1.1 Systems in physical geography

In this section you will learn about the concept of systems in physical geography and their application to the water and carbon cycles

What is a system?

You will be familiar with the term 'ecosystem'. An ecosystem describes the interrelationships between living and non-living components within a particular environment, such as a pond (Figure **1**) or a forest.

A simple diagram is often used to show the different components (parts) of an ecosystem and the relationships or links (**flows/transfers**) between them. This is essentially what is meant by a **system**.

Figure 1 *Garden pond ecosystem*

In geography, a systems approach helps us to understand the physical and human world around us. It enables us to see the whole picture. We can apply this approach to physical systems such as drainage basins or to human systems such as the operations on a farm or in a factory.

A systems approach helps us to understand how energy is transferred between the components of a system and how those components themselves can change. This approach also helps us to appreciate how both natural change and human activities can impact upon an environment.

Figure 2 *Systems approach terminology*

Systems term	Definition	Examples	
		Drainage basin	**Woodland carbon cycle**
Input	Material or energy moving into the system from outside	Precipitation	Precipitation with dissolved carbon dioxide (CO_2)
Output	Material or energy moving from the system to the outside	Runoff	Dissolved carbon within runoff
Energy	Power or driving force	Latent heat associated with changes in the state of water	Production of glucose through the process of photosynthesis
Stores/ components	The individual elements or parts of a system	Trees, puddles, soil	Trees, soil, rocks
Flows/ transfers	The links or relationships between the components	Infiltration, groundwater flow, evaporation	Burning, absorption
Positive feedback	A cyclical sequence of events that amplifies or increases change. Positive feedback loops exacerbate the outputs of a system, driving it in one direction and promoting environmental instability.	Rising sea levels (due to thermal expansion and melting freshwater ice) can destabilise ice shelves, increasing the rate of calving. This leads to an increase in melting, causing sea levels to rise further.	Increased temperatures due to climate change cause melting of permafrost. Trapped greenhouse gases are released, enhancing the greenhouse effect, raising temperatures further.
Negative feedback	A cyclical sequence of events that damps down or neutralises the effects of a system, promoting stability and a state of dynamic equilibrium.	Increased surface temperatures lead to an increase in evaporation from the oceans. This leads to more cloud cover. Clouds reflect radiation from the sun, resulting in a slight cooling of surface temperatures.	Increased atmospheric CO_2 leads to increased temperatures, promoting plant growth and rates of photosynthesis. This, in turn, removes more CO_2 from the air, counteracting the rise in temperature.
Dynamic equilibrium	This represents a state of balance within a constantly changing system	Remote and unaffected drainage basin/woodland where there has been no significant natural or human impacts, or one that has had time to adjust to change	

Applying the systems approach to the water and carbon cycles

In this chapter you will learn about the **water** and **carbon cycles** and the complex relationships between their many component parts. You will learn that natural change, and also change due to human activities, often upsets the dynamic equilibrium of the cycle. It is this complexity and the need for us to see the 'whole picture' that is the reason why a systems approach is the ideal mechanism for studying these two vital cycles together with other aspects of physical and human geography.

The water cycle system

Look at Figure **1** (1.2). It shows a simplified version of the water cycle. In its entirety, the water cycle system is a **closed system** – water is not lost to or gained from space. However, at a local scale, such as a drainage basin, it is an **open system**. Precipitation is an input and runoff to the oceans is an output. There are many components and **stores**, such as trees, built-up areas and soil. Flows and transfers include *throughflow* and *groundwater flow* (see 1.3).

The carbon cycle system

Figure **3** shows the carbon cycle in the form of a systems diagram. As this is the global carbon system, it is a closed system – there are no inputs to or outputs from the system as a whole. At a local scale, such as a forest, it is an open system with both inputs and outputs.

There are many components and stores, such as rocks, the oceans and the atmosphere. Flows and transfers include *photosynthesis* and *respiration*.

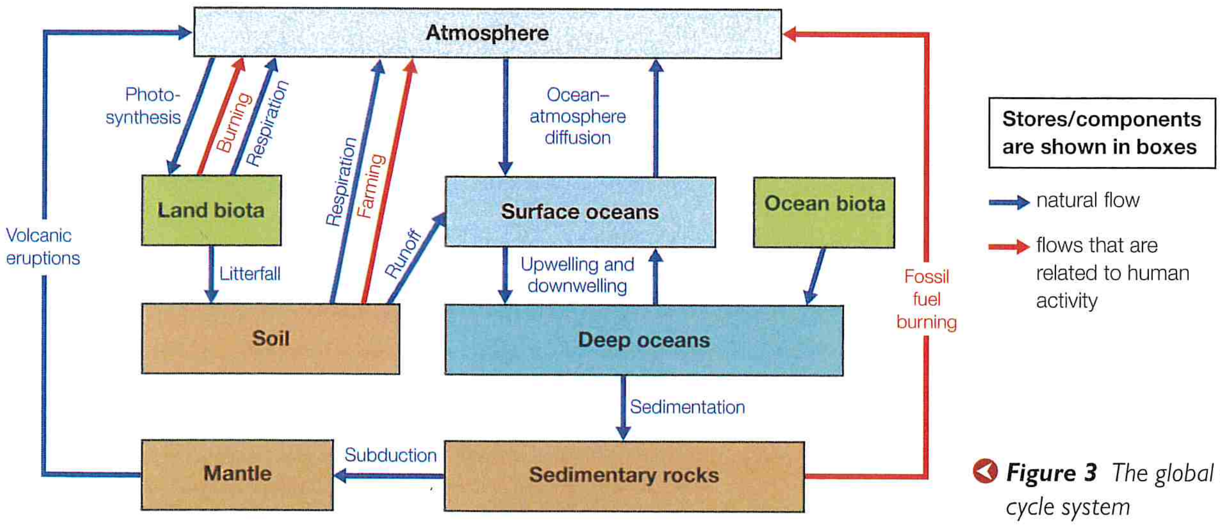


Figure 3 *The global carbon cycle system*

ACTIVITIES

1 Study Figure **1**. Work in pairs or small groups to consider how the systems terminology listed in Figure **2** can be applied to the pond ecosystem. Present your answers in the form of a table.

S 2 Study Figure **1** (1.2). Attempt to represent the information about the water cycle in the form of a systems diagram similar to Figure **3** above, which shows the carbon cycle system. You may need to construct several draft versions before completing your final diagram.

3 Explain why geographers find a systems approach useful in studying physical systems.

STRETCH YOURSELF

Use the internet to find further examples of positive and negative feedbacks within the water and carbon cycles. You might find it easier to focus on local scale cycles, say involving a drainage basin, a lake or a forest. Are these feedbacks good or bad? Is the ideal scenario to have a dynamic equilibrium?

1.2 The global water cycle

In this section you will learn about the global water cycle and its stores

What is the water cycle?

Water is our most precious resource and essential for life on Earth. It is constantly being recycled, stored and transferred between the land, oceans and atmosphere. Water is not evenly distributed across the Earth. Some regions enjoy plentiful supplies, others suffer severe shortages leading to human misery, migration and famines.

Ownership of water is a controversial political issue. Some people believe that future wars may be about securing water supplies. This suggests a pretty bleak future.

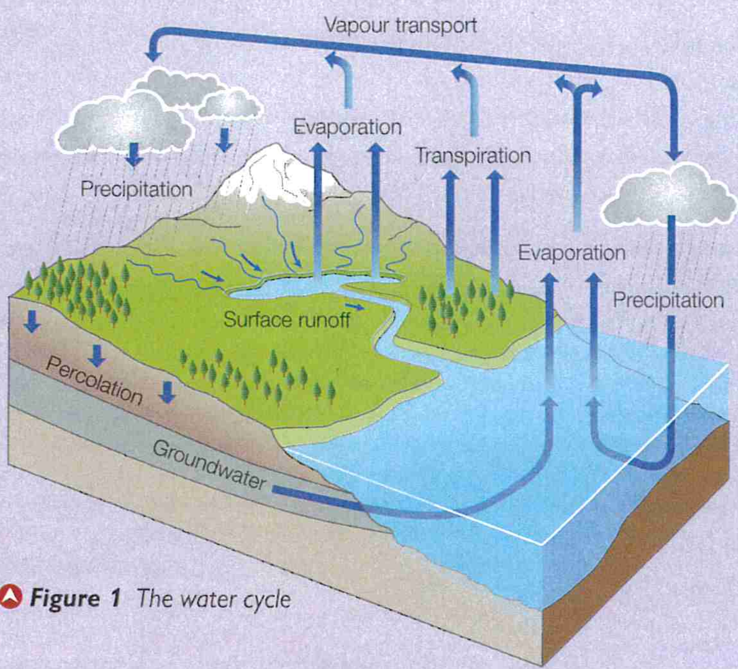


Figure 1 *The water cycle*

Figure **1** shows the global water cycle. Notice that there are a number of components which fall into two kinds of process.

- Stores – most of the Earth's water is stored as saline (salt) water in the oceans. Of the freshwater stores, ice sheets (Antarctica and Greenland) and groundwater are the main stores. Rivers, lakes and the atmosphere contain remarkably small amounts of the global water stores.
- Transfers – these are the processes involved in transferring water between stores. For example, precipitation transfers water from the atmosphere to the Earth's surface. Evaporation moves it back to the atmosphere. Water may infiltrate the ground or percolate slowly through the rocks as groundwater flow.

The main stores in the water cycle

Water is stored within four major physical systems – the **lithosphere** (land), **hydrosphere** (liquid water), **cryosphere** (frozen water – snow and ice) and **atmosphere** (air).

Look at Figure **2** to see the breakdown of water storage. There are some important, and maybe surprising, facts to notice.

- The vast majority of the Earth's water is saline water (97.4 per cent), most of which is stored in the oceans.
- Only 2.5 per cent of the Earth's water is freshwater, almost all of which is stored as snow and ice (68.7 per cent) and groundwater (30.1 per cent).
- Surface and other freshwater comprises only 1.2 per cent of all freshwater.

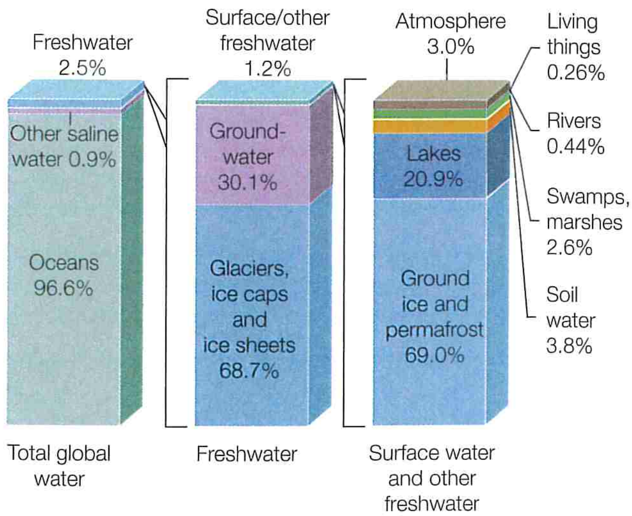


Figure 2 *Where is the Earth's water?*

The global distribution of water stores

Water stores have a geographical component in that they are not evenly distributed across the world. Consider the distribution of land, sea and ice sheets as shown in Figure **3**. This has a profound impact on the global distribution of water. On land, there is an uneven distribution of rivers, lakes and groundwater aquifers.

What is the global distribution of groundwater aquifers?

Just over 30 per cent of all freshwater is stored in rocks deep below the ground surface forming vast underground reservoirs called *aquifers*. These sources are crucial for sustaining civilisations across the world. Figure **3** shows the global distribution of aquifers.

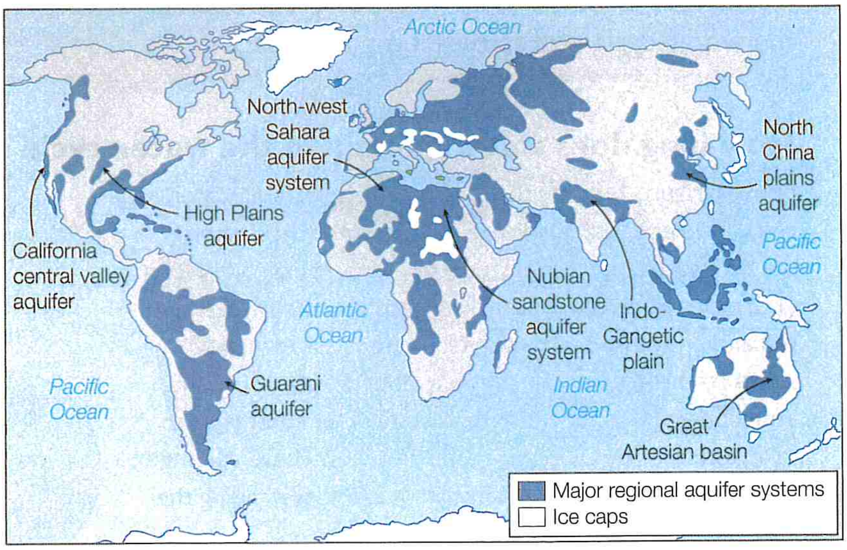


Figure 3 *Distribution of land, sea, ice sheets and major world aquifers*

Aquifers most commonly form in rocks such as chalk and sandstone, which are porous (contain pores – air pockets) and permeable (allow water to pass through). Water enters the rocks either directly, where they are exposed on the ground, or very slowly, as water drains through the overlying soil. Soils vary enormously in their capacity to store and transfer water – this is the **soil water budget**. Porous, sandy soils hold little moisture as water is easily transferred through the pore spaces. Clay soils tend to store water, with very limited water transfer.

The upper level of saturated rock is called the *water table*. This rises and falls in response to groundwater flow, water abstraction by people or by *recharge* (additional water flowing into the rock). Through careful management, the water table needs to be maintained at the same level – a state of equilibrium.

Aquifers in the deserts of Africa, the Middle East and Australia are called *fossil aquifers* and were formed thousands of years ago when the climate in those regions was much wetter. Many aquifers are being exploited unsustainably as more water is extracted. Saline aquifers exist where seawater has infiltrated into the rocks, often due to the over-abstraction.

ACTIVITIES

S **1** Make a copy of Figure **1**. Use different colours to indicate the stores and transfers (processes) in the water cycle.

2 a Study Figure **2**. The oceans are the main store of saline water. Can you account for the 'other saline water' stores?

b Many of the world's glaciers are melting. Where do you think this freshwater is going?

S **c** Calculate the percentages of rivers and also of lakes of the 'total global water'.

d Why is 'groundwater' a more important freshwater source than 'glaciers, ice caps and ice sheets'?

e Why do you think the atmosphere stores such a small amount of the world's water?

3 a Study Figure **3**. Describe the distribution of the major regional aquifers.

b Suggest why some aquifers are located in present-day arid regions. What are the issues associated with this?

STRETCH YOURSELF

Find out more about the distribution of lakes, an important store of freshwater.

- Are lakes distributed evenly across the world?
- What determines the location of lakes?
- How important are lakes in water supply?
- Are there any signs of stress on the world's lakes?

1.3 Changes in the magnitude of the water cycle stores

In this section you will learn about the processes driving changes in the magnitude of the water cycle stores over time and space

How long does water remain in the water cycle stores?

Look at Figure **1**. It lists the typical timescales that water remains in each store. Notice, for example, that water in the soil (soil water or moisture) does not remain very long (1–2 months). It may quickly soak into the underlying soil and be transpired by plants, be transferred into rivers by throughflow or simply evaporated back into the atmosphere. Groundwater replacement, in contrast, can take hundreds or even thousands of years! These varying time scales are extremely important in understanding the complexity of transfers within the water cycle.
Also consider how these will vary from place to place.

Figure 1 *Typical residence times of water found in various stores*

What are the processes of change?

In section 1.2 we have seen that the water cycle is made up of stores and transfers. The amount of water held in each store is largely determined by the transfer processes that act as inputs and outputs.

It is important to appreciate that the magnitude of water held within a store will vary over time and space. Consider the seasonal changes that occur in the Arctic, with the annual cycle of freezing and melting of the sea ice. Also consider the passage of frontal systems with their associated bands of rain and the recent trend of shrinking glaciers around the world. Over time and space, the magnitude of these stores has changed (Figure **2**).

Process (flow/transfer)	Definition
Precipitation	Transfer of water from the atmosphere to the ground. It can take the form of rain, snow, hail, dew.
Evaporation (evapotranspiration, if combined with transpiration, water loss from plants)	Transfer of water from liquid state to gaseous state (water vapour). The vast majority occurs from the oceans to the atmosphere.
Condensation	Transfer of water from a gaseous state to a liquid state, for example, the formation of clouds.
Sublimation	Transfer from a solid state (ice) to a gaseous state (water vapour) and vice versa.
Interception	Water intercepted and stored on leaves of plants.
Overland flow	Transfer of water over the land surface.
Infiltration	Transfer of water from the ground surface into soil where it may then percolate into underlying rocks.
Throughflow	Water flowing through soil towards a river channel.
Percolation	Water soaking into rocks.
Groundwater flow	Transfer of water very slowly through rocks.

Figure 2 *The main global transfer processes*

Climate change

At the peak of the last Ice Age (about 18 000 years ago), about a third of the Earth's land area was covered by glaciers and ice sheets . With water 'locked up' as snow and ice, the magnitude of this store increased significantly. With less liquid water reaching the oceans, sea levels fell by over 100 m compared with the present day.

During warmer periods in the past – say, about three million years ago – ocean levels were about 50 m higher than they are today as the amount of water stored as snow and ice declined. You can see why scientists are so concerned about the possible impacts of global warming on sea levels!

Cloud formation and the causes of precipitation

Cloud formation and subsequent precipitation varies considerably with time and space. If you look at a satellite photograph of the Earth, you will see that clouds are very unevenly distributed, as is associated precipitation. The driving force behind cloud formation and precipitation is the global atmospheric circulation model (Figure **3**).

Simplified to suggest the presence of three interconnected cells, the atmospheric circulation model identifies latitudinal zones of rising and falling air.

At the Equator, for example, high temperatures result in high rates of evaporation. The warm, moist air rises, cools and condenses to form towering banks of cloud and heavy rainfall in a low pressure zone called the ITCZ (Inter-Tropical Convergence Zone). Seasonally, this zone moves north and south, with the overhead sun illustrating both the spatial and temporal changes in transfers and store magnitudes that occur within the water cycle.

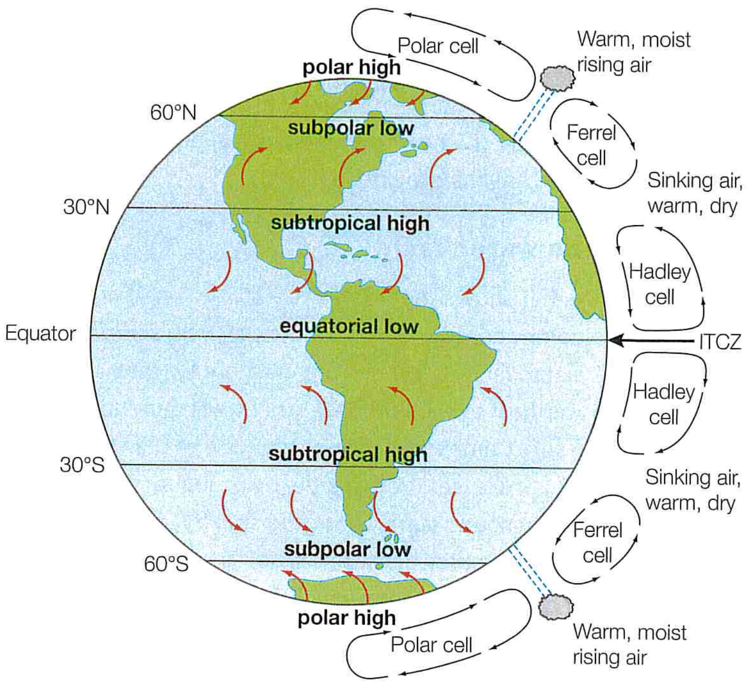


Figure 3 *Atmospheric circulation model*

In the mid latitudes, cloud formation is mostly driven by the convergence of warm air from the Tropics and cold air from the Arctic. The boundary of these two distinct air masses – the polar front – results in rising air and cloud (and rain) formation. Strong upper-level winds (the jet stream) drive these unstable weather systems across the mid latitudes, establishing the largely changeable conditions experienced in the UK.

Cloud formation can occur on a more localised scale. The formation of thunderstorms from intense convective activity is somewhat 'hit and miss', but it does clearly demonstrate the variations in both time and space of water cycle transfer processes.

Cryospheric processes

After oceanic water, the largest stores of water on Earth take the form of frozen water (ice) – 95 per cent is locked up in the world's two great ice sheets covering Antarctica and Greenland. While the Earth's ice masses may seem stable and lacking in change, this is far from the case – it is all a matter of the timescale involved.

Snow falling on glaciers and ice sheets becomes compressed and enters long-term storage, forming layers of glacial ice. Scientists in the Antarctic have drilled down into layers of ice over 400 000 years old!

On a shorter timescale, snow accumulated during the winter adds to the mass of a glacier or ice sheet. In the summer, melting occurs or ice calves (breaks away). On a glacier, the equilibrium line marks the altitude where annual accumulation and melting are equal. In recent decades the climate has warmed, causing the equilibrium line to move to ever higher altitudes. Most glaciers in the world are now shrinking and retreating.

The melting of freshwater ice has a profound impact on sea levels – the total melting of all the polar ice sheets could result in a 60 m rise in sea level, adding a great deal of water to the ocean store. We have already identified the **positive feedback** loop whereby rising sea levels destabilise ice shelves, triggering calving and further melting (Figure **2**, 1.2).

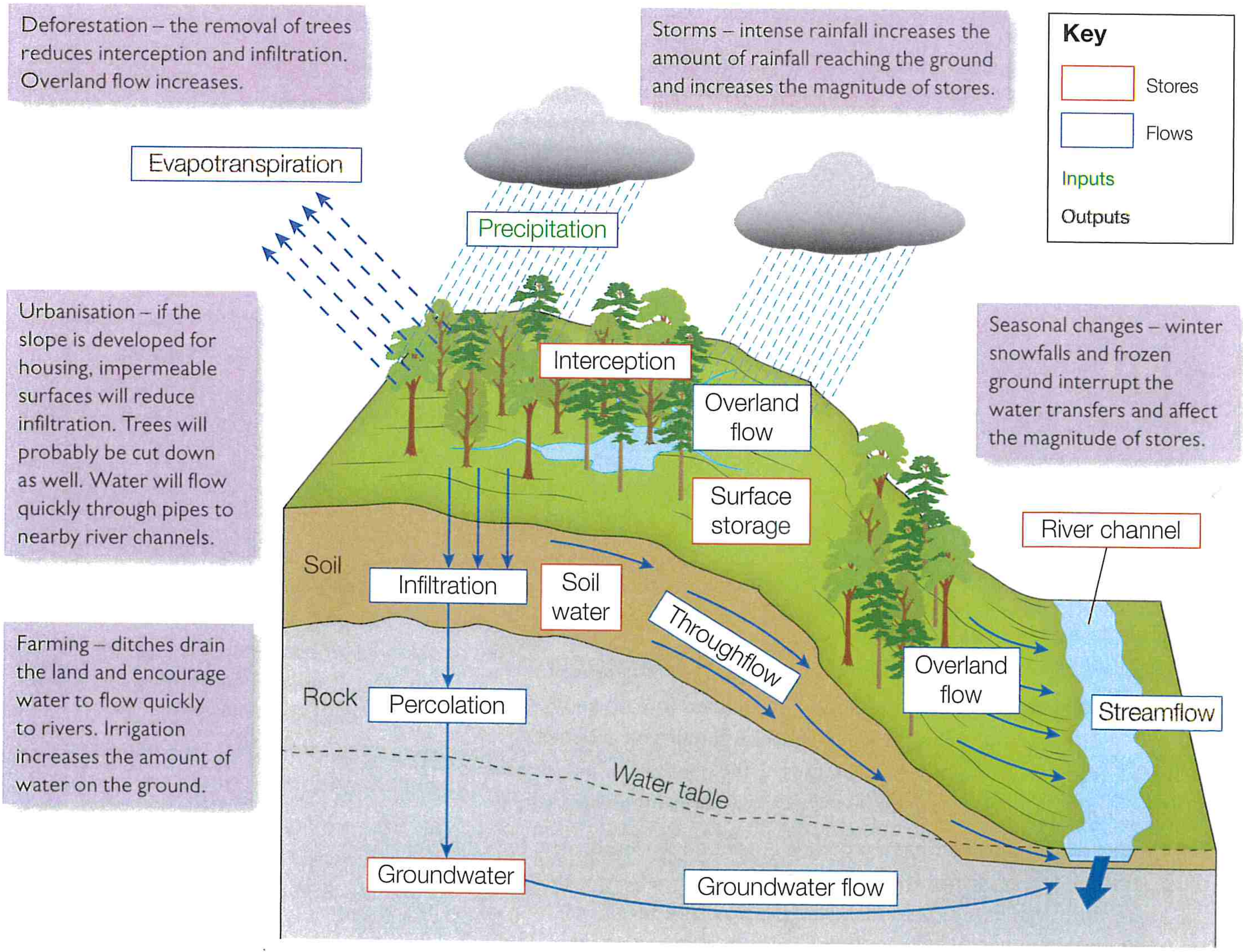
Processes of change at the local scale

So far we have mostly considered processes of change at the global scale. While alluding to local scale changes, say with thunderstorms or individual glaciers, it is worth focusing now on the processes operating on local hillslopes, considered by hydrologists to be the most important local unit of study. River basins will be addressed in 1.4 *The drainage basin system*.

The hillslope water cycle

Look at Figure **4**. It shows the water cycle stores and transfers on a typical hillslope. See how the components of a hillslope water cycle are affected by a variety of natural and human-related factors. Notice the different places where water can be stored. The amount of water held in each of these stores will depend on many factors operating over relatively short timescales. The magnitude of the stores changes in response to a wide variety of processes. Perhaps the most influential is *infiltration* – the movement of water from the ground surface into the soil. Water that is effectively trapped on the ground surface – either because the soil is saturated or frozen or because the rate of precipitation exceeds the capacity of the soil to absorb it – will either be stored as surface storage, evaporate or start to flow downslope as overland flow. The rapid transfer of water overland is, of course, a major factor leading to flooding.

Figure 4 *The hillslope water cycle system*



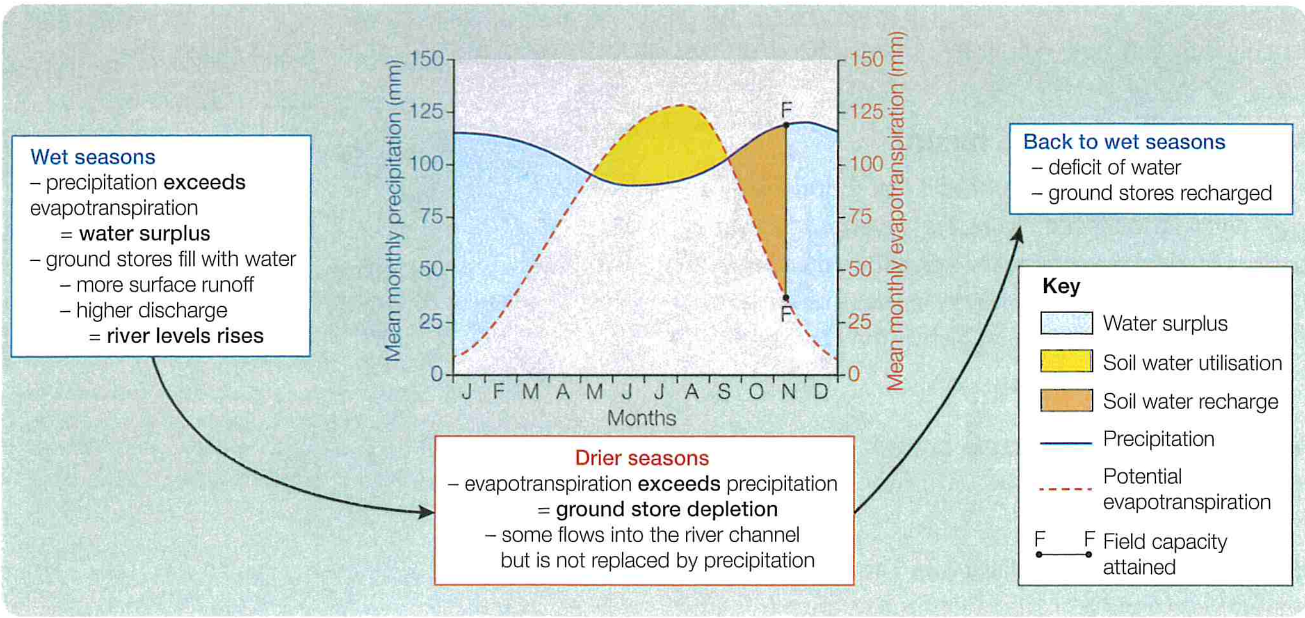


Figure 5 *The soil water budget*

Water that is able to infiltrate the soil may be stored for very long periods of time either in the soil or deep within the underlying bedrock. The soil water budget describes the changes in the soil water store during the course of a year (Figure **5**).

Notice that during the wetter winter months, precipitation exceeds potential **evapotranspiration**. This leads to a water surplus. Soils will be saturated, surface overland flow encouraged and river levels will be high. In the summer months, when potential evapotranspiration exceeds precipitation, the soil starts to dry out. In the early autumn, rates of evapotranspiration start to fall and the soil water is replenished (recharge).

When the soil holds as much water as it can without any outputs occurring, it is said to have reached its *field capacity*. Thereafter, a water surplus occurs and water transfer processes will become active.

Soil water budgets will vary considerably from place to place depending on the type and depth of the soil, its texture and permeability. Much the same is true of the underlying bedrock, as its capacity to store and transfer water will depend on its lithology and its structure (porosity and permeability). For example, water will move slowly through older, porous rocks such as some sandstones, yet it will move very rapidly through widely jointed limestones. Consider, for example, how potholers can find themselves in danger very quickly in limestone caverns when the water table rises rapidly in response to a rainstorm.

ACTIVITIES

1 Study Figure **1**.
   - **a** Which water store has the shortest residence time? Suggest reasons for this.
   - **b** Why does deep groundwater have the longest residence time?
   - S **c** Draw a simple diagram showing the inputs and outputs for the glacier store.
   - **d** Suggest how the glacier store may change in magnitude over time.
   - **e** Rivers have a very short residence time. What are the implications of this for the other stores and for human uses of rivers?

2 What are the major processes responsible for change in the magnitude of global water cycle stores over time and space?

3 Study Figure **4**. For each of the boxed factors, consider the impact on the magnitudes of the hillslope water stores. You could present your answer in the form of a table or as annotations on photos obtained from the internet to represent each factor.

STRETCH YOURSELF

Investigate the factors that affect the height of the water table on a hillslope. Consider rock type, soil characteristics, relief, vegetation and water abstraction. To what extent can the height of the water table be used to indicate the relative magnitude of water stores?

1.4 The drainage basin system

In this section you will learn about the drainage basin system and its stores and flows

What is a drainage basin?

A drainage basin is the area of land that is drained by a river and its tributaries (Figure **1**). The edge of a river basin is marked by a boundary called the *watershed*. Drainage basins vary enormously in size, from small local basins to major river systems such as the Mississippi, Nile and Amazon.

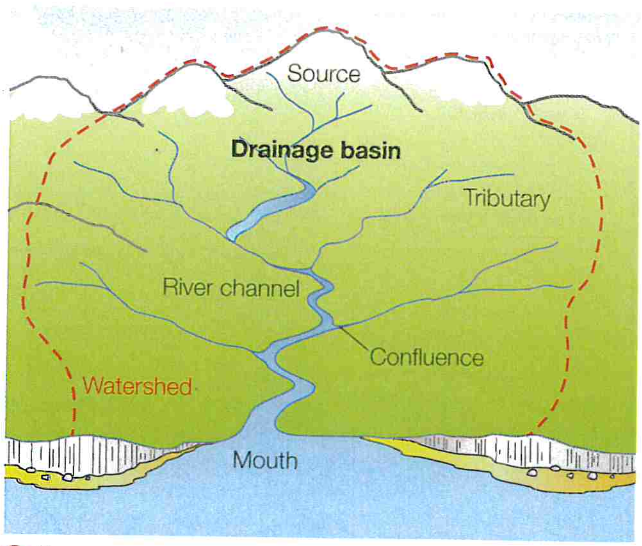


Figure 1 *The drainage basin*

What is the drainage basin system?

The movement of water within the drainage basin is illustrated by the drainage basin hydrological cycle or the *drainage basin system* (Figure **2**). This is an open system, with inputs (precipitation) and outputs (runoff, evapotranspiration). Notice that part of the diagram in Figure **2** shows the way that water moves down a hillslope towards a river – this is the *hillslope system* that we studied in 1.3.

In a hydrological sense the drainage basin is an *open* system. However, for planning purposes, it is often considered to be a *closed* system – the principles of cause and effect are contained and do not spread outside its area. So, in terms of flood management, water supply and pollution control, the drainage basin is the basic spatial unit used by planners and organisations such as the Environment Agency. What happens in a drainage basin is contained within that basin and will not affect neighbouring basins.

Precipitation

Water enters the drainage basin system as precipitation. Some of it may be intercepted by plants and trees where it may be stored before being evaporated. It takes time for the water to drip through the leaves or down the stems (**stemflow**) to the ground surface. Here, it is stored as puddles, flows over the ground as overland flow or infiltrates the soil. Some water may be taken up by plants before being transpired.

Groundwater flow

Groundwater flow feeds rivers through their banks and bed. Being generally a slow method of transfer, it carries on supplying water well after an individual rainfall event has occurred. This explains why rivers continue to flow during long dry periods. Eventually, water moves out of the system as runoff, when the river flows into lakes or the sea, or evapotranspiration.

Infiltration

The *infiltration capacity* (rate of infiltration) is an extremely important factor and will vary according to soil type and antecedent conditions, i.e. to what extent the soil is already saturated. Infiltration capacity is exceeded when the soil is unable to absorb water at the rate at which it is falling (or melting if it is snow). Thin, frozen or already saturated soils will usually have a low infiltration capacity. Trees may promote infiltration as the roots form pathways for water to percolate underground. Water actually soaks into the soil by a combination of capillary action (the attraction of water molecules to soil particles) and gravity, with the latter usually dominating.

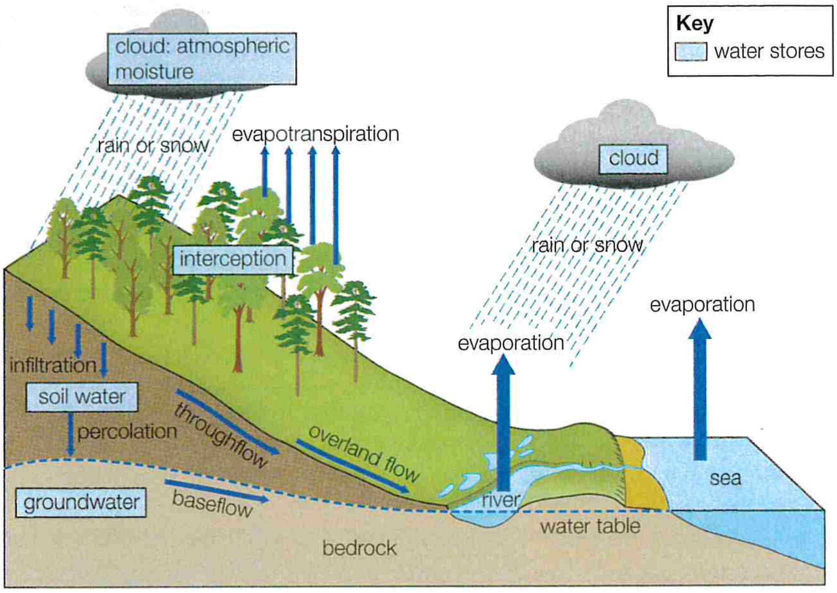
Overland flow

If water is unable to infiltrate it may run off the surface as overland flow, flowing across a large surface area (*sheetflow*) or concentrated into small channels called *rills*. Overland flow on agricultural land is not common in the UK as much of the land is covered by vegetation, although it can sometimes be seen in winter when the soil is bare. In urban areas, particularly on roads, overland flow is extremely common, often exacerbating flooding.

Throughflow

Once in the soil, water may be either stored as **soil water** or pass through as throughflow, dependent on the depth and texture of the soil – coarse, sandy soil absorbs and transfers water rapidly, especially through discrete 'pipes' within the soil, caused by animal activity or the growth of plant roots. This contributes significantly to the flood hazard. Such soils are said to have a *low field capacity* (retain little water). Clay soils drain more slowly and have a *high field capacity*. These soils tend to be wet as they have tiny pore spaces, which do not allow water to the transferred readily.

Figure 2 *The drainage basin hydrological cycle*



Water passes through the soil until it reaches the water table (the upper level of saturated ground) or the underlying bedrock. If the bedrock is impermeable, no further downward movement will occur. If permeable, water will seep into the cracks and holes within the rock. Water transfer through rock can take tens or even hundreds of years and is, therefore, an important water store.

However, some jointed rocks such as limestone and even granite can transmit water very quickly.

For example, a study of water flow through limestone in Cheddar Gorge, Somerset, calculated rates of 583 cm/hour, which is considerably faster than most rates of throughflow. As a comparison, flow rates through sandstones tend to be about 200 cm/hr and through unconsolidated gravels, up to 20 000 cm/hr.

EXTENSION

The role of vegetation

Most drainage basins are clothed by one or more types of vegetation that will, to some extent, intercept precipitation (scrub and bushes in semi-arid regions, grassland in temperate latitudes or coniferous forest and tundra in high latitudes).

Type of vegetation biome	Loss of water by interception (average per year)
Temperate pine forest	94% (low-intensity rain); 15% (high-intensity)
Brazilian evergreen rainforest	66%
Grass	30–60%
Pasture (clover)	40% in growing season
Coniferous forest	30–35%
Temperate deciduous forest	20% with leaves; 17% without leaves
Cereal crops	7–15% in growing season

A study of similar-sized upland catchments of the River Severn (contained 67.5 per cent forest) and the River Wye (contained 1.2 per cent forest) in the 1970s provided interesting comparative data on the role of forest interception in reducing runoff. Having received the same amount of rainfall during the study period, the Severn catchment 'lost' some 38 per cent of the total precipitation (e.g. through evaporation) compared with just 17 per cent for the Wye. The clear inference is that forest cover has an important impact on the drainage basin system.

ACTIVITIES

Study Figure **2**. Construct a flow diagram, using a series of boxes and arrows, to describe how water is transferred from the atmosphere into river channels.

- Use a colour-coding system to separate stores from flows.
- Refer to the relative transfer speeds, either in the text or by using proportional symbols such as different-sized arrows.
- Use simple diagrams, sketches or thumbnail photos to help you describe what is happening at each stage.

1.5 The water balance

In this section you will learn about the water balance and the causes of variation in runoff

What is the water balance?

In order to gain a better understanding of the drainage basin system we can use a simple equation called the **water balance**. This helps hydrologists to plan for future water supply and flood control by understanding the unique hydrological characteristics of an individual drainage basin.

What causes variations in runoff?

An important aspect of the equation is the total runoff (expressed as a percentage of precipitation). This is a measure of the proportion of the total precipitation that makes its way into streams and rivers.

The two river basins in Figure **1** record very different runoff percentages. This is because of the differences in soil water, rock type and vegetation cover. Also think about how the time of year will affect the rates of evapotranspiration and vegetation growth (interception).

The type and intensity of precipitation are also important. Intense rainfall is more likely to pass quickly into rivers, increasing the amount of runoff. Drizzle will be held in the trees and on the grass, much of which will evaporate. Snow will delay any runoff but when frozen soils melt, runoff values might be high.

The River Wye, Wales

With a total length of 215 km, the River Wye is the fifth-longest river in the UK. From its source in the Plynlimon Hills in mid-Wales, it flows south-eastwards before joining the Severn Estuary at Chepstow (Figure **2**). The river is rich in wildlife, with a variety of habitats. It is an Area of Outstanding Natural Beauty and also has a Site of Special Scientific Interest.

The upper part of the basin is characterised by steep slopes, acidic soils and grassland. Much of this area was originally forested but this has been largely cleared to make way for pasture and sheep grazing. This has reduced interception and increased the potential for overland flow. Ditches have been dug to drain the land to make it more productive, but this has increased the speed of water transfer, making the river more prone to flooding.

The rocks in much of the upper river basin are impermeable mudstones, shales and grits. Further south, the river flows over sandstones before cutting its way through a limestone gorge between Symonds Yat and Chepstow.

S

The water balance is expressed as:

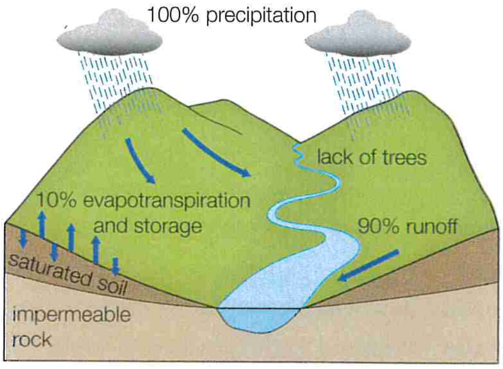
$P = O + E +/- S$ where

P = precipitation

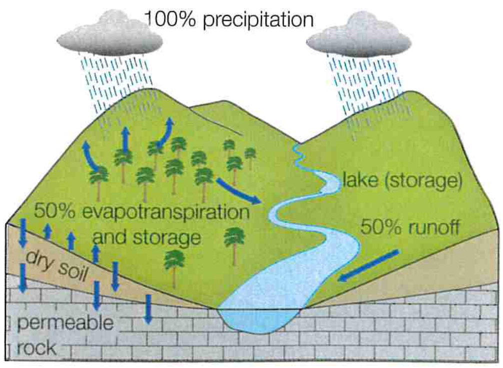
O = total runoff (streamflow)

E = evapotranspiration

S = storage (in soil and rock)



The runoff percentage is high (90%), so most of the precipitation is transferred straight to the river – little is lost or stored on the way. Under conditions like this, flooding is likely.



The runoff percentage (50%) is much lower than above (90%), so a higher proportion of the precipitation is lost or stored before it reaches the river channel. Reasons for this might include a heavily forested river basin, or one that has permeable rocks. Under these conditions, flooding is much less likely.

Figure 1 *Variations in runoff and water balance between drainage basins*

Because the underlying rock is mainly impermeable, groundwater flow is therefore limited throughout the basin: soils quickly become saturated and are unable to absorb excess water. This encourages overland flow, increasing the risk of flooding downstream – Hereford has been affected by flooding on many occasions.

Rainfall totals are highest in the western upland parts of the river basin while higher temperatures and rates of evapotranspiration occur in the east. Runoff tends to be higher in the winter when rainfall totals are high and rates of plant growth and evapotranspiration are low.

Figure **3** provides monthly data for the River Wye's drainage basin system. Notice that there are significant variations in precipitation and runoff during the year.

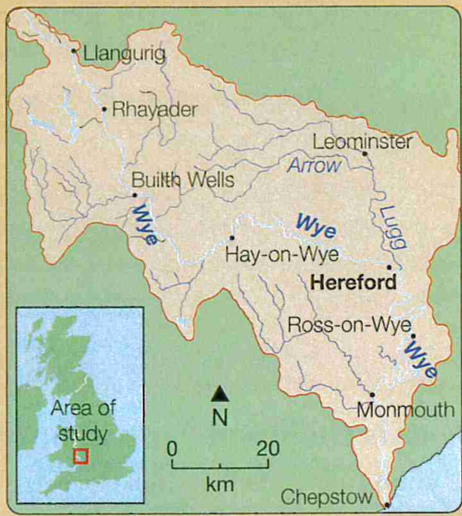


Figure 2 *The River Wye and its major tributaries*

Month	Precipitation	Runoff	Evapotranspiration	Storage	Runoff as a % of precipitation
January	280.8	275.7	10.6	−5.5	98.2
February	191.7	145.6	12.1	34.0	76.0
March	491.0	440.2	35.9		
April	103.8	43.7	62.2		
May	168.9	126.4	65.3		
June	98.7	92.8	71.0		
July	142.2	83.0	76.8		
August	93.8	50.8	75.6		
September	285.1	199.5	46.6		
October	497.9	449.8	25.5		
November	279.4	264.8	12.1		
December	188.4	141.2	3.7		

Figure 3 *River Wye water balance*

ACTIVITIES

1 Study Figure **3**.
   - **a** Use the water balance equation to help you complete the 'storage' column. (January and February have already been completed).
   - **b** Why are there some negative storage values?
   - **c** Do there appear to be any seasonal trends with the positive and negative values? Can you explain these trends?
   - **d** Why do you think there is a high positive storage value in September?

2 Now complete the final column. To do this you need to divide each runoff value by the precipitation value and multiply by 100.
   - **a** In which month is the value of 'runoff as a percentage of precipitation' the highest?
   - **b** Suggest reasons for this very high percentage.
   - **c** Why do you think there was a particularly high percentage runoff value in June?

3 Assess how the following factors cause variations in runoff: type and intensity of precipitation, climate, soil water, rock type, human activities (such as reservoirs, land use change and urbanisation).

STRETCH YOURSELF

Find out more about the characteristics of the River Wye's drainage basin. Look at the rock type, vegetation and land use and support your study with maps and satellite photos. Use your research to help to explain the water balance data in Figure **3**.

- Is flooding an issue?
- What are the issues of water supply?

1.6 The flood hydrograph

In this section you will learn about the flood hydrograph

What is discharge?

Imagine standing on a bridge looking down on a fast-flowing river. The volume of the water passing beneath you is the river's *discharge*. It is essentially a measurement of runoff at a moment in time.

Values for river discharge are expressed in 'cumecs' (cubic metres per second). Discharge is most commonly calculated using the following equation:

Discharge (m^3 per second) = cross-sectional area (m^2) × velocity (metres per second)

What is the flood hydrograph?

The **flood** (storm) **hydrograph** is simply a graph showing the discharge of a river following a particular storm event. Figure **1** shows a typical flood hydrograph and identifies its main features.

Despite the unique nature of river hydrographs, it is possible to identify two models representing polar opposites (Figure **2**).

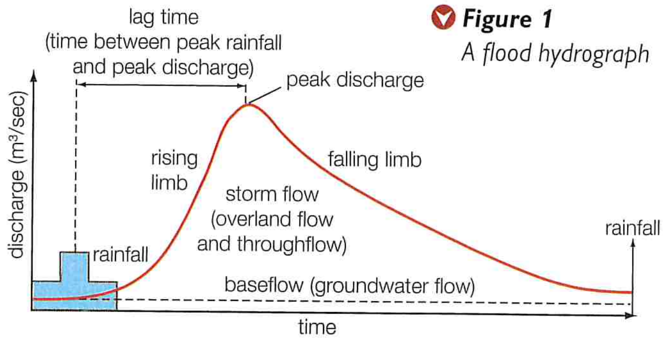


Figure 1 *A flood hydrograph*

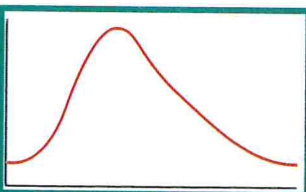
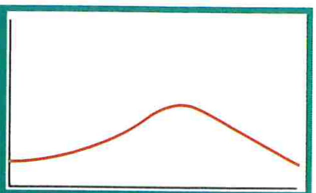
Drainage basin and precipitation characteristics	**'Flashy' hydrograph with a short lag time and high peak** 	**Low, flat hydrograph with a low peak** 
Basin size	Small basins often lead to a rapid water transfer.	Large basins result in a relatively slow water transfer.
Drainage density	A high density speeds up water transfer.	A low density leads to a slower transfer.
Rock type	Impermeable rocks encourage rapid overland flow.	Permeable rocks encourage a slow transfer by groundwater flow.
Land use	Urbanisation encourages rapid water transfer.	Forests slow down water transfer because of interception.
Relief	Steep slopes lead to rapid water transfer.	Gentle slopes slow down water transfer.
Soil water	Saturated soil results in rapid overland flow.	Dry soil soaks up water and slows down its transfer.
Rainfall intensity	Heavy rain may exceed the infiltration capacity of vegetation, and lead to rapid overland flow.	Light rain will transfer slowly.

Figure 2 *Characteristics that affect hydrographs*

Rivers tend to have unique responses to rainfall events, as illustrated by their 'typical' hydrograph. Some respond very quickly ('flashy') while others respond much more slowly, with the hydrograph being attenuated (spread out) over a long period of time. In the winter of 2015/16 there were serious floods in parts of northern UK. In the Lake District, rivers responded very quickly to the heavy rainfall events. The already, saturated soil conditions and steep slopes, meant water moved rapidly overland and along river channels to devastate villages such as Glenridding.

York was similarly affected, but it took days for the water to work its way down the tributaries and into the River Ouse, which flows through the city. The need to understand an individual river's response pattern (hydrograph) is essential if hydrologists are to plan effectively for flood control and mitigation.

STRETCH YOURSELF

Use the National River Flow Archive at www.ceh.ac.uk/data/nrfa/data/search.html to search for hydrological information about a local river or a river that you have studied. Find out about the river flow patterns and try to account for their variations.

Time from start (hours)	Discharge (m^3/sec)
0	0.35
1	0.39
2	0.55
3	2.11
4	4.79
5	4.25
6	3.36
7	4.70
8	6.08
9	6.20
10	6.76
11	5.56
12	4.52
13	3.51
17	1.78
20	1.38
24	0.95

Figure 3 *Discharge data for the River Easan Biorach during a 24-hour period in late October*

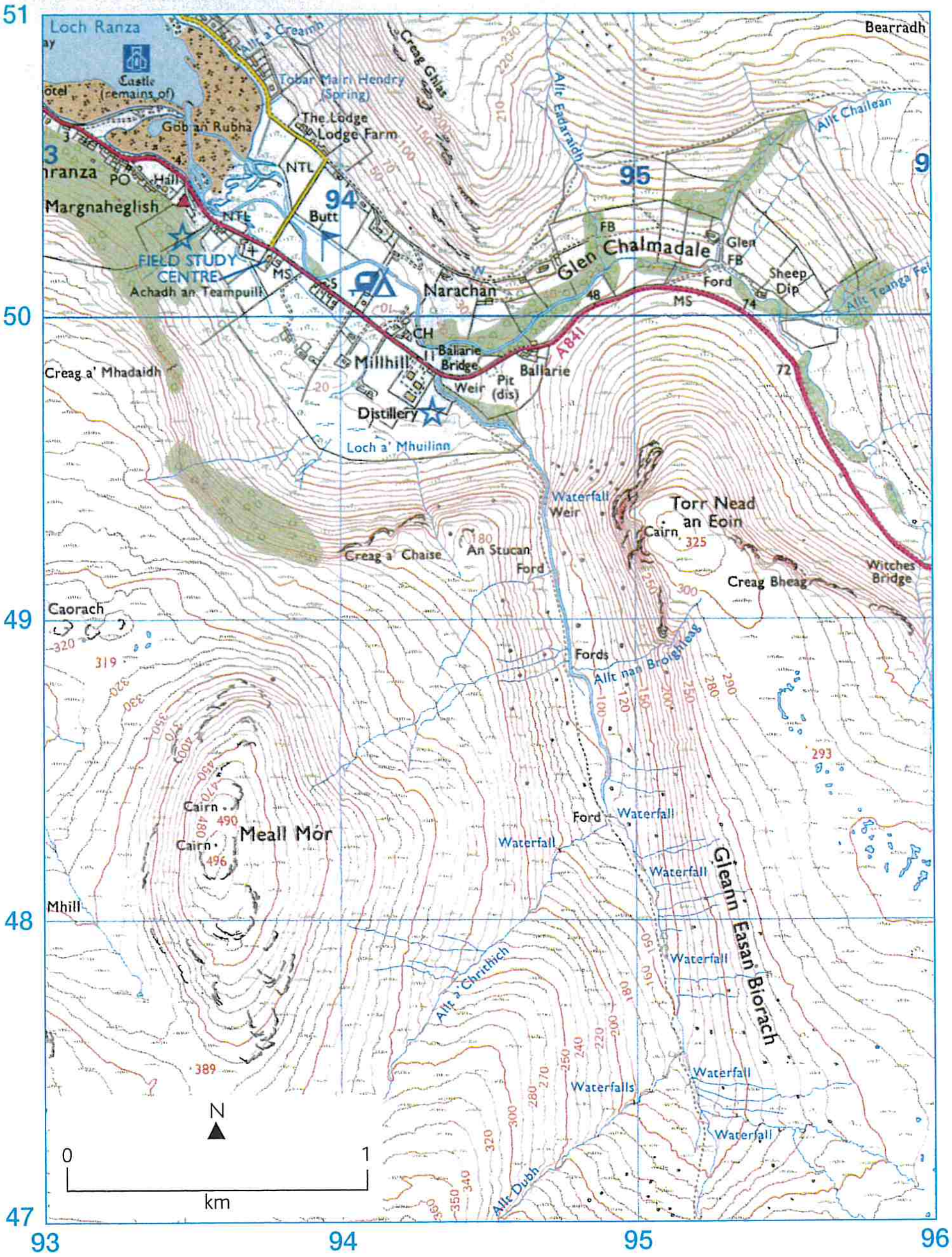


Figure 4 *OS 1:25 000 map of the drainage basin of the River Easan Biorach on the Isle of Arran in Scotland*

ACTIVITIES

1 Study the discharge data for the River Easan Biorach in Figure **3**. Figure **4** is a map extract showing the drainage basin of the river. The data in Figure **3** was collected at grid reference 938503.

a On a sheet of graph paper, draw the graph axes in Figure **5** (draw the horizontal axis in full, 0–24).

b Draw the rainfall histogram onto your graph.

c Now carefully plot the discharge data in Figure **3** to construct a hydrograph for the river.

d Use Figure **1** to help you add labels to your hydrograph to describe its main features.

e Calculate the lag time to the nearest hour.

f Use the OS map extract in Figure **4** to attempt to explain these features of the hydrograph:

- the steep rising limb
- the short time lag to the first peak
- the presence of two distinct peaks
- the second peak being higher than the first peak
- the gentle falling limb.

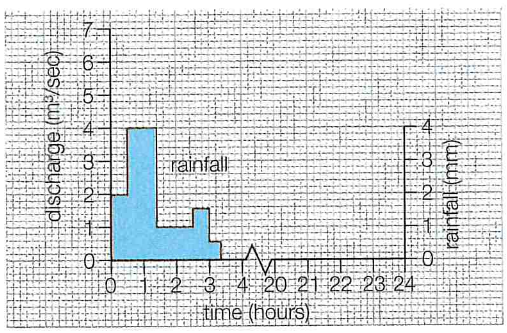


Figure 5 *Rainfall histogram for the River Easan Biorach*

1.7 Factors affecting changes in the water cycle

In this section you will learn about the factors affecting changes in the water cycle

Natural (physical) variations affecting change

Extreme weather events such as severe storms or periods of drought can have significant impacts on the water cycle. They can affect both stores and transfers.

Californian drought (2012–16)

California suffered a severe drought between 2012 and 2016 (Figure **1**). Rivers and lakes dried up, agricultural productivity declined and fires raged across tinder-dry forests and grasslands.

- Drought causes reduction in water stores in rivers and lakes.
- Vegetation dies back or is destroyed by fire – it affects processes such as transpiration, interception and infiltration.
- Groundwater flow becomes more important – it is a long-term transfer and not affected by short-term weather extremes.

- Heat and dry air causes initial high rates of evapotranspiration. This declines as water on the ground dries up (less water available to be evaporated) and trees transpire less.
- Soils dry out – the soil water store is reduced and throughflow ceases.

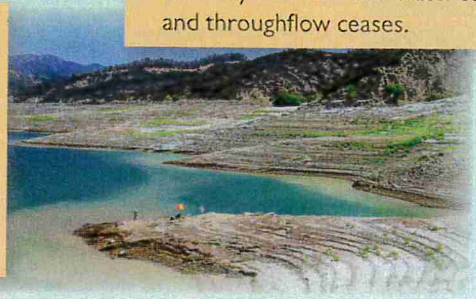


Figure 1 *Castiac Lake, California at half its usual capacity, 2014*

Seasonal changes are quite marked in mid- to high-latitude countries.

Figure 2 *Some of the effects of summer and winter variations on the UK water cycle*

Water cycle component	Summer	Winter
Precipitation	Total rainfall may be less but storms are more frequent.	Greater quantities of rainfall with a likelihood of snow.
Vegetation – interception, transpiration, etc	Vegetation grows rapidly increasing interception and transpiration.	Vegetation dies back reducing interception and transpiration.
Evaporation	Higher temperatures encourage rapid evaporation (warm air can hold more moisture).	Lower temperatures reduce rates of evaporation.
Soil water	Dry soils encourage infiltration. But hard, baked soils encourage overland flow.	Soils may become saturated, leading to overland flow.
River channel flow	Low flow conditions are more likely.	High flow conditions are more likely.

Human activities affecting change

Land-use change

The land-use changes that impact the most on the water cycle are urbanisation and deforestation.

- Urbanisation is the replacement of vegetated ground with impermeable concrete and tarmac. Water cannot infiltrate the soil, which increases overland flow and makes flooding more likely. Soil water and groundwater stores are reduced.
- Deforestation is the removal of trees, leading to surface runoff and soil erosion and reducing soil water stores.

Farming practices

Farmers are able to control the local water cycle through irrigation or land drainage. Soils covered with plants have higher infiltration and soil water rates, and, therefore, reduced runoff.

If **desertification** occurs (see 2.13), the capacity to retain water is much lower. This capacity is lost completely once the soil is sealed.

Water abstraction

The extraction of water from rivers or groundwater aquifers is referred to as *water abstraction*. Water that is abstracted for irrigation, industry and domestic purposes can have significant effects on the local water cycle.

Aquifers can become depleted. They can also become contaminated by inflowing saltwater if the water table drops below sea level – this has become an issue with the chalk aquifer beneath London. Abstraction can result in low flow conditions in rivers, which can have harmful impacts on ecosystems.

Irrigation in the Middle East

Irrigation has a significant impact on water stores (aquifers and rivers) and transfer processes (evaporation and infiltration). In parts of the Middle East, water is being abstracted from underground aquifers that were formed thousands of years ago. They are in serious danger of becoming depleted as the rate of recharge is far slower than the rate of use. Figure **3** shows how technology can be used to reduce evaporation in hot environments.

Figure 3 *Netting of a banana plantation, the Jordan Valley, Israel*

ACTIVITIES

1 Study Figure **1**.
   - **a** Draw a simple diagram to show the water cycle. Add annotations to show how a drought can impact on its stores and transfers.
   - **b** Work in pairs to attempt a similar diagram to show the impacts of a severe storm event.

2 Figure **2** describes the influence of seasonal changes on selected components of the water cycle. Suggest impacts for stores and transfers that are not listed in the table.

3 Outline ways in which human activities can lead to changes in the stores and transfers in the water cycle.

Land drainage in the UK

The low-lying land of the East Anglian Fens and the Somerset Levels were once submerged. Through the construction of deep drains and a network of ditches, which move water quickly through the system, this land is now highly productive farmland, although still vulnerable to occasional floods (Somerset in 2014). Moorland drainage ditches have been held partly responsible for increasing the flood risk in the city of York.

The drainage of peatlands can have significant impacts on both the water cycle and the carbon cycle – the water table is lowered, changing rates of infiltration and evaporation. Dry peat is friable and vulnerable to erosion. In the past, excessive drainage in the Fens led to clouds of peat being formed – during the infamous 'Fen Blows' peat would be whisked up into the air to create huge black clouds.

Peatlands are essentially thick deposits of partly decomposed vegetation and, as such they act as important carbon stores. English peatlands alone are thought to store some 584 million tonnes of carbon. Vegetation on top of the peat also absorbs carbon dioxide from the atmosphere. As the peatlands are drained, air penetrates deeper, enabling decomposition of the carbon, releasing carbon dioxide. Dry peat can also ignite releasing carbon. It has been estimated that if all the peat in England were to be destroyed, the amount of carbon released to the atmosphere would be equivalent to about five years of England's current carbon dioxide emissions!

STRETCH YOURSELF

In 2015 floods in South America, drought in East Africa and even the warmest and wettest December on record in the UK, have all been linked to the cyclical phenomenon, *El Niño*. Every six years or so, warmer water replaces the cold water in the Eastern Pacific off the coast of South America. This has direct consequences for the local weather patterns and also global weather conditions. These short-term cycles have implications for the water cycle – rainfall patterns become distorted which, in turn, affect other stores and transfers.

Find out more about the 2015/16 El Niño event. Describe the effects that it had on the world's weather and consider the implications of these effects on stores and transfers within the water cycle. Is there any connection between El Niño and climate change?