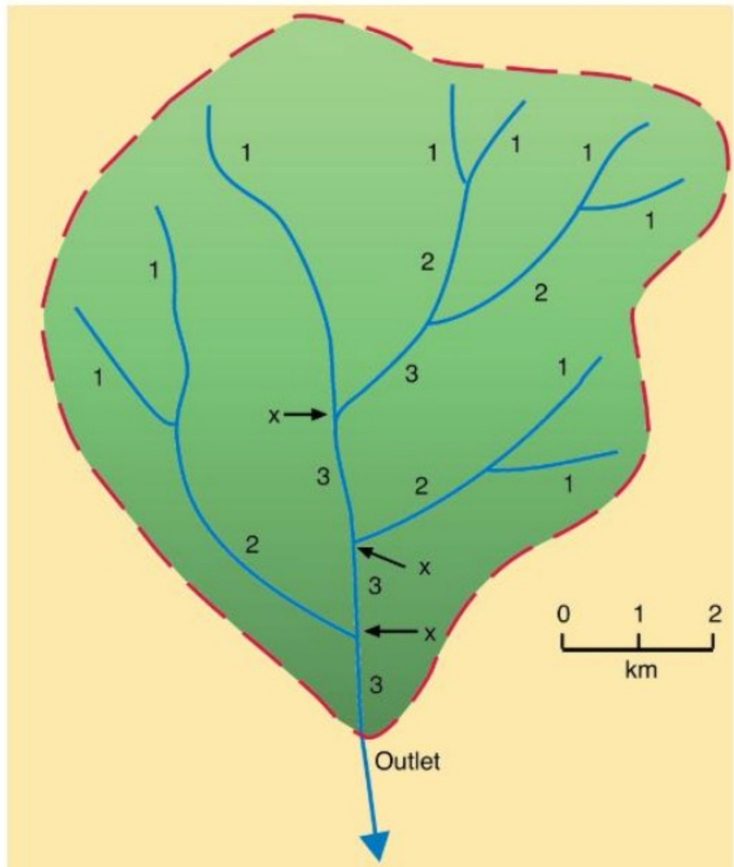
Question Bank 1C

1. *What does the term 'drainage basin' mean, and what are its components?*
2. *With reference to figure 1.7, describe in words the operation of the drainage basin system.*
3. *What would be the impact of an increase in the input of water in a stream?*
4. *What is the impact of the cryosphere on drainage basin systems in cold areas?*
5. *Which part of a drainage basin do you think is most important for (a) landform development, and (b) human life – the stream, the slopes or the watershed? Give reasons.*
6. *With reference to the water cycle (of which drainage basins comprise a sub-set), suggest a feedback loop that could be added to the open system shown in figure 1.7.*

River discharge

Stream order in a drainage basin

The usual way of describing the scale (size and extent) of a drainage basin is to refer to the **order** of streams within it. Streams that have **no tributaries** (or streams flowing into it) are termed **first order** streams. When two first order streams join together, they become a **second order** stream. Two second order streams join to form a **third order stream**, two third order streams join to form a **fourth order** stream, and so on as shown in figure



Order	Number of streams	Length of streams (km)
1	9	17.6
2	4	10.5
3	1	5.8
		TOTAL 33.9

Area = 53km^2

Drainage density = $\frac{33.9}{53}$

= 0.64km / km^2

1.11 Stream order. The red dashed line shows the watershed (interfluves) around this third order drainage basin. The inset shows a calculation of drainage density (see text).

1.11. However, a stream may have a tributary with a lower order without becoming a higher order stream, and this is shown at several points labelled x in figure 1.11.

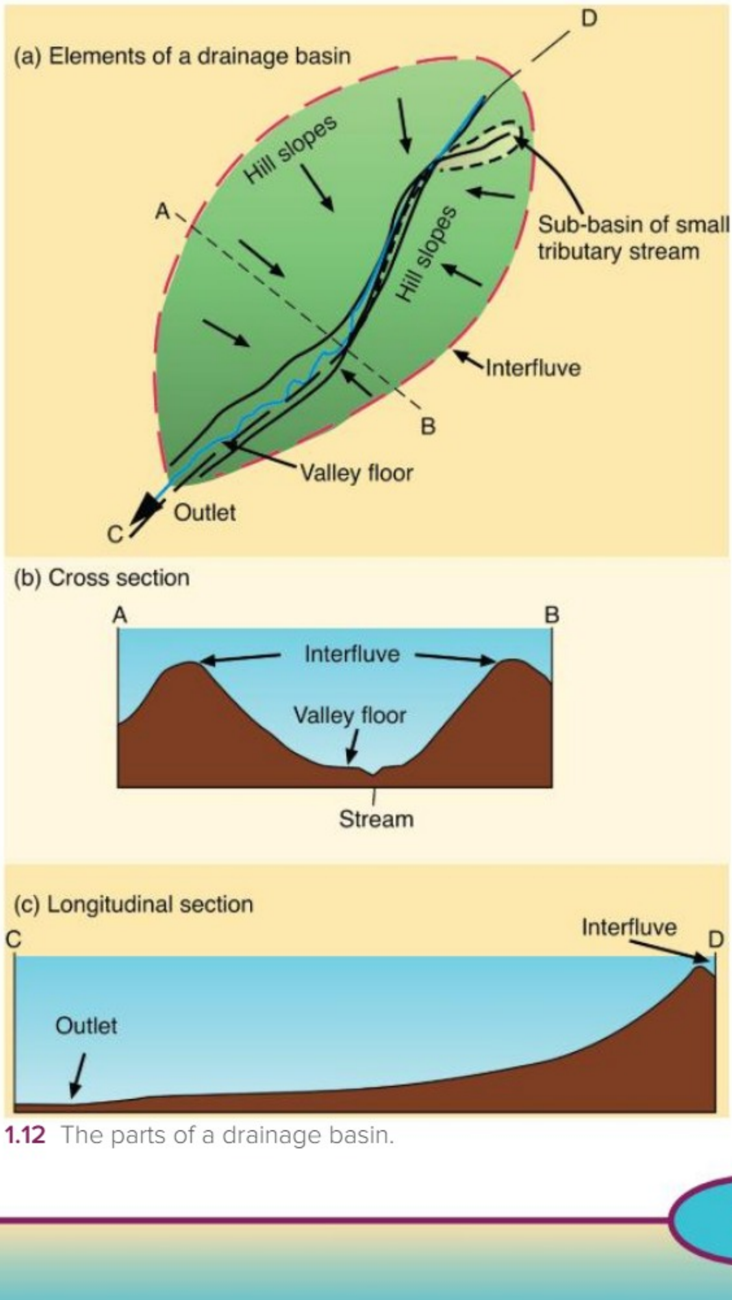
The **drainage density** is the ratio of the total length of the streams in a basin, measured in kilometres, to the total area of the basin, measured in square kilometres. This measure indicates the length of channel needed to drain each square kilometre of the catchment.

The **bifurcation ratio** measures the number of streams of one order to the next highest order, such as the first order to second order, second order to third order, and so on. Typically, bifurcation ratios range between 3 and 5. In figure 1.11, there are four second order streams and one third order stream; this gives a bifurcation ratio of 4. If we had a sixth order drainage basin with a bifurcation ratio of three, then the number of streams would be as follows:

6th order streams = 1
5th order streams = 3 (1 x 3)
4th order streams = 9 (3 x 3)
3rd order streams = 27 (9 x 3)
2nd order streams = 81 (27 x 3)
1st order streams = 243 (81 x 3)

As one travels **downstream** from the source of a stream, several **trends** can be observed. Usually, the valley floor widens, the average angle of the slopes decreases, and the heights of the interfluves diminish. The **profile**, or side-view, of the longest stream in the drainage basin is usually concave, which means that the stream's gradient, or slope, declines further downstream.

Drainage basins comprise several **components** – slopes, valley bottoms, stream channels and watersheds, and of these, **slopes** comprise the largest part in terms of area. Water and sediment



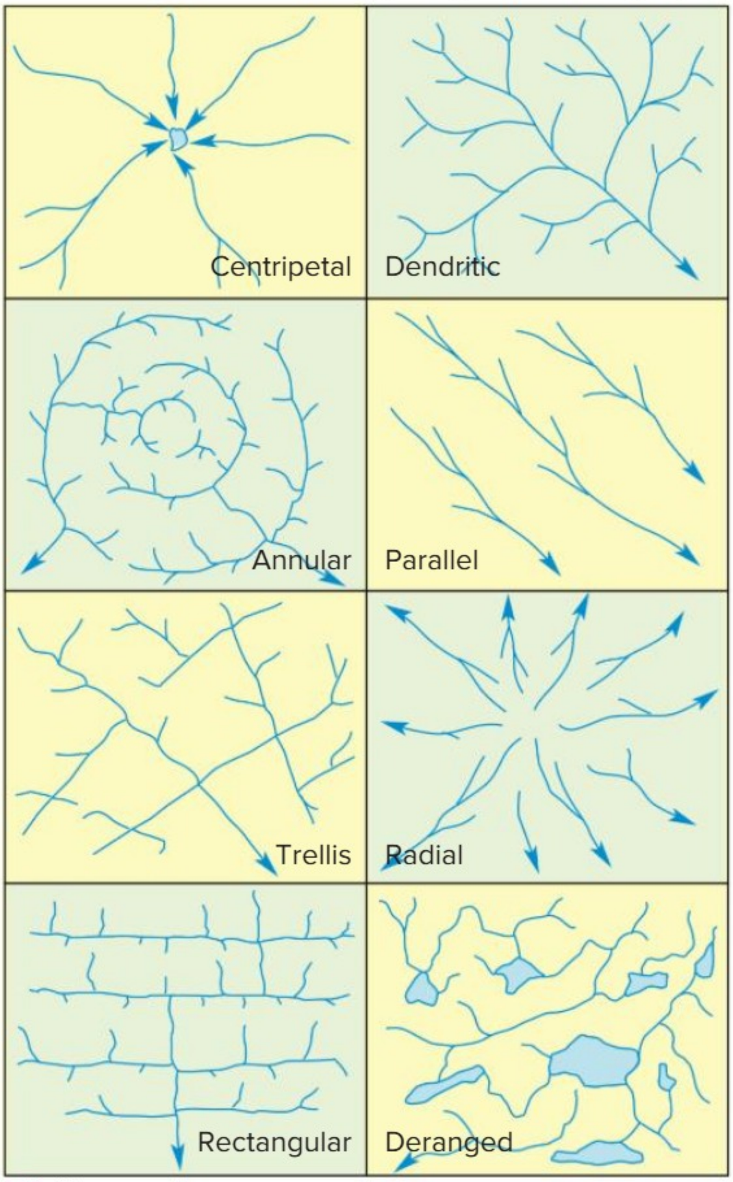
1.12 The parts of a drainage basin.

1.13 A large landslip in Qafa e Qarrit Pass, south of Korçë in Albania occurred as a result of mass movement, sending many tonnes of rocks down the slope to the valley floor.

1.14 Erosion caused by running water in the Vjosë Valley, east of Përmet in Albania.

1.15 Snow on the ground highlights the dendritic drainage pattern of tributaries of the Red River that forms the border of Oklahoma and Texas, USA.

are supplied to the channels and valley bottoms from the slopes. After it is eroded, the material from the slopes moves downhill by mass movement (the action of gravity), wash and gully erosion. When it reaches the valley floors, the eroded material may be removed further down the drainage basin through the **running water** of the stream. In this way, the **valley floor** can be thought of as a corridor for the removal of sediment and water, and **streams** can be seen as the natural transport routes of a drainage basin.



1.16 Stream patterns.

Water moves more rapidly than sediment through streams. As water and sediment flow downstream, they often trace out **regular patterns** when viewed from above. There are eight major stream patterns, and the differences are often caused by the underlying rocks.

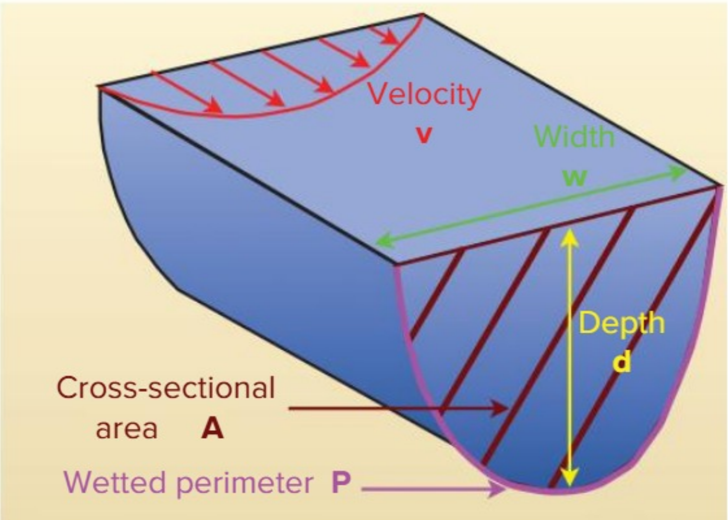
- **Dendritic** streams resemble the branches of a tree. All parts of the stream generally flow in the same overall direction, starting with small channels near the source that join together as it flows downstream.
- **Radial** streams radiate outwards from a central point, such as a volcanic cone.
- **Rectangular** streams have straight valleys that join at right-angles. This pattern is often found in areas where faults or joints in the rocks cross at right-angles.
- Where many small streams join a few large ones at right-angle junctions a **trellis** stream is said to exist. These are commonly found where the underlying rocks are tightly folded, as the larger streams flow along the valleys of the bottoms of the folds.
- **Deranged** streams appear to follow a largely random pattern, and do not connect together to form any coherent or continuous network. This pattern tends to be found where there has not been enough time to erode and develop a network of valleys. This can occur where channels are blocked with windblown sand, in areas that were recently glaciated, and where the land is flat, evaporation and infiltration are high and discharges are low.
- **Centripetal** streams flow inwards to a common point such as a desert lake or a limestone cave.
- **Parallel** streams flow in quite straight lines that flow parallel to each other. Usually it is only small streams on steep slopes that have this pattern, such as on road embankments.

- **Annular** streams form a circular or oval pattern that follows the rock structure of a basin or eroded dome. In general, only one or two of the larger streams managed to break through the concentric valleys.

The relationship of discharge to stream characteristics

The nature of a stream channel and the flow of water with it are to a large extent interdependent, as changes in one will affect the other. To understand why this is so, it is helpful to clarify some basic terminology:

- **Depth *d***, measured in metres, is the vertical distance from the stream bed to the stream surface, measured at any point across a stream.
- **Width *w***, measured in metres, is the horizontal distance across the surface of a stream, measured at any point.
- **Cross-sectional area *A***, is the area of a vertical slice across a stream at any particular place, measured in square metres.
- **Wetted perimeter *P***, is the length in metres of the distance across a cross-section of a stream where the stream bed and the stream's water are in contact.
- **Form ratio *FR***, is the ratio of average depth to average width, expressed as FR=d/w
- **Hydraulic radius *R***, is the ratio of the cross-sectional area to the wetted perimeter, expressed as R=A/P.



1.17 Stream channel geometry

1.18 The Aikwaa River near Timika, Indonesia, has a very large wetted perimeter because it is swollen with tailings from a large mine upstream.

- **Gradient**, or **slope *S***, is the angle made by a stream surface to horizontal. This can be expressed in metres per kilometer, or a ratio of vertical change to horizontal distance (usually scaled so that the vertical distance measures 1), or as a percentage grade. The gradient of a stream that drops 5 metres over 100 metres of horizontal distance could be expressed as a percentage grade of 5% or a ratio of 1/20.
- **Velocity *V***, is the speed of flow of the stream. The distribution of the velocity of water within a stream channel varies because of friction between the water and the wetted perimeter. Because of friction, the velocity of a stream is faster in its middle and slower towards its edges. As a result of these differences, it is more useful to describe the **mean velocity *V*** of a stream.
- **Discharge *Q***, is the volume of water that passes through a stream's cross-section in a given period of time. This is normally measured in cubic metres per second (m^3/s), which can be shortened to 'cumecs', or as megalitres per day. Discharge is calculated using the equation Q = VA.

Water flowing without any sediment is able to scour rock because of hydraulic action and turbulence. **Hydraulic action** is simply the erosive force of water beating on rocks – erosion by the impact of water. When water cascades down a waterfall and hits the rocks below, it exerts a hydraulic force that can scour holes into the rock, in much the same way that a hole is drilled into soil by a water jet from a hose. Weak rocks, and rocks with cracks and fractures, are easily broken down, although massive rocks (those with no jointing) resist breakdown by hydraulic action.

Although water by itself can produce landforms, most work is done by water that is carrying sediment. Materials carried by a river are referred to as the **load** of the stream. The rocks, sand, sediment and minerals that comprise the load can be carried by rolling along the river bottom (**bed load**), by being suspended in the water (**suspended load** or **wash load**), or by being dissolved in the water (**solution load** or **dissolved load**). Often, all four of these processes of **transportation** take place at the one time.

Material that is dragged or rolled along the bed of the stream because it is too heavy to be lifted is called **bed load**. Typical bed load materials have diameters greater than 2 millimetres, such as **gravel** and **cobbles**. Because of its large size, bed load usually moves slowly and is often broken down into smaller particles after being transported only short distances. Bed load particles are usually rounded because irregularities are removed rapidly during frequent collisions.

Smaller particles with diameters between 0.02 and 2.0 millimetres are known as **sand**, and these are usually carried as **suspended load**. Suspended loads are carried by the water above the level of the bed of the stream. Larger particles are carried by **saltation** motion, which means a series of repeated jumps. On the other hand, fine sand may be suspended for long periods and even carried to the stream surface before falling back to the bed.

1.19 A bed load of rounded rocks in the Urubamba River, Peru.

1.20 Mean velocity, cross-sectional area and slope change as this small stream in Montana, USA, flows from a section of rapids into a pool. In the rapids, cross-sectional area is small, mean velocity is large, and gradient is steep. In the pool area, cross-sectional area is large, mean velocity is small, and gradient is shallow.

Wash load comprises very fine particles of **silt** and **clay** that are suspended permanently in the stream. These particles are so fine that they can be carried by flows with velocities less than 0.1 cm/s, and even minor turbulence may hold them in the water for long periods. Some rock materials are dissolved during the process of weathering, and when these materials are carried by a stream, they are known as **solution load** or **dissolved load**.

Water flows in a stream in two main ways, laminar flow and turbulent flow. **Laminar flow** occurs when water particles move in sheets parallel to the channel bed, flowing slowly in a smooth and shallow channel. However, laminar flow is fairly rare, and **turbulent flow** is much more common.

1.21 As this stream flows from right to left, laminar flow breaks down into turbulent flow.

1.22 The irregular bed of the St Mary River in the USA causes the water to move in a turbulent flow.

Table 1.1

Typical Values of Manning's Roughness Coefficient

Bed profile	Vegetation (weeds, tree roots)	Manning's Coefficient Value: Sand and Gravel	Coarse Gravel	Boulders
Uniform	None	0.020	0.030	0.050
Undulating	None	0.030	0.040	0.055
Uniform	Some	0.040	0.050	0.060
Undulating	Some	0.050	0.060	0.070
Highly Irregular	None	0.055	0.070	0.080
Highly Irregular	Extensive	0.080	0.090	0.100

Source: Based on Goudie, A. (1984) p.286

1.23 Turbulent flow causes a rate of erosion, as seen here by the brown sediment in the Iguazú River that forms the border between Brazil and Argentina.

When water moves in turbulent flow, the water particles move in erratic paths downstream, criss-crossing and mixing with other particles. Turbulent flow results in more **erosion** of the stream channel than laminar flow and it is capable of keeping particles suspended for longer periods of time.

When people compare the rushing water in the small channel of a stream near its source, with the apparent sluggishness of water downstream, they often conclude that water flows more quickly near the source.

This was shown to be wrong as a result of the work done in 1891 by the Irish engineer, Robert Manning, who attempted to quantify the roughness of stream beds. Table 1.1 shows typical values of **Manning's roughness coefficient** depending on the material that makes up the bed of the stream.

Manning developed his roughness coefficient into an equation that described the **velocity** of flow. Manning's equation is: $V = \frac{R^{2/3} S^{1/2}}{n}$

where V is mean velocity (in metres per second), R is the hydraulic radius (in metres; in wide channels the mean depth is used instead), S is channel slope, or gradient (in metres per metre), and n is the roughness coefficient described above. This equation shows that **if bed roughness increases, then velocity and discharge will decrease.** Furthermore, **if the hydraulic radius or the gradient increases, then the velocity and the discharge will increase.**

Manning's roughness coefficient shows us that the water flows more quickly in the downstream

1.24 This small stream on the slopes of Vachkazhets Peak in Russia appears to flow quickly through its steep, rocky channel.

1.25 In contrast with the small stream in the previous photo, the middle reaches of the Lena River seem to flow slowly through its wide channel near the city of Yakutsk, Russia. In fact, this stream would flow much faster than the one in figure 1.24 because there is much less friction with the channel banks.

stretch of a river than upstream. This is because a greater proportion of the volume of water is in contact with the channel sides and bottom upstream, causing more **friction** that in turn slows the flow of the water.

As the discharge and velocity of a river increase, the stream becomes capable of transporting greater volumes of sediment, and sediment of larger sizes. The largest particle of sediment that a stream can carry defines the stream's **competence**. The more 'competent' the stream, the larger the particles it can carry. Competence tends to increase exponentially with velocity. In other words, if velocity doubles, then the maximum size of the particle that can be carried increases six-fold. Naturally, neither wash load nor solution load concentrations are related to the velocity of flow.

The amount of sediment carried by a stream over a certain period is its **sediment discharge**. In general, sediment discharge triples when water discharge doubles. This relationship is not precise because it depends on factors such as how much sediment is available, the sediment size, velocity of the stream and the shape of the channel. The **sediment yield** of a catchment is the total quantity of sediment leaving a catchment in a year.

1.26 The sediment comprising the bed of this stream near Aît Benhaddou in Morocco is clearly seen. The sediment is being supplemented by weathered material from the outside bank that is being undercut by the river. In this view, a herd of goats is being brought to the river to drink.

The direct sources of sediment for a steam are its bed and its banks. Most of the material comprising the bed and bank is sediment that has been weathered elsewhere in the catchment and deposited by the river. This is known as **alluvium**. Alluvium sometimes has a long history of transport, deposition and re-deposition, especially in streams with large catchments. The beds and banks of some streams are composed of **bedrock**, but even they may still provide some sediment as a result of the hydraulic action and abrasion of the stream by the particles that are being transported.

In the lower (or downstream) stretches of many rivers, **floodplains** develop over a long period of time. Floodplains are wide, flat areas of material beside rivers that are deposited during floods. Valley floors may consist of alluvium that has been deposited over many years. Because the sediments deposited by the river often contain useful plant nutrients, they make fertile soils that are often used by farmers for cultivation. Much of the sediment is moved and rearranged whenever the river floods or changes course.

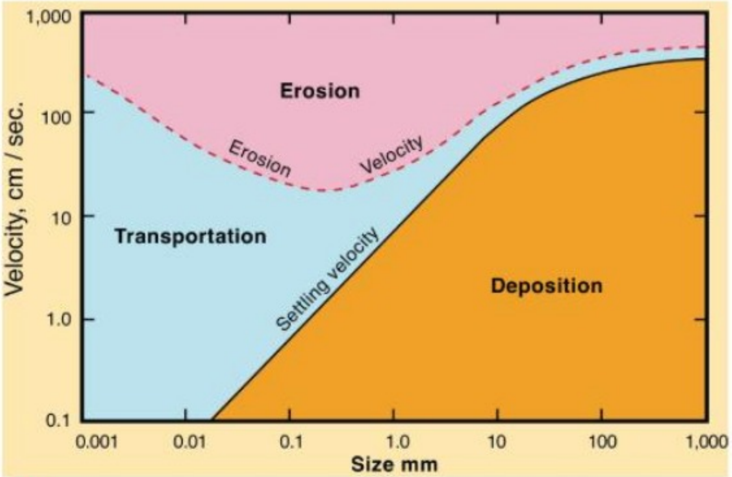
1.27 Part of the extensive floodplain of the Arkansas River in the United States. Water from the river is used for irrigation.

River processes and landforms

River processes

The main agent of change for landforms in a drainage basin is **water**. Water both erodes and deposits sediment, and it is the interplay between these two processes that determines the landforms found in any particular area. This is especially so on the floodplain of a river.

The **interaction** between erosion and deposition can be understood by examining the **Hjulström curve**, developed by the Swedish geomorphologist Filip Hjulström in 1935. We saw earlier in this chapter that more velocity, and thus energy, is needed to erode larger particles than smaller ones. Hjulström examined the stream velocity needed to erode and then transport particles of varying sizes, and compared these to the velocities at which streams lost competence to continue carrying them. He used his research to construct a curve showing these relationships.



1.28 The Hjulström curve shows the relationship between stream velocity and the size of particles carried.

The Hjulström curve shows that when the stream velocity is low, the water can only pick up very small particles such as clay and fine silt. As velocity increases, larger particles can be transported. The erosion velocity curve shows the velocity needed to erode and transport particles of various sizes. The settling velocity curve shows the velocity at which particles of varying sizes will be deposited because they are too heavy for the water to continue carrying. It is important to realise that the velocity needed to pick up a particle is greater than the velocity needed to keep it in motion.

Question Bank 1D

1. *How is it possible for water that is not carrying any sediment to erode a stream channel?*

2. *Describe the pattern shown in table 1.1, which outlines Manning's roughness coefficient.*

3. *Describe the typical trends as one moves from the source of a stream to its point of discharge in (a) gradient, (b) velocity, (c) form ratio, and (d) hydraulic radius*

4. *Describe the relationship between river discharge and (a) stream flow, (b) channel characteristics, and (c) hydraulic radius.*

The valley floor

The valley floor can be thought of as comprising three major parts – the channel, the floodplain and the terraces. **Terraces** are elevated remnants of abandoned floodplains. They are known as **relict** features because they are the result of processes that have ceased long ago. Where terraces are found, **rejuvenation** has often occurred. This means that the base level has fallen relative to the land where the stream is found, increasing energy and causing a renewed phase of downward erosion. This change in base level can be caused either by a lowering of sea level, such as happens during an ice age, or a rise in the land, as happens with tectonic uplift.

1.29 Two levels of terraces can be seen beside the Gardner River in Montana, USA.

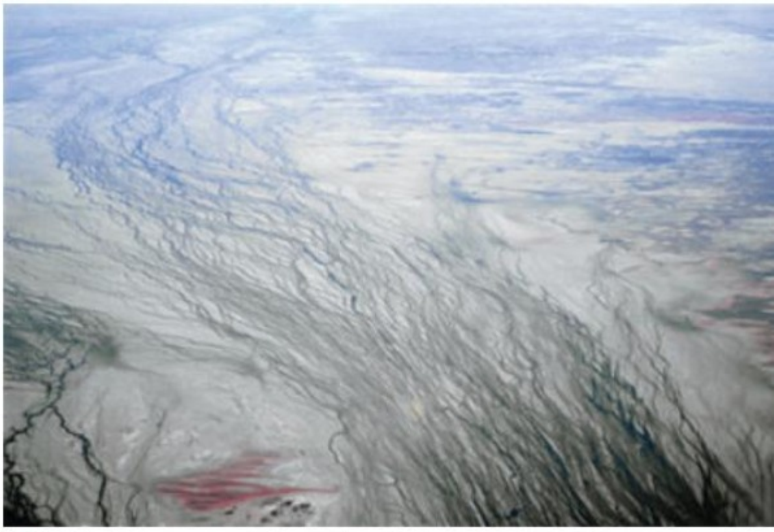
The second component of the valley floor, the **channel**, is the major route for the movement of water and sediment through the valley. There are two main channel patterns – **braided** and **meandering**. The differences between these two patterns arise mainly because of differences in the river's discharge and the amount of sediment carried.

Braided channels are made up by a large number of minor channels that are interconnected between bars of sediment. They usually have one or more of the following characteristics:

- **coarse sediment** in the bed and banks, often material of gravel size and larger;
- **steep gradients** along the channel;
- **discharges** which **vary** greatly from one **season** to another, such as on the edges of glacial areas;
- **a low form ratio** (shallow depth relative to width, or a high width to depth ratio);
- banks and a bed that are **easily eroded** because they are not cohesive; and
- a channel that does **not meander** very much.

It is thought that braided channels form when a river carries a large load of sediment relative to its discharge. As the sediment load of a river increases, a larger bed load (sediment on the stream bed) needs to be carried. By braiding, the river is able to **maximise the energy** spent on the stream bed. In this way, it seems that braiding is the most **efficient** way for a river to carry a large bed load. Braided channels also shift rapidly across the floodplain, and it is common for them to change their appearance completely after only one flood, with an entirely new set of channels and bars appearing.

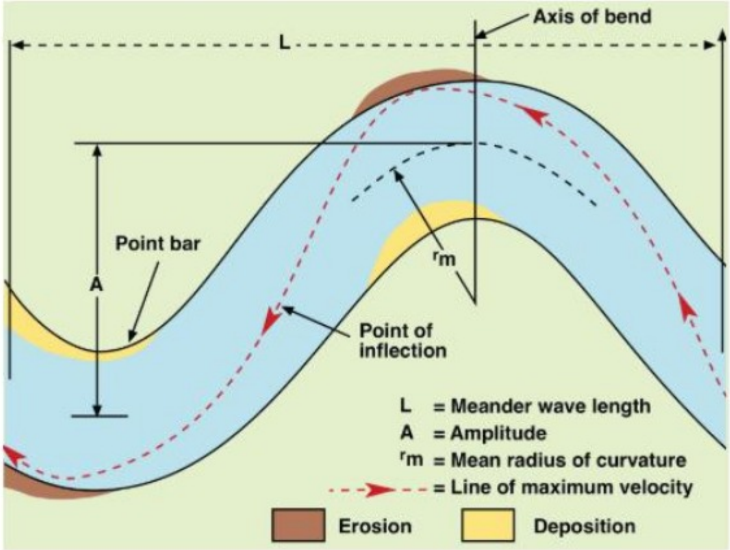
In contrast with braided channels, **meandering channels** comprise a single stream channel that



1.30 The Diamantina, a large braided stream in south-west Queenland, Austraiia.

1.31 Wolumla Creek, a small braided stream near Bega, Australia. Note the loose sediments and shallow depth relative to width that characterise braided streams.

1.32 A stretch of meandering channel in the Tami River, near Jayapura, Indonesia. Note the looping meanders. An ox-bow lake and some meander scars are visible, and more are likely to form in the future.



1.33 The parts of a stream meander.

follows a sinuous course, resembling a sine curve. The extent to which a stream meanders is measured by its **sinuosity**. This is measured as the distance between two points measured along the curving stream channel, divided by the straight line distance between the same two points. A stream with wide meanders would have a sinuosity index of 3 or more. In other words, the distance along the river channel is three times greater than the straight-line distance along the same valley. On the other hand, a low sinuosity would be less than 1.5, while a straight stream would have a sinuosity of 1.

It is known that most streams meander rather than braid, although it is not fully understood why this is so. It used to be thought that a fallen log or rock would obstruct the stream, causing it to divert in one direction. Then, when it diverted back again, it would over-compensate, creating another meander, and so on. We now understand that an obstruction such as fallen tree is not necessary for meanders to develop. Indeed, if you were to take a perfectly smooth surface (such as a laminated desk top) and allow a trickle of water to flow down, the water would meander even though there were no obstructions.

Modern research suggests that meandering occurs due to the **oscillation** of the **bipolar water molecule**. Because the water molecule, which comprises two hydrogen atoms and one oxygen molecule, is bent rather than straight, each molecule has a positively charged end and a negatively charged end. In a moving stream of water, there is a complex set of attractions and repulsions as the molecules come into contact with each other at seemingly random angles. It is thought that these attractions and repulsions initiate microscopic oscillations that take on a resonance as they work together. This causes small vibrations that send the water slightly off course. Once this happens, a pattern of meandering is initiated, and this pattern becomes established and grows as sediment is displaced.

One meander is defined as a complete loop or bend in a stream. The point where one bend crosses to another is the **point of inflection**, and it is often the shallowest part of the meander. These shallow inflection points are called **riffles**. When water flows in a meandering stream, it tends to do so in a spiral pattern. As the water flows downstream, it is thrown outwards towards the outside bank by centrifugal force as it flows round the bend of each meander. This causes the water level at the outside banks to rise above the level at the inside bank, which in turn sets up bottom currents of water that flow inwards. This circular motion **erodes** the bed on the outside of the meander, **scouring** the bed and causing pools to form, and undercutting the outside bank.

As a result of this effect, the line of fastest flow in a stream (known as the **thalweg**) is usually an exaggerated variation of the stream channel shape that crosses to the outside of each meander at the point of inflection. Because erosion is greatest where stream flow is fastest, the thalweg is also the deepest channel in the stream.

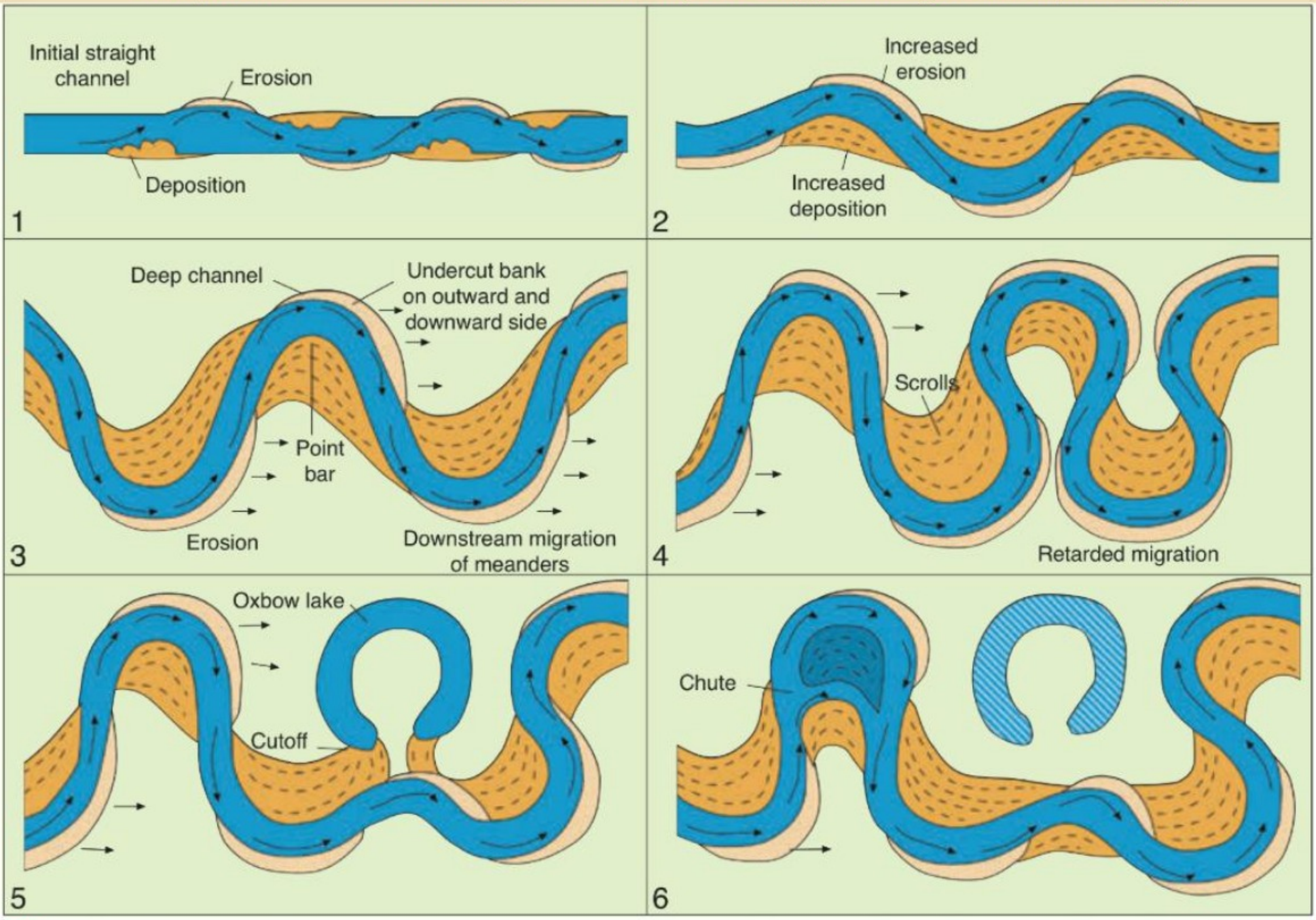
1.35 Meanders in the Kir River near Shkodër, Albania, show the classic pattern of point bars deposited on the insides of meanders, and erosion on the outsides of each meander. The meander in the centre of this photo has been reinforced by a stone wall to prevent further outward migration of the meander.

1.34 Snow highlights the wide floodplain and scars of old meanders, indicating that the Upper Mouth River in Alaska, USA, has a long history of floodplain formation by lateral migration of meanders and concave bank scour.

Braided and meandering streams tend to construct floodplains in different ways. Braided channels **migrate** across their valley floor, usually in times of flood, leaving bars of sediment behind them. The direction of this movement depends on the looseness of the bank material, the rock through which the stream is cutting, and the shape of the valley. Small channels that have been abandoned become infilled with plant material and with fine sediment deposited by floods and wind action.

By contrast, most floodplains built by meandering streams are formed by the **deposition** of **point bars**. Point bars are deposits of sediment found on the inside banks of meanders. They form as part of the same process that causes meanders to widen as water erodes the outside banks of meanders. This process also means that the flow of water on the inside of each meander decreases, reducing the ability of the stream to transport sediment at the inside bank. Deposition of sediment therefore occurs, forming a point bar. The point bar continues to grow upwards and outwards as the stream migrates across the floodplain. This sideways movement of the meander is called lateral migration.

The process of **lateral migration** causes rivers to shift their courses constantly. If meanders did not migrate laterally, floodplains would be very narrow and valleys would only be widened by the processes occurring on the hillslopes.



1.36 Stages in the process of concave bank scour, which leads to the growth of meanders and their downstream migration, and then eventually to the formation of oxbow lakes and chutes.

Streams migrate laterally in three ways – the process of concave bank scour, instability due to build up of the bed, and flood scour. All three of these processes may occur in the same valley and it is sometimes difficult to separate them.

1.37 Meanders, oxbow lakes, cutoffs and meander scrolls are all visible on the floodplain of the Ramu River, near its mouth on the northern coast of Papua New Guinea. The brown colour of the water shows the high volume of silt carried by the river, which is deposited after floods to form the floodplain features.

Concave bank scour, or wearing away of the outside banks of meanders, accounts for most of the lateral migration that takes place in rivers. As explained earlier, the concave (or outside) banks are the areas where most erosion occurs, and so meanders tend to migrate outwards. As time goes on, meanders begin to intersect with other meanders. This usually occurs in time of flood, when the river cuts through the narrow neck of the meander, leading to the abandonment of segments of channel. Once they have been abandoned, these segments are called **oxbow lakes**, cutoffs or billabongs. After some time, oxbow lakes fill in with sediment and become swamps called **backswamps**. Later still, they dry out and become colonised with vegetation, leaving only a depressed area of land called a **meander scar**.

When valley walls are undercut by migrating meanders, the angle of the hillslope is increased, resulting in instability. This instability leads to an increase in local rates of **mass movement**, which in turn increases the width of the valley floor.

Much of the deposition that forms floodplains occurs during times of flood when the river level rises so high that the water overflows the river's banks. In many humid terrains, this is a **seasonal** event, as the river becomes swollen with water from melting snows every spring. Rivers that carry large sediment loads can therefore eventually **build up their beds** to levels above that of the valley floor. During a flood, the channel wall will be breached and the stream will take a completely different course when the floodwaters recede. The former elevated channel then forms a **ridge** (or series of ridges) that remains until destroyed by later floods or lateral migration.

Levees are ridges or embankments of sediment, parallel to the channel, that are built up by floods as they burst over the channel banks. As the water overflows the banks and flows onto the surrounding floodplain, it slows down, rapidly losing energy. The decreased competence means that the stream drops large quantities of sediment near the bank. With the passage of time, these deposits (which usually consist of sand) build up into a ridge or levee. Levees are essential to the development of **raised channels**. Sometimes, levees prevent a tributary stream reaching the main channel. When this happens, the smaller tributary may flow parallel to the main channel for some distance before joining it. These smaller parallel streams are called **yazoo streams**, named after the Yazoo River, a tributary of the Mississippi.

The third process of floodplain formation is **flood scour**. Considerable erosion can occur during flood times. Where the sediments that make up the floodplain do not hold together well or are unprotected by vegetation, large floods can scour the valley floor. Usually, the scour channel has a steeper gradient than the meandering channel, because it is straight, and this may serve to speed up its capture of the meandering stream. Scour channels often develop across meander necks.

1.38 Scouring of the riverbank during flood times has eroded the sediments, exposing these tree roots beside the Niger River near Mopti in Mali.

1.39 A spectacular example of rejuvenation — the huge volume of the Grand Canyon (USA) has been eroded by the small Colorado River that flows through it.

Floodplains may be **abandoned** for two major reasons. First, a river may **aggrade** (i.e. build up sediment) and bury its former floodplain. Second, the river may **incise** (cut deeply) and create a lower floodplain. The remnant of the former floodplain on the valley side is then known as a **terrace**. Aggradation and incision are triggered by a change in base level, which in turn may be caused by a number of processes such as a **rise or fall in sea level**, movements in the earth's **crust**, or **climate change**. When base level is lowered (or the land is raised), **rejuvenation** is said to occur as the stream gains more energy to erode downwards.

Another landform that may result from a change in base level is the **nickpoint**. Nickpoints are breaks in the smooth long profile of a stream. In the field, they appear either as **rapids** or a **waterfall**.

Nickpoints can form in a variety of ways. Sometimes a **resistant layer** of rock creates a **temporary base level**, and the stream has difficulty eroding below this level. This is common in areas of sedimentary rock where bands of rock may have different degrees of hardness, and thus resistance to weathering.

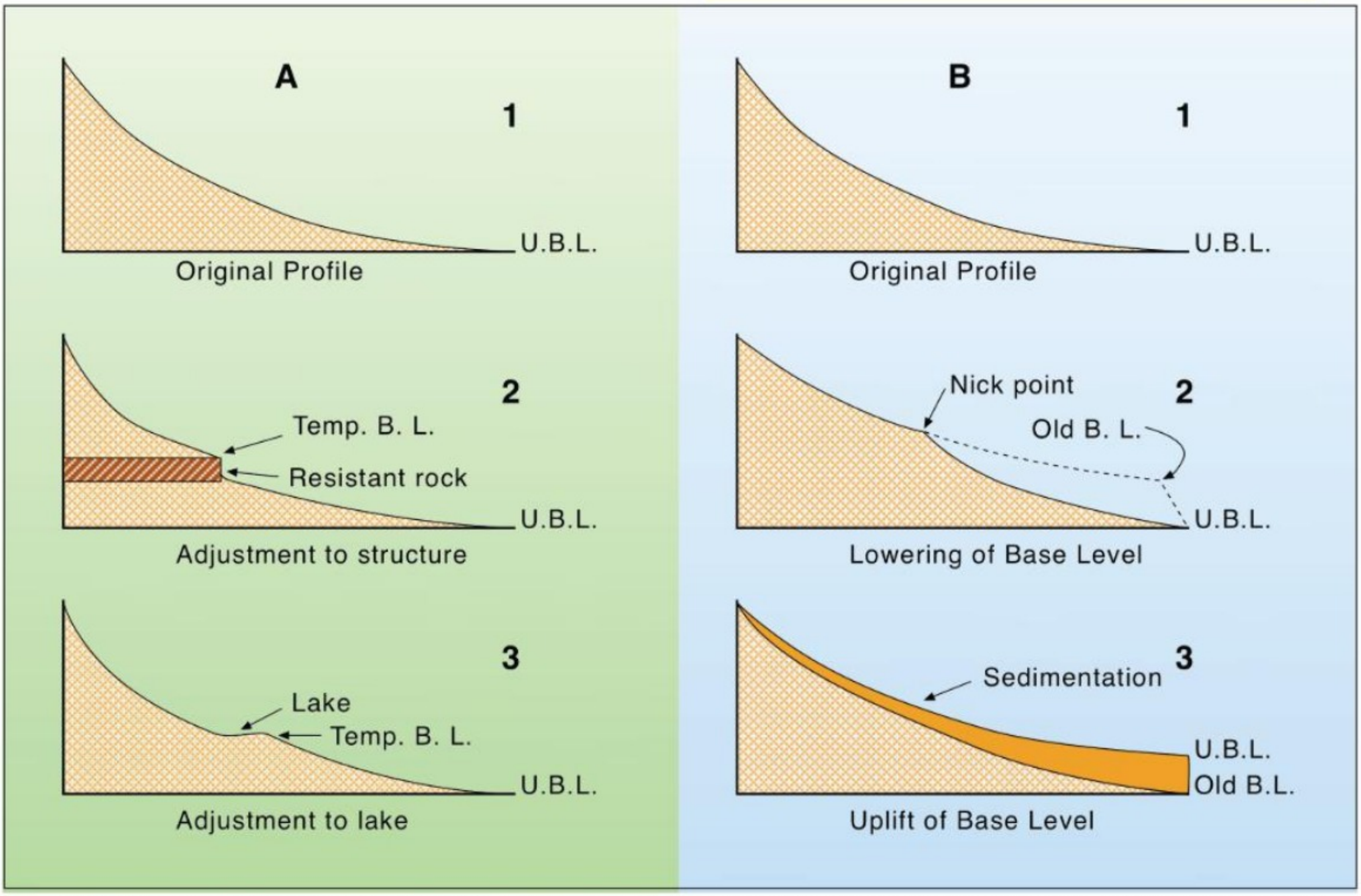
1.40 Iguazú Falls on the border of Brazil and Argentina is a waterfall formed by resistant layers of rock creating a temporary base level.

A second way that nickpoints can form is when **sea level falls**. When this occurs, rivers adjust to the lower base level by constructing a new long profile. Over time, **headward erosion** of the nickpoint thus formed gradually replaces the earlier long profile. There is a break in slope occurs at the junction of the two long profiles.

1.42 Rapids are a type of nickpoint as they represent a break in the smooth profile of a stream. The rapids shown here are in Red Rock Canyon, Alberta, Canada, where the stream flows through an area of argillite that was exposed after the last ice age ended about 11,500 years ago.

Question Bank 1E

1. *Construct a table to compare the origins and characteristics of braided and meandering channels.*
2. *Draw a series of diagrams to illustrate the formation of oxbow lakes.*



1.41 The long profiles of two streams, 'A' and 'B', showing nickpoints that have formed for different reasons. 'BL' means base level, and 'UBL' means ultimate base level.

3. *Explain why pools are usually found in the apex of a meander while riffles are usually found at the point of inflection.*
4. *Why does a stream erode on the outside of its meanders and deposit sediment on the inside? What happens to the course of the stream as a result of this?*
5. *Draw a table to classify the landforms described in this section as either (a) erosional or (b) depositional.*
6. *Choose any two erosional landforms and any two depositional landforms, and make a point form list to explain how they are formed.*
7. *Choose one photograph in the chapter up to this point, and draw a photosketch of it, labelling the main features of the river shown. Identify and describe the main landform features of the area, paying particular attention to evidence of change in the river system.*
8. *Name and locate a floodplain you have studied in the field. Select three landforms studied, and explain their formation. Comment on how closely the landforms you studied resembled those described in textbooks.*
9. *Name and locate a floodplain you have studied in the field. Describe the human modifications to the floodplain and their effect on the size and probability of floods.*

CASE STUDY
The processes of forming a large nickpoint - Victoria Falls

One of the world's largest **waterfalls**, Victoria Falls is located on the border of Zimbabwe and Zambia at latitude 18°S, longitude 26°E. The falls are 1.7 kilometres wide, and the water drops between 90 metres and 108 metres. An average of 550,000 cubic metres of water fall over the edge of Victoria Falls per minute, although during the wet season from March to May the volume rises to five million cubic metres per minute.

The stream which flows over Victoria Falls is the **Zambezi River**. The Zambezi rises in the mountainous highlands of northern Zambia near the point where Zambia, Congo and Angola meet. The river flows first to the south-west into Angola before returning into Zambia where it flows south across a vast wetland area known as the Caprivi swamps. After being joined by a major tributary, the Chobe River, the Zambezi flows east, forming the border of Zimbabwe and Zambia and broadening out to a wide braided stream as it approaches Victoria Falls.

1.43 Victoria Falls, seen from the Zimbabwean side.

1.44 Victoria Falls, showing the deep chasm and the spray that rises from the depths of the chasm.

Downstream of Victoria Falls, the Zambezi takes quite a different form, zig-zagging through a series of deep **canyons**. From there, the river continues to flow to the east marking the border between Zimbabwe and Zambia and into the huge Kariba Dam hydro-electric project.

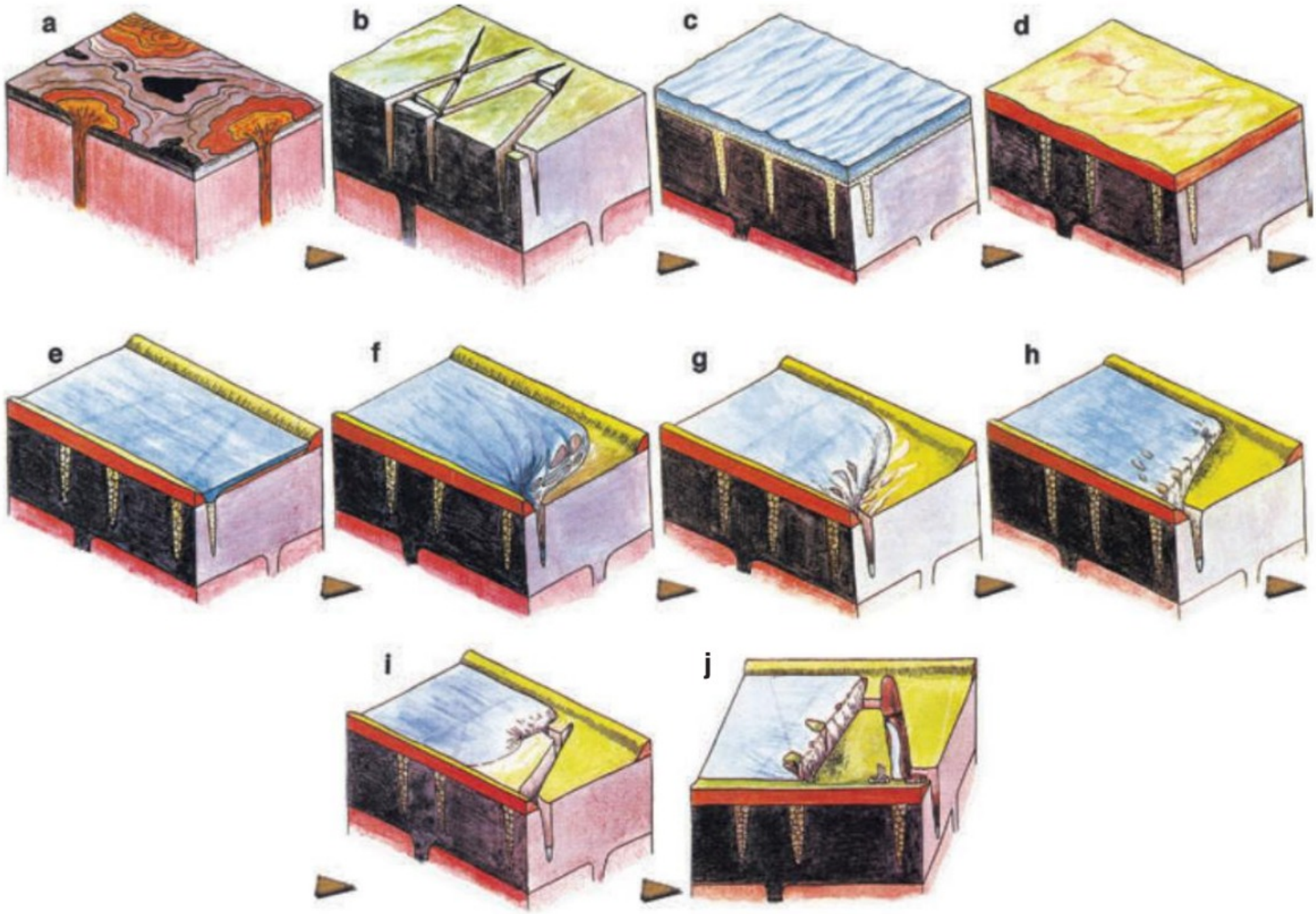
1.45 The Zambezi River downstream from Victoria Falls.

1.46 The Zambezi River widens before it flows over Victoria Falls into the first fissure.

Over the course of the Zambezi, the river flows across different types of rocks of different hardness. Where the **rock is hard**, the river cuts downwards forming waterfalls and rapids. In these areas, the river tends to be deep and narrow, eroding the easiest pathway through the rocks. Where the river bed comprises **softer rocks** of a fairly even type, the river flows smoothly in wide, gentle meanders.

Each of these environments is found near Victoria Falls. Upstream of the Falls, the Zambezi follows a twelve kilometre long stretch where the river is wide and its bed is smooth, so deposition forms islands in the river. The river widens still further as it approaches the Falls, at which point it is 1700 metres wide. At the Falls, the water plunges into a **narrow chasm** which is 108 metres deep and which runs at right angles to the flow of the river. As the water falls, it usually sends up **spray** to a height greater than the Falls themselves. This is the reason that the Falls are known locally as Mosi-oa-Tunya, which means 'The Smoke that Thunders'.

When the water plunges into the narrow chasm, the river's width of 1.7 kilometres narrows to just a few metres in a matter of seconds. This causes the water to **increase its velocity**, changing the river's main process of **deposition** above the Falls to **erosion** below the Falls. To understand the reasons for this abrupt change in the Zambezi River above and below Victoria Falls, it is necessary to understand how the Falls formed.



1.47 The processes that led to the formation of Victoria Falls. The perspective of these diagrams is similar to the angle of figure 1.46.

Formation of Victoria Falls

The evolution of Victoria Falls goes back approximately 150 million years. At that time, there was extensive **volcanic activity** in southern Africa. Molten rock forced its way up through fissures, or cracks, in the earth and spread out over the surface, covering large areas. The molten rock, known as **lava**, formed layer upon layer in this way, with each layer cooling to form rock before being covered by another layer of lava. The rock formed in this way is known as an **igneous rock** because it is formed by the cooling of liquid rock.

This process occurred in the area which is now Victoria Falls (figure 1.47a). The rock formed was **basalt**, a dark coloured, fine-grained rock which formed a layer about 300 metres deep at Victoria Falls — the rock can still be seen clearly on the sides of the deep gorges downstream of Victoria Falls. As the lava cooled and became solid, some **shrinkage** occurred. This caused cracks, or fissures, to appear in the basalt. After the volcanic activity ceased, these cracks became wider due to the effects of weathering. At Victoria Falls, the **fissures** generally run in an east-west direction, with smaller fissures running north-south (figure 1.47b).

After these fissures had weathered and become wider, it is believed that a large **lake** formed over the area. Perhaps there was a long period of heavy rains, or perhaps the entire area became lower causing it to fill with water. Deposits of **soft clay** and lime (formed from the remains of marine organisms) were deposited on the bottom of the lake. These deposits also filled the fissures that had formed earlier (figure 1.47c).

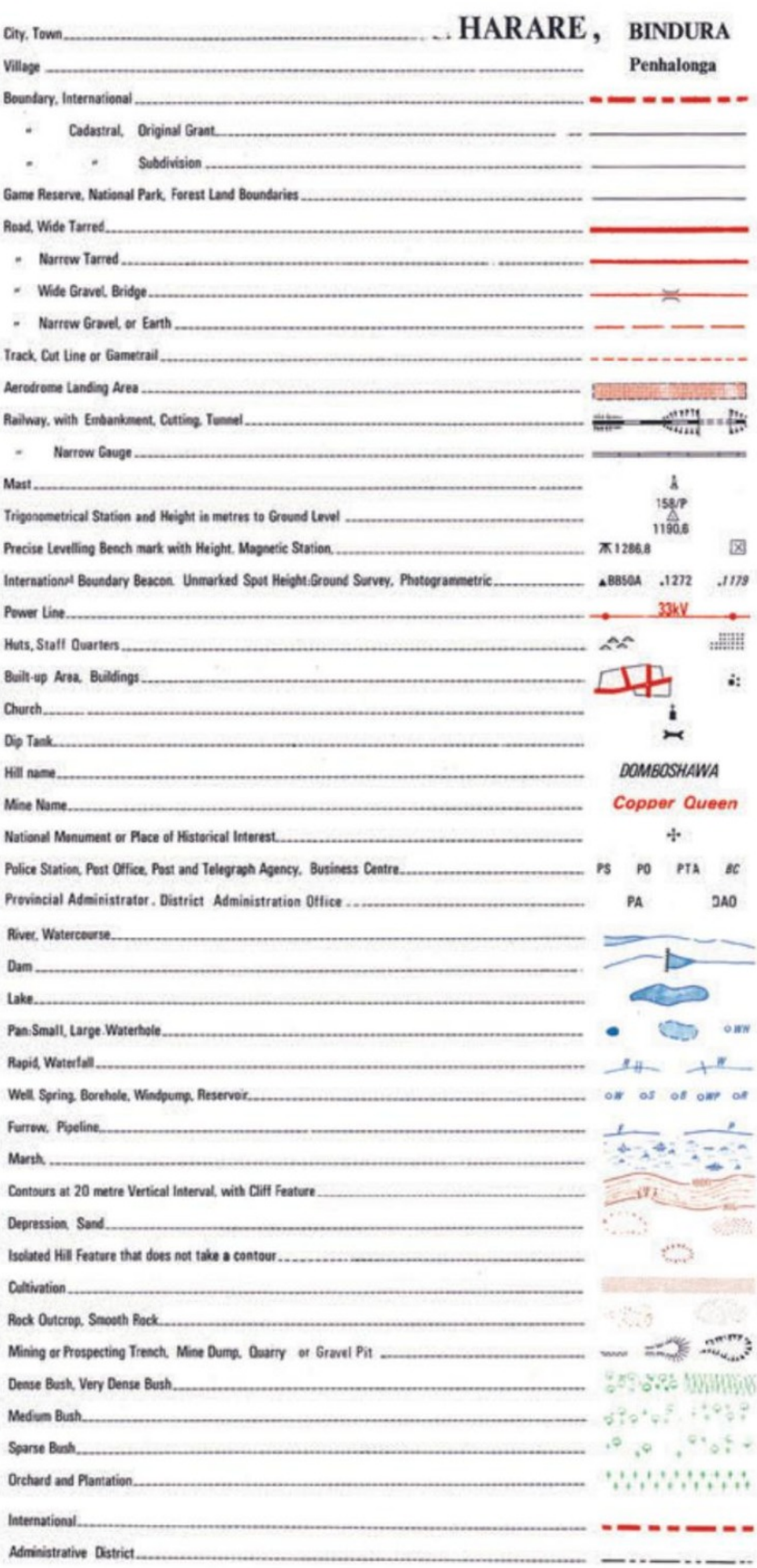
As southern Africa entered a long period of dry conditions, the lake dried out and the area turned into a **desert**. The soft clay and lime deposits were eroded away from the surface by the action of wind, but they **remained** in the fissures where they were protected. Over time, these deposits solidified further to become **limestone**. As time continued further, the earth became covered with **sand**. Movements of the earth caused the large east-west fissures to **widen**, loosening and breaking up the limestone deposits which filled them. This made the limestone deposits in these fissures easier to erode in the future. The same earth movements compressed the smaller north-south fissures, making the limestone in these more compacted and therefore more resistant to future weathering and erosion (figure 1.47d).

1.48 A close view of the Zambezi River just before it cascades over Victoria Falls, seen from the Zimbabwean side. The water in the foreground is the Devil's Cataract, which is where the river is actively cutting a new north-south fissure.

1.49 A close view of the Zambezi River just before it cascades over Victoria Falls, seen from the Zambian side.

1.50 The present east-west fissure at Victoria Falls, seen here from the Zimbabwean side, looking towards the east. This fissure is marked number 8 in figure 1.52.

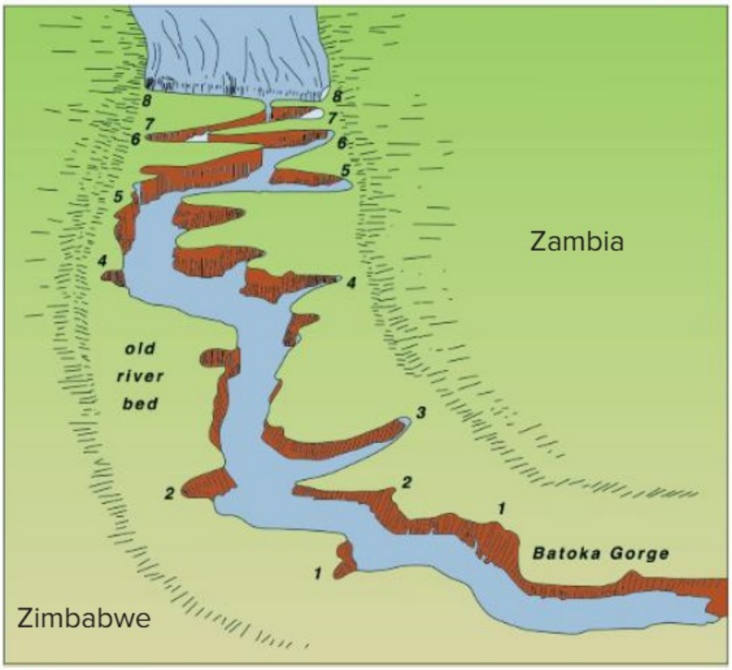
1.51 Victoria Falls 1:50,000 topographic map.



The Zambezi River did not always follow its present course. Originally, the Zambezi continued to flow south from the Caprivi swamps in Zambia to join the Limpopo River in southern Zimbabwe. However, land uplift across the old course of the Zambezi blocked its course, forcing the river to **divert** east along its present course. So for the first time, the Zambezi began to flow across the vast basalt plain that had been formed millions of years earlier. The river easily **eroded** a bed through the soft sandy deposits on the surface, but made little headway at first into the hard basalt beneath (figure 1.47e). The Zambezi was therefore a wide, shallow river for much of its course across the basalt plain.

The edge of the basalt plain was 100 kilometres further downstream from the present Victoria Falls. At that point where the Zambezi left the hard, resistant rock of the basalt plain, the river plunged down a spectacular 250 metre high **waterfall** to the lowlands beneath. This can be thought of as the **ancestor** of the present Victoria Falls because waterfalls move **upstream** over time in the opposite direction to the flow of water. The water falling over the edge of the basalt plain provided the **energy** needed to erode backwards (upstream) into an east-west fissure filled with soft limestone that ran along the river bed (figure 1.47f).

Eventually, the entire Zambezi River was being **channelled** into this fissure. The river rapidly cut its way down into the fissure and **eroded** the fissure backwards to the point where it was only eight kilometres downstream of the present Victoria Falls. At this point, the river began to cut through each of the small north-south fissures until it broke



1.52 The Zambezi Gorges that form the border between Zimbabwe and Zambia. Each pair of numbers represents an east-west fissure that once carried an 'old Victoria Falls'. Fissure number 8 is the present Victoria Falls.

1.53 The Devil's Cataract can be seen as the narrow band of fast-flowing water at the left end of Victoria Falls. It is the latest north-south fissure to be eroded.

through into the next upstream east-west fissure (figures 1.47g, 1.47h and 1.4i). Erosion of each east-west fissure continued until a new connecting north-south fissure enabled the river to erode backwards to the next east-west fissure. This **cycle** seems to have occurred eight times downstream at Victoria Falls, creating the zig-zagging series of deep gorges downstream of the present Victoria Falls (figure 1.52).

The **present Victoria Falls** is thought to be similar to the previous seven falls which have existed in each of the gorges over the past two million years (figures 1.47j). It is believed that erosion has already begun of the next north-south fissure which will take the 'next' Victoria Falls upstream to the next east-west fissure. This north-south fissure is known as **Devil's Cataract**, and it is found at the western end of Victoria Falls.

Question Bank 1F

1. *In your own words, describe the formation of Victoria Falls in one or two pages.*
2. *Explain why the views in figures 1.45 and 1.46 are so different, even though they show the same river (the Zambezi) and are less than one kilometre apart.*
3. *What evidence is there that Victoria Falls is in the process of moving upstream?*
4. *The drainage basin system was described in figure 1.7. Models always represent a compromise. A simple model tends to be unrealistic, whereas a realistic model tends to be very complex. Now that you have examined drainage basin processes in detail, how adequate is the model in figure 1.7?*

Answer the following questions by referring to the topographic map of Victoria Falls in figure 1.51. Note that the Zambezi River marks an international boundary, with Zambia to the north and east of the map extract and Zimbabwe to the south and west of the river. The two main towns in the area are Victoria Falls (in Zimbabwe) and Livingstone (in Zambia), which is just off the map extract to the north. The contour interval is 20 metres.

5. *The scale of the map is 1:50,000. Express this scale as a statement by completing the following: "1 kilometre of the map is represented by ___ centimetres on the map".*
6. *For each of the following photographs, state the direction in which the photograph was taken (i.e. the direction towards which the camera was pointing): figures 1.44, 1.46, 1.50 and 1.53.*
7. *For each of the photographs listed in the previous question, outline briefly the types of information shown on the map which are not shown by the photographs.*
8. *For each of the same photographs, outline briefly the types of information shown in the photographs which are not shown by the map.*
9. *Write about two pages to compare the landforms of the Zambezi River to the north of the Main Falls with the landforms south of the Main Falls, and describe the fluvial processes which would be operating in the two sections of the river.*

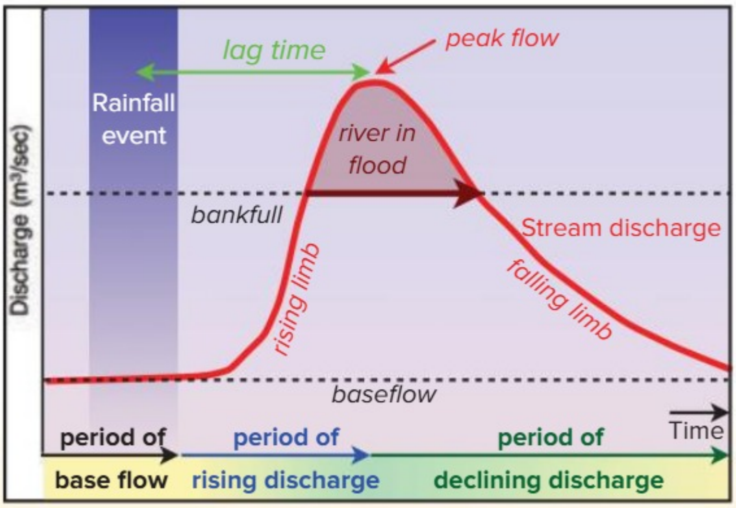
Chapter 2 Flooding and flood mitigation

2.1 Floodplains are the flat areas in the bottom of valleys where flooding occurs. They are formed over time by the deposition of sediments during repeated floods. This floodplain belongs to the Serdyakh River near Magadan, Russia.

Hydrographs

For most land use planning and water resource engineering projects, there is a need to measure stream discharge over a period of years. **Hydrographs** are diagrams that show stream **discharge** over **time** for a point in a drainage basin.

During the period between falls of rain, the normal, reliable flow of a stream is known as **baseflow**. The main source of water for baseflow is seepage from groundwater. Baseflow is almost always at a lower level than **bankfull discharge**, which is the discharge of a river that exactly fills the stream channel without spilling over onto the floodplain.



2.2 The basic structure of a hydrograph.

When rain falls in a drainage basin, overland flow soon begins to drain into the stream channels, raising the discharge and the water level. This is shown in a hydrograph by a rising curve, often referred to as a **rising limb**. A **steep** rising limb indicates that the river is responding quickly to the rainfall event because the rate of infiltration into the soil can't absorb the volume of rainfall, and so overland flow is high. This can occur in areas with **impervious rocks**, or in any area when rainfall is especially heavy.

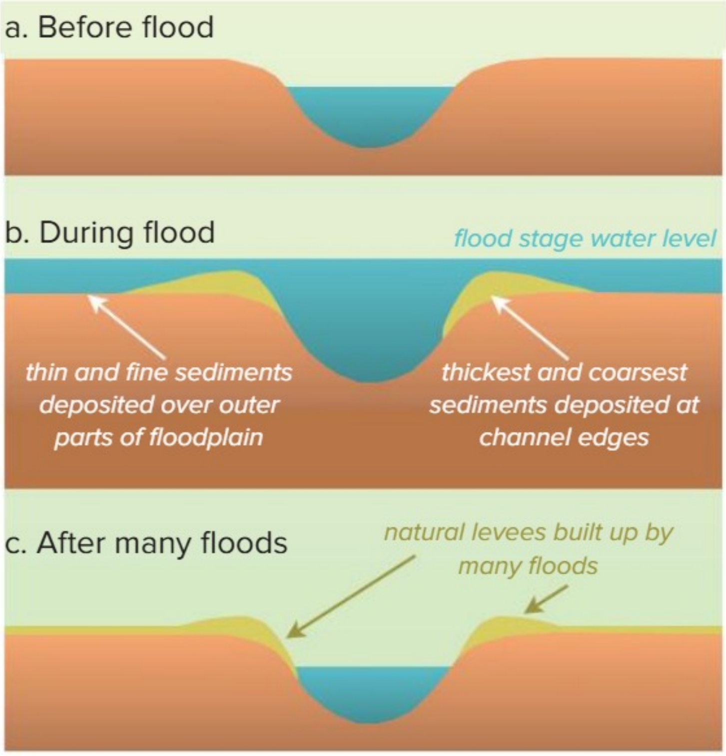
The hydrograph does not begin to rise immediately when rain falls because there is a delay while water drains down the slopes into the river. The discharge curve in the hydrograph continues to rise for a while after the rain has stopped falling because water will continue to drain into the river for some time from overland flow and water that infiltrated into the soil during the rainfall event.

If the discharge rises to a level that is greater than bankfull discharge, then the river will burst its banks, water will flow onto the floodplain, and the river is said to be in **flood**.

When a river bursts its banks and sends water across the floodplain, there is an immediate **reduction** in stream velocity. This occurs because the same volume of water is now flowing through (or across) a much larger cross-sectional area. Because of the slowing of the water, the stream loses some competence to carry sediments, and **deposition** of larger, coarser particles takes place immediately on the edges of the banks. After repeated floods, these deposits build up and form **levees**. Over time, levees increase the height of a river's banks, increasing the volume of water needed to reach bankfull discharge, thus providing some natural protection against future floods.

A few days after rain has stopped falling, the river will reach its **peak flow** (maximum discharge) and begin falling. If a stream's discharge exceeds bankfull and the river floods, peak flow occurs at the point when the river bursts its banks. The delay between the time of maximum rainfall and peak discharge is the **lag time**. During the period of declining discharge, the hydrograph falls as a **falling limb**. Falling limbs are usually gentler than rising limbs because some water continues to seep into the stream for a while. Unless there is another

2.3 The Bega River in south-east Australia has exceeded bankfull stage, and is therefore inundating the farmlands on its floodplain.



2.4 The process of forming levees.

rainfall event, discharge will normally return to baseflow.

The **rate** at which water is delivered from the hillslopes to the channel determines the **volume** of water in a stream at any one time. If delivery times are long, flood peaks are low and the flood periods are also long. On the other hand, rapid delivery results in a short flood period and high flood peak.

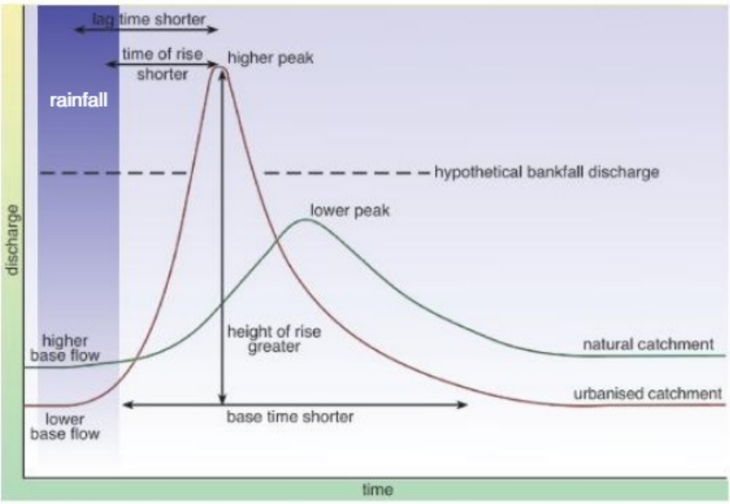
Streams that flow all the time are known as **perennial streams**, and they have a seepage flow source. In other words, they are fed by water from a place where the water table rises to the surface (such as a **spring**) to create a source for the stream. The stream continues to flow as long as the water table on each bank is above the channel level. If the water table falls below the channel level, then the water in the stream will seep underground and there will be no surface flow. Streams that flow only after rain do not have a permanent seepage source, and these are known as **intermittent** or **ephemeral streams**.

Human actions and flooding

People who live near a stream are not usually concerned about its velocity or discharge except when it either dries up completely or floods. **Flood frequency** is the number of times that a flood of a given magnitude will occur, on average, in a specified period. A flood with a frequency of 0.1 per year would occur on average of once every ten years. The opposite (or inverse) of flood frequency is the **recurrence interval**. A flood of frequency 0.2 per year has a recurrence interval of five years.

2.5 A small dry stream in Atka, Russia. In the absence of a fall of rain or seepage from groundwater, the stream's discharge has fallen to zero. Evidence of erosive discharge at other times can be seen by the undercut banks and the car tyres that have collapsed into the stream bed after being set in place as an anti-erosion wall.

Flood frequency and recurrence interval are only **statistical estimates** of the number of floods over a long period and they cannot, of course, be used to predict the exact period between floods. It is possible to find instances where the 5-year flood did not occur for fifty years , or where two 5-year floods occurred in one year.



2.6 Natural and urban hydrographs. The green line shows the hydrograph for a natural drainage basin that has been untouched by human activity. The red line shows the hydrograph for a drainage basin that has been urbanised.

Figure 2.6 shows the hydrographs for two streams, one that is **natural** (or unaltered by humans) and the other that is **urbanised**. Because an urbanised drainage basin has fewer trees, less grass and more paved areas than a natural catchment, there is **less infiltration** and **more quickflow**. Urbanised drainage basins also have artificial drainage, such as pipes and canals, that help to remove water quickly from the surface and transport it into natural streams. Consequently, when there is a fall of rain, the stream in the urbanised catchment rises more quickly and is **more likely to flood**. Furthermore, because there is less ongoing seepage from groundwater in the urbanised catchment, the stream there is **more likely to dry up** between falls of rain.

2.7 Urbanised catchments with large areas of paving, buildings covering the ground, artificial drainage and little natural vegetation are more vulnerable to flooding than natural catchments. This example of an urbanised catchment is in Humble, near Houston, Texas, USA.

The hydrographs of drainage basins that have been modified in other ways, such as **deforestation**, experience similar changes. When a forest is cleared, the soil surface is exposed and destabilised, leading to increased overland flow during and after rainfall. Increased overland flow across soil that is no longer held together by plant roots results in increased soil **erosion**, and so nearby streams are likely to receive a high **sediment load**. Like streams in urbanised areas, the hydrographs of streams in deforested drainage basins rise sooner and more quickly than natural catchments, they are likely to have a higher peak and therefore be more prone to flooding, and they are more likely to dry up between rainfall events because infiltration to recharge groundwater is reduced.

2.8 An area where deforestation has been undertaken near Sentani, Indonesia. Tree felling exposes the soil, resulting in increased rates of runoff and erosion.

2.9 This canal through the small town of Aguas Calientes, Peru, confines the course of the Rio Alcamayo to a fairly straight tract with high walls to prevent flooding during the spring snow melt in the surrounding Andes Mountains. Straightening the river has raised the rate of discharge, increasing erosion, washing away sediment and leaving only large stones in the stream bed.

2.10 This canal in El Alto, Bolivia, has sides that force the stream within it to meander within the confines of the canal walls.

Canals also have a significant effect on stream hydrographs, and this is the case whether the canal is in a rural or an urban area. Canals are built for a variety of **purposes**, such as erosion control, distribution of water for irrigation, drainage of wastes, flood management and land reclamation for urban construction. When canals have a sealed base and sides, the effect is to **reduce infiltration** compared with a natural catchment and to **straighten** the stream channel. Straightening the channel forces the stream to abandon its natural tendency to meander or to braid, and the result is to **shorten** the length of the stream and to increase its **gradient**, resulting in **faster flow**.

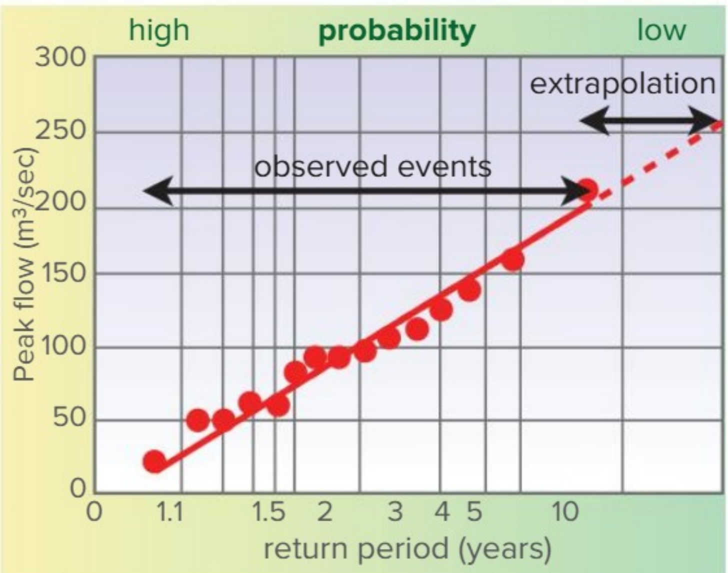
Canals are often built in a way that **narrows** the stream channel. Narrowing the channel has the effect of reducing the cross-sectional area of the stream, forcing the water to flow more quickly. The increased velocity of the stream can cause erosion of the banks of canals, especially when the banks are made of earth.

QUESTION BANK 2A

1. *How can hydrographs explain the magnitude, spatial extent and timing of floods?*
2. *Describe the differences between the urban and natural hydrographs shown in figure 2.6. Explain why the differences exist.*
3. *In what ways are the impacts of deforestation similar to the impacts of urbanisation on drainage basins?*
4. *Describe the likely impact on a natural stream's hydrograph if the stream were to be channeled into a canal.*

Flood prediction

The **size of floods** is measured using two main methods. One method is to refer to the **peak flow** discharge, while the other is to refer to the **maximum height** reached by the river water during the flood. These measures provide a basis to understand the frequency that floods of a certain magnitude recur in an area.



2.11 The probability of floods in a hypothetical river in a humid drainage basin. The red line shows the best fit trend line of recorded peak flows. The horizontal axis showing time is a logarithmic graph.

In any drainage basin, the **frequency** of small floods is greater than the frequency of large floods. Figure 2.11 shows how this applies for a hypothetical stream in a humid drainage basin. Each dot shows the peak flow (maximum discharge) of the river recorded during a flood. The horizontal axis shows the probability that a flood of that magnitude will recur within a certain period of time. For the river described in figure 2.11, we could, for example, say that a flood with a peak discharge of 100 cubic metres of water per second is likely to occur on average once every two years.

In practice, predicting floods is seldom this straightforward. The frequency of floods depends on a complex mix of several factors, including:

- intensity of rainfall in the drainage basin;
- frequency of rainfall in the drainage basin;
- topography of the drainage basin;
- obstructions in the flow of the river;
- contractions in the river cross-section;
- soil moisture;

2.12 The marker on the wall at the right of the photo shows the flood level of the Yangtze River at Chongqing, China, on 16th July 1981, filling the large valley in the background.

- sedimentation of rivers and reservoirs;
- vegetation cover;
- inadequate drainage works; and
- the season (whether or not snowmelt is underway).

Some causes of floods are almost **impossible to predict**, such as an earthquake, the failure of a dam or reservoir, or abnormally heavy melting of snow and ice.

In some countries, historical data is being combined with current variables such as soil moisture, weather forecasts and seasonality to try and predict floods more accurately using **satellite technology** and **computer modelling**. For example, NASA in the United States has developed a computer tool known as the Global Flood Monitoring System (GFMS). GFMS constantly takes world-wide readings from satellite data and provides detailed forecasts of the likelihood of flooding, including predicted flooding maps to a high resolution of one kilometre.

Despite such innovations, flood predictions are notoriously **unreliable**, not least because the weather forecasts upon which they are based remain imperfect. Until the reliability of weather forecasting and climate modeling can be improved, flood prediction will remain a work in progress.

Question Bank 2B

1. *Outline the two methods used to measure the magnitude of floods.*

2. *What is the relationship between flood magnitude and flood frequency?*
3. *For the river described in figure 2.11, estimate the frequency of a flood with a peak discharge of (a) 50 m³/sec, (b) 150 m³/sec, and (c) 220 m³/sec.*
4. *What technological innovations are underway to improve flood predictions?*

Flood mitigation

Flood mitigation refers to the management and control of streams to minimise the size and impact of floods. This is an important work that saves human lives and property, and improves the quality of life of millions of people around the world.

2.13 When floods occur, the rubbish that lies in and beside rivers washes through people's homes. This can lead to serious health problems in areas like Mopti, Mali, where local residents use the river banks as their toilet.

Flood damage falls into two categories, direct and indirect damage. **Direct damage** arises as an immediate consequence of the flood waters. Examples of direct damage would be a washed-away bridge, a drowned family, ruined crops, and a damaged house. **Indirect damage** occurs as a secondary consequence of the flood, and examples might include cancelled trains and temporarily closed factories.

Another way of viewing damage from floods would be as either tangible or intangible losses. **Tangible losses** can be measured in monetary value, and include damage to property such as buildings or crops, as well as the loss of business due to closures or people staying home. **Intangible losses** cannot be measured in monetary terms, and would include loss of life, stress, and poor health.

There are four possible **approaches** to flood mitigation:
- modifying the flood;
- modifying the vulnerability to flood damage;
- modifying the burden of losses from floods; and
- bearing the losses and learning to live with floods.

The strategies used to implement these four approaches fall into two broad categories, structural measures and planning.

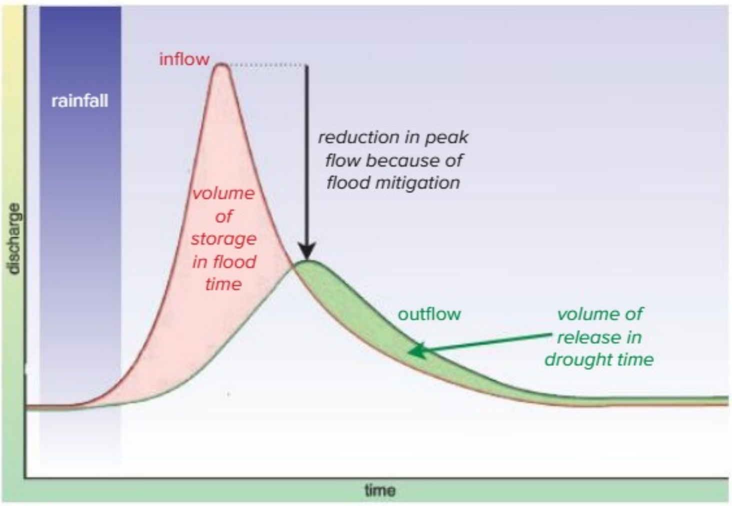
Structural measures

Structural measures to reduce the impact of floods are engineering works, such as dam construction and channel modifications, and land use practices, such as afforestation.

Dam construction

An effective way to control flooding is to construct a dam or reservoir to **control the flow** of the river. Water is held behind the dam wall, and then released in a controlled way that smooths the peaks and troughs of the natural flow of the river. Many dams are multi-purpose dams, so as well as controlling flooding, the water may be used to generate hydro-electricity or to provide water for irrigation.

A **shortcoming** of constructing dams is that they are very expensive. This is especially significant in poorer countries, where constructing a dam may



2.14 When water is retained in reservoirs, the water level in rivers is lowered, reducing the risk of flooding. During periods of low rainfall, water is released from the reservoirs to enable users of river water to function effectively.

2.15 In addition to flood mitigation, this small dam on the Salt River, north-east of Phoenix, Arizona, USA, serves to distribute water for irrigation during the periods between floods.

2.16 A green barrier wall separates the urban area of Dandong, China, from the waters of the Yalu River, visible between the trees at the right of this photo.

divert financial resources from other national needs. Another shortcoming is that dams trap the stream's sediments behind the dam wall. These sediments reduce the storage capacity of the dam over time, and it leads to erosion scouring downstream from the dam as the stream water flows with a sediment deficit. A further shortcoming of using dams to control floods is that large areas of a river's valley need to be flooded, and this may lead to a significant loss of agricultural land or force settlements to be relocated.

Barrier construction

Barriers can take several forms, including **flood walls** and **artificial levees**. Barriers are built along the sides of a stream channel to prevent water flooding into areas where damage may occur that leads to economic losses, such as urban areas and important agricultural land. **Artificial levees** are earth embankments built between the river and the area to be protected, normally with less pervious material lining the river and more pervious material on the outer sides of the levee. Because they take up quite a bit of land, they are built in places where land is fairly abundant, such as in agricultural areas. On the other hand, **barrier walls** tend to be built in places where land is scarce, such as in cities. Barrier walls are usually built using concrete, although bricks or stones are also used in some places.

The idea behind barrier construction is to **increase the capacity** of a river by raising its bankfull discharge, thus delaying the discharge that will

2.17 An artificial levee protects this area of rice farming near Sinchon in North Korea. The irrigation canal that has been built on the levee carries water at a higher level than the surrounding farmland.

lead to the stream's overflow. This can also be achieved by strengthening or raising natural levees, should they occur beside a river. The main **criticisms** of barrier construction for flood mitigation is that they are expensive and they are very difficult to make attractive.

Channel modification

Streams can be modified by making the channel wider or deeper in an effort to increase its capacity. Channel **widening** and **deepening** is often done by constructing a **canalised channel** for the stream, and this provides the opportunity to **straighten** the channel so that the water can flow faster and therefore drain the basin more quickly. The stream's flow can be made still faster in a canalised stream by **smoothing** the stream bed, removing

2.18 A small tributary of the Río Choqueyapu in La Paz, Bolivia, has been canalised, straightening and deepening the natural stream channel.

2.19 It is difficult to believe that the main channel of the Río Choqueyapu in La Paz, Bolivia, might be flood prone in this winter view. However, when the snow in the Andes Mountains that surround La Paz melts each spring, flooding can become a threat, which is why a retaining wall has been constructed.

2.20 Guyana's capital city, Georgetown, is flat, low-lying and flood-prone. The city's natural streamflow has been diverted through a network of canals to relieve the threat of flooding.

obstacles that would otherwise impede stream velocity. Canalising a stream provides an additional opportunity for flood mitigation, which is to **divert** the stream away from settlements, through less economically or environmentally valuable areas.

When rivers flow through **large cities**, their channel is invariably altered by strengthening its banks or even diverting the stream though underground pipes. The motivations for such changes often include flood mitigation, as flooding in large cities leads to significant economic losses.

There are three significant shortcomings of modifying stream channels for flood mitigation. First, it is an expensive engineering work. Second, it can devastate the natural ecology of the stream

2.21 The embankment along the River Thames in London, UK, was built to prevent flooding, and has been raised several times as the land has subsided and the flood threat has increased.

2.22 The Vodootvodny Canal in Moscow, Russia, is a four kilometre long artificial waterway that was built in the 1780s to control flooding. The canal cuts through a large meander in the Moskva River, thus providing an additional, shorter course for the river.

and its surrounds. Third, it can simply relocate the flood threat, moving the risk of flooding downstream by transporting the stream's water through the channel more quickly.

Afforestation

Tree planting (**afforestation**) is an effective flood mitigation strategy because increasing the number of trees raises the interception of rainwater, thus increasing infiltration of rainwater into the soil, prolonging the lag time between a rainfall event and peak discharge in the stream.

2.23 Large-scale afforestation to reduce the threats of flooding and soil erosion is underway on the slopes of the Kopet Dag Mountains, south of Ashgabat, Turkmenistan.

Afforestation is a relatively **inexpensive** way to reduce the impact of flooding in a drainage basin which also **enhances** overall **environmental quality**.

Planning

There are several ways that planning can be use to mitigate the impact of floods.

Floodplain zoning

Land-use zoning by government authorities can assist flood mitigation in several ways. One simple but effective method is to restrict residential development in flood-prone areas. A more restrictive variation of this technique is to designate **floodways**, which comprise a wide, low zone along both sides of a flood-prone river where no uses apart from recreational or wilderness purposes are permitted. Floodways are designed so that if a river floods, the water will be contained within the floodway, thus protecting valuable agricultural or

2.24 Until the 1970s, Parque Barigüi in Curitiba, Brazil was an area of slum housing for rural-urban migrants. Because the area was flood-prone, it was re-zoned as a park as the slums were cleared.

2.25 Historical records of past floods showed that the Trinity River, which flows through the green area in the foreground of this photo of Dallas, Texas, USA, is likely to flood the green area once every 100 years. Floodwaters would be expected to enter the built-up area of Dallas once every 500 years. In response to these predictions, a regulatory floodway (the green area) was set aside and levee banks have been constructed.

urban land. Although zoning does not reduce the incidence of flooding, it does relieve the **financial burdens** caused by flooding. In some places, restrictive land-use zoning has led to **resistance**, especially when the flood-prone areas are seen as desirable places to live for other reasons (such as accessibility to transport routes or proximity to services), and enforcement of land-use zones can be problematic in some countries.

A variation on floodplain zoning is **managed flooding**. This occurs when a basin located beside a section of a river, usually on low value land in a sparsely populated area, is left vacant for flooding to occur. When a river rises, water is diverted into the basin through an artificial channel for **temporary storage**. The waters that become trapped in that basin relieve the pressure of flooding in other parts of the river, such as in settled areas with houses, schools, hospitals, and so on. Between floods, the depression can be used for other purposes, such as grazing animals.

Flood preparation

Preparation for future flood events is most effective when the **pattern of previous floods** is analysed for a given area, examining the extent and distribution of past direct and indirect damage, taking into account both tangible and intangible losses.

Once past patterns of flooding have been ascertained, planners, government authorities, and university academics can develop **maps** and **action plans** to address future flood events. Such plans are most effective when they take into account the varying degrees of risk in different areas. Inevitably, damage will still occur during some flood events in spite of the best preparations, and in such cases, personal insurance protection helps individuals and companies overcome the losses they incur.

Flood warning technology

Flood warnings attempt to provide people who might be affected with advance notice of an imminent flood threat. There are **two steps** involved in issuing flood warnings. First, emergency agencies **monitor** the raw data gathered using remote sensing technology to ascertain the level of threat. If the threat level reaches a pre-determined level, then the second step comes into play, which is deciding whether to **issue warnings** to the general public. In most countries of the world, flood warnings are issued through the electronic media, mainly radios and television, but also increasingly through websites and social media.

Question Bank 2C

1. *What is the difference between (a) direct and indirect flood damage, and (b) tangible and intangible losses from floods? Give an example of each of these four categories that is not mentioned in the text.*
2. *Suggest an example of each of the four approaches to flood mitigation: (a) modifying the flood; (b) modifying the vulnerability to flood damage; (c) modifying the burden of losses from floods; and (d) bearing the losses and learning to live with floods.*
3. *Draw up a table to identify (a) the benefits, and (b) the shortcomings, of each structural measure used for flood mitigation.*
4. *In your opinion, which is more important for flood mitigation: structural measures or planning?*

CASE STUDY
Flood mitigation in the Nile Basin

Throughout history, Egyptians have found the Nile River to be both the source of their wealth and the cause of their famines. This is because Egyptian agriculture has always depended on the size and timing of the river's **floods**. Although the floods could be very destructive, they also deposited large amounts of rich, fertile silt on the Nile floodplain. Farming in Egypt was and still is almost completely confined to this area of alluvial silt.

The Egyptian people have always wanted to **control** the Nile's flooding. Two thousand years ago they threw virgins into the Nile to appease the river gods in an effort to try and stop the floods. These results were not very successful. During the 19th century, two dams were built to store water on an annual basis for irrigation. These were the Gebel el Awlia Reservoir and the Aswan Dam. They were also not very effective because the Nile's **flood level** can **vary** so much from year to year.

2.26 The hydro-electric power plant on the Aswan High Dam, Egypt.

In 1952 it was proposed to build a new, much larger dam upstream from the Aswan. This project became known as the **Aswan High Dam**. The idea behind this dam was that it would be so large that several years' **floodwaters** could be **stored** and **released** as the need arose. With Soviet assistance, the dam was built in ten years using a labour force of 35,000 people.

Besides regulating the flooding, there were two main aims in constructing the Aswan High Dam. First, additional **irrigation** water from the dam was to expand the area under agriculture in Egypt. Second, it was to be the basis of a new **hydro-electric** power scheme for the country. The project was therefore a **multi-purpose scheme**.

Since its completion in 1970, the dam has provided an extra 400,000 hectares of farming land which were not previously under cultivation. In southern Egypt, an additional 300,000 hectares of land which was **previously flooded** once a year and which was single-cropped, is now permanently irrigated and can produce two or three crops each year. The power station now produces 10 billion kWh (kilowatt hours) per year, the equivalent of saving two million tonnes of oil annually.

Despite these successes, the dam has had several undesirable **side-effects**. While it was being planned, it was realised that the 500 kilometre long lake that the dam would form (Lake Nasser) would flood priceless 3000 year old temples and statues. This included the colossal temples of Abu Simbel and 22 other temples in the Nubia Valley that would be lost forever.

Several **solutions** to this problem were proposed. One suggestion was to bury the temples in sand to protect them from the waters, but it was soon realised that the water would seep through and destroy the stone. Another proposal was to build a wall around the temples, but once again water seepage would have been a problem. Finally, it was decided to move the temples stone by stone and reassemble them on higher ground. The operation was co-ordinated by UNESCO and took eight years with a labour force of 900 to move 1,035 blocks of stone weighing over 20 tonnes each. The cost of this operation alone was US$24 million.

2.27 The Kiosk of Trajan in the temple of Isis at Aswan now sits on an island in the Aswan Lower Dam's lake. UNESCO has made a major effort to prevent damage to the temple from the rising waters.

2.28 The two huge rock-cut temples at Abu Simbel, 230 kilometres upstream from Aswan, were built in the 13th century BC. To avoid being flooded by the rising waters of Lake Nasser when the Aswan High Dam was built, the entire complex was relocated in 1968 on a new artificial hill beside the lake.

However, it was the **environmental costs** of the Aswan High Dam project that caused the greatest concern. These effects include:

- The Nile River **floods** were **reduced** by 90%, so the fertile **silt** from floodwaters is no longer available in effective quantities. As a consequence, the farmers in the lower Nile Valley now have to import **fertilisers**. To overcome the loss of silt, a new chemical fertiliser factory was built, but this factory needs so much electricity to produce the fertiliser that it is using the bulk of the hydro-electricity produced by the dam. Between the dam's completion in 1970 and 2013, chemical fertiliser use increased by 507%

2.29 Irrigated farmland in the Nile Valley. This area used to flood annually, but since the High Aswan Dam was built, the floods have stopped, along with the annual fertilisation of the soils from a layer of alluvial silt.

(although during the same period, Egypt's population increased by 250%, while calorie intake and meat consumption per person rose by more than a third).

- Half the water that flows into the reservoir is lost to **evaporation** and groundwater **seepage**. The high rate of evaporation occurs because of the large surface area in a hot, arid climate, while the porous sandstone rocks on the lake bed allow large losses of water due to seepage.
- Downstream **erosion** has caused the undermining of many bridges and small dams. The reason for this downstream erosion is that like all dams, the Aswan prevents the passage of silt. Silt collects in the reservoir and only clear water is discharged. Therefore, the water downstream of the dam has a great capacity to collect additional sediment. The cost to repair the damaged structures was estimated at 25% of the construction cost of the Aswan High Dam.

2.30 Lake Nasser, the 500 kilometre long storage lake behind the Aswan High Dam, experiences large water losses due to evaporation and seepage.

- **Bilharzia**, a parasitic disease spread by water-borne snails, has spread in the canals of the irrigated areas as a result of the need for perennial irrigation since the dam's construction. Larvae pierce the skin and the disease produces fever, stomach pain, coughing, skin rash, diarrhoea and swelling of the liver. Without treatment, the disease can lead to internal bleeding, cancer and even death.

QUESTION BANK 2D

1. *Use an atlas to locate the Aswan High Dam. Draw a sketch map to show its location within Egypt. Annotate (or label) the map to show where the dam's side-effects are most apparent.*
2. *Compare the costs and the benefits of the reduction in floods that have arisen because of the construction of the Aswan High Dam.*

CASE STUDY
Flood mitigation in the Lower Rhine Basin

The flood threat in the Netherlands

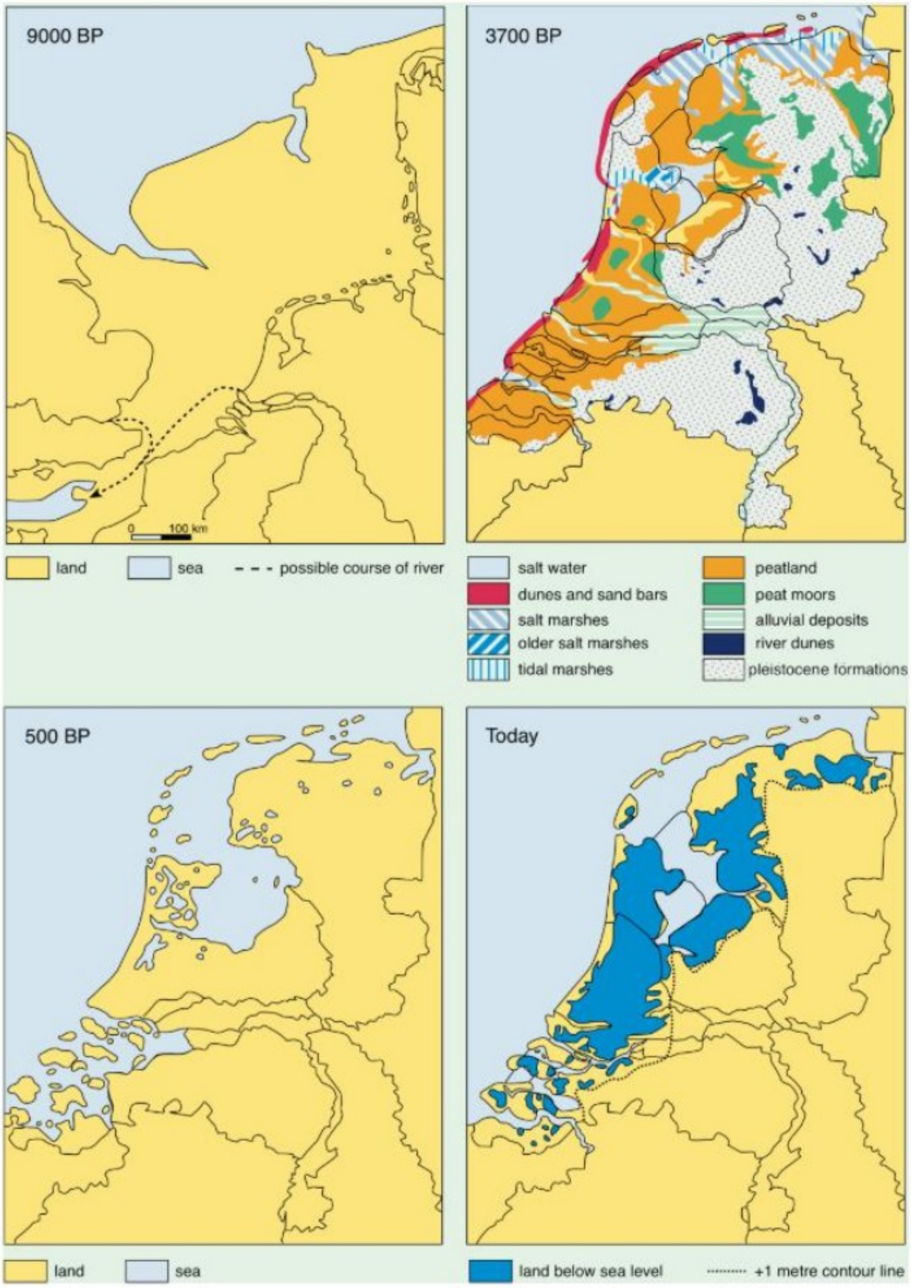
The Lower Rhine River drainage basin in the Netherlands faces quite a different flooding challenge to the Nile River basin in Egypt. The Netherlands, which is a small nation of about 41,000 square kilometres in western Europe, is engaged in a permanent struggle for survival because of the threat of **flooding** as 15% of the country's land area is below sea level.

The Netherlands exists only as a result of **human actions** to drain low-lying areas of marshland over the centuries. In fact, more than half of the Netherlands would be flooded if it were not for the dykes, dams and canals which have been built over the past 700 years. If constant efforts were not made to **pump groundwater** and **river water** from the low-lying areas, the land where more than nine million people live (of the Netherlands' total of 17 million) would be uninhabitable. A common expression in the Netherlands is 'God created the world, but its people created the Netherlands'.

The Netherlands is **sinking** at the rate of 20 centimetres per century, making the problem of flood mitigation necessary for the survival of the country. People in the Netherlands worry even more than most about future rises in sea levels that might be caused by global warming as the polar icecaps melt.

When the last ice age ended about 11,500 years ago and the ice sheets and glaciers over Europe retreated, the sea level was much lower than the

2.31 Map of the Netherlands showing the Rhine River in bold black.



2.32 Evolution of the Netherlands from the Pleistocene ice age to the present day. The letters 'BP' mean 'before present'.

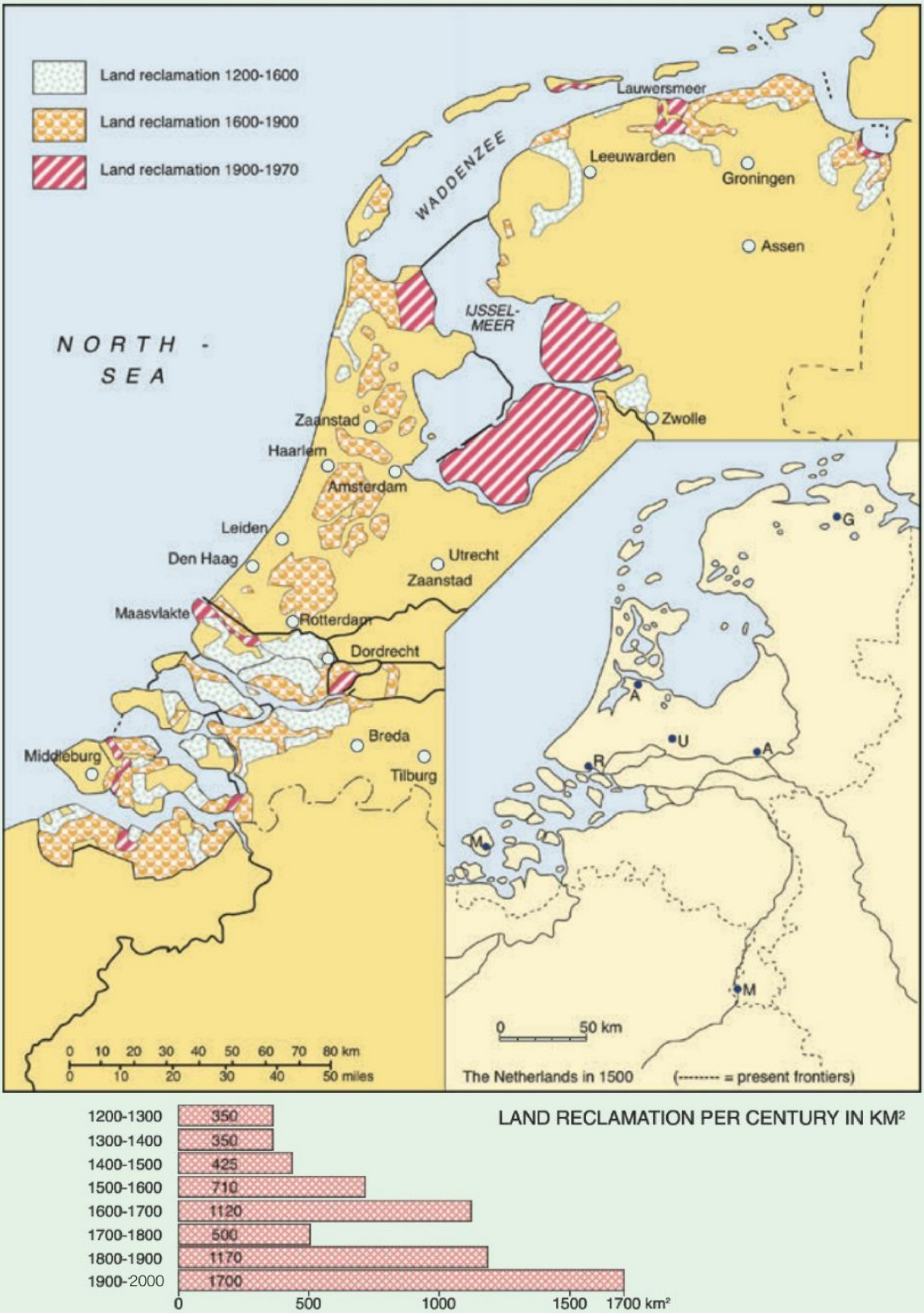
present level. Much of the present North Sea was dry land and the Rhine River flowed with the Thames River through what is now the English Channel to enter the Atlantic Ocean. As the ice caps melted, **sea levels rose** and filled the low-lying land through which the Rhine flowed, creating the English Channel that separates Britain from mainland Europe. This meant that the Rhine emptied directly into the North Sea, with much of the Netherlands turning to marsh and peatlands about 3,700 years ago..

During the period 1700 BC to 1500 AD, much of the area of the Netherlands was **lost to the sea**. This loss of land was due both to **natural** and **human** forces. One important natural factor was the continuing rise in **sea level**. The rate of sea level changed, sometimes speeding up and sometimes slowing down. When the rate of sea level rise slowed, new land was able to develop through sedimentation of clay from rivers and by the formation of peat bogs. In this way, much of the area of the Netherlands formed as extensive areas of **swamp** and **marshland**. However, when the rate of sea level rise increased, much of this new land was **eroded** away once again.

Around 500 years ago, there were large bodies of water covering northern and southern areas of the Netherlands. **Human actions** added to the effects of the rising sea. There was a period of rapid population growth in the seventh century, and at that time farmers cleared the peat bog areas to make them suitable for cultivation. In order to do this, the land had to be drained, and this led to the **land sinking** by up to two metres as the hydraulic pressure was taken away. In this way, the danger of **flooding** was increased.

A second human factor was the large-scale cutting of the peat. **Peat** was a valuable resource in the Middle Ages, as it could be dried for use as a fuel or burned to extract salt from the ash. The

2.33 A section of the coastal dyke near Kouderkerke in Zeeland. The land on the left of the photo is below sea level; the coastal inlet of Oosterschelde is at the right of the photo. Sheep grazing compresses the earth, reducing seepage.



2.34 Land reclamation in the Netherlands, 1200 to 2000.

peat cutters soon cut the peat down to the level of the groundwater, and then they developed techniques that enabled them to keep cutting away peat **below groundwater** level. This process led to the formation of **pools** after the peat was cut, with each pool separated from the rest by a narrow strip of land where the peat was laid out to dry. However, during storm times these strips of land were easily eroded, causing the pools to increase in size.

As land became **more prone to flooding**, people settled on the higher sand dune areas around the edges of the country and on artificial mounds of earth called **terps**. However, because even these areas could become flooded when tides were very high, embankments were built on the dunes to offer protection to the settlers. About 1000 years ago, the first **dykes** were built. Dykes were raised banks of earth that protected existing land from floods and which were later used to reclaim new areas from the sea. The new areas **reclaimed** from the sea were known as **polders**.

Large areas of **land reclamation** occurred from about the year 1200 onwards. In contrast with the defensive measures against sea attack undertaken by humans previously, the new measures were an attempt to **reclaim** land from the sea. Because these areas were so low, especially where peat had been mined, **canals** had to be dug to drain them constantly. However, when water is drained from a waterlogged area, the **land sinks**. Moreover, when the water covering the marshlands was removed, the surface **soil** began to **oxidise** and **disappear** into the atmosphere at a rate of 1.5 centimetres per year.

2.35 A flood-prone area below sea level where peat was excavated several centuries ago.

2.36 This windmill at Kinderdjke is one of a series that pumps water to a new level 4.5 metres higher from this polder that lies well below sea level.

In this way, the level of some areas that were drained fell by five to ten metres, and these processes are still happening.

A great breakthrough occurred in the 1400s with the invention of the **windmill**. Although they were first developed to mill grain into flour, they proved invaluable in **pumping water** from low lying polders, especially when arranged in a series. In the early 1600s, large scale rural-urban migration occurred in the Netherlands, creating a need for large food surpluses to feed to new growing urban population. The solution to this problem was to create more farming land by building a **double ring system** of dykes and using windmills to pump water into the ring between the two dykes. This was an enormous task and it led to the building of thousands of windmills during the subsequent centuries. By 1900 there were about 10,000 windmills in the Netherlands. However, during the period 1880 to 1910, steam, electric and diesel motors were invented, leading to the replacement of windmills by diesel or electric pumping stations. Only about 1000 windmills remain today.

Draining and **pumping** of low-lying areas is still needed for flood mitigation. Because many areas of the Netherlands lie below sea level, water **seeps** continually into the low lying polders, and needs to be pumped away to prevent the areas reverting to lakes. In some areas of the Netherlands, the water in the drainage canals is almost at the same level as the surrounding fields, and some houses in the Edam district have to bring in five to ten centimetres depth of soil each year simply to stay

2.37 Polders immediately north of Amsterdam, near the towns of Oostzan (left centre) and Landsmeer (lower right). the green area in the centre of the photo that is almost encircled by water and a road is reclaimed land. Note the dense network of canals needed to drain this land, which is below sea level.

2.38 The main canal at Oudewater is several metres higher than the vegetable gardens that it is helping to drain. This area is about four metres below sea level.

above the water table. The introduction of **electric pumping stations** has made it possible to drain larger areas than the windmills allowed. Today, many parts of the Netherlands are drained by canals that flow at higher levels than the fields they are draining. Many of the Netherlands' most productive farming areas comprise land that has been reclaimed from the sea. These areas are typically very flat, they lie below sea level and are drained by a dense network of canals.

Question Bank 2E

1. *Explain why people say 'God created the world, but its people created the Netherlands'.*
2. *Was the flooding of the Netherlands between 1700BC and 1500AD a natural or human process? Explain.*
3. *Explain the meaning of the terms 'terp', 'dyke' and 'polder'.*
4. *Explain how the invention of the windmill changed the geography of the Netherlands through flood mitigation.*

Polder management and water boards

As more and more polders were enclosed by dykes, they became more difficult to drain and keep dry. About 450 years ago, the ruler of the day, King Charles V, asked for the people's advice on how the polders could be maintained. The response came back that **locks** should be built into the dykes. The idea was that the locks could be opened at low tide to drain but closed at high tide to prevent flooding. This was the first attempt at democratic decision-making in Netherlands water management, and it set the scene for decision making processes which have continued to the present day.

2.39 A new drainage canal under construction near Utrecht.

Today, water management and flood mitigation in the Netherlands is controlled by a number of **water boards**. Water boards are elected bodies that have only one task – to manage water in a given area. They have a high degree of independence, they draw up regulations that local people must observe and they raise money by imposing a tax on the residents of the polders. Specifically, water boards have responsibility for three main tasks:

- **water control**: providing protection against flooding by building and maintaining dunes, dykes and canals;
- **water quantity**: managing the amount of water and making sure it is kept at the right level; and

2.40 This polder in Haastrecht is in a peat area and is just over one metre below sea level. Polders in peat areas are larger than elsewhere, and are marked by long, straight drainage channels for flood mitigation.

- **water quality**: fighting water pollution and improving the quality of surface waters.

Many of the areas controlled by the water boards are polders. **Polders** are reclaimed areas of land that are surrounded by dykes, within which groundwater levels can be controlled. Almost the entire west and north of the Netherlands (about 50% of the nation's land area) consists of polders. They do not necessarily have to be below sea level, although many are. The polders around Ijsselmeer are 3 to 5 metres below sea level, and those created by draining lakes can be up to 6 to 7 metres below sea level. Polders in the peat areas are typically about one metre below sea level.

The challenge in managing polders is that because they are generally below sea level, more water enters the polder areas than can be drained naturally. The 'natural' state of a polder is to be **flooded**. This is especially the case in the cooler months from September to April each year when evaporation rates are lowest. If the polder is not to become permanently flooded and become a lake, then the land must be kept dry and the **water table** (upper limit of the groundwater) must be kept low.

The **inputs** of water into a polder come from rain and seepage (water that seeps through the soil and the dykes, entering the polder through the groundwater). **Outputs** of water from a polder can occur in three ways – consumption, evaporation and the pumping of surplus water. In older (pre-1850) polders that are drained by windmills, it was impossible to lower the water table more than 0.5 to 1 metre below the ground surface. Such polders were always damp, and could only be used for cattle grazing. In polders created since the introduction of mechanised pumps on the other hand, it has been possible to lower the water table more than one metre, making the polders more suitable for crop cultivation.

There are two types of polders. **Type I polders** are those that are surrounded by a single dyke. These tend to be found along rivers, near the coast or beside lakes. In these polders, surplus water can be drained directly into the nearby rivers or lakes, either with or without pumping.

Type II polders are found at a lower level, having been formed by the draining of lakes. In these

2.41 This aerial view of Monnickendam shows two areas of type II polder (circular in shape), surrounded by large areas of type I polder. The large town in the distance is Purmerend.

polders, there is a second, or inner dyke, known as a ring dyke or **boezem**.

Polders form quite a distinctive landscape. The fields are very flat and are divided into regular, straight-sided individual fields. Each field is bounded by a canal that drains into a larger canal, which in turn drains into a still larger canal to form a hierarchy. The polder is surrounded by a canal that drains away the surplus water into a nearby river or lake.

Question Bank 2F

1. *What is a water board in the Netherlands, and what are its functions?*
2. *Why is it necessary for humans to intervene to ensure the survival of polders?*
3. *Draw a simple diagram to show the (a) inputs of water into and (b) outputs of water out of a polder.*

2.42 A map and cross-section of two types of polders. Type I polders are surrounded by a single dyke, while type II polders are lower and surrounded by an elevated ring canal which is used for drainage. Red arrows show the movement of drainage.

Flood mitigation in the Delta Project of Zeeland

The coastal areas of the lower Rhine Basin where the river approaches the sea face different issues of water management than the polder areas. The province of **Zeeland** (meaning 'land of sea') is located in the south-western part of the Netherlands, to the immediate south of the Rhine River's mouth to the sea at Rotterdam. Much of Zeeland lies below sea level, and so it was particularly badly affected by the severe floods of 1953. In response to the 1953 flood, a grand scheme was proposed to build a series of **sluice gates** across the estuaries of Zeeland's rivers where they enter the sea, effectively shortening the coastline from 700 kilometres in length to just 25 kilometres. The resulting structures, known as the Delta Project, has dramatically reduced the danger of flooding.

The dams and sluice gates across the estuaries of Zeeland were built over the period 1950 to 1986. The last of the barriers was also the largest, this being the barrier across Oosterschelde (or the Eastern Scheldt estuary). This line of sluice gates stretches 8 kilometres across the estuary and

2.43 The world's largest flood barrier is this sluice gate at Neeltje Jans that blocks the inlet of Oosterschelde from the North Sea. Its exposed location makes it ideal for generating electricity using windmills.

includes a road that is about 12 metres above water level.

Construction of this and the other sluice gates was often difficult because the Dutch coast experiences very strong **tidal currents**. The tidal range in the Netherlands can be as much as three metres. To ensure safety against flooding, a mobile storm surge barrier was built near Rotterdam in 1997.

The delta project has had an enormous impact on the safety of Zeeland, **reducing the risk** of flooding to almost zero. The dams have also improved access of Zeeland's people to other parts of the Netherlands by providing road access across the estuaries. By calming the waters of the estuaries, new areas have been opened up to manufacturing and shipping. Although the central estuary areas of Zeeland will retain an agricultural character, the coastal areas and inland waterways will be opened up and developed for tourism. On the other hand, some areas of fishing were lost when the dams were built, although new lakes have also been developed for oyster and mussel farming.

Conclusion

Flood mitigation is a matter of **national survival** for the Netherlands. The **essential target** of flood mitigation in the Lower Rhine Basin is to maintain the correct balance between the relative levels of the land and water. If the water levels of canals are lowered to improve the drainage of the polders, then the water table beneath will also fall. The loss of **hydraulic pressure** from this would mean that the **land sinks** even further below sea level, making drainage of the land even more difficult. On the other hand, if the water is not lowered enough, the land will **flood**, causing vast physical and economic damage, and causing the land to revert to lakes or even ocean.

QUESTION BANK 2G

1. *Has the Delta Project of Zeeland been a success in terms of flood mitigation? Explain fully.*
2. *Construct a table to compare flood mitigation in the Nile Basin and the Lower Rhine Basin. Use the following headings in the table: (a) location, (b) climate type, (c) causes of the flood threat, (d) flood mitigation measures implemented, (e) degree of success of flood mitigation, and (f) unforeseen problems.*

2.44 The Delta Project of Zeeland.

Chapter 3 Water scarcity and water quality

3.1 Much of the world's population cannot take for granted that they will have access either to abundant water or clean water. This small stream in Bobo-Dioulasso, Burkina Faso, called the Marigot de Houet, is used for washing and as a source for household water.

Water scarcity

The quantity of water on earth is **finite**. While the volume of water on the planet does not change, the number of people who want access to water is increasing, and so the quantity of water available to each person is **decreasing**.

Overall, the world has more than enough water to meet the needs of every person on the planet. However, it is estimated that about 2.8 billion people live in areas where there are shortages of water for at least one month per year. There are **three components** of water scarcity:

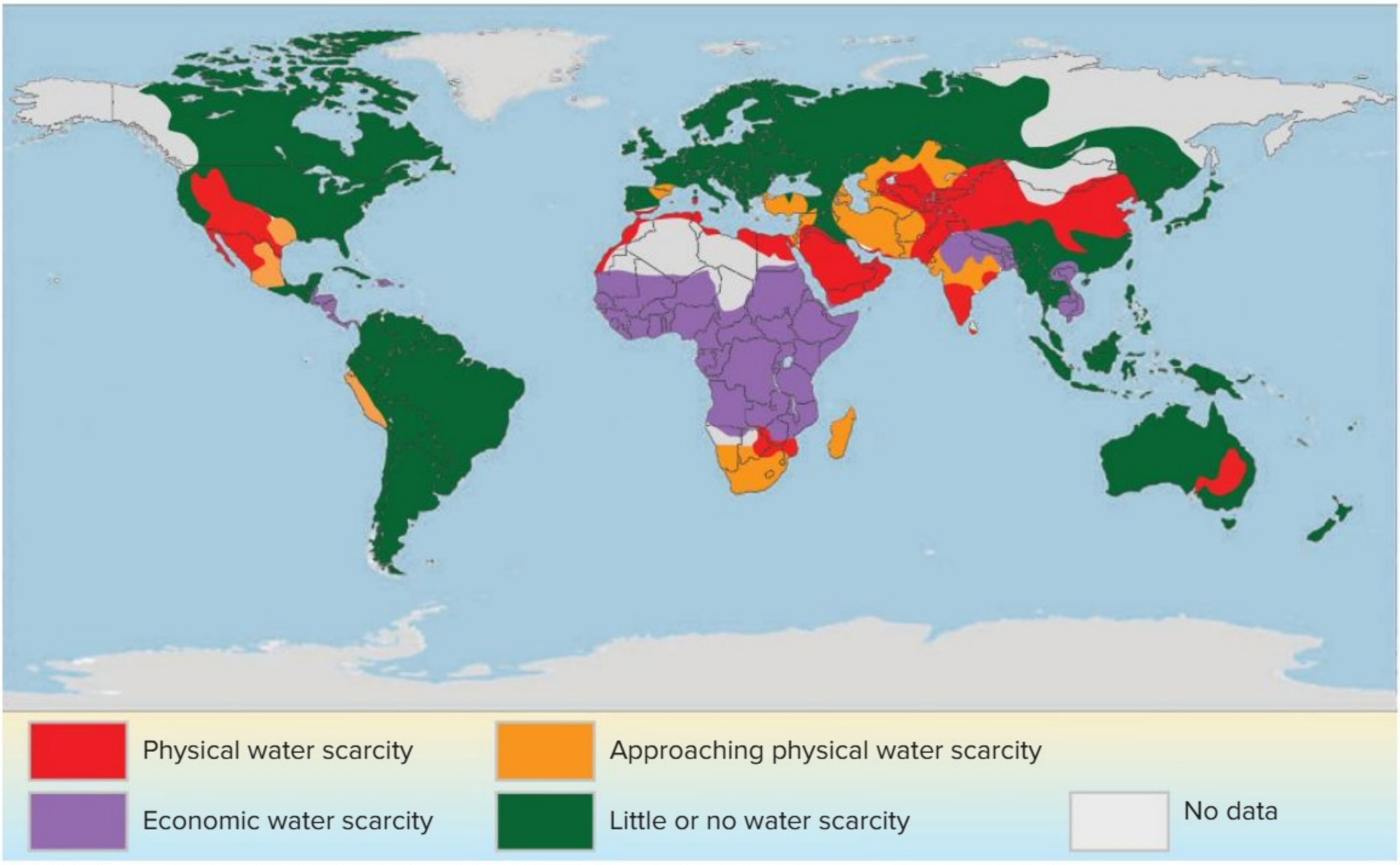
- **Water shortages** occur when the **quantity** of water available **declines** over time due to dynamic factors such as climate change, pollution of available water supplies or increasing demand for water by people. Water shortages may arise from **climate change** for a variety of reasons including the increased frequency or severity of prolonged **droughts**, and increasing losses of surface water due to **evaporation** as temperatures rise. Research in the *Journal of Climate* suggests that more water shortages result from increasing demands for water use by a growing population than climate change.

- **Water stress** occurs when the **demand** for water **exceeds** the amount available during a certain period or when the poor quality of the water that is available restricts its usefulness. The United Nations estimates that 1 person in 6 in the world today experiences water stress because they lack access to **potable** (safe to drink) water, and water stress is increasing in heavily populated parts of China, India and sub-Saharan Africa. In situations of water stress, using water exacerbates the water scarcity because it depletes the scarce supplies or lowers the quality of the water reserves.

3.4 In Gogoli village, Mali, water must be carried from the stream at the bottom of the steep escarpment. This work is done several times each day by children using buckets and bottles.

3.2 Poor infrastructure in many cities forces residents to overcome water scarcity by carrying water, as seen here in Monrovia, Liberia.

- **Water crises** refer to situations when the supplies of clean, usable water **cannot support** sufficient food production or other legitimate domestic, industrial and environmental needs of people in an area. Water crises can be temporary or long-term, and arise for a variety of reasons including over-use and pollution of water, excessive extraction of groundwater, and political conflicts



3.3 Physical and economic water scarcity. (Source: Based on data from International Water Management Institute).

over water resources. Water crises can also occur because of under-investment in water infrastructure, leading to economic water scarcity.

There are two types of water scarcity, physical water scarcity and economic water scarcity, each of which includes the three components listed above.

Physical water scarcity occurs when the natural water resources in an area cannot adequately meet the needs of people in an area. In general, physical water scarcity is primarily a problem in sparsely populated arid areas, but even so, it is estimated that about 20% of the world's population live in areas affected by physical water scarcity. As a result of the demands made on the scarce supplies of water, areas of physical water scarcity often experience problems of over-exploitation of groundwater.

3.5 An example of the type of infrastructure that can help overcome water scarcity in poorer countries — a community well in the grounds of a school near Ifaty, Madagascar. As seen in this photo, even small children help by carrying water to their homes in bottles and plastic cans.

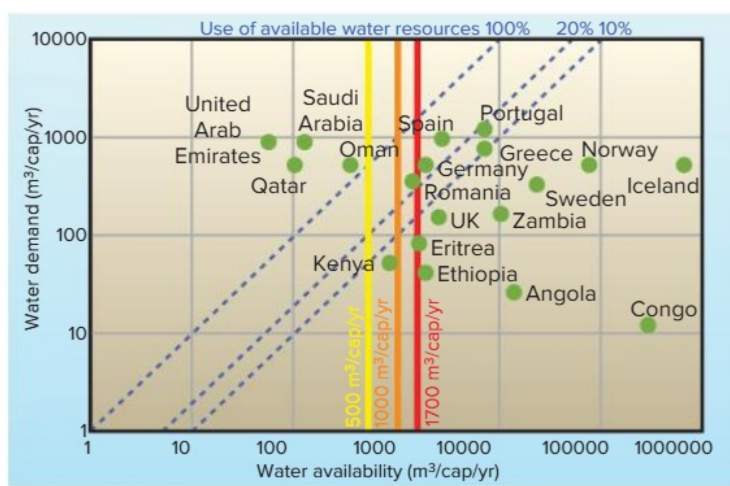
Economic water scarcity occurs when poor management of available water supplies in an area results in water stress for residents. Economic water scarcity arises from under-investment in infrastructure for water storage and distribution, as well as under-development of wells. It is mainly a problem in less economically developed countries where it affects society's poorest people the most. As a result of economic water scarcity, millions of people around the world must fetch water by carrying it long distances from scarce wells, the alternatives being to use contaminated water or purchase bottled water.

The greatest increase in the demand for water in the future is likely to come from **agriculture** as food production increases to feed a growing population. Water **consumption** is likely to soar as more people around the world adopt western lifestyles and diets that consume meat and a diminishing proportion of grains and vegetables.

Water scarcity is measured by comparing water availability to population size in an area. The **Falkenmark Water Stress Indicator** (FWSI) is the most common means of measuring water scarcity. It looks at the renewable surface and groundwater flows of water, and relates these to the population size of an area, using bands as shown in table 3.1 and figure 3.6.

Table 3.1
Falkenmark Water Stress Indicator Bands

Renewable fresh water (cubic metres per person per year)	Classification	Situation
2500 +	—	Little or no water scarcity
1,700 - 2,500	Water vulnerability	Water shortages occur irregularly or locally
1,000 - 1,700	Water stress	Water stress appears frequently
500 - 1,000	Water scarcity	Water scarcity is a limitation to economic development and human health and well-being
Less than 500	Water crisis	Water availability is a major constraint to life



3.6 Examples of water scarcity in selected countries, measured by the Falkenmark Water Stress Indicator.

3.7 This freshwater lake in the Russian city of Yakutsk has become unusable as a green algal bloom has covered the surface of water, fed by excessive inputs of nutrients in the form of untreated sewage, deoxygenating the lake by the process of eutrophication, making life for other water organisms impossible.

Water scarcity is not simply a matter of comparing the quantity of water to the population size and its demands. **Water quality** is also an important consideration, because non-potable water is largely an unusable resource for many people who lack the resources to purify it. Factors that cause deterioration of water quality include:

- **pollution** from sewage, factories, agricultural runoff and garbage
- **turbidity** (cloudiness caused by suspended solids) as a result of stream erosion
- **siltation** and **sedimentation** from erosion of hillslopes
- **salinity** from over-irrigation of agricultural fields
- **bacterial diseases** from animal manure in the water

Question Bank 3A

1. *Explain the differences between (a) water shortage, (b) water stress and (c) water crisis.*
2. *What is the difference between physical water scarcity and economic water scarcity?*
3. *Using figure 3.3, describe the distribution of (a) physical water scarcity, and (b) economic water scarcity.*
4. *Using figure 3.6 and table 3.1, name a country that is experiencing each of the following: (a) water crisis, (b) water scarcity, (c) water stress, and (d) water vulnerability.*
5. *Using figure 3.6, name four countries that consume more water than the quantity of total water that is available.*
6. *Explain why water quantity and water quality are both components of water scarcity.*
7. *Describe the Falkenmark Water Stress Indicator.*

Environmental consequences of agricultural activity

Agriculture and eutrophication

Farms almost everywhere in the world now use **fertilisers** to boost productivity and raise production levels. Most commonly, the fertilisers used are chemical fertilisers, adding specific chemicals that are deficient in the soil such as nitrates or phosphates. In many societies, organic fertilisers such as animal manure are used, either in addition to chemical fertilisers or as an alternative.

3.8 Farmers on the Nile River floodplain near Cairo, Egypt, spread fertiliser by hand on their crop of corn.

A consequence of fertiliser use is that **excess nitrogen** and phosphorus often flows into nearby streams as **agro-chemical runoff**. The addition of vast quantities of nutrients into the stream often causes an **algal bloom**. An algal bloom occurs when there is rapid growth of microscopic algae or cyanobacteria (blue-green algae) in streams as a response to the additional nutrients, often resulting in a coloured scum on the surface.

The growth of algae **shades** the water beneath the surface, placing a shadow over the plants and aquatic life below, and in many cases, completely cutting off the available light. When the algal plants grow exponentially, they can consume all the available oxygen in the water, causing an **anaerobic**

3.9 Agricultural runoff and animal wastes have drained into this water reservoir in the village of Kawkaban, Yemen, leading to an algal bloom. The water in this reservoir is used for domestic consumption, but even after boiling it often causes diseases such as diarrhea.

(oxygen-starved) environment that starves other organisms of oxygen, leading to their death.

Before long, the algal bloom may grow so large that it uses up almost all the oxygen in the water, and having reached this limit, it begins to die off. As the algal bloom dies off, aerobic decomposers (bacteria that require oxygen) multiply and consume the last vestiges of oxygen.

3.10 A heavy algal bloom caused by agro-chemical runoff at Ranworth, UK.

Although eutrophication is a widespread problem that reduces water quality, leading to water scarcity in many parts of the world, it is not a difficult issue to **resolve** with environmentally sound farming practices. The simple act of using **lower quantities** of nitrate fertilisers (both chemical and organic) reduces eutrophication. This involves **educating** farmers so they understand how using fewer

3.11 Agro-chemical runoff from these irrigated onion fields east of Bandiagara, Mali, has caused an algal bloom in the creek that flows through the area.

nitrate fertilisers both reduces their costs and helps maintain water quality. In extreme cases of eutrophication, it may be necessary to **remove the anaerobic mud** from the bottom of an affected lake or stream to allow the water body to regenerate.

Pesticides and herbicides

In recent decades, pesticides and herbicides have been widely used by farmers in many parts of the world to control insect pests, diseases and weeds. **Pesticides** are designed to attract, seduce and then destroy pests such as snails, rats, mosquitoes, grasshoppers and fungi. They have been shown to be effective in controlling pests and diseases, and it has been estimated that without the use of pesticides and herbicides, grain production would decline by 25% after one year and 45% after three years. **Herbicides** are specific type of pesticide that targets unwanted plants, known as weeds, while leaving the desirable plants (the crops) unharmed.

Although pesticides (including herbicides) that are used by farmers are supposed to be tested and found safe for humans, they do cause issues for many people, especially those with allergies or sensitivities. In poorer countries, safety regulations are often inadequate, and 99% of pesticide-related deaths occur there, even though these countries account for only 25% of global pesticide use. Concerns about pesticides and herbicides arise due to the principle of **biological magnification**, which is the progressive concentration of pollutants in organisms at each higher level in the food chain.

3.12 A farmer sprays pesticide onto a crop of potatoes at the edge of a rice padi on the Migok Co-operative Farm near Sariwon, North Korea.

3.13 Irrigating fields using buckets of water carried by hand from the nearby creek in Bongo village, Mali.

Over 98% of sprayed insecticides and 95% of herbicides reach a destination that is not their target species, and this can cause a **build-up** of pollutants in the soil and water of farming areas. **Pesticide drift** can carry pesticides through the air into other areas, polluting water that is located some distance from the farming activity.

In order to address the potential (and often unproven) dangers of pesticides and herbicides, **regulations** have been implemented to ensure that pesticides should be **biodegradable** or quickly deactivated in the environment. Such regulations add to the cost of pesticides, which explains why the pesticides used in many poorer countries are more toxic and dangerous than those in countries with stronger environmental regulations.

Another response to the potential dangers of pesticides has been to encourage the development of **biological pest controls**, such as breeding insects that attack unwanted pests, developing sterile insects that mate with other insects but don't reproduce, or developing bacteria and viruses that kill unwanted insect pests.

Irrigation and agriculture

Irrigation, or artificially adding water to farmland to boost plant growth, is widely practised in many parts of the world. It takes several forms, from total flooding (as with rice padis), to broad spraying, through to drip irrigation that supplies precise amounts of water matched to plant needs. The world is now heavily dependent on water management through irrigation to produce about

3.14 Extensive spray irrigation using travelling irrigators on agricultural fields east of Alexandra, New Zealand.

one-third of the world's crops. These irrigated crops are grown on land that is, on average, about twice as productive as land that is watered only by rainfall. Irrigation is an important component of any program to increase the world's food supply. The spread of irrigation has been a key factor behind the 400% increase in world grain production between 1950 and 2016.

This growth in irrigation has brought many **benefits**, such as more availability of food, lower food prices, higher employment and faster agricultural and economic development. These benefits sometimes blind people to the environmental consequences, however.

At its most basic level, the most obvious environmental effect of irrigation is that the **downstream flow** is reduced when water is removed from the river. For this reason, many countries impose government controls on the volumes of water that farmers can remove to ensure a fair share of water use.

The **physical impact** of using water for irrigation is that water is removed from the stream and added to fields where there was previously little or no water. The water then soaks downwards into the soil store, after which it can either percolate downwards and be added to the groundwater store or it can be lost to the atmosphere by evaporation.

3.15 The dark green fields seen here south-east of Madrid, Spain, send saline runoff into the Jarama River, seen at the right of the photo. Salinisation can be seen in the small field in the left foreground as a white deposit of surface salt.

One of the common consequences of irrigation is **salinisation**. As water passes over and through the soil, it dissolves various minerals and nutrients. Salts are very easily dissolved and therefore if there is salt in the soil it is likely to be absorbed into the irrigation water. This problem can be aggravated if too much irrigation water is added to the soil. This can lead to waterlogging (where the water table rises to the ground surface), which frees salts that have been washed downwards by rainwater infiltration over many years to rise once again by capillary action into the root zone of the crops, and perhaps even right up to the surface.

Many good farming areas are ancient sea beds, and so contain salts, although usually at levels that are too deep to affect plant growth. However, if soils are saturated, salts are liberated and they rise to the surface, reducing crop productivity. If the process continues on a particular piece of land, it can poison the soil and make it useless for cultivation.

Excess water from fields usually runs off back into the irrigation channels and eventually back to the river. As it does so, it carries **dissolved salts** from the rocks and soils where it has been flowing. On farms where pesticides and chemical fertilisers are used, the runoff also carries pollutants from these sources. When irrigation water is used and re-used in several fields, quite **high concentrations** of salt and agro-chemical pollutants can build up, severely reducing the quality of the water for downstream users.

3.16 A large layer of surface salt lies on irrigated fields on the northern outskirts of Ashgabat, Turkmenistan. Water for irrigation is taken from the Karakum Canal, visible in the foreground of this photo as a brown strip of water. Salinisation of these fields has made them useless for cultivation.

According to estimates made by the United Nations Food and Agricultural Organisation (FAO), about one-third of the world's irrigated land is badly affected by salinity. Salinity that is caused by irrigation is equally likely to occur in large-scale and small-scale irrigation systems, and it has been the reason that many farmers have had to abandon their fields in some places such as the Sahel region of sub-Sahara Africa and the arid regions of northern Australia.

Question Bank 3B

1. *Why do farmers use (a) fertilisers, (b) pesticides, and (c) herbicides?*
2. *Describe the problems caused by agro-chemical runoff.*
3. *Define the terms (a) eutrophication, (b) anaerobic, (c) biological magnification and (d) pesticide drift.*
4. *How can the problem of eutrophication caused by agro-chemical runoff be addressed?*
5. *How can the problem of water pollution from agricultural pesticides and herbicides be addressed?*

6. Outline the benefits of irrigation.

7. Describe the process whereby irrigation causes salinisation.

8. Explain why water quality often deteriorates as one moves downstream in areas where irrigation is practised.

CASE STUDY
The impact of agricultural activities on the Colorado River

The **Colorado River** drains much the south-western United States and a small part of Mexico. Its source is in the Rocky Mountains of north-east Colorado and it flows in a generally south-western direction for 2,334 kilometres to the Gulf of California (also known as the Sea of Cortez). The river flows through the US states of Colorado, Utah, and Arizona, and it marks the boundary between Arizona and Nevada and California. The final 120 kilometres of the river flows through Mexico into the Gulf of California.

The area where the river flows is a region of very low rainfall. Indeed, much of the course of the river flows through **desert**, including several deep gorges that have been carved by the Colorado River, including the Grand Canyon and Red Cliffs Canyon.

3.18 The Colorado River flows through an incised meander of its own making at Gooseneck, south-west of Moab, Utah.

In the early 20th century, the warm climate made the area attractive to farmers wishing to grow crops using **irrigation**. However, the large demand for water in an area of scarcity led to significant **international tensions** between the US and Mexico over issues of water **quantity** and water **quality**.

3.17 Enhanced satellite image of the Colorado River (after Google Earth).

As a result of the large-scale use of water for irrigation and urban use in the south-western USA, the Colorado River effectively **dries up** before it even reaches the sea. Furthermore, the water that does reach Mexico is of such poor quality that the Mexican Government has complained. **Salinity** at the headwaters of the Colorado is 50 parts per million (ppm). In contrast, at the point where the river crosses the border into Mexico, salinity was about 400 ppm in the early 1900s, the increase arising because one of the tributaries flowed across a layer of rock salt. By the 1960s, the figure had risen to 1,200 ppm as a result of increased runoff from irrigation in the Colorado River basin.

Early agreements between the US and Mexico dealt with the **quantity** of water in the Colorado River that the US agreed to deliver. However, with the decrease in the **quality** of water, Mexico pursued new negotiations that would ensure a maximum level of salinity in water reaching Mexico from the United States.

The demand for scarce water

Aridity in the south-west of the United States has created a situation of **physical water scarcity**. The aridity is caused by the cool ocean currents that travel south along the Canadian and United States coastline from Alaska. Moisture blowing onshore from the Pacific Ocean brings high rainfall as the winds meet the coastal ranges in the east of California, but as they blow over the mountains, there is little moisture left. The descending winds near Los Angeles are very dry and, for many months each year, quite hot.

Ironically, it is this dry, warm, coastal climate with water scarcity that has **attracted people** to the area in ever increasing numbers. At the end of World War II the state of California had approximately the same population as the whole of Australia — about seven million people. Now this one state has over 37 million people, with Los Angeles alone having over 15 million in its metropolitan area. In fact the dry southern one-third of California has more than 25 million people, or two-thirds of the total state population. In nearby states such as Nevada, new cities were being established in the desert, one of the largest being the tourism and gambling centre of Las Vegas.

3.19 Las Vegas, a city in the Nevada Desert, survives on water piped in from the Colorado River.

At the same time as the growing urban population was demanding more water, the Colorado Basin's **farmers** were demanding more water to expand the area under cultivation. Increasing **affluence** has added to the water shortages, and in the area around Palm Springs alone, which is a desert in its natural state, more than 70 golf courses stand out for their rich green colour. Surrounding urban areas are dotted with lakes and the surrounding homes of the wealthy are pictures of watery lushness.

3.20 Irrigated farmland beside the Colorado River, adjacent to the city of Grand Junction, Colorado.

Evolution of water scarcity

To the casual observer, regulating the **allocation of water** of the Colorado River might seem a simple task. After all, if too much water is being used by upstream users, why not simply restrict access to water by upstream people to allow sufficient flow for downstream users, including those south of the international border with Mexico?

Perhaps surprisingly given the problems experienced by downstream users, this approach has been followed since the early days of using Colorado River waters. Attempts were made to **measure** the flow of the river as early as the 1890s, and several measuring stations were built at various points on the river from the 1890s to the 1920s.

3.21 A stream discharge monitoring station operated by the US Geological Survey as part of the National Streamflow Information Program on the San Juan River, a tributary of the Colorado River, at Bluff, Utah.

On the basis of these measurements, the Colorado River basin was divided into **two sections**, the upper basin and the lower basin, with the boundary being placed somewhat arbitrarily at Lees Ferry, a point in the channel of the Colorado River in Nevada, about 50 kilometres south of the Utah-Arizona boundary, immediately downstream of the Glen Canyon Dam.

Each US state with the Colorado flowing through it entered into an agreement known as the '**Colorado River Compact**' in November 1922. The allocation of water between the two parts of the basin were based on an estimated annual river flow of about 18.5 billion cubic metres (18,502,228,000 m^3). It was known that the annual flow of the Colorado River fluctuates greatly, so this figure was obtained by taking the average of several years of readings at Lees Ferry in the years leading up to the signing. According to the Colorado River Compact, 9.25 billion cubic metres of water per year from the Colorado River was allocated to each of the upper and lower basins in perpetuity. The needs of Mexico were not considered.

Signing the Colorado River Compact cleared the way for a large number of **dams** to be built along

3.22 The Hoover Dam, on the Arizona-Nevada border, USA.

the river to **regulate** the flow. Some dams were built to provide hydroelectric power, while others were built for flood control, to provide water for irrigation, recreation, and municipal use. One of the dams, the 221 metre high Hoover Dam, is the largest producer of hydroelectric power as well as the main flood-control dam on the Colorado River. To carry the irrigation water from the dams to urban and farming areas, a network of long **canals** was also constructed. These include the Colorado River Aqueduct, which goes all the way to the southern California coast, the All American Canal, which carries water just north of the US-Mexican border to California's Imperial Valley, and the Gila Canal, in Arizona.

The **engineering** behind the works is impressive, and includes tunnels through the Continental Divide to bring water from the Colorado River to cities and farmlands on the high plains of Arizona. Despite the impressive engineering, the problem of

3.23 A canal through irrigated farmlands distributes water from the Colorado River just north of the Mexican border near Yuma, Arizona.

insufficient water persisted in the lower basin and especially in Mexico.

Recent studies of the Colorado River Basin's discharge have been undertaken using **dendrochronology** (analysis of tree rings). Dendrochronology measures the extent of wet and dry years over long periods by examining the thickness of the annual growth in tree trunks. These studies have shown that the early 1920s was a period with **unusually wet conditions** in the mountains near the source of the river. Tree ring analyses for the past 300 years indicate that the correct long-term average flow of the Colorado River is about 16.65 billion cubic metres. Furthermore, it seems that the river's discharge is highly erratic, ranging from 5.4 billion m^3 to over 27 billion m^3. Therefore, the assumed annual flow of 18.5 billion m^3 seems to have been an **over-estimate** of the typical flow, which explains the water scarcity in the lower sections of the river.

The water shortages in the lower Colorado River led to representations from the Mexican Government, and as a result, the United States and Mexico entered into a treaty on February 3, 1944 which guaranteed Mexico 1.85 billion cubic metres of Colorado River water annually, this figure being subject to increase or decrease under circumstances provided for in the treaty.

Nonetheless, over-allocation of water in the US means that the 1.85 billion cubic metres allocation does not arrive at the Mexican border every year. The Colorado River often **soaks** into its river bed and **evaporates** before reaching the sea. Many regard this as an environmental tragedy because

3.24 The Colorado River runs dry on the US/Mexico border, a few kilometres downstream from the Morelos Dam.

3.25 The now-dry Colorado River delta branches into the Baja/Sonoran Desert just eight kilometres north of the Sea of Cortez, Mexico. Note the white deposits of salt remaining on the surface where the Colorado River has evaporated.

this area, which is now often a dry salt flat, was a vast wetland, teeming with more than 400 species of plants and animals, before the waters of the Colorado were diverted.

Much of the water that does reach Mexico contains runoff from alfalfa and cotton farms in Arizona and California. Many of the soils in these areas are **salty**, as they comprise an ancient sea bed. Therefore, the waters that reach Mexico are heavily **saline** and **polluted**.

When **salinity** levels of Colorado River water flowing into Mexico reached 1200 ppm in 1961, the Mexican Government complained to US officials that the poor water quality was reducing crop yields in the Mexicali Valley. As a result, the United States agreed to limit the salinity of water flowing into Mexico to a level less than 115 ppm.

This promise was put into effect with the construction just over 20 years later of the **Yuma Desalting Plant**, which can process 270 million litres of water per day using a process known as reverse osmosis. Although completed in 1992, the high costs of operation have limited its operations. The plant has operated for only three short periods since its completion; a brief time when it was first completed, a 90 day demonstration at 10% capacity in 2007 and a year-long pilot run in 2011. The Mexicans, whose protests had led to the construction of the plant, are understandably disappointed by the continuing poor quality of the water they receive.

3.26 Irrigated cropland beside the Colorado River, which forms the border between Arizona (foreground) and California (background). This shows part of the Colorado River Reservation, a Native American reservation territory whose residents have senior water rights to the Colorado River amounting to nearly one-third of Arizona's total water allotment.

3.27 Irrigated cropland on the outskirts of Yuma, Arizona, using water pumped from the Colorado River.

The future

Climate records across the Colorado River basin suggest that temperatures in the region are rising. If this trend continues, the higher temperatures are expected to result in **less precipitation** in the upper basin of the Colorado River. As much of the precipitation in this area falls and is stored as snow, the combination of reduced precipitation and increased losses due to evaporation could shift the timing of peak spring snow melt to earlier in the year. Reduced discharge may also increase the **salinity** of the river. The overall effect of this could be to reduce discharge and water availability in the future, thus making Mexico's problems even more severe. Reduced discharge could also contribute to greater frequency of droughts, with such droughts becoming longer and more severe.

Question Bank 3C

1. *Describe the physical features of the Colorado River basin.*
2. *Explain why the Colorado River often dries up before it reaches the sea.*
3. *What is the cause of the Colorado River's salinity?*
4. *Explain why the Colorado River Compact allocated more water to US states than was usually available in the river.*
5. *Describe the impact on Mexico of the management of the Colorado River in the US.*

CASE STUDY
Irrigation for rice farming in Bali

When practised properly, irrigation can be implemented sustainably on a long-term basis. A good example of this is the Indonesian island of Bali, where irrigation has been practised for more than a thousand years.

Bali is a small Indonesian island with an area of 5,620 square kilometres and a population of over 4.3 million people. It is situated to the east of Java (Indonesia's most populated island) and west of Lombok. As shown in figure 3.29, Bali's **location** is just 1,000 kilometres south of the equator, lying between latitudes 8°04'S and 8°52'S, and between longitudes 114°26'E and 115°42'E. Shaped like a diamond, Bali measures about 140 kilometres east to west and about 80 kilometres north to south.

Rice is more central to the lives of the Balinese people than anything else. The cultivation of rice has radically transformed the landscape and the ecosystems of the island. Rice forms the centre of the Balinese diet, economy, culture and way of life.

The field where rice is grown is called a **padi** and it can be thought of as a **manipulated ecosystem**, an artificially created structure designed to copy a natural wetland ecosystem. To create a padi, the natural biophysical environment must be totally transformed, and in many areas of rice cultivation, this manipulation of the natural ecosystem has been going on for many centuries. The key element in controlling the ecosystem is water management through **irrigation**.

Farmers have no control over the quantities of rain that fall on their fields. However, they can exert quite a deal of control over the water by irrigation and drainage techniques. At its simplest level, this

3.28 Bunds separate padi fields at Jatiluwih in Bali, Indonesia. A complex system of water management allocates water to a succession of farmers, starting at the top of the hill and working down the slope. Several flows of water downhill can be seen in this view.

involves building earth banks called **bunds** around the padi fields. The bunds act as small dams preventing water from flowing to the next padi field down slope until the farmer chooses to release the water. At a more sophisticated level, **terraces** can be constructed on the sides of hills to control the water. Terraces form a series of steps up the side of the hill, creating a succession of flat padi fields each one of which can be flooded with an even depth of water. Some terraces are engineering masterpieces, being centuries old and having been constructed by hand with almost no tools but a massive communal effort.

Maintenance of the bunds and (especially) the terraces is a crucially important task for rice farming families. If the terraces were poorly maintained and allowed to slide downhill, the means of livelihood of an entire community would be lost, together with the labours of many decades or even centuries.

Like rice cultivators in other parts of the world, farmers in Bali replace the natural pattern of drainage through creeks and rivers by a complex

3.29 The location of Bali.

3.30 The entire hillside at Tegallalang has been cultivated in terraces. The lower terraces were planted before those at the top because water was available sooner at the foot of the slope near the stream. The upper terrace in the foreground shows rice shoots that were planted recently in the structureless mud.

network of irrigation canals, bunds and terraces. Irrigation **reduces** the farmers' **dependence** on rainfall and enables water to be used over and over again. For example, water used by a farmer at the top of a slope may be used by ten or even twenty other farmers further down the hill, as the water is released successively by each farmer. Furthermore, the water will carry **nutrients** down the hill, making highly efficient use of both the water and any fertilisers that are applied to the padi fields.

3.31 Irrigation canals at Jatiluwih, Bali. A complex system of irrigation using canals and gravity-fed channels has been organised co-operatively for about 1,000 years.

The key to successful rice farming in Bali is water management. The **Hindu beliefs** of the farmers have a strong influence. Almost all the water used by farmers in Bali comes from two mountain lakes that have formed in the craters of volcanoes. Beside each of these lakes is a water temple. The temple called Pura Bata Kau controls all the irrigation water for use in western Bali, while another called Pura Ulu Danau controls the irrigation for the rest of Bali. **Channels** flow from the lakes near these temples to provide irrigation water for every farm in Bali. As the water flows across the soils of each farm, it dissolves **nutrients** and **minerals** that are carried on to other farms down slope. In this way the irrigation water provides natural **fertiliser** for the padi fields as well as moisture.

3.32 Pura Ulu Danau is the water temple beside Lake Bratan, which controls most of the irrigation water used by farmers in Bali.

The complex system of irrigation channels has worked in Bali for more than 1,000 years, although it has been updated, expanded and maintained during that time. The organisation of water management and irrigation is done through a uniquely Balinese system of co-operative groups called **subaks**. The rice growers in each valley or area group themselves into a subak. The members of each subak elect a leader from their number, often the farmer who lives at the bottom of the slope because that farmer has the most to lose if the water is not allocated fairly.

Each subak has its own water temple where offerings are made twice each year. The aim of the subak system is to **regulate** the supply of water and distribute it fairly to all farmers. This means that farmers must discuss among themselves who will plant in which months of the year, as the demand for water would be very erratic if every farmer in a subak decided to plant at the same time. Fortunately, the temperatures in Bali are very even throughout the year, so planting is possible all year. This is why it is possible to see every stage of rice

3.33 The network of irrigation channels in Bali is complex and well established. In this view, water from a single canal in Bangkiang Sidem is diverted into several different farms in measured proportions according to the widths of the channels.

3.34 Six people work together to plant a padi field in Tegallalang.

cultivation at any time of the year in Bali. Farmers within each subak agree to stagger their times for planting so that the demand for both water and labour will both be spread out. In this way, the subak becomes an agricultural planning unit. The subak is probably the most important unit in Balinese society – it is a religious community, a social unit, a legal entity and a defined area of land.

The other task of the subak is to **maintain** the complex network of irrigation **channels**. This requires a large amount of co-operation among all the farmers in each subak. If irrigation canals become damaged, then all the farmers downstream will suffer as the quality and quantity of water deteriorate. As farm numbers change, new areas are opened and old areas close down, the network of irrigation channels must change accordingly. Like all subak activities, this is done co-operatively and by general agreement among the members.

3.35 Padi fields near rivers have abundant water all year, so they are often used as the nursey beds for young seedlings.

The **planning** of irrigation channels varies according to the type of topography under the control of the subak. In fairly flat areas, padi fields can be quite large. However, even in flatter areas, there will be differences in the height of the land that must be taken into account in planning irrigation. Main canals are usually built along ridges, with smaller canals branching off, and smaller ones again forming a hierarchy of canals.

As slopes become steeper, the problems of drainage become more complex. Terraces need to be built on steeper slopes. As Eiseman (1990, 284) comments:

> *"The padi fields are also marvels of hydraulic engineering. Streams are dammed far uphill from the fields, and the water is directed by hand-built aqueducts to fields far away from the dams. Weirs and smaller dams divide and re-divide the streams, settling basins allow the silt to drop out, and finally the water reaches the highest terraces".*

The water continues working as it flows step by step down the terraces of the hillside. The water is released in measured amounts, carrying nutrients down slope to the lower levels, being used over and over in successive rice terraces.

Question Bank 3D

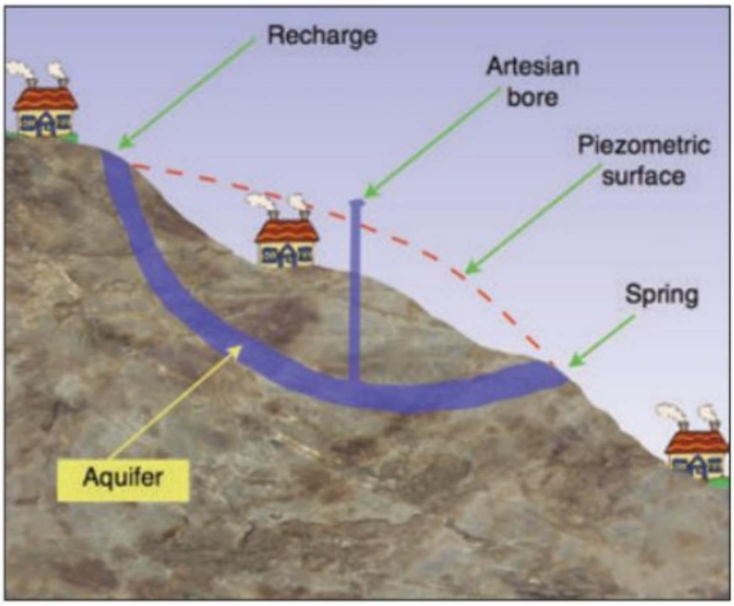
1. *Describe the evidence that supports the claim that Balinese padis are 'a manipulated ecosystem'.*
2. *What is the subak, and why it so important in the organisation of irrigation in Bali?*
3. *Suggest why irrigation in Bali has been sustainable for so long when irrigation has caused so many environmental problems elsewhere.*

Pressures on lakes and aquifers

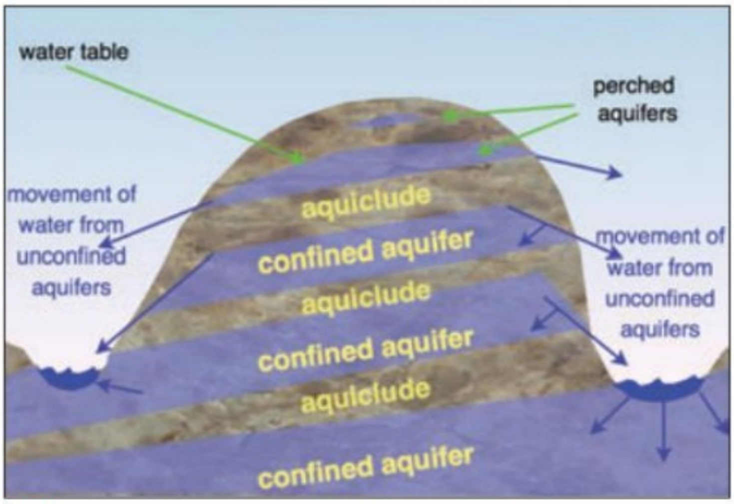
Aquifers and groundwater

Groundwater is important in many drier countries for both farming and mining. **Aquifers** are bands of permeable rock that can contain or transmit groundwater. If an aquifer is confined above and below by layers of rock with low permeability (**aquicludes**), then water may flow through the rock and emerge on the sides of cliffs or slopes. Indeed, whenever an aquifer intersects with the surface of the ground, a **spring** arises. If the top surface of the water table has no confining bed of rock, then the surface of the unconfined saturated zone is generally referred to as the **water table**.

3.36 An aquifer discharges water at the surface in a natural spring in the Highlands of West Papua, Indonesia.



3.37 The formation of artesian bores.



3.38 The movement of water through aquifers.

If the water in the confined aquifer has the potential to rise above ground level, as shown by the piezometric surface in figure 3.37, then the aquifer is **artesian**. A bore sunk into such a confined aquifer would result in water flowing to the surface without pumping.

In areas where there is a large artesian aquifer covering an expansive area, it is referred to an **artesian basin**. One example of is the Great Artesian Basin, the largest artesian basin in Australia and one of the largest in the world. It occupies an area of 1.7 million square kilometres, or about 20% of Australia's land surface area. A total of 536 million cubic metres of water is withdrawn from the basin each year.

Extraction of groundwater in Australia for over a century has resulted in major sources such as the Great Artesian Basin being over-exploited (more water taken than replaced). The upper level has fallen 120 metres since it was first tapped. As a consequence, many of the bores are no longer artesian and the water has to be pumped to the ground surface.

Storage of water in groundwater is another way in which groundwater can be used by people. In some areas, it is economical to pump excess surface water into the ground to maintain the groundwater store. Sometimes **waste water** from sewage treatment works is pumped back, although this practice may create problems of water quality control.

There are two main ways in which water is **inserted** into a groundwater reservoir. First, water can be **pumped** down a bore hole, usually the same one from which water has previously been withdrawn. Second, it is possible to use **recharge** basins, which are large surface reservoirs with porous bottoms to allow water to seep into aquifers.

Basins are often built beside streams so that they can refill when **floods** occur. Recharge basins work best when the aquifer is near the surface and has no major aquiclude between it and the ground surface.

Groundwater stores can be over-pumped, or 'mined'. **Mining** takes place when more water is taken out of the aquifer than flows into it. In most rocks the rate of movement of water is slow, and the recharge rates are therefore slow. For example, water in the Great Artesian Basin in Australia is thought to take tens of thousands of years to move from the recharge areas to the deep stores.

3.39 The Templo de Nuestra Señora de Loreto in Mexico City was completed in 1816. Since that time the facade has been sinking slowly towards the east because of the extraction of groundwater from beneath the building. The effect can be seen here as the walls rise from the pavement at different angles.

Mining of groundwater has two effects. First, the **head** (surface level) **falls** and it is harder to get water out of the bore or well. The further the level falls, the more expensive the cost of pumping becomes. Second, the **rocks** may **compress** as a result of the removal of water, and this consolidation may lead to subsidence of the surface. Mexico City, which is built on an old lake bed, has sunk by more than eight metres as a result of the withdrawal of groundwater. There are old buildings that have subsided to the extent that one must now walk down a flight of steps to reach the original ground floor. London experienced subsidence of about eight centimetres between 1865 and 1931 as a result of groundwater use.

Question Bank 3E

1. *Explain the difference between aquifers and aquicludes.*
2. *Summarise the principles needed to use artesian water on a sustainable basis.*
3. *What are the effects of 'mining' groundwater? What can be done to overcome these problems?*

Lakes

Lakes and **ponds** are basins that are filled with water and are surrounded by land. They vary greatly in size, and consist of relatively still water. With the exception of crater lakes in volcanoes, which are **fed** by overland flow, lakes are always fed by one or more rivers (or glaciers, or groundwater aquifers). Although most lakes and ponds are also **drained** by rivers, this is not the case for all lakes. Lakes and ponds are not part of the ocean, and they are thus different from lagoons. Although there are no strict specifications, ponds are usually smaller than lakes, and both can either be **natural** or **artificial** (made by humans).

Most of the world's lakes are freshwater, and the largest number are found in formerly glaciated areas in the Northern hemisphere, such as in northern Canada, Alaska and Russia. However, lakes are found in all parts of the world, including arid environments. Lakes **form** in several ways:

- **Oxbow lakes** are crescent-shaped lakes that form when rivers change course and abandon meanders.
- **Crater lakes** form in the craters and calderas of volcanoes when the rate of precipitation filling

3.40 A large crater lake — Lake Chon occupies much of the crater of Mount Paektu on the border of North Korea (in the foreground) and China (in the distant background).

3.42 Earthquake Lake in Montana, USA, formed when a huge landslide on the slope in the left of this photo slid down the mountainside, damming the Madison River.

the lake exceeds the loss of water through evaporation.

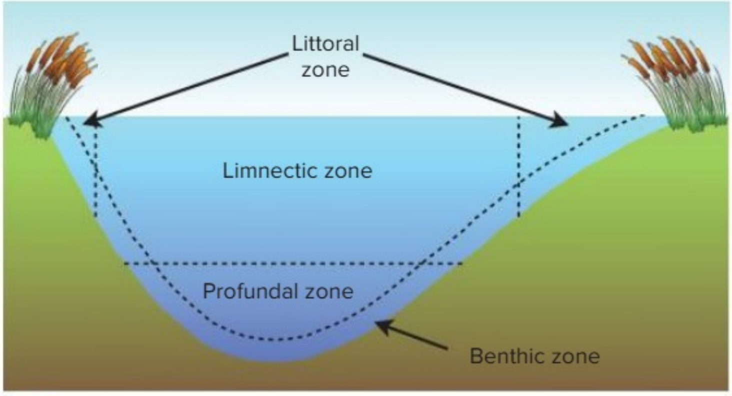
- **Glacial lakes** form in ice-scoured depressions in areas where glaciers and ice sheets have retreated; these depressions may be very large as with the Great Lakes on the border of Canada and the United States.
- **Salt lakes** form in hot, dry places where there is no natural outlet and water evaporates, causing a high concentration of salt in the water. Salt lakes can be quite large in size, with examples being the Aral Sea (Uzbekistan/Kazakhstan), the Dead Sea (Jordan/Israel), Lake Eyre (Australia) and Lake Etosha (Namibia).
- **Landslide lakes** form when a landslide blocks a river, as happened with Earthquake Lake in Montana (USA).

3.41 Lake Etosha in Namibia is an ephemeral salt lake, which means it is dry for much of the year as evaporation exceeds precipitation in the lake's catchment area.

- **Tectonic lakes** form when orographic uplift forms mountainous areas with depressions that accumulate water (such as Lake Titicaca in the Andes Mountains on the border of Bolivia and Peru), or where subsidence occurs on the margins of crustal plates that are being torn apart, such as Lake Tanganyika (Tanzania/Burundi, Congo/Zambia) and Lake Baikal Russia).

Freshwater lakes and ponds have distinct **ecological zones**:

- The **littoral zone** is the area of shallow water beside the shore. Plenty of sunlight reaches this area, so it is warm and photosynthesis can occur easily, making this an attractive environment for rooted plants. These rooted plants, such as grasses and reeds, become food for aquatic life such as turtles and ducks.
- The **limnetic zone** is the open area of surface water away from the shoreline that also receives abundant sunlight. The sunlight



3.43 The ecological zones of a typical freshwater lake in a humid environment.

enables a variety of freshwater fish and plankton to live in this zone.

- The **profundal zone** is the very deep water that is found in some larger lakes. Light cannot penetrate through the water above to reach this area, and so photosynthesis cannot take place and the temperature is cold. Consequently, no plants and almost no aquatic life can survive in this zone.
- The **benthic zone** is the bottom of the lake or pond, and it is covered by a layer of dead organisms and sediment.

3.44 The littoral zone of lakes are important for preserving the lake's biodiversity and environmental health. This view shows the littoral zone of Lake Titicana, near Huatajata, Bolivia.

Lakes and ponds are important for a range of **environmental** reasons. Lakes and ponds promote biodiversity, providing important habitats for wildlife, including breeding grounds for many birds in the littoral zone. Lakes and ponds also perform important roles in the water cycle, protecting surrounding areas from flooding and recharging groundwater and aquifers.

Lakes and ponds are also significant for a wide range of **human uses**. They provide water for agricultural, industrial and domestic uses, and many lakes are used for recreational purposes such as swimming, boating, fishing and bird watching. Larger lakes, such as the Great Lakes in North America, are used for trade, transport and as a source of water for manufacturing industries along the shoreline. Some lakes, especially artificial lakes, are used to generate hydroelectricity.

3.45 With a population of 2,7 million people, the large city of Chicago on the shore of Lake Michigan has a significant impact on the ecology of the Great Lakes.

3.46 Some idea of the large scale of the Great Lakes can been seen in this view along one of the lakes, Lake Erie. In the distance, a plume of steam rises from the Davis-Besse nuclear power station on the southern shore of Lake Erie.

Population growth and **economic development** in areas around lakes and ponds are placing increasing pressures on their **water quality**. This is especially so for lakes which are situated in areas with large surrounding populations, or where **migration** is bringing more people into the area surrounding a lake. The Great Lakes on the US-Canadian border — Lake Superior, Lake Michigan, Lake Huron, Lake Erie and Lake Ontario — are the world's largest group of freshwater lakes, containing 21% of the world's freshwater with a surface area of 244,106 square kilometres. There are 23 cities with populations exceeding 100,000 people around the Great Lakes, including Chicago (2.7 million people), Toronto (2.6 million), Cleveland (2.1 million) and Detroit (690,000).

3.47 Copacabana is a tourist town, religious centre and farming hub with abouit 6,000 people on the shore of Lake Titicaca, Bolivia. Lake Titicaca is the world's highest navigable lake at an altitude of 3,812 metres.

3.49 Fertilisers from small farms beside Lake Titicaca, west of Tiquina in Bolivia, have washed into the lake's waters, causing unnaturally high growth rates of littoral reeds and grasses.

The combination of a high level of **economic development** with a **high population density** around the Great Lakes has resulted in discharges of **chemical pollutants** such as mercury, phosphates and detergents, organic pollutants such as sewage, as well as **agro-chemical flows** of pesticides and fertilisers. These pollutants have lowered the quality of the water for domestic use and threatened aquatic life. Pollutants such as mercury and pesticides **biomagnify** through the food chain, threatening fish and other organisms.

Pollution from **hydrocarbons** such as oil and petrol also threaten lakes in populated areas. Hydrocarbon pollutants mainly originate from **motor vehicles**, although oil spills from **boating** is also a threat in larger lakes. Many of the hydrocarbon pollutants wash into lakes through **stormwater** runoff from urban areas, combining with other pollutants in the stormwater such as pesticides, fertilisers, bacteria and plastics.

3.48 Boats are used for transport between Santiago Atitlán and Panajachel across Lake Atitlán, a caldera lake in Guatemala. Oil leaks and spills from the boats, together with domestic sewage and agricultural runoff, present environmental threats to the lake's ecology.

3.50 Lakes can have a high economic value as well as environmental value when they are preserved in a pristine state. This view shows tourists on Kuril Lake on Russia's Kamchatka Peninsula, observing wild bears feeding on the lake's abundant salmon.

Another threat to lakes and ponds arises as aquatic **invasive species** attach themselves to animals or boats that come into contact with the water, mainly in the littoral and limnectic zones. These invasive species disrupt the food webs of the lake's ecosystem, reduce **biodiversity** and alter the natural balance of species within the ecosystem. This threat impacts **recreational users** of lakes as the littoral zones becomes uninviting to visitors because of unpleasant odours and destruction of natural vegetation.

In some parts of the world, lakes and ponds are **drying up** as farmers draw too much water from them or their tributary rivers to irrigate their farmland. This is occurring in such diverse parts of the world as the Aral Sea (Kazakhstan/ Uzbekistan), Lake Chad (Niger/Chad/Nigeria), Lake Poopó (Bolivia) and the Salton Sea (USA).

At a larger scale, **climate change** affects lakes and ponds in several ways that influence the timing and quantities of water entering and leaving the lake. For example, when temperatures rise, runoff is reduced and evaporation from the lake or pond is increased. If the temperatures remain high for a long period of time, cold water species in the limnectic zone may migrate down to the profundal zone, while species in the profundal zone may have to move to a more favourable habitat, if one exists, to be able to survive.

QUESTION BANK 3F

1. *What is the difference between a lake and a lagoon?*
2. *Outline the various ways that natural lakes can form.*
3. *Which ecological zones of freshwater lakes are most vulnerable to human impact?*
4. *Giving reasons, say which is the more important reason to limit human impact on lakes: environmental or economic.*
5. *Outline the ways in which humans place pressure on lakes.*
6. *Why do population growth, migration and economic development tend to increase human pressures on lakes and aquifers?*

CASE STUDY
Human pressures on a large lake - the Aral Sea

The **Aral Sea** is a large inland sea, or more precisely, a huge **inland lake** that has no outlet. It is situated across the border of Kazakhstan and Uzbekistan, in central Asia. Until 1991, Kazakhstan and Uzbekistan were two of the republics within the Soviet Union (USSR). When the Soviet Union disintegrated in late 1991, Kazakhstan and Uzbekistan emerged as two separate independent nations.

The Aral Sea has only **two tributaries**, the Amu Darya and the Syr Darya. Both rivers rise in the Tian Shan mountains to the east, in the border areas of China, Tajikistan and Kyrgyzstan. From their sources, the two rivers take different courses before flowing into the Aral Sea. The **Syr Darya** flows west through Uzbekistan and Kazakhstan, entering the Aral Sea from the north-east edge. The **Amu Darya** flows towards the north-west through

3.51 Map of Uzbekistan and its surrounding countries, showing the location of the Aral Sea before it shrunk to its present size.

Turkmenistan and Uzbekistan, entering the Aral Sea from the south.

The two rivers are quite large, with a combined **average annual flow** of 111 cubic kilometres; this compares with the average annual flow of 90 cubic kilometres for the River Nile (in Egypt) and 225 cubic kilometres per annum for the Zambezi River (which flows through Zambia, Zimbabwe and Mozambique). Although much of the water is lost naturally to **evaporation**, **transpiration** and **seepage** as the rivers flow across the deserts, there is enough water in the rivers' natural state to **maintain** the Aral Sea's normal surface area of 68,000 square kilometres, an area which makes the Aral Sea the world's fourth largest lake. Unless there is human intervention, water entering the Aral Sea leaves only either by **seepage** downwards into the rocks below or upwards by **evaporation**.

3.52 The Syr Darya at Dzhusaly, Kazakhstan.

The biophysical environment

The area around the Aral Sea comprises dry, flat plains with few rivers. Being near the middle of the Asian land mass, Uzbekistan and Kazakhstan experience hot, dry climates which have made most of the land in the two countries into either **desert** or **steppe grasslands**. Average annual **precipitation** rarely exceeds 150 mm per year. The range in **temperatures** is very large, with minimum temperatures dropping to -20˚C in winter and maximum temperatures rising to 47˚C in summer.

The air around the Aral Sea is very dry. The relative **humidity** by day in summer is always less than 25% and around midday it can fall below 10%. Even in winter, relative humidity averages only 40 to 65% during the day. Many parts of Kazakhstan and Uzbekistan experience hot, dry winds called the sukhoveya, which can damage crops severely.

The **soils** of the deserts and semi-deserts surrounding the Aral Sea are **sandy**. This means that they do not retain even the little moisture that falls on them. Moreover, many of the soils are **salty**. The Aral Sea has affected the soils over a wide area; the lake was once much larger and salt infiltrated down into the soil at that time. Even today, salt is blown from the shrinking Aral Sea across Kazakhstan and Uzbekistan, continuing to make the surrounding soils salty. This process is called **salt deflation**, and it averages about 8,200 tonnes per square kilometre each year.

Scattered through the desert area are oases, areas where underground **aquifers** from groundwater come close enough to the surface for people to drill and use it for **irrigation**. It is around these oases that most naturally occurring plants are found, and it is where the towns have been established.

3.53 Sandy soils beside the Amu Darya where it enters the Aral Sea near Moynaq, Uzbekistan.

Water management in the desert

According to historical records, agriculture using **irrigation** water has been practised in Kazakhstan and Uzbekistan for up to 6,000 years, making this one of the world's oldest areas for practising irrigation. Indeed, farming would be practically impossible in the dry deserts around the Aral Sea without taking water from the rivers and using it for irrigation. Nonetheless, agriculture is so difficult in the dry desert that the large plain between Tashkent and Samarkand became known as the **Hungry Steppe**.

3.54 Farming on the Hungry Steppe of Uzbekistan.

3.55 Irrigated cotton fields west of Samarkand, Uzbekistan.

A **steppe** is a large flat plain, and the name Hungry Steppe referred to the starvation that the population often experienced. After the Russians conquered Uzbekistan in the late 1800s, irrigation expanded by a massive program of canal building.

By 1990, Uzbekistan had 20 large reservoirs and over 150,000 kilometres of irrigation ditches. It is important to note that the main reason irrigation expanded under Soviet rule was not to grow more food, but to grow **cotton**. The dry climates of Kazakhstan and Uzbekistan were ideal for the cultivation of cotton, and vast areas to the east of the Aral Sea were made the Soviet Union's chief cotton producing areas.

In 1921, three years before it officially became part of the USSR, Uzbekistan produced 14,000 tonnes of raw cotton. By 1935, the cotton harvest reached one million tonnes, and it passed two million tonnes in 1950. By 1990, annual cotton production in Uzbekistan had reached six million tonnes and the combined total for the five countries using water diverted from the Aral Sea (Uzbekistan, Kazakhstan, Turkmenistan, Tajikistan and Kyrgyzstan) was over eight million tonnes. Under Soviet rule, cotton exported from these five republics was exchanged for food grown elsewhere.

Table 3.2
Factors behind the decline of water runoff to the Aral Sea, 1960 to 2012

Indicator	1960	2007-2012
Population of the Aral Sea basin	14.1 million	60.4 million
Irrigated agricultural lands	4.5 million hectares	8.0 million hectares
Total water withdrawal	60.6 cubic kilometres per year	105 cubic kilometres per year
Total runoff to the Aral Sea	55.0 cubic kilometres per year	10.6 cubic kilometres per year

Source: World Meteorological Organisation

Cotton is not the only crop produced in the desert areas near the Aral Sea. The area also produces desert roses for commercial sale locally and for export. Large crops of melons are also produced, largely for export but also for local consumption.

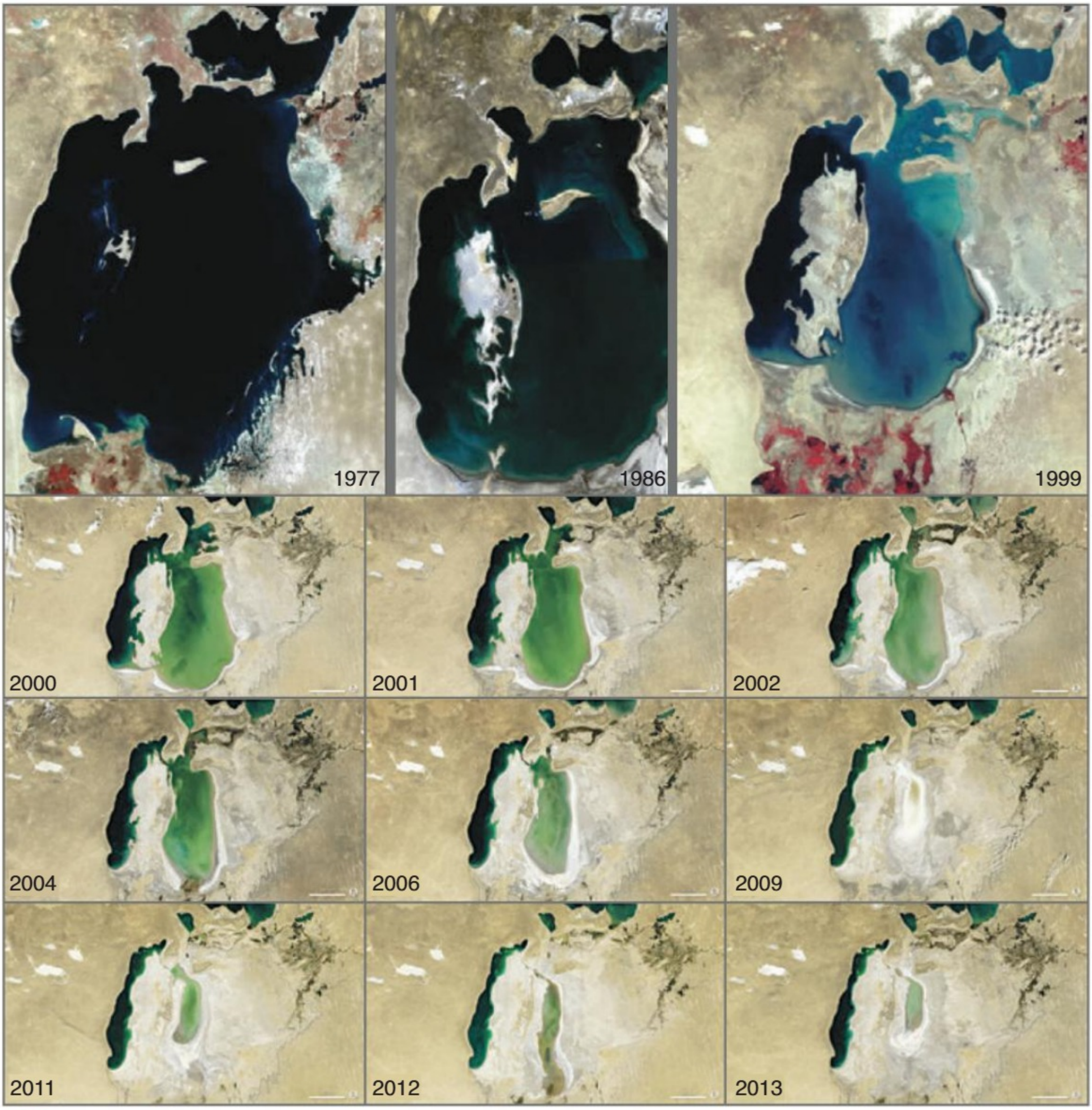
3.56 Melons from irrigated fields in the markets of Khiva, Uzbekistan.

The impact of water management

Irrigated cotton growing in the Aral Sea catchment has had quite a number of environmental side-effects. As cotton production expanded, more and more water had to be **diverted** from the rivers flowing into the Aral Sea, with the result that less and less water has flowed into the Aral Sea. Although in the natural state these rivers brought an average of 111 cubic kilometres of water annually into the Aral Sea, this figure had been reduced to just two cubic kilometres per year by the early 1980s. At the same time as this was happening, more and more **pesticides** and **fertilisers** were draining into the rivers from the cotton fields, and industrial **pollutants** from factories beside the rivers were growing rapidly.

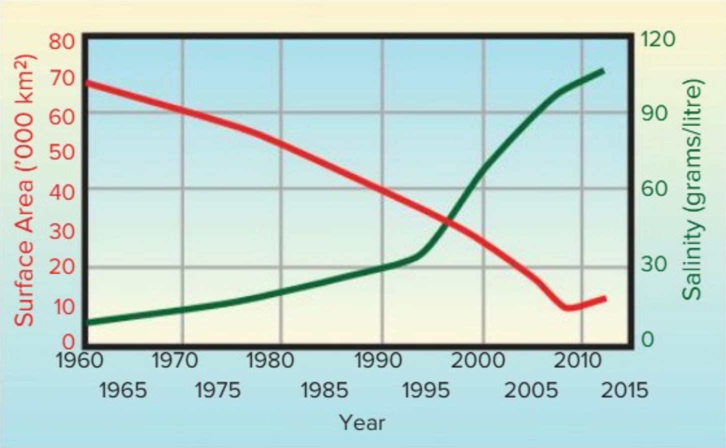
These agricultural and industrial pollutants all made their way to the Aral Sea. Evaporation and seepage are the only ways water leaves the Aral Sea, and so the **concentration** of pollutants became stronger and stronger with the passage of time.

The Aral Sea used to be the fourth largest lake in the world. Because of the reduced flow of water, its **surface area** has shrunk by 90% and its **volume** has fallen by 90%. Between 1960 and 2013, the area of the Aral Sea shrank from 68,320 square kilometres to about 10,464 square kilometres, and the level of the water fell by 20 metres. The volume of water in



3.57 Satellite images showing the shrinkage of the Aral Sea, 1977 to 2013.

the Aral Sea fell from 1,090 cubic kilometres to 175 cubic kilometres. This has meant that salts, pesticides and fertilisers washed into the sea have become even more **concentrated** as the water has evaporated. Indeed, between 1960 and 2013, the concentration of salt in the Aral Sea increased from 10 grams per litre to up to 110 grams per litre. As the Aral Sea has shrunk, the shoreline has receded by up to 80 kilometres.



3.58 Changes in the Aral Sea's surface area (red line, left axis) and salinity (green line, right axis), 1960 to 2013 [the latest reliable statistics].
Source: derived from World Meteorological Organisation data.

Key changes to the Aral Sea are summarised in figure 3.58. To place the **salinity** figures in context, the average salinity of sea water is 33 grams per litre. The average level of the lake fell by 20 centimetres per year during the 1960s as water was diverted for irrigation. The rate of fall of the sea surface accelerated to 60 centimetres per year during the 1970s, and then to almost one metre per year during the 1980s.

As a result of the shrinkage of the Aral Sea, the remains of the pesticides and fertilisers have become **exposed** on the dry bed. These exposed deposits are now free to blow over the farmlands and villages of Kazakhstan and Uzbekistan to the east, dumping poisons as well as salt across a huge area. The salt is **toxic** for plant growth, and is resulting in an ongoing **expansion of the deserts** near the Aral Sea. The soils of the area are naturally salty, and without adequate rainfall to flush away the newly deposited salt, more areas of land can be expected to become unusable for agriculture.

Farmers have **responded** by putting even more water onto their crops, hoping that the excess water will wash away the salts. Unfortunately, the poor drainage of the area means that the excess water

3.59 The rusting hull of this fishing vessel rests on the dry bed of the Aral Sea east of Akespe, Kazakhstan.

3.60 One of many ships that lie stranded in the sands of what used to be the Aral Sea at Moynaq, Uzbekistan.

usually **raises the water table**, bringing even more salts upwards to the surface zone of plant growth. As long ago as 1985, Soviet soil scientists were claiming that 60% of the irrigated soils in Uzbekistan and almost 70% of the irrigated soils in Kazakhstan were experiencing moderate to strong problems of salinity.

The increased salinity of the soils is the main factor being blamed for **declining yields** of cotton in Uzbekistan. The chemicals which are being blown from the exposed Aral Sea bed are causing severe damage to people's **immune systems**, and have resulted in hepatitis, throat cancer and respiratory diseases. Between 1970 and 2007 the death rate among Kazakhstan's population increased significantly as people had to drink increasingly poisoned water, and although the death rate is now falling, it has not yet reached the lower level of the 1960s.

Over 80% of women of child-bearing age in the areas of Kazakhstan and Uzbekistan east of the Aral Sea are affected by anaemia. The rate of typhoid has risen by 3000% since 1970 and the rate of viral hepatitis has risen by 700% during the same period. The rate of cancer of the oesophagus in the area east of the Aral Sea is 50 times greater than the world average.

There are well-founded fears that health problems from the shrinking of the Aral Sea will become disastrous at some stage in the future. This is because it is now known that during the 1980s, the Soviet Armed Forces conducted **germ warfare** experiments in the deserts near the Aral Sea. The bacteria were especially developed to be resistant to any conventional forms of treatment. Deadly left over bacteria such as anthrax, plague, tularemia, brucellosis, typhus, Q fever, Venezuelan equine encephalitis and smallpox were subsequently buried on Vozrozhdeniye Island in the Aral Sea, near its western coastline.

As the Aral Sea shrinks, the risk increases that the bacteria will be disturbed, possibly by **rodents** such as gophers and marmots, which are natural carriers of plague and other diseases. The risk is that they may burrow into the bacteria stores, spreading disease over vast areas.

It is suspected that two environmental disasters are the result of bacteria near Vozrozhdeniye being exposed. In 1976, a **mass death of fish** in the Aral Sea occurred which has never been explained, and in May 1988 some 500,000 Saiga **antelope** died in the steppes north-east of the Aral Sea in a single one-hour period.

3.61 A thick layer of salt covers the surface of the lake bed where the waters of the Aral Sea have retreated in Kazakhstan.

3.62 Stranded fishing boats on the exposed sands of the Aral Sea at Moynaq, Uzbekistan.

3.63 A rusting boat on the northern edge of the Aral Sea in Kazakhstan disintegrates after years of exposure to salt. Adding iron to soil is not dangerous, but adding iron that has been in contact with oils or solvents contaminates the soil with toxic chemicals.

Life for people living around the Aral Sea has also changed for the worse. The Aral Sea used to provide food for people living on its shores. It supported a large **fishing industry**, with catches averaging 50,000 tonnes of fish per year. As the concentration of salt in the water increased, 20 of the Aral Sea's 24 species of fish have disappeared. The fishing industry has collapsed and the fishing boats lie where the edge of the Sea used to be, many kilometres from the shore.

The town of Moynaq in Uzbekistan had a thriving harbour and fishing industry that employed approximately 60,000 people. Today, Moynaq lies about 100 kilometres from the shoreline and the only significant fishing company remaining in the area brings its fish all the way from the Baltic Sea, thousands of kilometres away. As a result of the decline in fishing, the town's economy is dying.

The Aral Sea once provided a **breeding ground** for migratory birds. The breeding grounds were in swampy delta fringes of the Aral Sea. In the 1950s, 173 different species of animals and birds were recorded in the delta lakes of the Syr Darya and Amu Darya. By 1980, most of these lakes had dried up, the forests had dwindled to only 20% of their earlier size and only 38 animal species remained.

The Aral Sea is now **divided** into three parts, and the **shrinkage** is continuing. It is estimated that to maintain the Aral Sea at its present (reduced) size, average annual inflows from the two rivers needs to be increased to about 30 cubic kilometres. As the surface area of the Aral Sea declines, the loss of water by evaporation also declines. It is estimated that if present rates of inflow of water into the Aral Sea continue, the Sea will continue shrinking until it could disappear altogether in about 2025, by which time its salt concentration would have reached about 180 grams per litre.

3.64 Although Moynaq in Uzbekistan now lies about 100 kilometres from the shoreline of the Aral Sea, the town's badge recalls its former fishing industry when it was a port beside the lake. The grassy area used to be part of the lake.

The shrinking of the Aral Sea has also led to **climate change** in the surrounding area. Because less water is available for evaporation, average **humidity** has been reduced by 9%. The number of **days without rain** each year has increased from 30 in the 1950s to about 150 today. Summers are now hotter and drier, and winters are colder and longer – they now last four months rather than three as previously. As well as being disastrous for agriculture, these climatic changes make living in the area much less pleasant and comfortable for the inhabitants.

3.65 The economy of the town of Aralsk, Kazakhstan, has been in sharp decline ever since the waters of the Aral Sea receded from the town, killing the town's fishing industry. This shows the former port area.

One problem is that each of the five countries using water diverted from the Aral Sea pursues its own **individual water management** policy. For example, Turkmenistan lengthened the Karakum Canal (which takes water from the Amu Darya) by 300 kilometres in 1995 in order to irrigate additional areas in the country. This increased the amount of water diverted from the Amu Darya to 18 cubic kilometres per year, making the task of stopping the shrinkage of the Aral Sea even more difficult. Of the five countries, only Uzbekistan has reduced the amount of irrigated land used for cotton.

To some people, the environmental challenges in the region surrounding the Aral Sea seem out of control. Nonetheless some experts have suggested **measures** that they believe might help the situation, including:

3.66 The weir in the Kokaral Dam helps manage the water level of the northern Aral Sea, which is rising once again.

3.67 As waters rise once again in the northern Aral Sea, natural ecosystems are re-establishing with vegetation, birds and animals returning to areas that were just barren salt and sand.

- improving the quality of irrigation **canals** to minimise water loss by seepage;
- installing **desalination** plants to improve the quality of water in the Aral Sea;
- **charging farmers** to use the water from the rivers as a way to regulate water use and minimise wasteful use;
- growing **alternative species** of cotton that require less water;
- using **fewer chemicals** on the cotton to improve the quality of water flowing into the sea; and
- installing **dams** to store and divert water into the Aral Sea;
- **diverting water** from large rivers in Russia; and
- **pumping diluted sea water** from the Caspian Sea via pipeline into the Aral Sea.

The most successful action to restore the Aral Sea has occurred in Kazakhstan where the **water level in the northern part of the Aral Sea is now rising**. Reed-fringed waters once again cover land that had been dry for decades, bringing abundant bird life back to regenerated wetland areas.

The main factor leading to this improvement was construction of the **Kokaral Dam**. Built by the Kazakh Government between 2002 and 2005, the Kokaral Dam was designed to restore the depleted waters of the Aral Sea. It comprises a low, six metre earthen dam wall that extends for 13.7 kilometres with a set of sluice gates in its centre that regulate the water level by controlling the flow of water towards the south. Before the dam was built, the height (altitude) of the surface of the North Aral Sea was 36 metres.. With the construction of the dam, it has now stabilised at a height of 42 metres. Consequently, the waters of the Aral Sea, which in their natural state reached the port city of Aralsk but later retreated 100 kilometres to the south, have now returned to within just 12 kilometres of Aralsk.

Proposals are being considered to **raise the height** of the dam wall by a further six metres, which would raise the level of the North Aral Sea to 48 metres, completely restoring its natural surface area. The challenge is the **high cost** of this proposal. The initial dam wall and associated works cost US$86 million, of which US$64 million came as a loan from the World Bank with the balance being paid by the Kazakh Government. The dam extensions would cost far more than this amount, and the Kazakh Government would need substantial foreign aid to pay the cost.

Today, no water from the Amu Darya (the Aral Sea's tributary in Uzbekistan) reaches the Aral Sea due to over-allocation of water resources for agriculture. By contrast, the Syr Darya, which flows into the Aral Sea through Kazakhstan, contributes a viable flow of water into the lake. Unlike Uzbekistan and Turkmenistan, Kazakhstan grows almost no cotton, which is a major user of irrigation water in Central Asia.

Question Bank 3G

1. *Describe the biophysical environment of the area around the Aral Sea, mentioning (a) climate [temperatures and precipitation], (b) soils, (c) landforms, and (d) water.*
2. *Why is the area between Tashkent and Samarkand called the Hungry Steppe?*
3. *Why were the area's water resources developed on such a large scale?*
4. *Describe the changes in Uzbekistan's cotton production since the 1920s.*
5. *How was farming organised during the Soviet period?*
6. *Make a point form list of the impact of human actions on the Aral Sea's environment in descending order of their importance, adding 2 to 3 lines to describe each impact.*
7. *What practical measures have been implemented to remedy the environmental situation of the Aral Sea, and what additional practical initiatives could help in the future?*

Internationally shared water resources

In the **Colorado River** case study earlier in this chapter, we saw how problems of **water quality** can escalate into international **disagreements** when a water resource is shared between countries. Fresh water resources are **unevenly distributed**, and some parts of the world experience significant **water scarcity**. In situations where access to more water is crucial for people's survival, or where a country feels a neighbour is restricting their **legitimate access** to water, governments may feel motivated to take drastic steps to secure a reliable supply of water. The pressures for secure access to water increase as populations grow and demand a more affluent lifestyle.

There is tremendous **potential** for international conflict over water resources as there are 276 **trans-boundary river basins** in the world — 68 in Europe, 64 in Africa, 60 in Asia, 46 in North America and 38 in South America. There are 148 countries that have land within one or more trans-boundary river basins, and 39 countries have more than 90% of their territory within one or more trans-boundary river basins. In addition to these, there are about 200 **trans-boundary aquifers**.

3.68 The Danube River flows through heavily populated regions of ten countries — Germany, Austria, Slovakia, Hungary, Croatia, Serbia, Bulgaria, Romania, Moldova, and Ukraine. Its drainage basin includes nine more countries — Bosnia-Herzegovina, Czech Republic, Slovenia, Montenegro, Switzerland, Italy, Poland, Macedonia and Albania. Conflicts between these countries over water use is managed through an international organisation with headquarters in Vienna, Austria— the International Commission for the Protection of the Danube River (ICPDR). The Danube is seen here at Budapest, Hungary.

Most water disputes are handled through **diplomacy**, and there is a long history of such negotiations. It is rare for a dispute over water to be the major cause of **war**, but it can be a contributing factor in wars that arise due to other factors. Furthermore, co-operation over water scarcity is more common than conflict, and the United Nations reports that between 1820 and 2007, almost 450 **agreements** on international waters were signed covering issues such as hydro-electric energy generation and use, allocation and use of water, flood control, allocation of water for industrial purposes, navigation, pollution and fishing.

One of the significant priorities of the United Nations and many aid organisations is to enhance **access** to potable water supplies for disadvantaged populations and to upgrade **sanitation** infrastructure to reduce the social impacts of waterborne diseases.

Four factors that make **conflict** over water more likely are:

- the degree of water **scarcity**;
- the extent to which a water supply is **shared** between countries;
- the relative **power** of the countries sharing the water resource; and
- the ease of access to **alternative** water supplies.

International conflicts over water for **irrigation** can arise when there is pressure to increase food production to feed growing populations. For example, the **Nile River** flows through some of northern Africa's most **arid** areas, and the population is highly dependent on the river's flow. The Nile Basin is shared by nine countries: Burundi, Rwanda, Tanzania, Uganda, Congo, South Sudan, Sudan, Ethiopia, and Egypt. The Nile is especially important for Egypt as it provides 97% of Egypt's water. Moreover, about 95% of the Nile's flow originates in countries upstream from Egypt, making Egypt **vulnerable** to actions by upstream countries that might affect the flow of water north into Egypt.

The Nile's upstream countries also rely on water from the Nile. **Sudan** needs to increase its food production, but it suffers severe water scarcity.

Sudan has enough land to increase food production, but to secure the water needed to achieve this goal, it would need more water from the Nile River. However, Egypt and Ethiopia have both been unwilling to renegotiate long-standing agreements with Sudan to provide the water Sudan seeks.

3.69 The waters of the White Nile flow from Lake Victoria in Jinja, Uganda, one of the two sources of the Nile River. Effective management of the upper reaches of the Nile River has a huge bearing on the quality of life of millions of people downstream.

Many large **hydro-electric projects** involve more than one country. For example, the **Kariba Dam** was built on the Zambezi River on the border of Zambia and Zimbabwe. Although it is operated by a joint Zambian-Zimbabwean corporation, the Zambezi River Authority, **tensions** between the two countries are frequent over allocations of water, such as when Zimbabwe proposed unilaterally to build an additional pipeline to drain water from the dam to its southern city of Bulawayo. The Kariba Dam is **deteriorating** as its concrete walls swell from slow chemical reactions and cracks appear. Experts are warning that the decaying dam wall may collapse if urgent repairs are not undertaken. This is **threatening** a third country — Mozambique — which could face a tsunami-like wall of water rushing down the Zambezi River valley, reaching the border with Mozambique within about eight hours.

3.71 The Itaipú Dam on the border of Brazil and Paraguay has caused a number of international disagreements. It is seen here from the Paraguayan side of the Paraná River.

The **Itaipú Dam** was constructed on the Paraná River on the border of Brazil and Paraguay. Because Brazil has a larger population and land area than Paraguay, and is more industrialised, a majority of the electricity produced at the dam goes to Brazil. As Paraguay's power needs have increased, the allocation of electricity has had to be renegotiated. The dam also affects a third country, Argentina, which lies downstream from the dam, as the timing and amount of stream discharge is determined solely by the operators of the dam. Argentina expressed a wish to build its own dam on the Paraná River, but as the proposed storage lake would interfere with the operations of the Itaipú Dam, the proposal led to a dispute between

3.70 A panoramic view of the 7.9 kilometre wide Itaipú Dam, looking from the Brazilian side of the Paraná River.

Brazil and Argentina. The dispute was eventually settled with a compromise agreement that allowed Argentina to construct the Yacyretá Dam downstream on the Paraná River on the Argentine-Paraguayan border.

Conflicts over water have been less successfully handled in the **Middle East** than elsewhere, perhaps because of the extreme water scarcity that exists in much of the region. One focus of such conflict is the **Jordan River**, which is a small river in terms of the water flowing through it, but its basin is shared by several countries that have a wider set of political differences (Lebanon, Syria, Jordan, Israel and the Palestinian Territories of the West Bank). Water is scarce in the region, and as Israel has allocated more water to **irrigation,** Jordan has complained about the inadequate flow reaching its territory. As a result of Israel's water diversion projects, the flow of the Jordan River along Jordan's border with Israel has been reduced from an average of 1.4 billion cubic metres per year to 0.27 billion cubic metres per year. Much of the water that does arrive at the Jordanian border is of such low quality that it is unusable because of pollution from agricultural irrigation and saline springs upstream.

3.72 The Jordan River at Al-Maghtas, where it forms the border between Jordan (near side of stream) and Israel (far side of stream). Before large volumes of water were extracted upstream for irrigation, the river level was near the top of the bank in the foreground, covering the area now covered by vegetation in the bottom of the course of the river.

There is an ongoing conflict between Turkey and Syria over the use of water from the **Euphrates River** following Turkey's construction of the GAP (Grand Anatolia Project). This is examined in detail in the case study below.

The potential for future conflicts over water is increasing as the impact of **climate change** becomes more evident. Measurements of current trends show increasing **temperatures** world-wide, including in areas of water scarcity such as the Middle East and sub-Saharan Africa. Increases in temperature mean the losses of water through **evaporation** also increase, placing additional pressures in scarce water resources, especially in areas where **population growth** is high.

The impact may be amplified in areas where **droughts** become more intense or prolonged, as forecast in several areas of the world experiencing water scarcity such as the Middle East and Sub-Saharan Africa. Some studies have estimated that the discharge of the Nile River, for example, may decrease by 25% due to the impact of climate change, which would be catastrophic for the people who depend upon its waters. Perhaps that is why, as long ago as 1979, the then-President of Egypt (Anwar Sadat) said "the only matter that could take us to war again is water". Later, in 1988, the Egyptian Foreign Minister (Boutros Boutros-Ghali, later Secretary-General of the United Nations) echoed these thoughts, saying "the next war in our region will be over the waters of the Nile, not politics".

3.73 The Nile River at Aswan, Egypt. It is predicted that the Nile's discharge will decline by 25% due to climate change.

In some parts of the world, **excess water** and **flooding** rather than droughts is the cause of international tensions. Climate change forecasts predict that **rainfall** will become more intense in South Asia and South-east Asia, increasing risks of flooding and placing additional pressures on dams, levees and floodplain drainage channels. This raises the potential for further conflict between the countries sharing the Ganges River basin — Nepal, India and Bangladesh — which already have several disputes over water management. For example, India built and operates the **Farakka Barrage** on the Ganges River, 10 kilometres upstream from India's border with Bangladesh. The Barrage diverts water from the Ganges River along a feeder canal to the Hooghly River near Kolkata to flush the Hooghly and reduce its level of silt. However, construction of the Farakka Barrage was undertaken by India without any prior agreement with Bangladesh, which is located downstream.

3.74 The banks of Tolly Canal, a tributary of the Hooghly River in Kolkata, India, show some of the silt (and rubbish) that construction of the Farakka Barrage was designed to flush.

In order to reduce the potential for conflict over water resources, **seven principles** are desirable, although not always implemented in practice:

- Countries should follow the principles of **international law**, complying with treaties and principles established by bodies such as International Law Commission of the United Nations and the International Law Association;
- Countries should follow the principle of **equitable utilisation**, which means each country sharing a drainage basin is entitled to a reasonable and equitable share of the water. Equitable use is not the same as equal use, as equitable use takes factors such as population size, geography, access to alternative sources of water, and so on into account. This contrasts with the principle used by some countries to justify their use of water, which is the Harmon Doctrine. The **Harmon Doctrine** asserts that a country can use the water within its borders without any restrictions, even if that use hurts other countries.
- Countries should act in ways that **avoid causing significant harm** to other countries. Sometimes this principle is applied by allowing harmful actions to be taken provided adequate compensation is paid or mitigation measures are undertaken.
- Under the Helsinki Rules on the Uses of the Waters of International Rivers, and recommendations of the International Law Commission, countries have an obligation to **notify and inform** other countries of actions on shared rivers and streams that might affect them.
- Countries have an obligation to **share data**. In some parts of the world, such as India and Israel, water is considered to be a strategic resource, and governments use this as an excuse to keep data on river flows a secret.
- Countries should work together to manage water resources **co-operatively**, recognising it is the duty of all countries sharing a river basin to protect the water resources within it. This principle is often implemented by forming **joint basin commissions** with the power to negotiate disputes and resolve questions about the allocation of resources.
- Countries have an obligation to **resolve disputes peacefully**, a principle that is a requirement of the United Nations Charter. Rather than resorting to war, countries are encouraged to take disputes before the International Court of Appeals at The Hague in the Netherlands. Another way that wars over water can be avoided is by signing legally binding treaties that specify the allocation of resources and outline dispute procedures.

QUESTION BANK 3H

1. *Why do conflicts arise over internationally shared water resources?*
2. *List four factors that make conflict over internationally shared water resources more likely.*
3. *Why does the Nile River offer potential for international conflicts over water? Give an example of a conflict involving the Nile River.*

4. *Describe the actual and potential international conflicts surrounding the Kariba Dam and the Zambezi River.*
5. *Describe the international conflicts surrounding the Itaipú Dam and the Paraná River.*
6. *Describe the international conflicts surrounding the Jordan River.*
7. *Explain how climate change increases the potential for conflict over internationally shared water resources.*
8. *Describe the international conflict arising from construction of the Farakka Barrage.*
9. *Outline the seven principles that help to reduce international conflict over shared water resources.*

CASE STUDY
Water conflict in the Euphrates River basin

The **Euphrates River** flows from the high mountains of eastern Turkey across Turkey's southern border into semi-arid Syria and through the deserts of Iraq before emptying into the Persian Gulf. About 40% of the Euphrates River is in Turkey, 25% is in Syria and 35% is in Iraq.

With a **length** of almost 3,000 kilometres, it is the longest river in western Asia, and historically one of the most **significant** as its waters provided the basis of ancient civilisations in Mesopotamia (the area between the Euphrates and Tigris Rivers). Mesopotamia was one of the first places in the world where agricultural cultivation developed, and the water from the Tigris and Euphrates Rivers was essential for this and the development of political control of the region.

Most of the water that flows through the Euphrates River begins as rainfall and annual snowmelt in the Armenian Highlands of eastern Turkey, and thus the flow of the river is highly **seasonal**. About 98% of the Euphrates River's discharge originates within Turkey, with very little additional water being added in Syria or Iraq. Indeed, as the river flows through Syria and Iraq, there is a net loss of moisture due to high rates of evaporation. The three countries of Turkey, Syria and Iraq are known as **riparians**, which means they are countries through which the river passes. As such, all three countries have legal rights that are known as **riparian rights**.

In 2000, research by Aysegul Kibaroglu and Ünver Olcay in the journal International Negotiation estimated that the percentages of Euphrates River **water needed** for each country's development work were Iraq 65%, Turkey 52%, and Syria 32%. As these figures total 149%, it was clear that the demands for water exceeded the supply available, setting up a situation that is ripe for conflict over the internationally shared water resource. Since that time, population growth in the Euphrates River basin has increased the demand for water.

3.75 The Euphrates River basin (in light green), with the location of the South-eastern Anatolia Project (GAP) in dark green. National boundaries are shown in red.

Although Syria and Iraq have both built dams on the Euphrates River, by far the largest water project is the **South-eastern Anatolia Project** in southern Turkey, also known by its Turkish name Güneydoğu Anadolu Projesi, or more commonly, simply '**GAP**'. GAP is one of the largest water management projects in the world, and includes dams on both the Euphrates and Tigris Rivers, and their tributaries. The large scale of GAP has given Turkey effective **control** over the Euphrates River's water as it flows into other countries downstream, control that is strengthened because Turkey is politically a stronger country than Syria or Iraq.

GAP was launched in the 1970s, and its construction is still continuing. It is a **multi-purpose** water scheme to provide water for **irrigation** and **hydro-electricity** in Turkey's south-eastern provinces, an area of about 75,000 square kilometres containing some seven million people. The Project aims to build 22 dams to irrigate 17,000 square kilometres of farmland, and 19 power stations to supply electricity to an area containing about 10% of Turkey's population. South-east Turkey is less economically than other areas of Turkey, and GAP was designed to give the region a significant boost.

3.76 South-east Turkey is less economically developed than other parts of Turkey. This shows part of the city of Harran, the largest town in the irrigation area that stretches from the city of Şanlıurfa to the Syrian border.

Originally, the construction of GAP was originally due for completion in 2010, but completion was delayed to 2047 when the **World Bank** withheld funding because Turkey had not concluded negotiations with Syria and Iraq regarding the sharing of the Euphrates' water. The largest dam in GAP is the **Atatürk Dam**, completed in 1992 about 80 kilometres upstream from Turkey's southern border with Syria. The dam has a 1,820 metre wide wall that holds a lake containing 49 cubic kilometres of water. The Atatürk Dam is large enough to hold the entire annual discharge of the Euphrates River.

3.77 The Atatürk Dam, near Şanlıurfa, Turkey.

3.78 Part of the Atatürk Dam's reservoir, the largest reservoir in the GAP (South-eastern Anatolian) water management project.

Water for irrigation is distributed through a comprehensive network of **canals** that mainly flow to the south from the dams on the Euphrates River. The canals form a loose grid layout that follows the roads of the flat Harran Plain. **Sluice gates** have been built at regular intervals to regulate the flow of water and allocate in precise quantities to different farming areas. If the water flows too quickly, the channels will overflow, causing flooding and damage to the canals, so the sluice gates are used to regulate the speed as well as the quality of water released. After the water is released through the sluice gates, it flows through a network of **distribution canals** that become progressively smaller as they reach the periphery of the GAP area. Finally, water is brought to the fields from the distribution canals using a mix of techniques such as **earth furrows** and **drip tubes**.

3.79 Major open canals carry water from dams, such as the Atatürk Dam, throughout the Harran Plain.

3.80 Sluice gates regulate the flow of water through the canals of the GAP scheme according to need.

3.81 In the GAP scheme, small distribution canals carry water to individual farms.

3.82 Drip tubes take water from a distribution canal onto the fields near Harran, Turkey.

GAP has brought significant **economic benefits** to south-eastern Turkey. Since the Atatürk Dam was completed, **production** of cotton, wheat, barley and lentils have all tripled on the Harran Plain, which is the irrigated area between Şanlıurfa and the Syrian border. **Hydro-electricity** from GAP supplies about a quarter of Turkey's total electricity needs. The **standards of living** in south-eastern Turkey have risen as job creation has occurred, including the ethnic Kurdish minority whose economic welfare has been significantly at a lower level than the wider population.

On the other hand, construction of GAP had some significant negative impacts on the natural and social **environments** of south-east Turkey and northern Syria. In order to build the dams, almost 200,000 people in 380 villages had to be **relocated**, 55,000 of these people moving to allow the building of the Atatürk Dam. Many ancient archeological sites were flooded by the rising waters of the dam.

Construction of large lakes behind the dam walls and expansion of irrigation has resulted in significant losses of water through **evaporation** in the warm, dry climate of the area. The **water quality** of the Euphrates declines downstream as **spent irrigation water** containing fertilisers and pesticides is returned to the river, and salinity increases downstream for the same reason. Consequently, the Euphrates has become less useful for domestic use and human consumption in Syria, and even less so in Iraq.

As GAP has expanded, Syria and Iraq have complained that the **volume of water** extracted by

3.83 Excess water lies on the irrigated fields in this farming scene near Harran, Turkey. The excess water dissolves farm chemicals, including pesticides and fertilisers, as well as salts from the soil, and carries these back to the Euphrates River, lowering water quality for downstream users in Syria and Iraq.

Turkey has been excessive, leaving too little water for the needs of users downstream. Satellite photos show that while the area of farmland under irrigation has grown significantly in Turkey, the extent of irrigation **declines** markedly at the Turkish-Syrian border.

3.85 Sluice gates regulate the flow of water to irrigated fields near Harran, Turkey.

Syria developed extensive areas of irrigation on the assumption that water would be available from the Euphrates River. The **Tabqa Dam** (also known as al-Tabqah and al-Thawra) was built in 1973 to the west of Ar Raqqa with help from the Soviet Union, creating a large reservoir of water called Lake Assad that extends about 100 kilometres upstream to the Turkish border. Like the Atatürk Dam in Turkey, the Tabqa Dam was intended to provide

3.84 A satellite view of southern Turkey and northern Syria in the area of the South-eastern Anatolia Project (after Google Earth).

3.86 In contrast with irrigated areas in Turkey's GAP, irrigated fields in Syria are considerably drier. This shows irrigated cultivation near Aleppo, Syria.

3.88 Agricultural cultivation near Aleppo, Syria.

hydroelectricity and water for irrigation, but during the mid-1970s when the dam's lake should have been filling, Turkey **reduced the cross-border flow** of the Euphrates to little more than a trickle. The Tabqa Dam has never reached its full potential, partly because the flow of water from Turkey has been less than expected, and in recent years because the dam has been under the control of anti-government rebel militia groups.

Cross-border tension has escalated in recent years as the northern areas of Syria near the Turkish border have been occupied by Islamic State and other anti-government rebel groups. For this reason, and because of military actions in the region by Kurdish guerrillas in the PKK, the dams and other infrastructure in GAP have a high level of

3.87 A closer view of the area in figure 3.84, showing the extent of irrigation near the border of Turkey and Syria (after Google Earth).

security, including anti-aircraft defences. The Turkish Government has blamed the PKK for damaging several dams and canals, and for killing some engineers.

The **lack of formal agreements** between Turkey and Syria has made the tensions over water somewhat difficult to resolve. Turkey and Syria signed an **agreement** about water allocations in 1987 in which Turkey agreed to allow a minimum flow of 500 cubic metres per second of water across the border into Syria through the Euphrates River in return for Syrian help in fighting Kurdish rebels within Turkey. However, when the Atatürk Dam was completed in 1990, Turkey announced that it would fine-tune this agreement by guaranteeing a cross-border flow equivalent to half the Euphrates' natural seasonal discharge, which may be less than 500 cubic metres per second. Consequently, flows of water across the border from Turkey into Syria quickly fell to a lower level than the 1987 agreement specified. Syria and Iraq claimed that the minimum flow should be at least 700 cubic metres per second, but **political instability** in both Syria and Iraq has weakened their bargaining position in trying to pursue their claim, so the Turkish stance has remained in practice.

Most water is released from the Atatürk Dam each **winter** (December and January) because that is when the demand for hydroelectric power is greatest in Turkey. Therefore, most water flows across the border into Syria at that time, in contrast to the Euphrates' **natural peak flow** during April and May as the snows melt in the mountains of the river's headwaters. This places a challenge to the Syrians as they have to catch the peak flow in winter in Lake Assad to avoid water shortages at the times when farmers need most water for irrigation (August and September). The challenge for Syria is that the hot, dry climate of northern Syria results in large losses of water from Lake Assad through **evaporation** before the farmers are ready to use the water for irrigation.

Another problem for Syria is that significant quantities of water flowing across the border from Turkey are agricultural runoff from irrigated farms in Turkey. About 20% of water used for irrigation in GAP makes its way back into irrigation canals or infiltrates downwards into aquifers, making its way back into the Euphrates. The **water quality** of this runoff is degraded as it is polluted by agricultural chemicals, fertilisers, salinity, hydrocarbons and animal wastes. The problem of poor water quality is even more significant for Iraq which receives water containing agricultural runoff from both Turkey and Syria.

3.89 Wastes in a watercourse in Harran, Turkey. Rubbish such as this, together with invisible dissolved pollutants, are washed into the Euphrates River, degrading water quality for downstream users.

International tensions over water use in the Euphrates River have been ongoing for about half a century, and show no signs of calming. From time to time, tensions escalate and diplomats speculate that armed conflict could begin. On two occasions, in 1975 and 1998, war between Syria and Turkey was avoided only after intervention by international mediators. The tensions seem to arise because of poor communication, differing approaches towards water use and unilateral actions taken by all the countries at different times.

The tensions are unlikely to be resolved without meaningful **negotiations** between Turkey, Syria and Iraq, but political instability in the region make such talks unlikely in the foreseeable future. Turkey is in the strongest **bargaining position** because it already controls the upstream water, it has the most extensive program of water use (GAP), and it is the most economically developed and politically powerful country in the Euphrates drainage basin. Turkey would have the most to lose in negotiations, whereas the weaker countries (Syria, and especially Iraq) have the most to gain.

A significant cause of conflict is the different **perspectives** of the key **stakeholders** (the riparian countries). Iraq and Syria see the Euphrates River as an **international watercourse**, which means it should be managed as an integrated entity by all riparian users. On the other hand, Turkey sees the Euphrates River as a **trans-boundary stream**, which means the river is under Turkey's exclusive sovereignty until it flows across the border into Syria. Turkey's position was made clear at the opening of the Atatürk Dam in 1992, when the then-President Suleyman Demirel stated: *"Neither Syria or Iraq can lay claim to Turkey's rivers any more than Ankara* (Turkey's capital city) *could claim their oil. This is a matter of sovereignty. We have a right to do anything we like. The water resources are Turkey's, the oil resources are theirs. We don't say we share their oil resources and they cannot say they share our water resources"*.

Turkey's view on water rights is the reason it is the only country in the Euphrates basin to vote against the **United Nations Convention on the Law of Non-navigational Uses of International Watercourses**. Turkey argues that if it signed the Convention, the law would give Syria and Iraq the right to **veto** Turkey's development plans. Consequently, Turkey has insisted that the Convention does not apply to its situation and it is therefore not legally binding.

On the other hand, Syria and Iraq have portrayed Turkey's construction of the Atatürk Dam as a **hostile** and **aggressive** act because it deprives them of water they need for economic development, and indeed, perhaps survival in the face of growing populations with food and energy needs.

It seems likely that conflict over sharing the Euphrates River's water will continue in the foreseeable future as **demand** continues to exceed the available **supply** of water, and diplomatic processes are hampered by the **imbalance of power** and **political stability** between the riparian countries. The situation is further complicated because any discussions that have taken place in the past have focussed exclusively on **water quantity**, whereas poor **water quality** is a significant and growing issue, especially in Syria and Iraq.

3.90 Spray irrigation on fields near Aleppo, Syria.

3.91 A distribution canal near Harran, Turkey, leaks water through the joint between concrete sections. Water losses are significant due to leaks, seepage and evaporation.

Question Bank 3I

1. *Locate the Euphrates River basin, and describe its characteristics.*
2. *Define the term 'riparian'.*
3. *Describe the South-eastern Anatolia Project (GAP).*
4. *Compare and contrast the development of water infrastructure in southern Turkey and northern Syria.*
5. *What are the benefits and the problems that GAP has brought to Turkey?*
6. *Why is there disagreement between Turkey and Syria over sharing water resources?*
7. *Explain the reasons why Syria receives water from Turkey at a time of the year when it is least useful, and describe the consequences of this timing for Syria.*
8. *What are the consequences when different stakeholders view water resources as an 'international watercourse' as opposed to a 'trans-boundary stream'? Which stakeholders hold these different views?*
9. *What needs to be done if the different stakeholders in the Euphrates River basin are to find a resolution to their conflict?*

Chapter 4 Water management futures

4.1 Children and women obtain water from a shared well in the middle of their village in Songo, Mali.

Improving water management

Most of the world's poorer people do not have access to an adequate **supply of safe water**. In fact many of the world's major health problems would be more quickly relieved by a safe water supply than by the provision of medicines, trained medical workers and well-supplied hospitals. Care in the use of such an essential resource is clearly needed. This places great responsibility on local communities to manage water **efficiently** and **sustainably** to ensure a supply of clean, safe and affordable water.

The problem of **water supply** is the result of many interacting factors. Water is an example of a natural resource that is **distributed** very **unevenly** across the world. Rainfall and surface runoff are abundant and reliable in some places, while they are almost non-existent in others. In most places where large populations have grown, the water supply is adequate; indeed, sustained population growth is impossible otherwise. In most places, an adequate supply of water comes from local rainfall, but in arid areas, water is more likely to come as runoff brought by rivers from other wetter areas. Egypt is an extreme example of this, where the desert can support a large population only because of reliable flow in the Nile River.

In almost every inhabited part of the world, the **retention** and **distribution** of water consumes vast resources. This varies from the individual effort and time needed to dig wells and carry water to homes in semi-arid rural communities, to the building of massive dams and canal/pipeline systems to ensure water is available to cities of millions and even tens of millions of people.

4.2 Millions of people around the world have no access to piped water, which means water must be carried from rivers or wells to people's homes, often over long distances. In this photo, water is being carried into the village of Sanga, Mali.

4.3 This roadside well was built by the local community to provide water for the population in and around Kouré village, Niger.

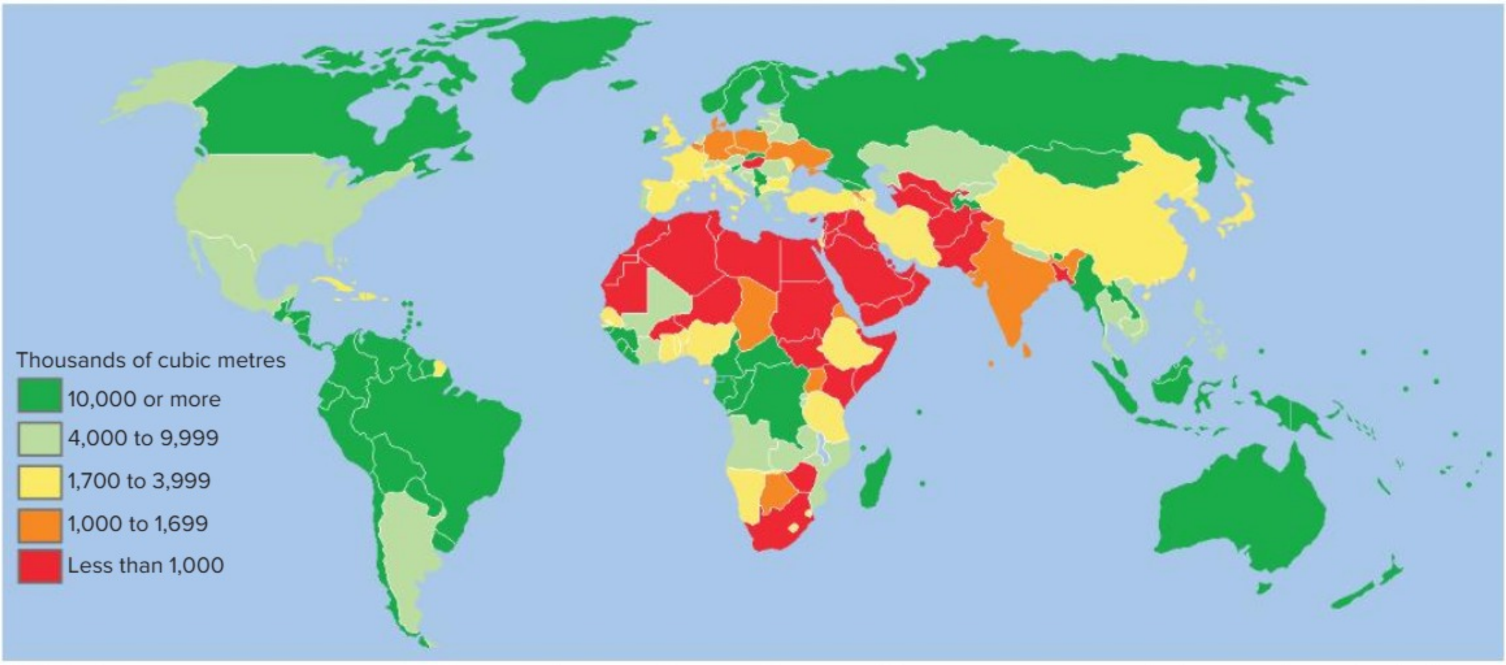
The daily task of collecting water consumes an enormous amount of time for hundreds of millions of people in the world's poorer countries. An offer was made by international development agencies to Myanmar in the late 1990s to replace hundreds of village wells and reservoirs with piped water. However, the offer was turned down on the basis that collecting the water is traditionally women's work, and the men wanted their wives kept busy

4.4 Girls obtain water from a shared well near Ifaty, Madagascar.

collecting water. They argued that while the women were collecting water they could not get into mischief and have illicit relationships while they (the husbands) are away during the day working. In the view of the Myanmar decision-makers, it was worth the peace-of-mind it gave to forego the piped water.

4.5 Many villages in Myanmar do not have access to potable water because there is no piped infrastructure and local pools of water are heavily polluted, such as in this view of Dala village.

Figure 4.6 shows the very **uneven distribution** of the availability of freshwater around the world. About 97.5% of the world's water is saline, which is unusable for human or animal consumption, or for crops. Of the 2.5% of the world's water that is freshwater, 99% is **inaccessible** or difficult to access because it is held in ice caps, snowfields and glaciers. This makes the world's accessible freshwater — just 0.007% of the world's total quantity of water — a very valuable **resource** that supports the world's population, providing moisture for life, for generating energy, and for many industrial and biological processes.



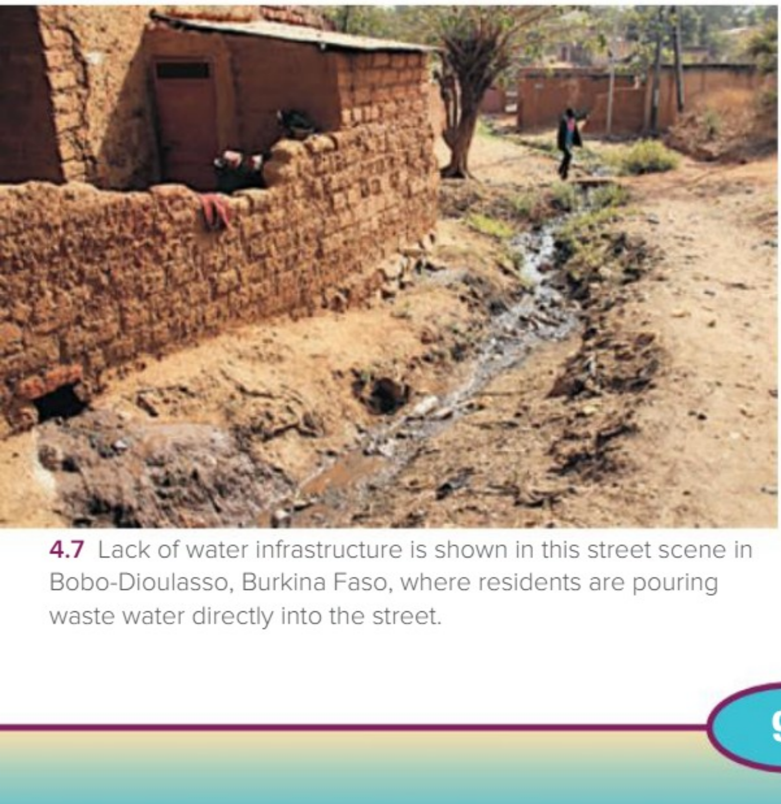
4.6 Freshwater resources per capita. This map shows each country's renewable water resources, including river flows, divided by the number of people in the country.

Over the past 100 years, water use by people has grown at double rate of population increase, placing greater **pressures** on managing scarce water resources. Much of the responsibility for managing water resources falls to **local communities**.

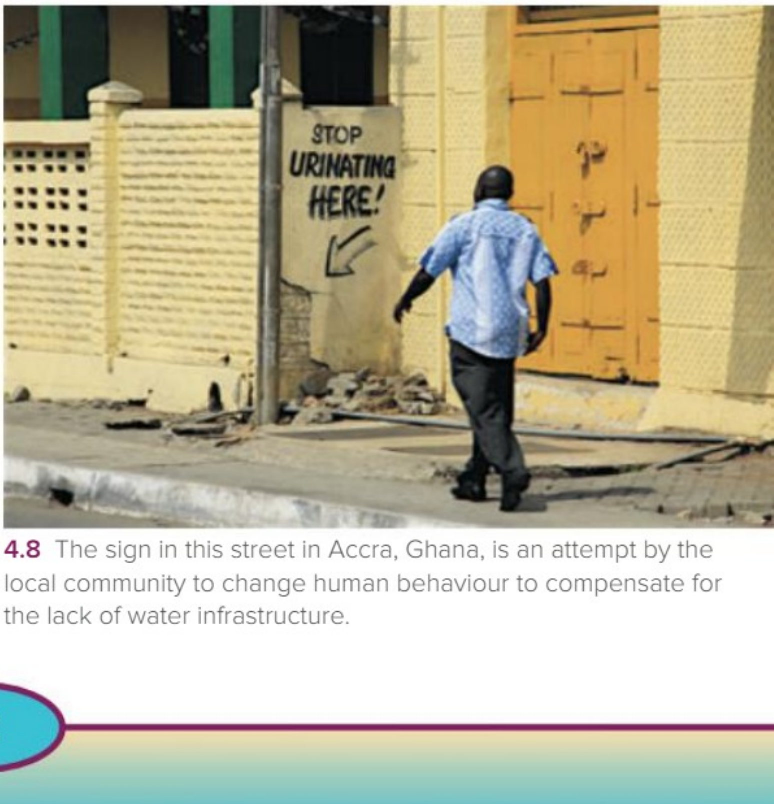
As defined by Davey, Emery and Milne, a **community** is "not just a place: it is the common ground on which people join to meet needs and satisfy wants through activities with other people. In an community, each person feels he or she belongs and has an important part to play".

A local community functions at the **local scale,** which refers to the area that is familiar to individual people, such as a neighbourhood, where a person is likely to recognise a significant number of people even if their names are not known.

The **issues** facing local communities as they seek to manage water differ in various places because of the degree of water scarcity or excess, the culture (including religion) of the people, and the economic health of the society. **Poorer societies** often lack infrastructure such as drainage, sewage treatment facilities and water purification plants. In order to compensate for the lack of infrastructure, water management in such societies relies on changing individual or group behaviours. On the other hand, **technology** in **wealthier societies** can be used to overcome poor water management



4.7 Lack of water infrastructure is shown in this street scene in Bobo-Dioulasso, Burkina Faso, where residents are pouring waste water directly into the street.



4.8 The sign in this street in Accra, Ghana, is an attempt by the local community to change human behaviour to compensate for the lack of water infrastructure.

4.9 In stark contrast with the scenes in the previous two photos, the large industrial facility in this photo is the Newtown Creek Wastewater Treatment Plant in Brooklyn, New York, USA. Its eight 42 metre high 'digester eggs' make it the largest sewage treatment facility operated by the New York City Department of Environmental Protection.

practices such as using excess quantities of water, flushing chemicals into the sewerage system or using excessive amounts of detergents or cleansers.

Most of the worldwide efforts to manage water have focussed on first-time water use, and much more work must be done on how to **re-use** and **recycle** water.

Industry and modern urban lifestyles both **waste** a high proportion of water that is supplied through expensive reticulation schemes. Furthermore, most homes have the capacity to **collect** about 50% of the fresh water used every day if rainfall run-off were retained. However, many local government authorities still have **regulations** prohibiting tanks, even though there is growing encouragement for people to use tank water for watering gardens to reduce use of the treated, reticulated supply.

4.10 A sign encouraging tourists in Zimbabwe to conserve water.

In wealthier countries, it is still only dedicated environmentalists who use the special valves that are available to re-direct **grey water** (used water from baths, clothes and dish washing) to a second use such as garden watering, car washing and flushing toilets. Challenges include the inconvenience of making regular decisions about when to activate the valve, where to store the grey water until it can be used, what organisms will be in the water (and whether they will cause a problem), and whether gravitational flow will be sufficient for transport to the area of re-use. In most countries, the **cost of water** is generally too low to act as an incentive for recycling.

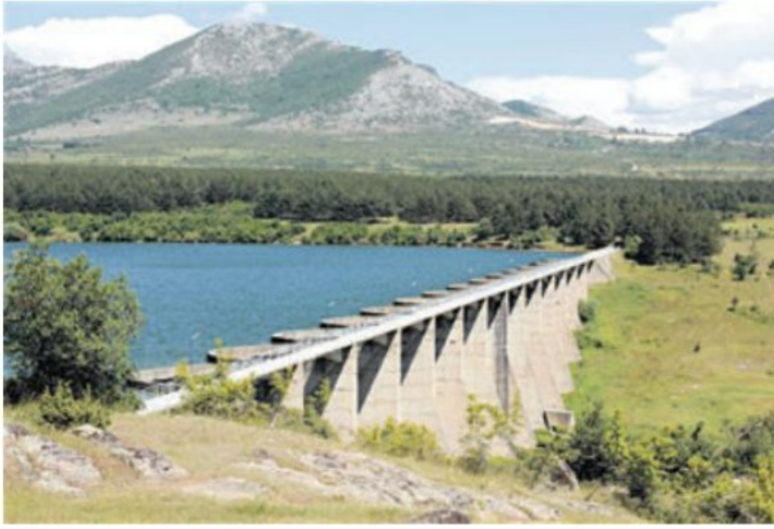
4.11 Women in the local community of San Pedro Las Huertas in Guatemala work together to manage water effectively by washing clothes in a large covered 'pila' (collective water tank).

The **technology** exists to purify water that has been used for almost any purpose. However, the cost can seem prohibitive if fresh water supplies are abundant. Overall, water scarcity is increasing, so people everywhere are going to have to become better at preventing water from being polluted in the first place and then more ready to pay for the treatment that will allow it to be re-used.

Question Bank 4A

1. *Describe the world pattern of the distribution of freshwater per capita.*
2. *Why is it important for local communities to improve their water management if they wish to have clean, safe and affordable water?*
3. *How does water management differ in countries at different levels of economic development?*

Dams for multi-purpose water schemes


4.13 Prilep Lake in Macedonia, which is an artificial lake on the Orevoechka River that was formed in 1967 when a dam was built, is a small multi-purpose water scheme. The water is used for irrigating downstream farms, supplying potable water to the nearby city of Prilep, and for recreational purposes such as boating, picnicking and walking.

Artificial surface storage of water for human use is usually achieved by building **dams**. The **reservoirs**, or artificial lakes, that form behind the dam walls range in size from small farm dams that may store less than 100 m^3 to the very large dams that supply urban and irrigation complexes. At the extreme end of large dams is the **Three Gorges Dam** on China's Yangtze River, which was designed to create a reservoir about 660 kilometres long with an average width of 1.1 kilometres and a capacity of 39.3 billion cubic metres (or cubic kilometres) of water.

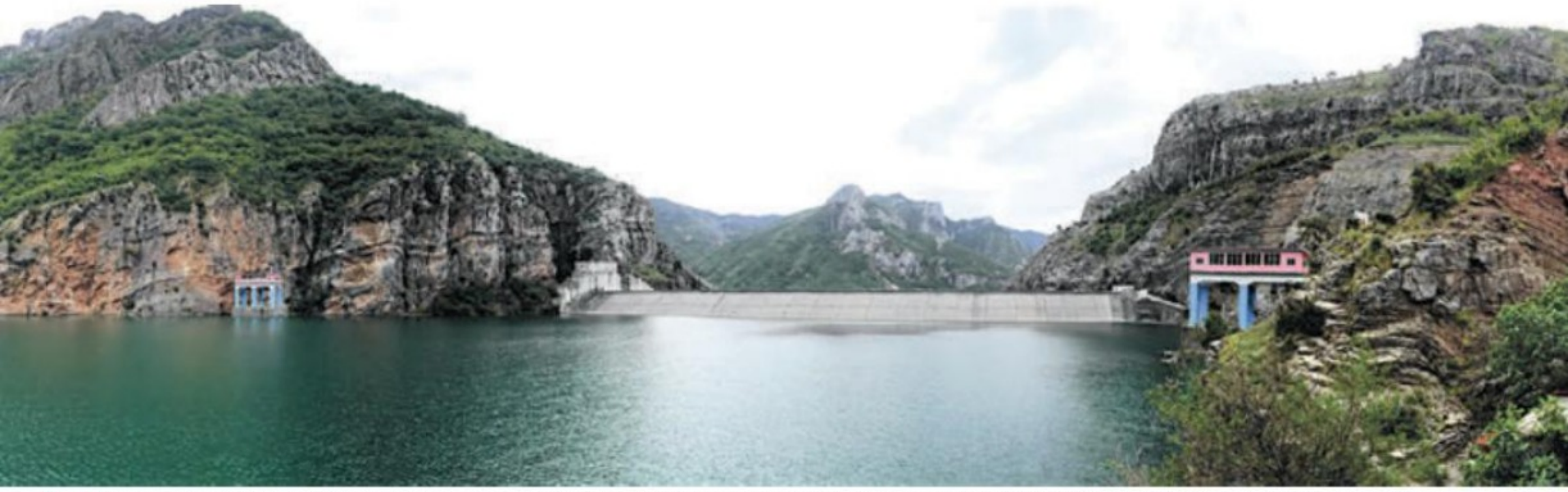
Large multi-purpose dams are designed to serve several **functions**, such as some or all of the following:

- irrigation;
- hydro-electric power generation;
- control of floods by controlling discharge;
- domestic and industrial water supply;
- transport of people and freight; and
- recreational water uses.

Large dams and multi-purpose dams have become increasingly **controversial** over recent years because significant unintended problems often emerge along with the planned benefits. Debates arise as to whether the benefits outweigh the problems or not.

Among the **benefits** that dams bring are:

- The water and power provided may encourage **economic development** through increased agricultural and other economic activity;
- Hydroelectricity is a relatively **clean** form of energy;
- **Water supplies** become more secure and reliable;
- **Food production** can increase with the expansion of **irrigation**;
- Local **employment** is generated, especially during the construction phase, but also after completion to a lesser extent;
- Downstream **flooding** is reduced;
- The reservoir of water provides insurance against **droughts**;


4.12 The Koman Dam on the Drin River in northern Albania is primarily a dam for generating hydro-electricity. Secondary uses include recreation and transport by boats and ferries.

4.14 Water skiiing is an example of recreational boating on Lake Havasu, the reservoir behind the Parker Dam on the Colorado River, USA.

4.16 The reservoir behind Canning Dam near Perth, Western Australia, has a surface area of just five square kilometres, but this leads to an increase of evaporation in the warm, dry climate.

- Reservoirs are often used for **recreation**, such as boating and fishing, thus attracting **tourism**;
- Commercial **fishing** is often possible;
- Large bodies of water usually have a moderating effect on **climate**;
- Regulated flows may **reduce flood risks** and improve the quality and availability of water;
- Downstream **scouring**, or erosion, may be beneficial in streams used for navigation;
- **Wildlife** attracted to reservoirs may improve the ecological balance as well as attractiveness of the area.

On the other hand, the **environmental problems** that can be caused by increased dam building include:

- Reservoirs usually **increase evaporation losses** in the local area. Large surfaces of water that are exposed to the wind and sun lose more water than bare ground surfaces.
- Reservoirs **increase the groundwater stores**. No reservoir bed is entirely sealed from water seepage. The great depth of water in a large reservoir creates a head which forces water down into the underlying soil and rock. The groundwater may reappear downstream of the dam wall or may lead to the development of springs in areas that are quite distant from the dam. The actual losses and routes that the groundwater takes are dependent on the geology of the area in which the reservoir is located.
- Reservoirs **reduce the volumes** of water moving through the downstream channels. Reduced frequency of **flooding** and **discharge** are typical results. Some rivers have been dammed to the extent that they only flow during exceptionally wet years or because legal requirements demand

4.15 Wildlife has been attracted by the waters of Lake Nasser, the reservoir behind the Aswan High Dam in Egypt.

4.17 The Parker Dam on the Colorado River, USA, was built to provide irrigation water and hydroelectricity.

that certain volumes of water be released downstream. A good example of this is the Colorado River, where US dams have markedly reduced the flow of water to Mexico.

- Reservoirs can increase the frequency and severity of **earthquakes** if they are built in areas with unstable geology and many fault lines. Earthquakes can be triggered when the increased weight of water on the surface causes downward pressure on sensitive seismic faults in the underlying rocks.
- Reservoirs have several effects on **water quality**, **water flow** and **sediment transport**. First, there are the effects **within the reservoir** itself:
  - Increased water may encourage the **growth of weeds** and water-borne plants, some of which are noxious, such as water hyacinth and alligator weed.
  - Large bodies of water can **deteriorate chemically** as plant and animal debris decays within them. Extreme deterioration results in all the oxygen in the water being used up, a condition which produces stagnant pools that only support anaerobic life forms.
  - Water-borne **diseases** or diseases carried by organisms that favour water may be introduced. Mosquitoes that carry malaria and snails that carry schistosomiasis (bilharzia) have been introduced into many tropical lakes as a result of dam construction, such as in Lake Kariba, Lake Nasser and Lake Volta.

4.18 Phreatophytes on the Colorado River. Phreatophytes are plants with deep root systems that draw their water from the water table. They have expanded in the Colorado River basin as dam construction has released cold water and lowered the water table downstream, conditions that favour phreatophytes more than competitors. The phreatophytes use large quantities of water, reducing the river's flow downstream to Mexico.

- Second, there are the effects **downstream of the reservoir**:
  - The water released from deep reservoirs is extremely cold, and the **cold water** can disrupt sensitive ecosystems in the river downstream from the dam.
  - Reduced flow may cause the death of riverbank and floodplain **vegetation**.
  - Lowered frequency of flooding reduces the **flushing effect** of floods and therefore water quality may deteriorate.
  - **Fish** that migrate upstream for breeding are prevented from doing so by the dam wall unless separate channels are provided.
  - Sediment loads decline because sediment is trapped in the reservoir. **Erosion** of the bed and banks by **scouring** may result because the stream below the reservoir has a sediment load deficit, and therefore great capacity to erode.
  - **Lowered nutrient content** of the downstream water (because nutrients are trapped in the reservoir) may cause deterioration of aquatic life.
  - **Groundwater tables** downstream from the dam may fall because less water is available for recharge.

4.19 These ancient monuments would have been flooded by the construction of the Aswan High Dam, shown in the background. However, this and other monuments were saved by relocating them stone by stone at great expense by UNESCO.

In addition to environmental problems, increasing dam construction can also lead to **socio-economic problems** such as:

- **Historical** or **archeological sites** may be inundated;

- People are forced to **relocate** as their homes, settlements and farmland are flooded by the waters of the new reservoir;
- As sediments become trapped behind the dam wall, they build up over time, **reducing the capacity** of the reservoir.
- Farmlands that maintained their **fertility** by regular coverings of silt during floods become less fertile after the flooding ceases.
- In areas where water-borne diseases are a problem, such as in the tropics, expansion of reservoirs can lead to the spread of **diseases**;
- The rising waters of the reservoirs may flood **wildlife habitats**.

Question Bank 4B

1. *What are the potential benefits of building dams for multi-purpose water schemes?*
2. *What are the significant environmental problems of building dams for multi-purpose water schemes?*
3. *What are the significant socio-economic problems of building dams for multi-purpose water schemes?*

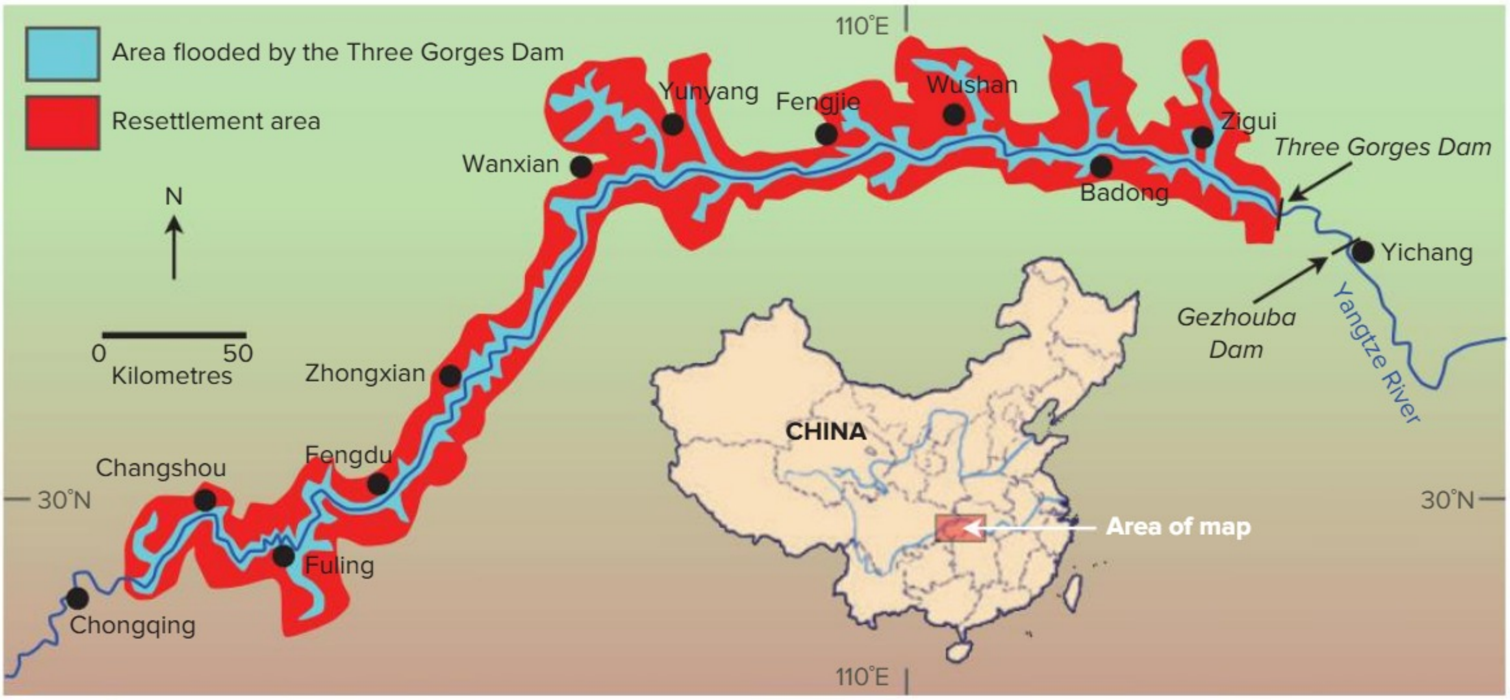
CASE STUDY
The Three Gorges Project

In April 1992, the Chinese Government announced that it would begin construction of the world's biggest water management project in the Yangtze River basin, the Three Gorges Project.

The **Yangtze River**, also known as the Chang Jiang, or 'Long River', flows thousands of kilometres from the mountains of Tibet through the Sichuan Basin, past the megalopolis of Chongqing, and into the East China Sea near Shanghai. As the river flows east from the Sichuan Basin, it cuts through a steep range of mountains in enormous, V-shaped valleys known as the **Three Gorges**.

4.21 Freight transport on the waters of the Yangtze River near the Three Gorges Dam.

The **source** of the Yangtze River is located at the edge of the river basin in the snow-capped mountains of Tibet. Each spring, some of the snows melt and the level of the Yangtze rises greatly. In its natural state, the Yangtze River flooded every year, often with the loss of many lives and much of southern China's grain crops. For several decades, the Chinese Government looked to the Three



4.20 Map of the Three Gorges Project.

Gorges area as a possible site to build a multi-purpose dam to achieve **three main purposes**: to control the annual flooding, to generate hydroelectricity and to increase the shipping capacity of the Yangtze River, which functions as a major transport artery through central China.

Construction of the Three Gorges Dam began in December 1994 just upstream from the city of Yichang, and it was sufficiently completed to allow operations to begin in 2003. The **scale** of the dam was huge — a dam wall 2.3 kilometres wide and 181 metres high holding a reservoir 650 kilometres long with 39.3 cubic kilometres of water collected from a catchment area of one million square kilometres. When first planned, the dam was expected to provide 10% of China's power needs, but as China's electricity consumption has increased, the dam is meeting a little less than 2% of China's power needs at present.

4.22 Some of the locks that allow passenger and freight vessels to pass through the Three Gorges Dam are shown in this view, looking downstream. The main dam wall is to the right of this photo. The town in the background is Sandouping, built specifically to service the Three Gorges Dam.

The **benefits** that the water scheme brought came at some cost. The **economic cost** of the project was $US28 billion, one-third of which was the cost of having to relocate about 1.3 million people, re-build large parts of several towns, and relocate (or lose) a number of archaeological, historic and cultural sites.

Geographers have raised significant concerns about the likely impact of the Three Gorges Project. Table 4.1 summarises the likely **environmental impacts** of the Three Gorges Project on the Yangtze drainage basin, split into categories depending on which part of the environment is affected.

4.23 The red wood temple of Shibaozhai was built in the mid-1700s. This shows Shibaozhai before the Three Gorges Dam was built, built on the side of a rocky outcrop beside the Yangtze River.

4.24 Now that the Three Gorges Dam has been built, Shibaozhai sits on an island formed by the rising waters of the reservoir.

Table 4.1

Environmental Impacts of the Three Gorges Project

Environment/system	Impact of the Three Gorges Project	Desirable or Undesirable	Intended or Unintended
Economic environment	The pattern of electricity use in China is changing, with more energy becoming available in poorer inland areas.		
	The Yangtze River is a major transport route for China; the dam is making shipping safer but slower.		
Demographic environment	Population in central China is increasing because more employment has been generated.		
	More than one million people had to be resettled to avoid the rising waters of the new reservoir.		
Social environment	Re-housing over a million people has led to some social problems as families who had never left their villages have been relocated.		
	Some important cultural monuments, temples and landmarks were lost under the waters of the new reservoir, while others needed expensive measures to preserve them.		
Political environment	The provinces near the dam are becoming wealthier, but those away from the dam have suffered a shortfall of funds because the dam cost so much to build.		
	The dam has made China more vulnerable to military attack because the country has become so dependent on one single source of energy.		
Hydrological environment	The dam traps sediment that the river used to transport downstream. Over time, the reservoir behind the dam will fill with sediment.		
	The annual spring 'flush' of water in the river is now held by the dam, reducing the flood hazard.		
Landforms environment	The likelihood of earthquakes rises as the mass of stored water places stress on the rocks beneath it. The area has many faultlines and is earthquake-prone.		
	Water released from the dam carries no sediment, and is therefore eroding the river bed and banks downstream from the dam, leading to scouring.		
Biotic environment	Many habitats for fauna have been drowned, threatening wildlife such as the freshwater dolphin, Siberian crane, sturgeons, giant salamanders and alligators.		
	Deforestation of the slopes is slowing down as farmers who used to cut down the trees have been resettled to new areas.		
Atmospheric environment	Increased evaporation from the new reservoir is increasing rainfall in nearby hills.		
	There is a reduction in greenhouse gases and air pollution as hydroelectricity replaces electricity generated in coal-fired power stations.		
	The new reservoir moderates temperatures, so temperatures are rising in winter but cooling in summer.		

These cells are designed for use in responding to a task in Question Bank 4C.

4.25 The main wall of the Three Gorges Dam, showing the spillway in the centre of the wall and four of the hydro-electric plants, two on each side of the spillway.

QUESTION BANK 4C

1. *Where is the Three Gorges Dam and reservoir? Give as specific location as possible, referring to latitude, longitude, and situation in relation to surrounding cities.*
2. *Describe the terrain where the Three Gorges Project was built.*
3. *Describe the scale (size) of the Three Gorges Project.*
4. *The environmental impacts of the Three Gorges Project have been listed in Table 4.1. These impacts have been split into categories according to the part of the environment that has been affected. For each of the effects mentioned, decide whether the impact is desirable or undesirable, and write "D" or "U" accordingly. Similarly, decide whether the effect described was intended or unintended, and write "I" or "U" accordingly.*
5. *In your opinion, is the Three Gorges Project a successful use of that section of the Yangtze River drainage basin? Give reasons and factual data to support your opinion.*
6. *Undertake research to investigate whether any additional impacts of the Three Gorges project, positive and negative, have emerged since the dam's construction.*

Integrated drainage basin management

The environment of a drainage basin is highly **inter-related** and **inter-dependent**. In other words, a change in any one of the elements of the drainage basin, such as the slopes, river, soils, vegetation, lakes, aquifers or groundwater, is likely to lead to consequent impacts on one or more of the other elements. Therefore, it makes sense to manage drainage basins as a single integrated unit.

This approach is becoming more common in many parts of the world under the label '**integrated drainage basin management**' (IDBM). **IDBM** is sometimes referred to by the alternative label IRBM (integrated river basin management) and the related concept of IWRM (integrated water resources management), which extends the IDBM methodology beyond a single drainage basin.

A leading advocate of IDBM is the **Global Water Partnership** (GWP), an international advisory body based in Sweden with over 3,000 partner organisations in 182 countries. Founded in 1996 with the specific purpose of advancing the use of IDBM planning, GWP's partner organisations

4.26 Effective management of drainage basins involves analysing the relationships between all the individual elements in a holistic manner. This view shows canals for irrigation and flood control in a farming area on the outskirts of Langar, Tajikistan. The Panj River in the background separates Tajikistan from the hills of Afghanistan in the background.

include a variety of organisations involved in water resources management, including government authorities, various United Nations agencies, international development banks, professional associations, academic and research institutions, non-government organisations (NGOs), and private companies.

In the words of the GWP, IDBM is "*the process of co-ordinating conservation, management and development of water, land and related resources across sectors within a given river basin, in order to maximise the economic and social benefits derived from water resources in an equitable manner while preserving and, where necessary, restoring freshwater ecosystems*".

IDBM plans are usually co-ordinated by government or semi-government authorities, drawing upon the expertise and financial resources of organisations such as water distribution companies, advocacy groups such as farmers and conservationists, university academics, planners and water user groups. In 2010, the GWP adopted **five principles** of IDBM to guide drainage basin managers across the world:

- **Multiple uses:** Water is a resource for drinking and washing but is also necessary for livelihoods.
- **Holistic management:** Both the supply of and the demand for water should be considered when creating management strategies.
- **Multiple perspectives:** Water is an economic, social and environmental necessity.

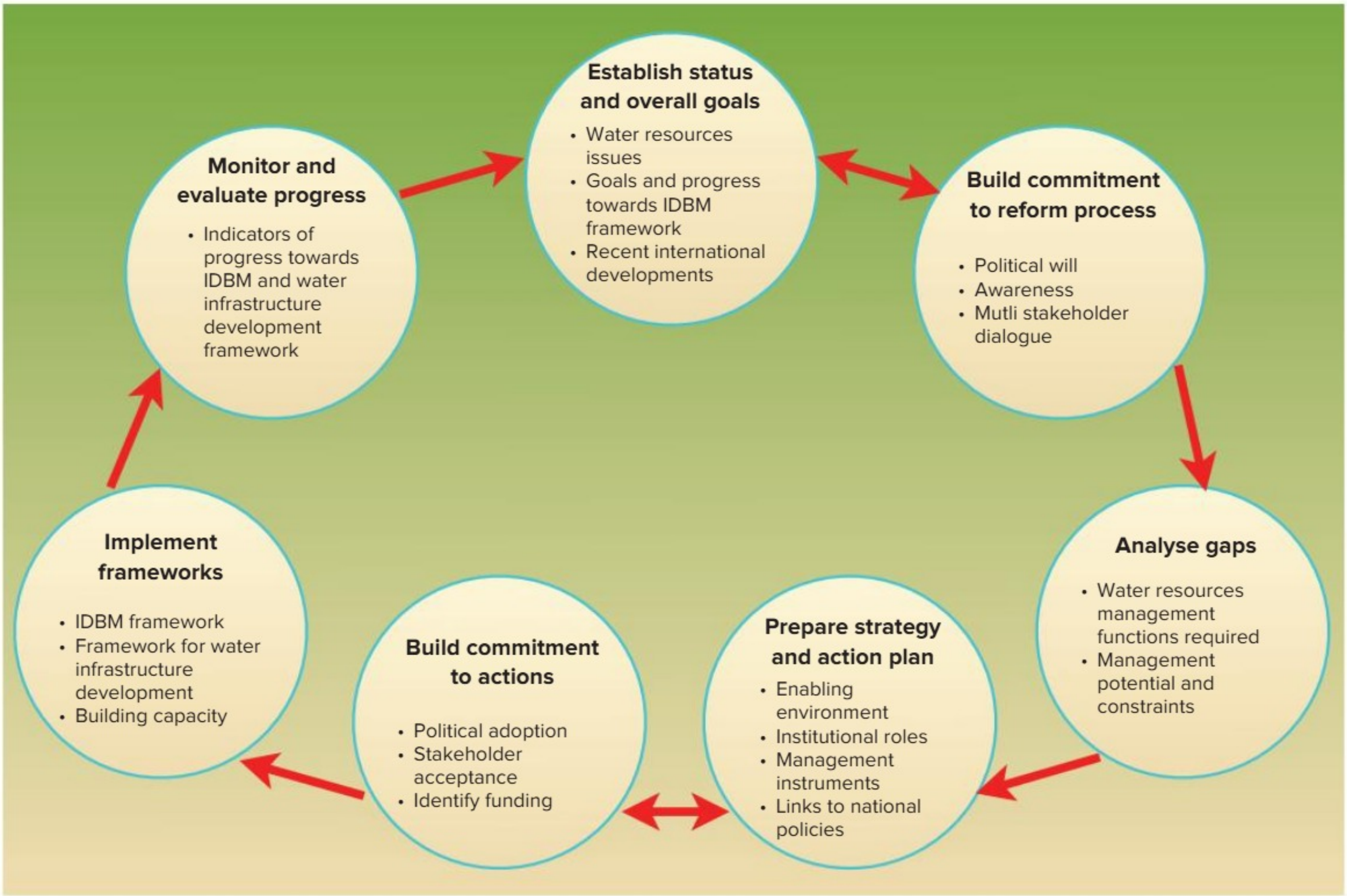
4.27 A young woman carries a large bowl of water for domestic use to her home in Abomey, Benin.

4.29 Integrated drainage basin management can be difficult in poorer countries where the needs are great but the finances are small. This view shows residents using the Niger River for washing in Mopti, Mali.

- **Participatory approach:** Local communities must help make decisions about their resources.
- **Women's involvement:** The role of women in collecting, distributing and managing water must be recognised.

The implementation of IDBM should be an ongoing process that adapts and changes as the drainage basin evolves. IDBM aims to transform water use that is unsustainable into sustainable management, using a **planning model** such as figure 4.28.

In order to implement effective IDBM, **all the elements** of the drainage basin — land, river, groundwater, lakes, people and economic activities — need to be considered. This involves understanding the draining basin's **natural**



4.28 The Integrated Drainage Basin Management (IDBM) planning cycle (after Global Water Partnership).

4.30 This sign is painted on the gutter beside a streetside stormwater drain in San Francisco, USA. Many such signs have been placed beside drains in the city, reminding residents that pouring wastes or toxic materials adds them to the drainage basin's water.

processes, and also the consequences of **human actions** such as wastewater disposal and the potential for recycling. In order the develop an IDBM plan, the cost of **alternative strategies** needs to be considered, including options such as the polluter pays, the user pays, and various forms of cost subsidies for people with specific needs. An IDBM plan should also ensure that everyone has **access** to good quality water irrespective of ability to pay, gender or ethnicity.

It is difficult to compare the **benefits** of IDBM compared with the **costs** in a particular drainage basin because many of the benefits cannot be quantified, unlike the costs which are more easily calculated. The great strength of the IDBM approach is that all the inter-related elements of the drainage basin are considered **holistically**, and changes in one element are understood in terms of consequences for the rest of the drainage basin.

The **costs** of IDBMs vary according to the individual drainage basin, but typical **challenges** for effective integrated drainage basin management include:

- **insufficient funding** to meet the needs;
- **conflict** between stakeholders diverting attention away from the common good;
- **lack of data** in areas such as stream discharge, climatic statistics and flood history;
- **lack of authority** among those responsible for implementing the IDBM plan; and
- **excessive focus** on financial costs and benefits, thus **neglecting social needs**.

In 2015, a team of researchers conducted a ground-breaking study on behalf of the European Commission, investigating the costs and benefits of IDBM in the **Werra River Basin** of central Germany. The IDBM plan for the Werra River basin had attempted to achieve three goals:

- improve the basin **morphology** (shape) and **stream flow** within the basin;
- **reduce agro-chemical flows** from farms into the river; and
- **reduce stream pollution** by improving treatment of waste water.

4.31 A branch of the Werra River at Bad Sooden-Allendorf, Germany.

Expenditures for the project were made for engineering works, farm improvements, and work on waste water treatment facilities. The **benefits** of the project were found in greater biodiversity, improved recreational facilities and better water quality as agricultural wastes were held in buffer strips alongside the river. The team concluded that the **benefit-to-cost ratio** for the IDBM plan was between 1:4.1 and 1:5.0, meaning that for every euro spent, there was a benefit of between €4.10 and €5.00.

Question Bank 4D

1. *What is meant by the term integrated drainage basin management?*
2. *What is the role of the Global Water Partnership in supporting IDBM plans around the world?*
3. *With reference to figure 4.28, outline the process of IDBM planning.*

4. *Explain why each of the GWM's five principles to guide drainage basin managers is important for achieving effective IDBM.*
5. *What are the benefits of the IDBM approach to planning drainage basins?*
6. *What are the likely problems of implementing an IDBM plan?*

CASE STUDY
The Broadland Rivers Catchment Plan

The **Broadlands River Catchment** is the area that supplies water to the Broads in eastern England. It has a **population** of 850,000 people, plus **tourist visitors** numbering about 7.5 million annually. The main **industries** are tourism, farming and food processing. The largest of these industries is **tourism**, which brings over $US600 million into the area each year and supports over 6,000 jobs. The main forms of tourism are boating, fishing, walking and bird watching.


4.33 Arable (wheat) farming beside Ranworth Broad. European Community policies have encouraged Broads farmers to replace cattle grazing with grain cultivation.

4.32 The Broadland Rivers Catchment Drainage Basin.

Farming supports an additional 8,500 jobs and occupies about 80% of the land in the Broadland Rivers Catchment. The main types of farming are arable agriculture, such as wheat growing, and grazing meadows for sheep and horses. Both farming and tourism make extensive use of the area's water resources.

A **broad** is a term used in eastern England for a large, shallow sheet of fresh water. Broads, which are a form of **wetlands**, are found in the eastern English counties of Norfolk and Suffolk, forming an area in East Anglia between the towns of Norwich and Great Yarmouth which is also known as **Broadland**. More precisely, the Broads are located in an area centred at latitude 52°40′N, 1°20′E. The area is dominated by three larger rivers that converge and flow into the sea at Great Yarmouth, thus making **one drainage basin**. These rivers are the Bure, the Yare and the Waveney, which in turn have smaller tributaries including the Thurne, the Chet, the Wensum and the Ant.

4.34 Reeds beside the River Bure.

Each of the broads has quite a different **character**. They vary in size from the large Hickling Broad, which is about 140 hectares, down to small relict pools with areas of 0.25 hectares of less. Most of the broads are very shallow, and none has an average depth of more than four metres; most are shallower than this. The rivers that join the broads are quite wide and flow slowly, and they are made salty by sea water in their lower reaches as they are tidal. For most of their length, the broads and the rivers are lined by marsh and swamp vegetation such as reeds and water plants.

The Broadland area is very well known in Britain and other parts of Europe for its natural beauty, as the lakes are joined by some 200 kilometres of rivers and canals which are well suited to recreational boating, fishing and other water activities. Thus, the Broads are a major area of **tourism** in Britain.

4.35 Many towns in the Broads depend on tourism for their livelihood, especially in summer. This hotel beside the River Bure in Horning is a typical example.

4.36 Guesthouses for tourists beside Malthouse Broad.

The waters of the Broads are in demand for a wide range of **competing uses**, so to manage the area's water resources, an **IDBM plan** was adopted in 2014. The Plan was developed by the **Broads Catchment Partnership**, a representative group of organisations that was brought together by the Broads Authority and the Norfolk Rivers Trust for the purpose of developing the IDBM plan. Among the participating organisations are Anglian water, the Environment Agency, the Water Management Alliance, The Rivers Trust, Farm Conservation Limited, the Norfolk Wildlife Trust, the Royal

Society for the Protection of Birds, the National Farmers Union, and the University of East Anglia.

Before examining the Integrated Drainage Basin Management Plan in detail, we need to understand the distinctive environment of the Broads and the **pressures** it faces.

The natural systems background to the Broads

The Broads environment is a combination of individual **inter-related natural systems**. The main natural systems are the climate, the soils and geology, the relative levels of the land and water, and the vegetation.

Today's Broads have **evolved** over a period of 2000 years. During that time, the **climate** has changed several times, although there has always been a marked contrast between cold dry winters on one hand, and warm dry summers on the other. The average daily maximum **temperature** for the year is 14˚C, ranging from 6˚C in January to 22˚C in July. The average daily minimum temperature for the year is 6˚C , ranging from 1˚C in January to 12˚C in July. The average monthly temperature (average of maximum and minimum) for the year is 10˚C.

The average annual **rainfall** is between 600mm and 700mm. As rain falls on about 50% of days, and the relatively cool climate means there is little evaporation, the area seems much more damp than one might expect where the average rainfall is so low. Rain is distributed quite evenly throughout the year.

The **soils** of the area have formed from a thick layer of chalk, the type of rock found beneath the whole of East Anglia. However, in most parts of Broadland, the chalk is quite deep beneath the surface, and it is covered by deep layers of shell-sands deposited in marshes between 300,000 and two million years ago. In places, the sands are quite deep, being up to 40 metres in places. These in turn are covered in many parts of Broadland by more recent deposits of sand and gravel that were deposited by melting ice. These were deposited towards the end of the last ice age, which ended only 11,500 years ago. Most of the surface soils have formed from these newest sands and gravels. These produce quite rich soils that are well suited to agriculture.

In the lower areas, where the marshes and swamps called fens were found, the soils were somewhat different. In those areas, the soils were quite young and were formed as a result of changes in the relative levels of the sea and land. At the end of the last ice age, sea levels were lower than today because much more of the world's water was trapped in glaciers and larger polar ice caps. In England, the bottoms of valley floors were up to 30 metres lower than today, and the rivers in the valleys flowed more quickly than they do today.

As temperatures increased after the ice age, the ice caps and the glaciers melted, causing a rise in sea levels. As this happened, the rivers flowed more sluggishly, allowing swamps (the fens) to form in the valley floors. Over time, this change in vegetation allowed deposits of **peat** to form as the decaying swamp vegetation built upwards, layer upon layer. However, sea levels continued to rise for a long time after the end of the ice age because of the 'lag' effect, causing siltation at the mouths of the rivers where they entered the sea. This had the effect of slowing the flow of the rivers even more than previously.

Most of Broadland is a very **flat** area that lies at or slightly below high tide level; the highest elevation in the Broadland Rivers Catchment is around 100 metres above sea level. The area is separated from the sea only by a long ridge of sand dunes lining the coast. As the sea rose relative to the land, there were occasions when the sea broke through the coastal dunes, **flooding** the lower areas of land and forming shallow lakes – the broads. Particularly serious floods have occurred in this way, with major floods in 1608, 1617, 1622, 1717, 1718, 1720,

4.37 A gauge to measure water height in Cockshoot Broad.

1770 and 1791. In 1806, the coastal dunes were strengthened, preventing major floods until the land subsided still further. This had happened by the beginning of the 20th century, and severe floods occurred again in 1912, 1938 and 1953.

Human occupancy of the Broads

Human occupancy of Broadland has continued for many centuries, and during this time there has been a great variety of impacts on the Broads ecosystem. Traditional economic activities have included farming and sedge-cutting (cutting the reeds for roof thatching), and these continue today, but compete with newer activities such as recreational walking and boating. Over the years, these impacts have taken many forms, and have become more and more intense up to the present day.

4.38 A canal fills an old peat excavation pit that now joins Cockshoot Broad to the River Bure.

The Broads in the English counties of Norfolk and Suffolk were formed by a **combination** of human and natural factors. During the Middle Ages, peat was dug for use as a household fuel. Peat is highly organic soil, largely consisting of decaying vegetation, and mining of peat in eastern England began in about 1100. In the late 1400s England's climate became wetter, and at about the same time the land sank relative to sea level. These effects combined to flood many of the old peat-mining sites, and they became the shallow broads. This is why we can say that the broads are both a natural and a human landform. There are 48 broads together with 200 kilometres of lock-free, navigable waterways.

In the centuries that followed, the broads became the basis of peasant life in eastern England.

4.39 A windpump drains swampy land beside the River Bure.

Channels were built to join broads together for transport, marsh hay was cut, eels and fish were trapped and birds were snared or shot for food. Over time, the pressures on the broads from various human uses have increased. From the late 1700s onwards, some of the broads and their adjoining swamps (the fens or carrs) were **drained** to expand agriculture for the growing population. Another intention of draining the fens was to try and remove breeding grounds for mosquitoes. During the twentieth century, there was also pressure to use the broads for disposal of sewage and for tourism, especially recreational boating.

Changes in the water chemistry

The broads are fresh water lakes fed by the rivers flowing into the area. The **chemical composition** of each broad depends on the water that flows into it. These chemical flows determine the type and quality of the ecosystem. The presence of **phosphorus** is especially important because phosphorus is a scarce chemical that is nonetheless necessary for algae and other plant growth.

Algae are simple water-borne plants, some of which are microscopically small. A typical clear mountain lake would contain about 5μg (micrograms) of phosphorus per litre, while a natural lowland lake would contain about 10 to 30μg. Before 1800, the broads fitted this typical lowland pattern, with between 10 and 20μg of phosphorus per litre. The water was clear, and there was little growth of algae, although there were low-growing water plants on the bottoms of the broads. These provided breeding grounds for fish and other animals such as crustacea. **Reed swamps** grew around the edges of the broads, and these were essential for fish breeding and feeding.

An important new phase of human impact began around 1800 when draining of the broads by **wind pumps** began. The aim was to lower the water table and so create 'dry land' suitable for arable crop production. Although the draining succeeded in its aim of providing extra farmland, it led to some environmental side effects. Peat forms only in swampy, saturated conditions. Therefore, the loss of flooded areas meant that the area of **peat production shrank**. Banks had to be built to prevent the new farmlands being flooded. These banks stopped the movement of fish and wildlife between the rivers and swamps, thus restricting the habitat of the fish. However, the most important impact of these changes was in the **chemical balance** of the broads, and especially in the quantities of phosphorus and nitrogen present.

4.40 A canal that once joined Cockshoot Broad to the River Bure is now blocked, preventing the movement of fish.

4.41 The brown turbid water of Malthouse Broad prevents light penetrating to the bottom of the water, causing the elimination of aquatic plants and allowing intrusive weeds to take over.

When the new farmlands were created, much of the swamp vegetation at the edges of the broads was **destroyed**. The phosphorus and nitrogen stored in these plants was then **released** into the rivers. This led to an increase in phosphorus levels to about 80μg/litre over a very short period of time. The vast addition of **extra nutrients** such as these into a stream or body of water is called **eutrophication**. Problems occur when eutrophication leads to greatly increased growth of algae in the water.

In the broads, eutrophication led to strong growth of algae at the surface, which prevented light from reaching the lower parts of the water. Because of the shading of the deeper water by the algae, the low water plants on the bottom surface could no longer survive, and they were replaced by tall **water weeds**. The amount of weed increased greatly as this trend continued over time. By the 1940s weed growth had become so profuse that many thought that the broads would be choked by the weeds. However, they provided a very good environment for fish breeding, and the area became a resort area for fishing.

Eutrophication only occurred to a fairly minor extent from changes in agriculture. Until the 1800s, **sewage** was disposed of in the district by septic tanks. Sewage contains up to 1,000 times more phosphorus than any water draining from natural lands. When septic tanks were used, a little effluent percolated down to the groundwater, but the broads themselves were not affected. In the mid to late 1800s, sewerage systems were introduced. The effluent was treated and then dumped into the rivers of the broads. Sewage inputs have built up since that time, resulting in major additions of phosphorus to the broads. Today, some twenty sewage outlets discharge into the catchment rivers.

4.42 Ducks add phosphorus to the River Bure at Cockshoot Broad, leading to algal blooms and a loss of habitats for species dependent on clean river water.

The typical levels of **phosphorus** today are between 150 to 300μg/litre, although levels of up to 2000μg/litre have been recorded. The levels are highest in those broads that are downstream from centres of population and connected to the rivers. On the other hand, isolated broads such as Upton Broad and Martham Broad have phosphorus levels that are only 5% of those in the 'connected' broads such as South Walsham Broad, Ranworth Broad and Barton Broad.

Levels of this magnitude produce serious changes in the balance of the ecosystem. Very large crops of **algae** have grown, eliminating other water plants from many areas. A consequence of this growth of algae was the loss of breeding and feeding grounds for **fish**, and none of the broads now has its pre-1800 ecosystem. All the broads have new communities of both flora and fauna. The growth of algae has also resulted in visual pollution, in that natural clear water has been replaced by turbid green or brown water. There has been a consequent decline in **recreational fishing**.

Effects of bank erosion

The effects of agriculture and sewage have been further aggravated by the increased use of the broads for **boating**. Recreational boating began in the broads in the late 1890s, first with sailing boats plus a few steamboats. By 1920 there were 165 hire boats, of which only four were motor cruisers. Since the Second World War, the number of boats has increased enormously, with greater use of motorboats, privately-owned launches and hire cruisers.

4.43 A traditional steamboat on the River Bure.

By 1949 there were 547 hire boats, of which 301 were motor cruisers; by 1979, these figures had increased to 2257 hire boats, of which 2,150 were motor cruisers. The figures have declined a little since then, and currently there are about 2,000 hire boats available in the Broads, plus another 6,000 private licensed boats and holiday facilities for almost 250,000 people.

The increase in boating has resulted in greatly increased **erosion** of riverbanks. The wash from pleasure boats (particularly power boats) **undercuts** the riverbanks, which in turn release **sediment** into

4.44 Typical motor boats on a canal connecting Malthouse Broad with the River Bure.

4.45 Speed limits have been imposed on many waterways in the Broads to minimise erosion from the wash of boats.

the streams. This problem has been aggravated by the loss of waterweeds, which would have dampened wave energy from the wash of the boats.

At times, eroded banks have had to be **protected** by pilings. It has been estimated that maintenance of these floodwalls in the broads costs tens of thousands of pounds each year.

The boats stir up the bottom **sediments** now that the bottom grasses have gone, leading to a steady movement of sediments downstream. Many of the broads are filling at a rate of over a centimetre per year, and with depths already less than a metre, will be full in less than a century. Sedimentation rates are now reported to be between ten and a hundred times the pre-1800 levels.

Persistent siltation and eutrophication of the broads has led to a **loss of habitats** for many species. Large-scale destruction of broadleaf plants such as

4.46 Protective defence has been built on the bank of the River Bure where bank erosion has occurred.

4.47 An area of bank re-stablisation has been established in an attempt to restore the damage from erosion by boat wake.

4.48 Boats pose a threat to the natural ecosystem of the Broads by carrying unwanted pests.

water lily, water soldier and hornwort has occurred. These plants provide the habitat for many small creatures such as snails and beetles and also provide the source of food for many larvae. Thus,

4.49 Water lilies, seen here on the River Bure, are an important part of the ecosystem as birds feed on them. As the water lilies have declined, birds are feeding on reed shoots, leading to a decline in reed banks.

4.50 Refuges have been built in several parts of the Broads where loss of habitat has occurred, forming zones where water plants can become established, protected from the wash of boats. Birds and fish are attracted to these refuges to breed. This example is in Ranworth Broad.

the first steps in many food chains have been removed from parts of the broads, leading to reduced numbers of fauna higher in the chain.

All the losses of **reed-banks** cannot be attributed to boating activities. The reeds seem to pass through cycles of growth and decline, and a naturally occurring decline might coincide in time with an expansion of boating activities. Another possible reason for the decline in reed-banks could be that birds which once fed on broadleaf plants such as water lilies (which are now being replaced by weeds) have now switched their feeding to the reed shoots to survive. This may be causing greatly increased demands on the reed species.

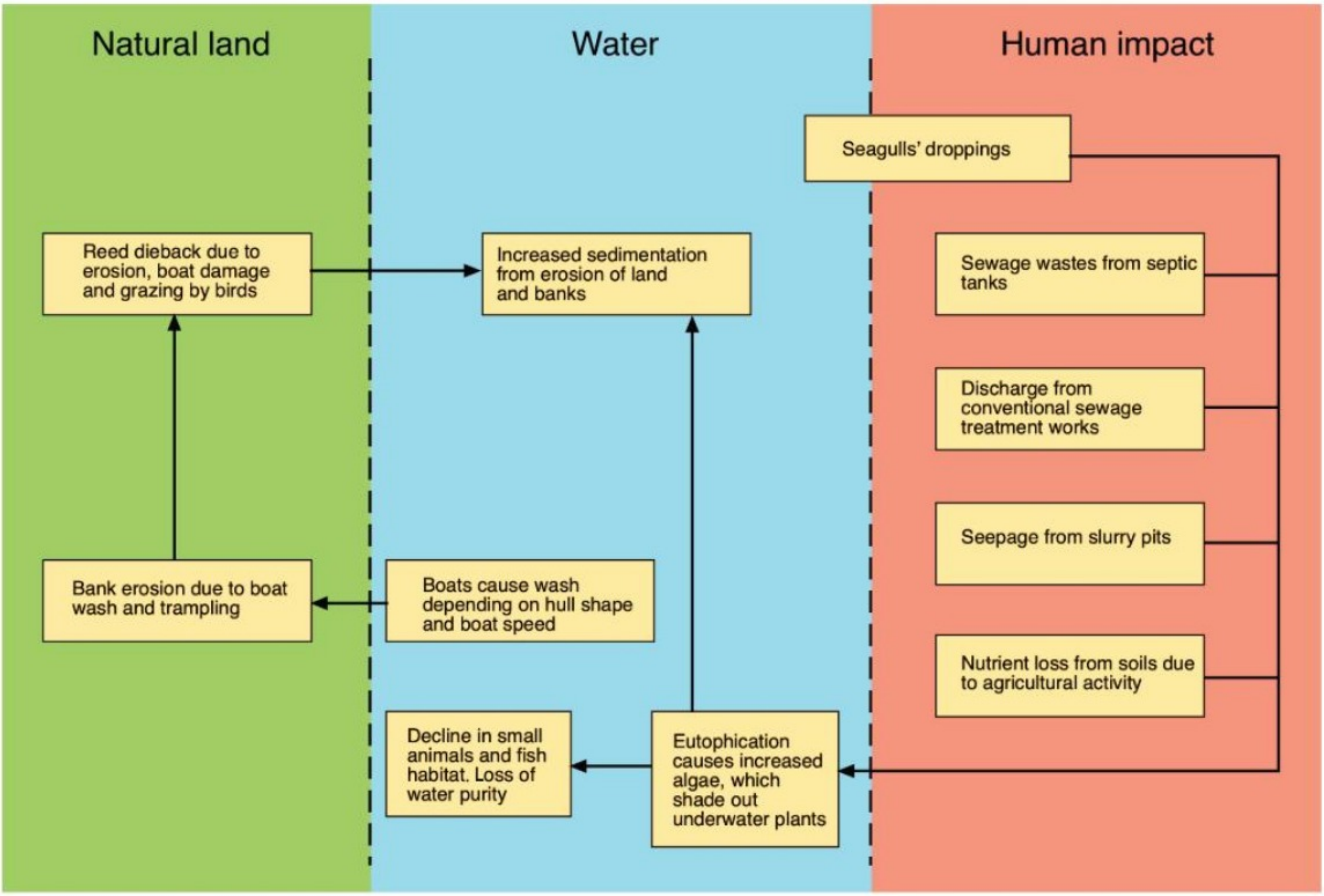
4.51 Reeds are becoming re-established on the banks of the River Thurne near Martham Broad.

Agriculture has accelerated these trends. Trampling by cattle causes the sides of bank to collapse, increasing siltation and leading to the decline of plant species that provided the habitat for dragonflies and some species of butterflies, which are now endangered in the broads. Some species of birds (such as the heron and some breeds of ducks) whose feeding and breeding depend on the same habitats are also threatened. Thus, the complex structure of the Broads environment means factors that once affected just one or two natural systems now have widespread impact throughout the natural systems of the area.

Planning on the Broads

For many years, solving the environmental problems of the Broads was very difficult because control rested with many **different organisations**. For most of its history, overall land-use planning was done by two county councils and six district councils. At the same time, water management was controlled by two authorities, one controlling boating (including registration and speed limits), and the other looking after water supply, water quality, sewage treatment, recreation, fisheries and land drainage.

To overcome the problem of unco-ordinated control, it was recommended in 1947 that the Broads become a national park. The proposal was rejected on the basis that the area was already developed too intensively for this to be possible. In 1970 another study committee developed a management plan for the region, and this provided the basis for independent decisions made by all



4.52 Impacts on the environment of the Broadland Rivers Catchment drainage basin.

authorities that had jurisdiction over the Broads until the 2014 Plan was released.

In the mid-1970s, there was a second attempt to have the Broads declared a national park. The controlling bodies could not agree to all that this involved, and the proposal again failed. Nonetheless, in 1978 the **Broads Authority** was formed to supervise overall control of the area. The Broads Authority was just an advisory body, consisting of representatives of local councils, water commissions and some other government authorities. Nonetheless, it was active in studying the environmental problems of the region, particularly the effects of motor boats.

4.53 One of the challenges of IDBM planning in the Broads is working out ways that boat use can be made environmentally sustainable. This marina is at Horning on the River Bure.

The Broads Authority was **re-constituted** in 1989 with much greater powers, including control over navigation of boating. In effect, an area of 287 square kilometres began to be governed similarly to a national park by the Broads Authority, which had three main tasks:

- conserving and enhancing the **natural beauty** of the broads;
- promoting the **enjoyment** of the Broads by the public; and
- protecting the interests of **navigation**.

The 2014 IDBM Plan

The 2014 **Broadland Rivers Catchment Plan** aimed to address the environmental challenges in several

key areas, these being water quality, water quantity, wildlife habitats and recreation. Consultations during the development of the Plan revealed **eight significant problems** that the Plan should address:

- More than 90% of the rivers in the catchment **failed to meet the targets** of the European Water Framework Directive for reasons such as physical modifications, water quantity, high levels of phosphate, dissolved oxygen and fish populations.
- At times, some groundwater and river sources exceed **drinking water standards** for nitrate and pesticides, resulting in the need for expensive treatment, which generates greenhouse gas emissions as well as increased water bills.
- Some **habitats**, especially those for aquatic species and wetland wildlife, need to be protected because they support internationally important bird life species or rare and diverse wildlife; however the habitats do not meet European Habitats Directive standards because they have excessive nutrient and sediment loads.

4.54 Protection of wildlife habitats is a key issue that the Broadland Rivers Catchment Plan seeks to address.

- Some landowners are losing valuable **topsoil**, nutrient and pesticides due to erosion, run-off or leaching, sometimes linked to soil structure and compaction.
- **Water levels** in some areas are too high for agriculture or too low for wildlife and amenity, while recent droughts resulted in a lack of available water for agriculture, wildlife and public garden use.
- Heavy rainfall running off rural and urban areas causes **surface flow** and **river flooding** in specific locations. Tidal surges continue to threaten lives, property, farmland, fish populations and important freshwater wildlife habitats.
- Many local farmers felt that proposed new environmental land management agreements were too **short-term**, with some options lacking the flexibility to suit individual farm circumstances.
- Some local communities felt that their views and knowledge had been **ignored** and that there was a lack of opportunity to experience, learn about, or carry out voluntary action to their local waterways.

4.55 This large shallow-bottomed paddle steamer is one of several boats taking tourists through the waterways of the Broads. The shallow bottoms of the boats mean that few large waves are generated and wildlife habitats are left undisturbed.

- The **goals** of the 2014 Plan flowed from the environmental challenges facing the drainage basin. Specifically, the goals were to improve:
- **Land management** to reduce run-off, and soil, nutrient and pesticide loss, and to link habitats and access;
- **Waste water management** to reduce nutrients in watercourses from public and private waste water;
- **Water management** to increase water capture and water efficiency;
- **Flood risk management** and **sustainable drainage** to reduce and slow run-off and increase aquifer recharge;
- **River** and **floodplain management** to increase connectivity, reduce fish barriers and control invasive species;

Table 4.2
Broadland Rivers Catchment Plan - Goals and Action Plan

Goals	Partnership Action Summary
1. Land management Reduce run-off, and soil, nutrient and pesticide loss, and link habitats and access	1.1 Seek funding for additional independent advisers to provide face-to-face advice and support to land managers and farmers.
	1.2 Through existing advisers and agronomists, make surface water run-off risk maps available to farmers to help locate effective measures and demonstrate this to funders.
	1.3 Hold talks with farmers and their advisers to get their views on effective environmental land management measures and how best to incentivise these.
	1.4 Agree, with all interest groups, suitable key locations for targeting environmental land management measures to provide multiple benefits.
2. Waste water management Reduce nutrients in watercourses from public and private waste water	2.1 Raise awareness of effects of misconnections, washing products, waste disposal and septic tank best practice at community events and on school visits.
	2.2 Explore potential locations for reed beds and constructed wetlands and seek funding for local trials in areas where waterbodies have high phosphorus levels.
3. Water management Increase water capture and water efficiency	3.1 Raise awareness of water efficiency, water capture and water friendly gardening and promote free water saving packs at community events and on school visits.
	3.2 Support the whole farm water management approach by Essex & Suffolk Water in part of the Waveney sub-catchment and promote in other sub-catchments.
4. Flood risk management and sustainable drainage Reduce and slow run-off and increase aquifer recharge	4.1 Agree key areas of high flood incident and upstream run-off risk, including roads, with landowners, communities, flood and highways authorities and drainage boards.
	4.2 Seek funding for demonstration projects for rural drainage in high run-off risk areas in each of the Bure, Wensum, Waveney and Yare sub-catchments in association with local communities.
5. River channel and floodplain management Increase connectivity of river habitats, reduce fish barriers and control invasive species	5.1 Agree potential locations, in non-tidal areas, to reconnect river with floodplain, and seek funding for projects.
	5.2 Scope potential woody debris installation project on the upper River Bure with relevant farmers and landowners.
	5.3 Establish priorities for fish barrier bypass, or removal, and eel projects involving local community action, and seek funding for demonstration schemes.
	5.4 Promote workshops for landowners and encourage co-ordinated invasive species control on rivers, including extending 'Check, Clean, Dry' messages beyond the Broads.
6. Recreation and understanding Increase sustainable use of, and learning about, water and wetlands	6.1 Raise awareness of riparian owner responsibilities, river care, canoe trails and angling opportunities at community events and on school visits.
	6.2 Co-ordinate volunteer catchment walkover surveys of tributaries and compare findings with run-off and habitat models.
	6.3 Populate website and promote information sharing to include mapping, projects, events and activities at a sub-catchment scale.
	6.4 Raise awareness of catchment processes and the water cycle at community events and on school visits.
7. Investment Increase, combine and attract new funding for projects	7.1 Seek funding opportunities around sustainable catchment management and climate change adaptation, with European partners where necessary.

Source: Broadland Rivers Catchment Plan (2014), p.31

- **Recreation** and **understanding** to increase sustainable use of, and learning about, water and wetlands; and
- **Investment** to increase, combine and attract funding for projects.

4.56 Boardwalks have been built over several broads, enabling visitors to get close to the natural environment without disturbing fragile ecosystems.

The **Action Plans** that follow from these goals are shown in table 4.2. More detailed working documents allocate the work to achieve the outcomes of these action plans to specific organisations that participated in developing the IDBM Plan as part of the Broadland Catchment Partnership.

The measure of the **effectiveness** of any IDBM plan is the outcomes achieved. The Broadland Rivers Catchment Plan has set clear, measurable **targets** that by 2027, it is hoped that:

- Rivers and broads would meet the requirements of European legislation and local aspirations;
- Nature conservation areas would achieve national and European guideline standards; and
- No raw water supplies would regularly be at risk of failing drinking water standards.

Question Bank 4E

1. *Describe the characteristics of the Broadland Rivers catchment.*
2. *What are the Broads? Describe their location.*
3. *Describe the different natural systems that combine to form the Broads environment.*
4. *How did the Broads form?*
5. *Describe the human effects on the environment that are displayed in the photographs in this section.*
6. *What is eutrophication? What are its (a) causes, and (b) effects in the Broads?*
7. *List the environmental effects of recreational boating. An effective way to do this may be to draw a flow diagram, so that effects which cause other effects can be linked together.*
8. *What is the Broads Catchment Partnership?*
9. *What are the problems that the Broadland Rivers Catchment Plan is trying to address?*
10. *What are the goals of the Broadland Rivers Catchment Plan?*
11. *In your opinion, does the Broadland Rivers Catchment Plan address the significant issues facing the Broads? Give reasons to justify your answer.*

Pressures on wetlands

Ramsar, and the efforts to protect wetlands

As recently as half a century ago, **freshwater wetlands** were often referred to using derogatory words such as 'swamp'. Looking through the eyes of farmers or land developers, wetlands were seen as wastelands. Worse, they were often seen as breeding grounds for pests such as mosquitoes and therefore drained with the aim of improving people's health and livelihoods.

Today, wetlands are generally seen as a **valuable biotic resource**. Wetlands serve as valuable wildlife habitats, fish breeding grounds and centres of biodiversity.

4.57 An area of wetlands near Mombasa, Kenya.

Wetlands also have increasing economic value as tourist attractions. Indeed, the Okavango Delta (or Okavango Swamp), which is the world's largest inland delta, is Botswana's major tourist attraction. Each year thousands of tourists visit the region to watch wildlife and enjoy the pristine environment. Provided it is conducted responsibly, **recreational use** of wetlands is **non-consumptive**, although it may reduce the availability of water for other users at specific times and places.

Most wetland areas of the world are **sparsely populated**, but some support large numbers of people. For example, the Sepik River in Papua New Guinea is over 1,000 kilometres long, and has a wide floodplain with serpentine (winding and twisting like a snake) meanders and extensive areas of swampland, the largest of which is the Chambri Lakes. The swamplands of the Sepik River supports a population of about 400,000 people, most of whom depend upon the river and its swamps for their livelihood, which is based on fishing, hunting and sago palm cutting.

4.58 Kanganamun, a typical village in the wetlands of the Sepik River, Papua New Guinea.

Another area of wetlands inhabited by large numbers of people is the **Iraqi Marshlands**, also known as the Mesopotamian Marshlands, in south-eastern Iraq. The wetlands are situated around the mouth of the Tigris and Euphrates Rivers, just upstream of Iraq's border where the Tigris and Euphrates Rivers empty into the Persian Gulf.

The Iraqi Marshlands are divided into **three major areas**, the Hawizeh Marshes to the north-east of the Tigris River, the Central Marshes between the Tigris and Euphrates Rivers, and the Hammar Marshes south of the Euphrates River.

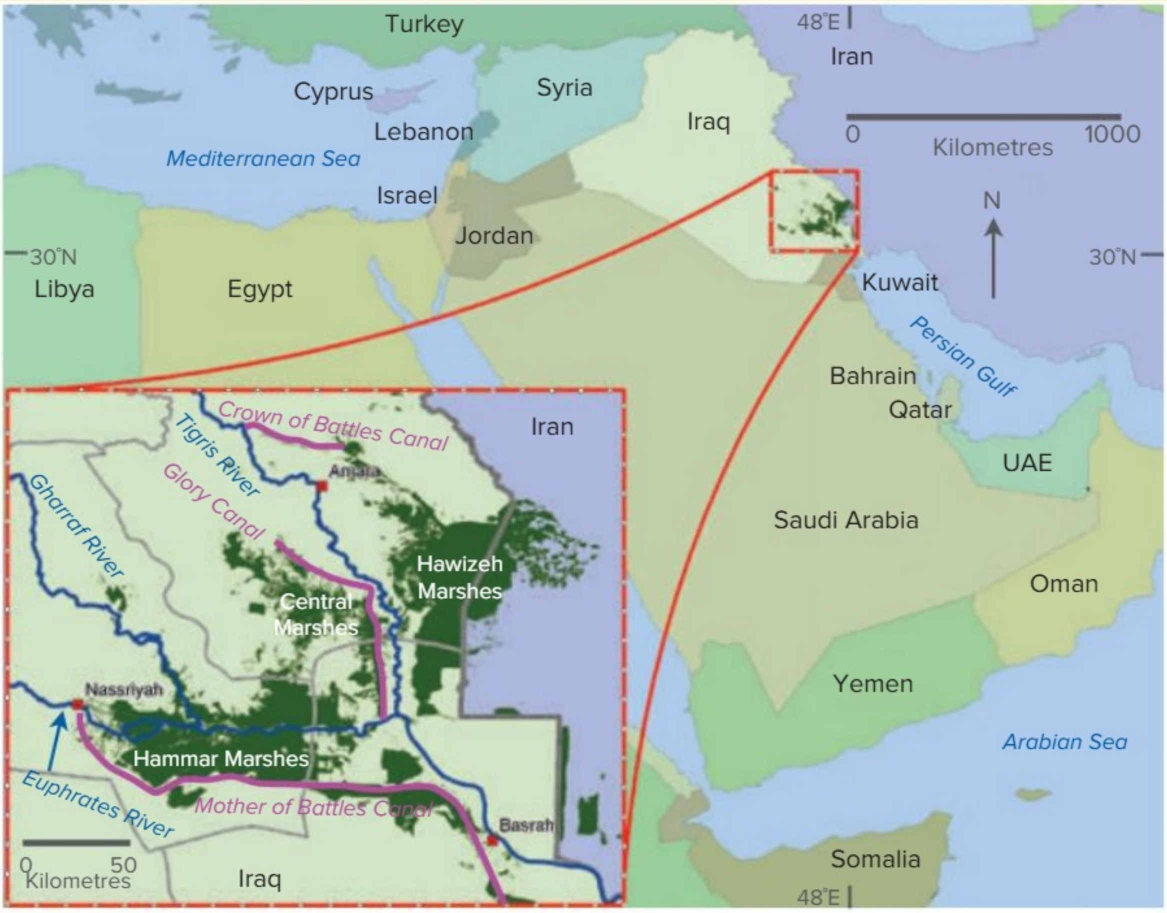
The Iraqi Marshlands are inhabited by descendants of the ancient Sumarians known as the Ma'dan, or Marsh Arabs. They live in villages scattered through the marshes that can only be reached by boat, where they live by fishing and growing rice. In the 1950s, about 500,000 Ma'dan lived in the wetlands, but this number shrank to 300,000 during the regime of Saddam Hussein, who persecuted this ethnic group. Numbers have started to grow again in recent years.

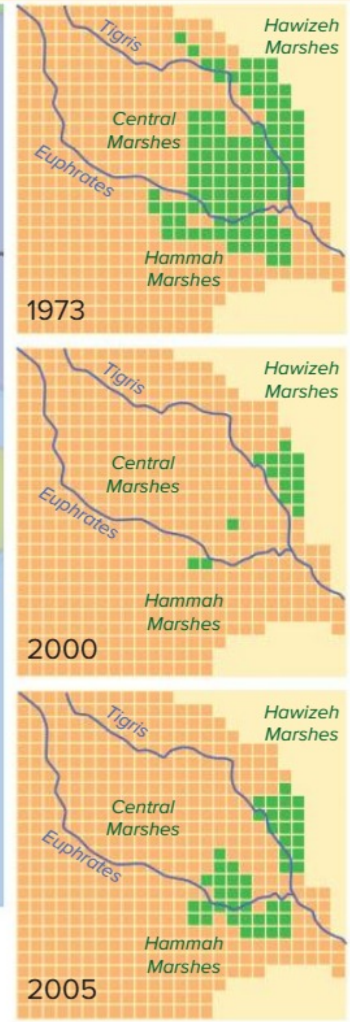
4.59 Ma'dan women in the Iraqi Marshlands.

The area of wetlands in the area was about 20,000 square kilometres until the 1950s when a program of **draining** the swamps began by constructing a network of canals, initially to reclaim land for agriculture, but later to facilitate oil exploration.

During the 1991 intifada (revolution), anti-government rebels from many parts of Iraq found refuge from the government in the wetlands, accommodated by the Marsh Arabs. The Iraqi Army tried to eliminate the rebels from the Marshlands, but when they were unable to do so, the government built hundreds of kilometres of **canals** to divert water away from the wetlands to drain the area. Three large canals, the Crown of Battles Canal, the Mother of Battles Canal and the Glory Canal, had reduced the Iraqi Marshlands to an area of just 760 square kilometres.

By the time of the 2003 invasion, the wetlands had lost 90% of their original area. The Central and Hammar Marshes were almost completely **drained**, and only 35% of the Hawizeh Marshes remained. Following the invasion, local people destroyed many of the canals, and a combined effort by the United Nations, the new Iraqi Government and various US agencies had restored some of the





4.60 The location of the Iraqi Marshlands. The infographic at the right shows the change in the area of wetlands between 1973 and 2005, with each green square representing 85 square kilometres. (Sources: Base map courtesy Keith Holmes, University of Victoria; infographic based on the work of Amr Thameen).

wetlands, helped by high rainfalls upstream in Turkey. By 2006, more than half of the original wetlands had been **restored**.

Today, local people are speaking more optimistically of developing the Iraqi Marshlands into an **ecotourism** zone, hoping to build on the region's supposed location as the original Garden of Eden.

Concerns about the threats to wetlands world-wide resulted in the signing of the **Ramsar Convention** in 1971. Also known as the Convention on Wetlands, the Ramsar Convention is an international treaty to promote the conservation and sustainable use of wetlands. The treaty is named after Ramsar, the city in Iran where the signing was done in 1971.

The Ramsar Convention has been successful in helping to protect wetlands. The Ramsar Convention has now been signed by 169 countries, and representatives of the signatory countries meet every three years for the Conference of the Contracting Parties (COP), which makes policies and monitors the state of wetlands around the world.

The Ramsar Convention operates under '**three pillars**', which are commitments by all member countries to:

- work towards the **wise use** of all their wetlands;
- designate suitable wetlands for the **List of Wetlands of International Importance** (the 'Ramsar List') and ensure their effective management; and
- **co-operate internationally** on transboundary wetlands, shared wetland systems and shared species.

The **Ramsar List** comprises all the wetlands that have been designated by their country as having international significance. When a government decides to include an area of wetlands on the Ramsar List, it commits to take whatever steps are necessary to ensure its **ecological integrity** is preserved, while also ensuring that use of the wetlands is 'wise' and **sustainable**.

By 2016, there were 2,230 Ramsar Sites around the world covering a total area of 2.1 million square kilometres.

QUESTION BANK 4F

1. *Why are wetlands sometimes considered worthless?*
2. *What value do freshwater wetlands have?*
3. *Using the infographic in figure 4.60, calculate the area of wetlands in the Iraqi Marshlands in 1973, 2000 and 2005.*
4. *Explain why the Iraqi Marshlands have shrunk so much in recent decades.*
5. *What is the Ramsar Convention, and why is it such an important effort to protect wetlands?*

CASE STUDY
The Florida Everglades

The **Everglades** is a vast area of low-lying **wetland** in south Florida, USA that forms the lower part of the Kissimmee River basin. It is so flat and low that no part of the Everglades is higher than 2.5 metres above sea level.

The Everglades is recognised as an internationally significant wetlands environment, and thus it is included on the **Ramsar List**. The area is also listed as an **International Biosphere Reserve** and a UNESCO **World Heritage Site**.

The Everglades is a complex **ecosystem**, a term that means a community of plants and animals that depend upon each other, together with the surrounding environment to which they have adapted.

In an ecosystem, disturbing one type of living thing causes a **chain reaction**. This is because every living thing feeds upon another organism, and it in turn is the food for yet more organisms. In the natural Everglades ecosystem, plants and animals were in harmony with each other and with their surroundings before human settlement. This fragile, delicately balanced ecosystem that had developed over 6,000 to 8,000 years has now been disturbed by the competing demands for water by humans.

In the 1940s, the pioneering conservationist Marjory Stoneman Douglas studied the Everglades and called the area a "**River of Grass**". Before the impact of humans, this was an accurate description

4.61 The Everglades 'River of Grass'.

of the Everglades. To understand the impact of people on the Everglades, it is necessary to look at the area as it was before humans arrived.

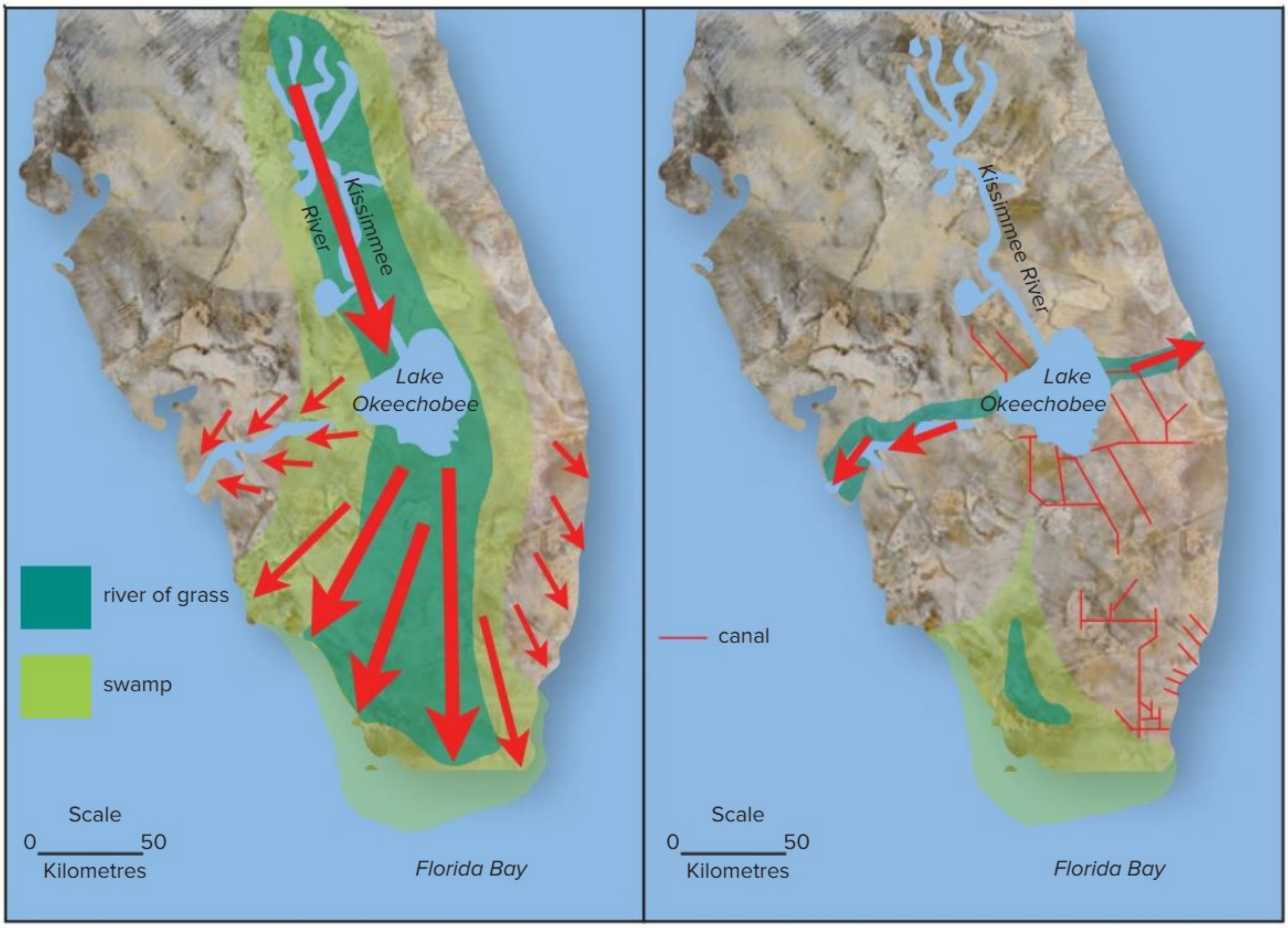
The 'natural' Everglades

The source of all life in the Everglades has always been **water**. South Florida receives quite heavy **rainfall**, between 1,000 and 1,500mm each year on average. About 70% of this rain falls during the warmer months of May to October, and winter is much drier. Before humans changed the Everglades environment, 80% of this rainfall was lost through **evaporation**, **transpiration** and **runoff**. The remaining 20% of the water flowed through the **Kissimmee River** into a large, shallow lake in central Florida called Lake Okeechobee, where the water was stored. This lake was less than four metres deep but covered an area of 1,900 square kilometres.

4.62 A general view of the Everglades 'River of Grass'.

4.64 An oblique aerial view of the Everglades 'River of Grass'.

Each year, when the heavy rains came in summer, Lake Okeechobee would **overflow** and the water would flow slowly southwards across the Everglades in a wide shallow 'river'. This 'river' was about 80 kilometres wide and 160 kilometres long, but only one metre deep in the deepest channel and about 15 centimetres deep elsewhere. This vast river flowed southwards very slowly about 30 metres each day towards the Gulf of Mexico. The speed of flow was very slow because the **gradient** was so flat — only three centimetres fall per kilometre. The water was not deep enough to cover the tall grass, which is why it was labelled the '**river of grass**'.



4.63 The flow of water in southern Florida before human impact (left) and after human impact (right).

During the winter dry season, the 'river of grass' was reduced to a series of swampy **water holes**. The wildlife of the Everglades retreated to these water holes to await the next summer's overland flow. As the water flowed slowly southwards, large quantities of it soaked down into the porous rocks beneath. The rocks beneath the Everglades were a limestone **aquifer** and they acted like a sponge, soaking up the fresh water from the surface. The rocks remained saturated from the surface downwards, even during the dry seasons.

All the plants and animals depended on each other, directly or indirectly, in the natural ecosystem. The main **vegetation** was the tough, long grass called '**saw grass**', named because of the small, sharp teeth along the edges of each blade of grass. Growing in the water around the saw grass was a yellow-brown ooze-like algae called **periphyton**. The periphyton was the first step in the food chain and had several other uses as well. It provided refuge for fish when they were under attack, it sealed moisture in the ground during droughts, it provided a home for minute crustaceans and it actually decomposed to make the soil in which the saw grass grew.


4.65 Saw grass in the Florida Everglades.


4.66 Periphyton, a yellow-brown algae in the Everglades water.

Across the Everglades were some slightly higher **mud islands** called **hammocks**. The hammocks were only a few centimetres higher than the surrounding land. Nonetheless, a very different type of vegetation was found on these islands. On the hammocks, a complex tangle of ground ferns, air plants and tropical hardwoods such as cabbage palms and mahogany trees were found.


4.67 A hammock rises above the flat land of the Everglades.


4.68 A solution hole in a hammock, where the vegetation is quite different from other parts of the Everglades. Solution holes form where limestone rock dissolves, forming a depression that becomes a micro-environment for aquatic plants and animals. They hold water that sustains life for animals during the dry season.

The **animals** and birds of the Everglades were species that had adapted well to the swampy conditions. The Everglades region was infested with **alligators**, probably numbering about two million in 1950. The alligators were at the top of the food chain, and fed on other creatures such as **turtles** and **fish** which in turn fed on **shrimps** and small **aquatic organisms**. The Everglades had huge numbers of **birds** of many species, many of them wading species. In the 1930s there were 265,000 wading birds, in contrast to today's figure of just 18,500. Species of birds included anhingas, ibises, herons and egrets. Other species of **wildlife** in the Everglades included otters, raccoons and tiny deer.

4.69 An alligator in the Everglades.

4.70 A water bird in the Everglades.

4.71 An anhinga, one of the larger birds in the Everglades.

Fire was an important part of the natural Everglades environment. They were common during the dry months, being started by lightning strikes during storms. The fires were useful in clearing away old vegetation and making way for new growth. The burnt grass returned to the soil as nutrient, providing 'fertiliser' for new plants. The saw grass was protected from the fire because its roots and lower stems were covered in water. This meant that only the top part of the saw grass burned and the plant survived.

Human impact on the Everglades

In the early 1900s, more and more people began to move into southern Florida. Although some moved into the large cities like Miami, others came to start farms. The **farmers** wanted to grow vegetables in the warm climate to supply the colder northern states during winter. The Everglades seemed like an ideal area. As well as having a warm climate, its soils were rich and fertile as they were made from the organic periphyton. Large areas of the Everglades were cleared for farming.

The farmers faced one serious problem, and that was the annual **flooding**. In an effort to solve the problem, **drainage canals** were built to carry the water away to the ocean in the east. However, during the 1920s, several **hurricanes** (tropical cyclones) dumped huge amounts of rainfall on the

4.72 Drainage canals on the edge of the Florida Everglades.

4.73 A weir crosses a drainage canal in the Florida Everglades.

4.74 Canals bring water drained from the Everglades into the city of Miami.

Everglades. Even the drainage canals could not cope with the large amount of water, and widespread flooding occurred. A major flood in 1928 killed over 2,000 people. The farmers demanded that better flood control be put into place. In 1930, a long, low dam called the **Herbert Hoover Dyke** was built around the southern edge of Lake Okeechobee. This stopped the flooding, but it also stopped the annual spillage. Discharge in the 'River of Grass' was drastically reduced.

Over the years, the water of south Florida has become more and more **regulated**. This occurred because of the competition for water, especially the amount of water demanded by Florida's residents. Today, Florida's population is growing by an average of 1,000 people per day. As well as its permanent population of over 20 million people, more than 100 million people holiday in Florida each year, of whom about 33 million go during the dry winter months when water is most scarce. This population growth requires that water be provided.

The impact of human water use on the Everglades

To meet the needs of the population, **wells** have been sunk into the porous limestone rocks beneath the Everglades and **groundwater** has been pumped out from the aquifer. However, this has caused major problems.

As the fresh water has been pumped out, **salt water** from the nearby ocean has soaked in to replace it. The underground water is now becoming saline because of human actions. To make matters worse, all the new **construction** of roads and buildings seals off the surface so that water can no longer seep down and replenish the underground water. Drillers must go further down into the rocks to find fresh water, and when they do pump it out they make even more room for useless salt water. Humans cannot drink salt water, plants cannot grow with it and it destroys plumbing and appliances when used in manufacturing.

There is now **little water available** to flow across the Everglades because so much is taken away in canals for use elsewhere. This has caused a **chain reaction** of disruptions to the environment. As a result of the loss of water, the ground has **dried out** in many areas. Consequently, **fires** now cause much more damage than previously. Fires now burn the entire saw grass plant, the roots of which are no longer protected by water. Therefore, when a fire burns through the Everglades, large areas of **saw grass** are killed.

4.75 A gauge measures the water depth in the Everglades.

The drying out of the soil has had other effects. The **soil** of the Everglades is made up almost entirely of pure organic matter — periphyton and decaying saw grass. As the soil is exposed to the air, it **oxidises** and literally disappears — dissolves — into the atmosphere. This is happening at a rate of two to three centimetres per year in areas where the water cover has gone. This is lowering the level of the soil, exposing tree roots and some under-ground pipes and power cables.

Outcries by **conservationists** forced government officials to allow some water to flow across the Everglades once again. However, this has not solved all the environmental problems. Water is released when it is not needed elsewhere by farmers and others. The **timing** of the releases of water might be quite different from the natural cycle upon which the ecosystem is dependent. Alligators build their nests at the high water level when water levels are high. However, if more water is released later, the nests are flooded and the eggs destroyed.

The impact of tourism

In an effort to restore the biophysical environment, the Everglades was declared a **national park** in 1947. However, much of what happens in the National Park is affected by actions outside it. Farmers 'upstream' release **fertilisers** and **pesticides** into the waters that will flow into the Everglades. When water is enriched with nutrients, it affects the growth of plants and the natural pattern of vegetation. High levels of **mercury** have been discovered at all levels of the Everglades food chain — fish in the marshes, raccoons and alligators.

4.76 An electric mini-train brings visitors through the Everglades.

4.77 An elevated boardwalk protects the Everglades ecosystems while allowing visitors access. Information boards educate visitors about the history and workings of the ecosystems.

Declaring the Everglades a national park has had both good and bad effects. On the positive side, **boardwalks** and other **facilities** such as bird watching towers, information boards and wildlife viewing trams have been built. Such facilities enable visitors to see the Everglades while causing little damage to plant and animal life. Another positive effect is that more people are encouraged to visit the Everglades and thus understand their biophysical environment.

Ironically, encouraging visitors is also a negative factor. Although tourists are only allowed to enter some parts of the park in organised groups, some environmental damage cannot be avoided. The Everglades attracts hundreds of thousands of visitors each year. Some of these visitors camp in their mobile homes, while others are day trippers keen to view the wildlife by tram or air boat.

Future possibilities for the Everglades

In his book about human impact on the Florida Everglades, *The Swamp*, the author Michael Grunwald described the Everglades as "too wet to farm, too dry to sail, too unpredictable to settle". In the opinion of many conservationists, the state of the wetlands environment in the Everglades continues to **decline** because of human greed and the perceived need for more and more water, land, money and power.

4.78 The Shark Valley Visitor Centre in the Florida Everglades has a variety of displays to inform visitors about the wetlands environment of the area.

4.79 An information sign at the beginning of the Anhinga Trail educates visitors about aspects of the natural ecosystems and the issues of freshwater use facing the Everglades.

4.80 Facilities have been provided within the Everglades National Park to reduce pollution and wastes that might harm freshwater in the Everglades wetlands.

On the other hand, **conservation measures** such as releasing more water to maintain the 'River of Grass' and removing invasive plant species are helping to restore elements of the natural Everglades ecosystem and reverse some of the developmental excesses of the 1970s.

It could be argued that **protecting** the quality of the Everglades environment is a wide community responsibility and a strategic priority because of the area's international significance. From an **economic perspective**, this is most likely to be achieved through tourism, and especially ecotourism, which has the potential to bring substantial finances into the region. Tourism also has considerable potential to **educate** and inform visitors — the general public — about wetlands and the challenges facing their management.

From an **environmental perspective**, there is an even stronger imperative to preserve the natural environment of the Everglades. Although it is difficult to reverse more than a century of mismanagement and wilful destruction, it will be necessary to ensure the survival of many types of wildlife and to improve the quality of water available to Florida's rapidly growing population.

Question Bank 4G

1. *The Everglades environment comprises many individual parts. Show the individual parts of the environment on a diagram to show how they link together.*
2. *We say that the parts of the Everglades environment are interdependent. What do we mean when we use this word?*
3. *Why could the Everglades ecosystem be labelled 'fragile'?*
4. *How did the natural environment of the Everglades affect people in the early 1900s?*
5. *Describe the ways in which people's use of water has changed over the years in Florida.*
6. *People's use of water has affected the Everglades environment in many ways. What have been the positive effects of people?*
7. *What have been the negative effects of people on the Everglades environment?*
8. *Make another copy of the diagram you did when answering question 1. Modify the diagram to show how the causes-and-effects of human impact the Everglades environment.*

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