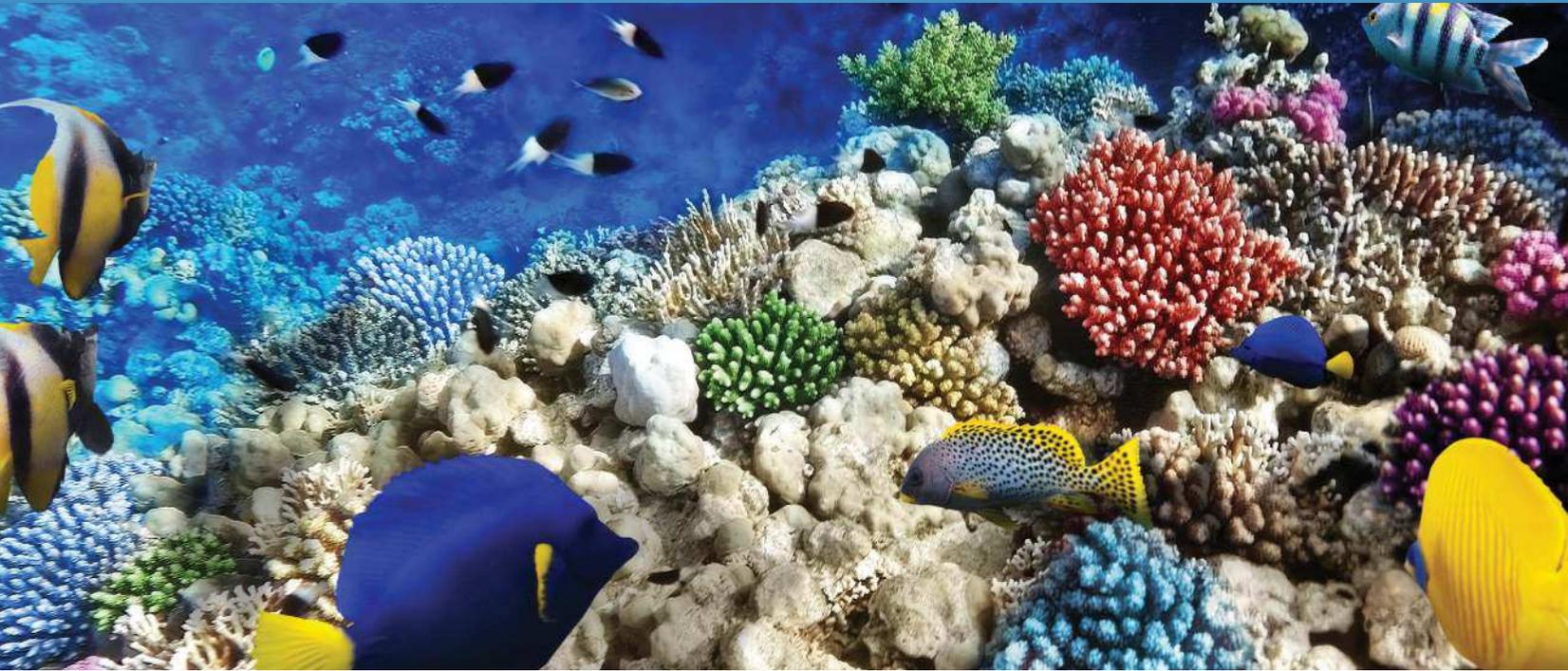


1

Water and carbon cycles



By the end of this chapter you should know:

- what a natural system is and how to describe the water and carbon cycles as natural systems
- the global distribution of major stores of water
- the main factors driving changes in the magnitude of these water stores
- how drainage basins and other geographical features function as natural systems
- the global distribution of major stores of carbon
- the main factors driving changes in the magnitude of these carbon stores
- the carbon budget and the impact of the carbon cycle on the atmosphere, ocean and land.

Figure 1.1 The ocean is the most obvious store of water on the planet, but did you know that it is also the second largest store of carbon? Carbon is stored as dissolved carbon dioxide in organisms such as coral and in seafloor sediments.

Before you start...

You should know:

- water is continuously being recycled between the land, atmosphere, rivers, lakes, oceans and living things in a process called the water cycle
- carbon is linked to fossil fuels – these are non-renewable energy resources
- the amount of carbon dioxide in the atmosphere is increasing, and this is leading to global warming.

1.1 Water and carbon cycles as natural systems

Systems in physical geography

Rain falling, wind moving the branches of a deciduous tree, meltwater dripping from the front of a glacier or sand cascading down the front of a sand dune – they all involve energy, physical geography and a change in the environment. They are natural processes, and are all also part of a larger natural system. The systems explored in this chapter are bounded.

The systems approach is a way of exploring physical processes, by focusing on one aspect within the larger environment, sometimes simplifying it so that its operation can be understood. The simplest explorations of systems view them as a 'black box'; little is known of their workings, but the inputs and outputs can be compared. The water balance of a drainage basin would be an example of this, as it could be calculated without really understanding what was going on. To understand the system, we have to open the box, and explore the internal workings. This chapter will do that for two large scale cycles.

A natural system is therefore a portion of the larger environment chosen for analysis. There are two types, and both have a number of components.

Some systems are **open**, and have inputs and outputs as well as stores and flows through the system (transfers or flux, also called throughputs). **Closed systems** tend to be cycles, with some outputs becoming inputs, and others with no inputs or outputs. In physical geography, we are particularly concerned with natural systems and the physical processes, powered by the Sun, which lead to their continued functioning without human interference.

The cycling of both water and carbon are essential to all life, and also provide us with the basis for much of the environmental change that is explored in other chapters of this book. Systems theory is useful in helping us to make sense of processes that may be global in scale, but also operate within our local area. Water could be explored at the scale of a local drainage basin, for example, but also circulates around the global hydrological cycle. Similarly, the life and death of a tree in a garden, or the management of an allotment garden involve some of the same processes as the changing use of thousands of acres of tropical rainforest.

Throughputs within the larger system may be called sub-systems. The example of the water cycle would provide us with the drainage basin sub-system. The cycling element requires there to be stores, which will change in their volume over time, fluxes, which will operate at different rates and processes which help drive the fluxes.

The water and carbon cycles are both closed systems on a global scale. On a smaller scale, however, they include open sub-systems, such as drainage basins or the workings of a tropical rainforest. The interactions between different locations on Earth, sometimes as remote tele-connections, are sometimes hard to visualise. The interactions between the water and carbon cycles are often invisible in the same way.

1.2 The water cycle

We can think of a **drainage basin** as a complex system, which is the result of the hydrological cycle operating within a geographical area of the Earth. **Hydrology** refers to the study of water on the surface of the Earth, although water is also capable of entering the surface layer of the Earth and moving



Key terms

open system: a system that has both inputs and outputs of energy or other material, and which involves a flow or exchange of material

closed system: a system that has no inputs or outputs, but which cycles energy or resources around a closed loop

drainage basin (catchment area): the area of land that provides water to a river system

hydrology: the study of water on the surface of the Earth



Making connections

Can you find a chapter in this book where there is no connection with the natural cycling of either water or carbon to some extent?

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Excerpt

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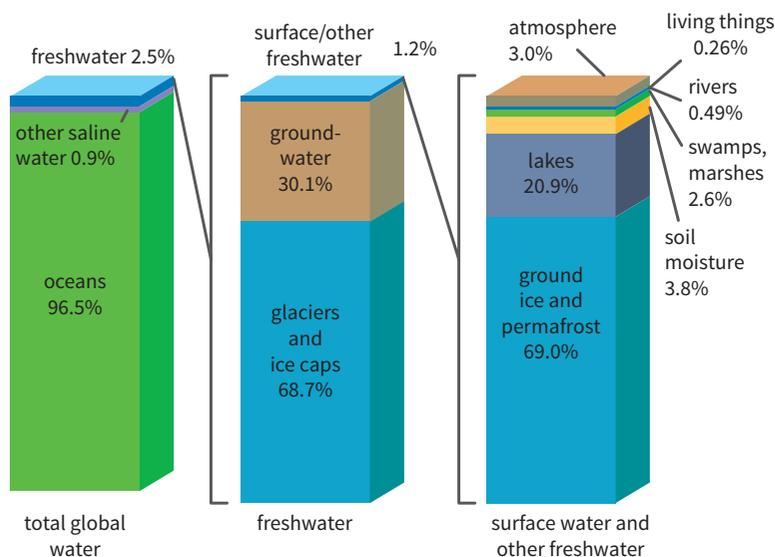
1 Water and carbon cycles

between the surface and the troposphere (the lowest layer of the atmosphere). The systems approach means that we focus on the way that water enters and leaves the drainage basin, as well as the places it may be stored, and how it moves between those stores at different rates, and over different time scales. The combination of these provides the complexity, and also means that different rivers respond differently to similar precipitation events.

Global distribution and size of major stores of water

There is a fixed amount of water on Earth and in its atmosphere, so the whole of Earth can be thought of as a closed system. The vast majority of the Earth's water is saltwater: only 2.5% of the Earth's water is fresh, and 96.5% of the saltwater is, unsurprisingly, stored in the oceans. Of the Earth's freshwater, almost 69% is locked up in glaciers and ice caps, and 30% is stored below the ground.

This leaves just 1.2% of the original freshwater available for potential use. However, much of this is locked up in ground ice. Figure 1.2 shows the distribution of major stores of water on the Earth's surface.



Note: Numbers are rounded, so total % may not be 100.

Figure 1.2 The major stores of water on the Earth's surface.

Water moves between these stores at different rates, and remains in storage for different periods of time. In moving from one store to another, water passes between different planetary 'spheres' or domains (also see section 1.3 The carbon cycle), including:

- **the lithosphere:** the rocks and soil, which may contain groundwater
- **the hydrosphere:** all the water on the Earth's surface including rivers, lakes, seas and oceans
- **the cryosphere:** the water held in the form of ice, as glaciers, ice caps and ice sheets, as well as sea ice
- **the atmosphere:** water held in the atmosphere as water vapour, including clouds.

Water is able to exist in three states: liquid, solid (ice) and water vapour (gas). It can move between these states by processes which require a change in temperature (Figure 1.3).



Making connections

The Sun's energy is used to drive all natural systems. This is explored further in section 6.2 Ecosystems and processes.

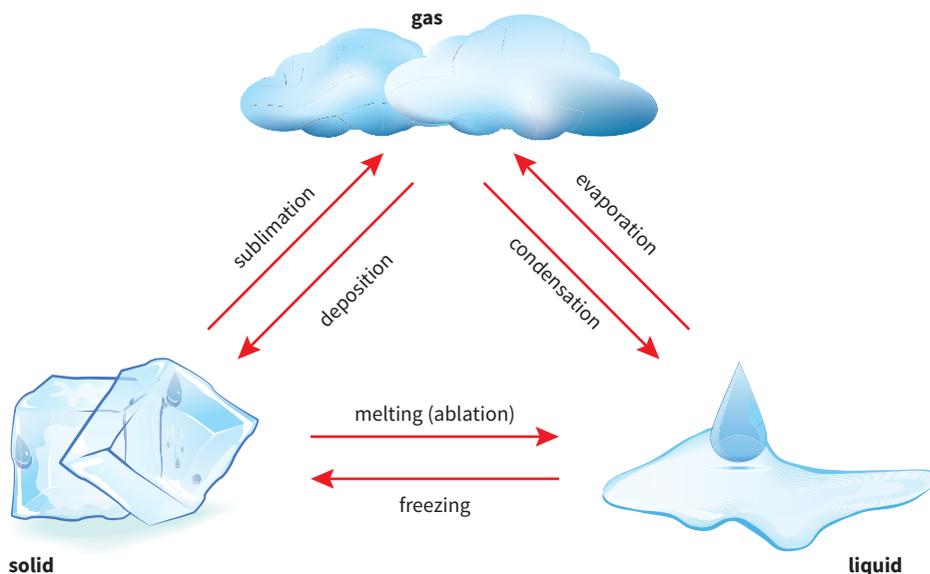


Figure 1.3 The movement of water between different physical states.



For a copy of Figure 1.3, download Worksheet 1.1 from **Cambridge Elevate**.

ACTIVITY 1.1

- 1 On a copy of Figure 1.3, add labels in the correct place to show the different movements of water between the states, and whether they require an increase or decrease in temperature to occur.
- 2 Explain the processes of evaporation and condensation, and how important they are within the hydrological cycle.

Factors driving change in the magnitude of major stores of water

The stores shown in Figure 1.2 vary temporally and spatially in the amount of water that they hold. Over time, the amount of water held in ice caps has fluctuated as global temperatures have changed. During the Ice Ages, the amount increased dramatically; at present, the Arctic sea ice is at a historical minimum. There have also been significant losses from the world's Polar ice sheets – Greenland and Antarctica. As the ice sheets decline, water is released into the oceans.

Similarly, changes in weather patterns cause the relative position of atmospheric moisture to change. Increasingly large areas of Earth are becoming affected by desertification (see Chapter 2 Hot desert systems and landscapes), with reduced soil moisture, and in some parts of the world rivers are drying up. This does not change the overall amount of water on Earth, which remains unchanged, but controls the way that is distributed globally. This may cause shortages more locally.

Rising warm air holds water vapour. As the water vapour rises, such as over relief barriers, it cools and **condenses** into clouds. These form on the windward side of a relief barrier or at the summit. Latent heat, which is used in **evaporation**, may be released at this point, slowing down the rate of cooling.

Cryospheric processes act when the temperature gets close to freezing point, or below. When water freezes, it is no longer part of the diurnal circulation. During the Ice Ages, global sea level dropped as water was 'locked away' as ice on the land. Today, some communities rely on glaciers for their water supply, but these are rapidly melting. For example, the rate of melting of Andean glaciers is threatening many cities in Peru.

A startling image created by the USGS (Figure 1.4) shows how fragile our water supply is. The blue sphere represents the amount of water relative to the size of the Earth, and of course the freshwater is a tiny fraction of that.



Key terms

condensation: a change in state from water vapour to liquid as a result of cooling

evaporation: a change in state from liquid water to water vapour, as a result of heating

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1 Water and carbon cycles

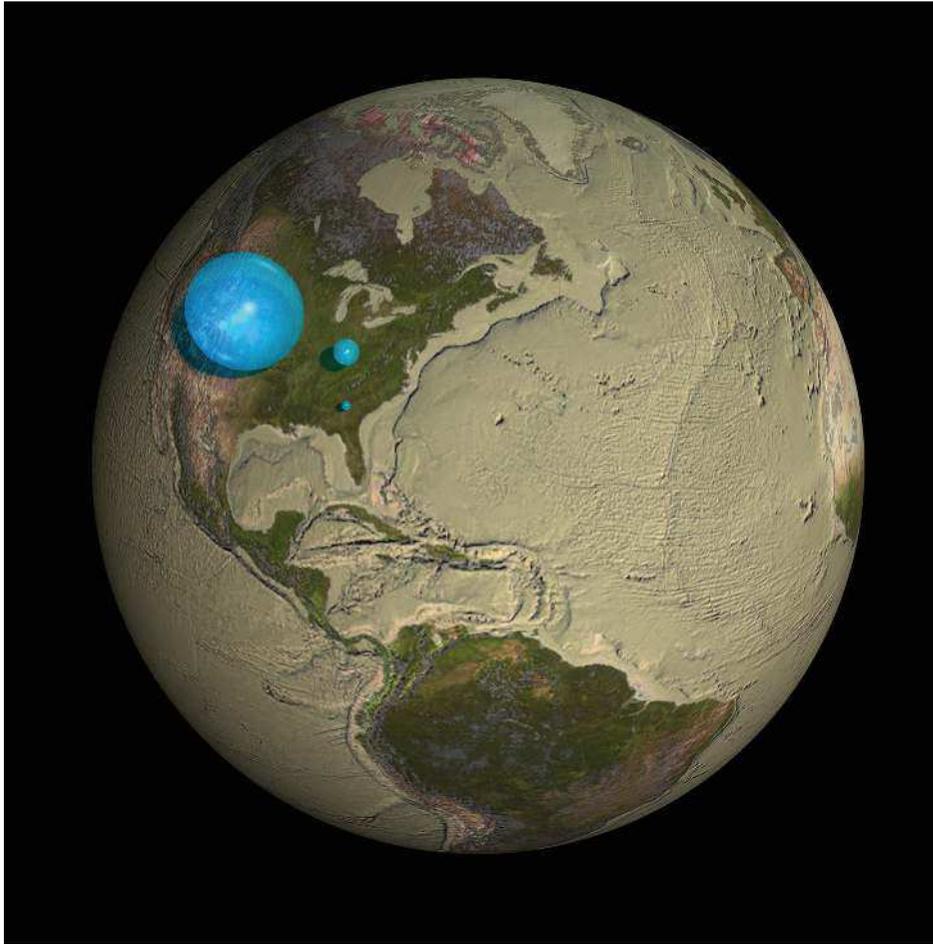


Figure 1.4 All Earth's water is contained in the blue spheres.

Drainage basins as open systems

A drainage basin or catchment area is the area of land drained by a particular river and its tributaries. Drainage basins can vary in size from a few square kilometres to millions of square kilometres, such as the area drained by the River Nile in north-east Africa. The physical boundary of a drainage basin is called a **watershed**. The watershed is marked by higher land than the surrounding area, sometimes by high mountains; from here, water is directed downslope towards the nearest river channel. Water is drained into rivers via their tributaries.

Figure 1.5 shows the different components of the drainage basin system: the inputs, outputs, stores and flows through the system. The stores are different sizes and store water for different lengths of time.

The overall balance of inputs and outputs is shown in the **water budget** or water balance equation:

$$\text{precipitation} = \text{evaporation} + \text{transpiration} + \text{river flow} \pm \text{storage}$$

The UK's water balance has a seasonal pattern in which groundwater is filled up during winter and drawn on during the warm summer months, when plants also use more water. At the end of a long dry period, there may be a water deficit. If there are several dry years in a row, river levels might be affected and crop yields could decline. Soil moisture is important in influencing other flows within the cycle. The top of the **saturated** soil is marked by the **water table**. If this is at the surface there will be higher surface runoff.



Key terms

watershed: the edge of a drainage basin

water budget: the overall balance of inputs and outputs in a drainage basin over time

saturated: all the available spaces between the soil particles are filled with water

water table: the level of the top of the saturated soil beneath the ground

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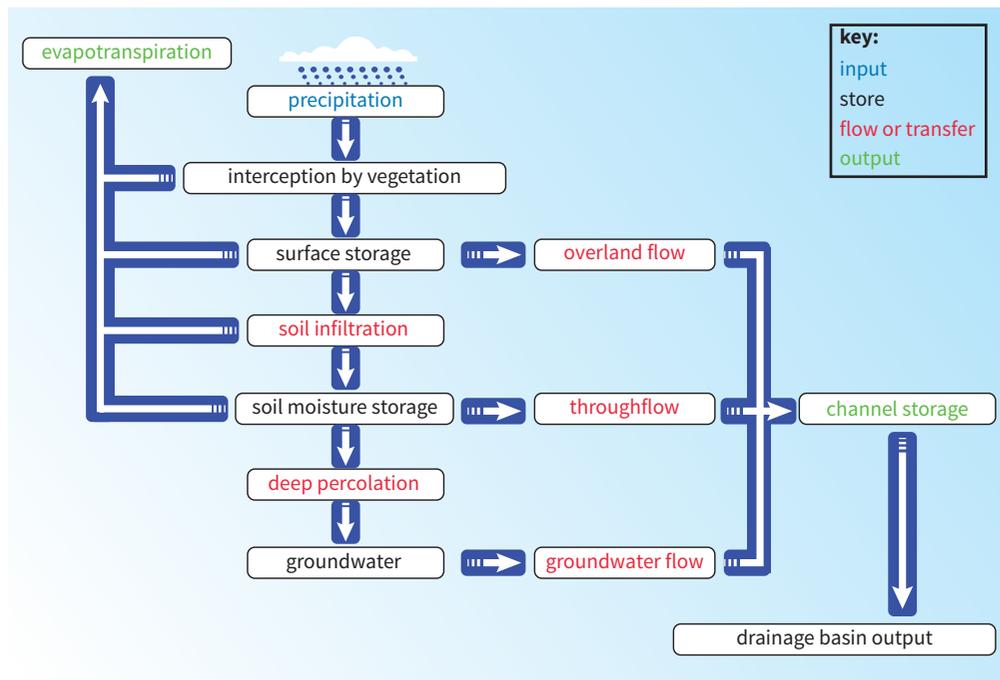


Figure 1.5 Drainage basin hydrological cycle.

Inputs

The only input for the drainage basin is **precipitation**, which is water moving from the atmosphere to the ground. Its quantity, distribution, duration and intensity will affect the pattern of flow of the river. The route that a rainfall event takes as it moves across the basin will also influence the **response** of the catchment. A storm spending a lot of time over the catchment will result in higher inputs than one that just clips the edge of it. The flowing water results in a movement of sediment.

Stores

Stores are those parts of the system where water is held in some state for a period of time. They include:

- **Interception storage:** water held on vegetation for a short period of time after precipitation has fallen. The amount of water held in interception storage will vary according to the time of year and the type of ground cover. A typical tree will catch water on its leaf surfaces: broadleaved trees will catch more than coniferous trees. This may then evaporate from these open surfaces without ever reaching the ground (hence the term 'interception'). Water will also fall off leaves as throughfall (stand under trees after rain has been falling and you will experience this) or stemflow (where water flows along branches and down tree trunks).
- **Vegetation storage:** water taken up by vegetation and absorbed into it. This will remain in the vegetation for a variable period of time, before being lost by **transpiration**.
- **Soil moisture storage and soil water:** water will soak into most soils at a rate that depends on the nature and structure of the soil (the **infiltration capacity**). Previous precipitation may fill up some of this storage and be held as soil water. Water held in the soil may evaporate if it is close



Key terms

precipitation: the movement of water from the atmosphere to the ground surface. It can take several forms, including rain, snow, sleet, hail and fog

response: the way that a river responds following the input of precipitation: some rivers rise quickly and are said to be 'flashy'; others rise and fall more slowly

transpiration: the process by which plants lose water through stomata (pores) in their leaves into the atmosphere

infiltration capacity: the rate at which water is able to pass through a soil (measured in mm/hr) – this will be high for a sandy soil; lower for a clay soil

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1 Water and carbon cycles

to the surface or be taken up by vegetation, from where it is lost by transpiration. Trees take up huge quantities of water through their root systems (Figure 1.6). They also shade nearby soil, which reduces water loss.

- **Surface (depression) storage:** water will be stored on the surface if the ground below is impermeable. Water will naturally flow into surface depressions, such as those found on roads and in car parks, and remain there until it evaporates. This may also happen where the ground is saturated, for example in fields, forming temporary depression stores.
- **Channel storage:** water is temporarily stored in river channels as it passes through a drainage basin. This store will increase after rainfall, particularly if the river overtops its banks or reaches the bankfull stage.

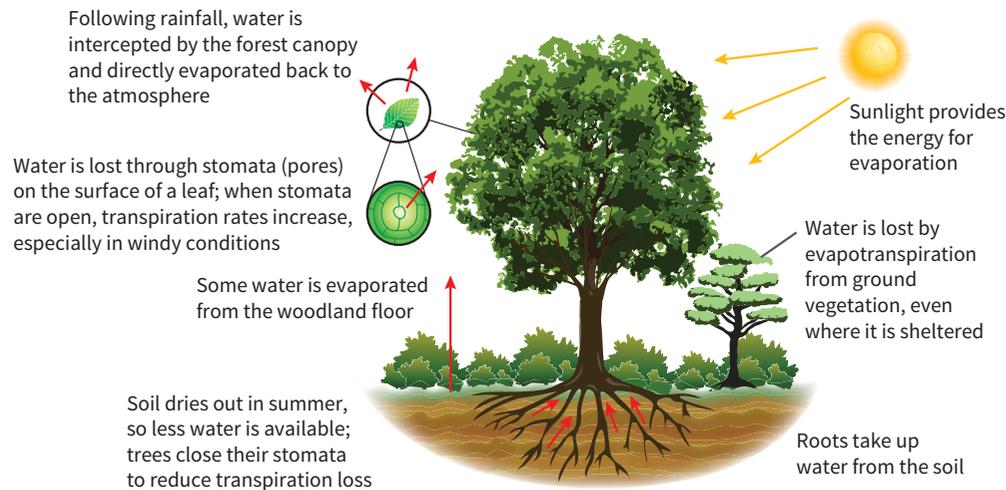


Figure 1.6 How trees use water.

Flows

Water moves between stores at different rates. Any water that falls onto an **impermeable** surface will flow downhill. It then may enter artificial drainage systems or soak into the ground in processes known as **groundwater flow** and **throughflow (interflow)**. As rain starts to fall, it may also run off normally **permeable** surfaces in the form of **overland flow (surface runoff)** if the rainfall is sufficiently intense. Over time, the ground may become saturated. Water running over the surface may also wash fine particles into any gaps between soil particles and seal them.

Once water finds its way into surface water channels, it will move as **channel flow**. This tends to be quite turbulent flow, as can be seen in rivers which are seldom clear.

Outputs

Water is lost from the drainage basin back into the atmosphere as evaporation and also as transpiration from the vegetation that grows there (**evapotranspiration**). Amounts will vary depending on the climate, the soil type and geology, and the nature of the surface drainage.

Runoff may form the main output in some drainage basins, either over the surface (see overland flow) or in the river channels, which exit the drainage basin



Key terms

impermeable: a surface that does not allow water to pass through it

groundwater flow: water moving through the soil

throughflow (or interflow): water moving through the rocks beneath the soil at a very slow rate

permeable: a surface that allows water to pass through it

overland flow (surface runoff): water flowing over the ground surface; this may be a result of impermeable surfaces, including frozen ground, or infiltration excess during heavy rainfall

channel flow: water held in the channel as it moves through the drainage basin. This will also act as temporary storage

evapotranspiration: the loss of water by evaporation and transpiration combined – a term sometimes used in equations representing water balance

runoff: water and sediment being moved down the river channel, and out of the catchment area



Making connections

The movement of water through the landscape and the importance of the cryosphere are relevant to a number of topics, including Chapter 4 Glacial systems and landscapes and Chapter 11 Resource security.

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as a result of infiltration excess. The area from which runoff occurs will increase during a precipitation event, as more of the drainage basin reaches saturation point. This increases the area of land that may contribute water to the channel as surface runoff. Management of drainage basins sometimes involves controlling the speed of runoff.



Maths for geographers

Table 1.1 shows data relating to the movement of water in and out of a drainage basin in north-west England over a year. It shows the pattern of precipitation (input) and evapotranspiration (output).

	J	F	M	A	M	J	J	A	S	O	N	D
precipitation (mm)	130	126	120	115	110	96	105	112	123	130	134	112
evapotranspiration (mm)	22	34	60	90	110	128	133	136	125	80	42	18

Table 1.1 Water balance values for a location in north-west England.

- Construct a line graph for each of the two variables on the same set of axes. Use a different colour for each.
- Using the water budget equation:

$$\text{precipitation} = \text{evaporation} + \text{transpiration} + \text{river flow} \pm \text{storage}$$

- Identify months when there is a surplus of water available.
 - Identify months when there is a water deficit, and where soil moisture may be depleted because evapotranspiration is greater than precipitation.
 - Identify months when groundwater is being recharged.
- Add up the total value.
 - How much water is available for river flow and storage?
 - What would be the impact on river flow of a year with above average precipitation?
 - What changes could be made to this drainage basin to reduce the amount of water available for river flow?



For a copy of the axes for question 1, download Worksheet 1.2 from **Cambridge Elevate**.

Runoff variation and the flood hydrograph

The response of a river to a period of rainfall can be shown on a **hydrograph**. This generally shows a steady **base flow**, which may rise or fall during periods of rainfall or drought, but is usually within specific parameters based on the local geology and average monthly precipitation levels. River gauges, which measure **discharge**, are now monitored constantly and send back readings remotely. River discharge is the volume of water flowing through a river channel at any given point in a given time. The hydrograph that is produced by a particular river will reflect its response to the initial input of precipitation.

The discharge of a river (Q) is calculated using the equation:

$$Q = VA$$

where V is the velocity of the river (in metres per second) and A is the mean cross-sectional area (in metres squared). This results in a measurement of discharge in cubic metres per second (cumeecs).



Key terms

hydrograph: a graph of the water level or base flow in a river over a period of time, such as a year, and the response of the river to a precipitation event

base flow: the normal day-to-day flow of a river

discharge: water flowing through a river channel at any given point and is measured in cubic metres per second (cumeecs)

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A typical value for a small mountain stream would be less than 1 cumec, whereas the River Thames through London after rainfall has a flow of hundreds of cumecs.

Figure 1.7 is a flood hydrograph for a typical river and shows the response of the river to a precipitation event. Flood hydrographs are drawn over a short time period of hours or days.

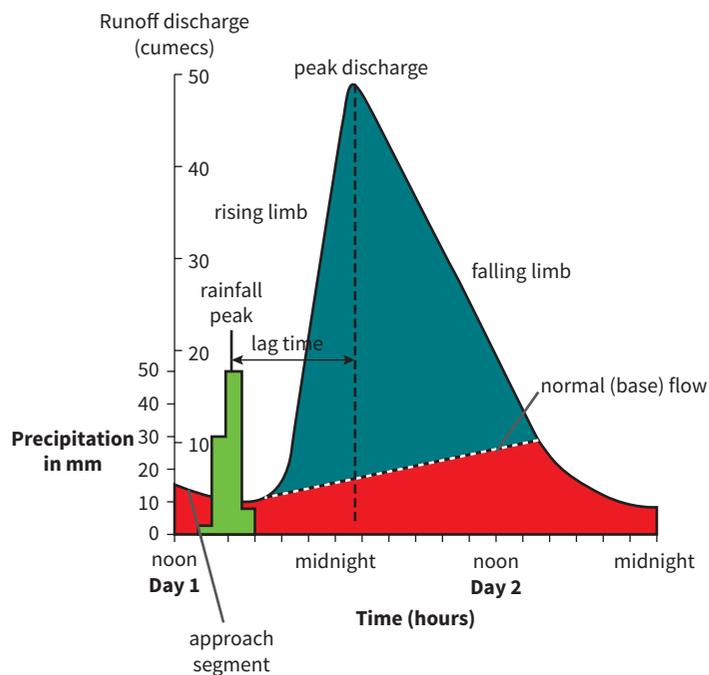


Figure 1.7 A typical flood hydrograph.

The peak rainfall time is marked on the hydrograph. You can see how the river rises a few hours after the rainfall event (**rising limb**). However, there is a time delay (the **lag time**) between peak rainfall and peak discharge as water needs to make its way to the river channel by various means. The delayed arrival from some types of flow might extend the peak of the graph (peak discharge) and therefore the lag time. The graph shows a **falling limb**, where the river is gradually returning to its normal, or base, flow. The total area under the hydrograph can be used to calculate how much water a rainfall event has contributed to the river.

The shape of the hydrograph for each river will vary depending on the nature of the rainfall that caused the discharge to increase. Intense rainfall will cause a more rapid increase than less intense rainfall.

Prolonged rainfall may take time to register, but the period of high flow might be extended. Water takes time to enter the river by different routes, and the falling limb will have a different gradient depending on the nature of these flows.

The route taken by any precipitation event may influence how river gauges respond. They are located at a few places down the course, and will not respond to rainfall that falls lower down the channel.

Factors affecting river discharge

Both physical and human factors can cause a river's discharge to vary over time (Tables 1.2 and 1.3 respectively). Although these are often local changes, some of the controlling factors may change as a result of processes of change on a

1 Water and carbon cycles



Key terms

rising limb: the part of a hydrograph that records the increase in a river's flow

lag time: the time difference between the peak rainfall and the peak discharge that occurs as a result

falling limb: the part of a hydrograph that records the decrease in a river's flow

ACTIVITY 1.2

The rivers in England are monitored by the Environment Agency. All river gauges now have a weblink so that the recent flow is monitored and displayed live, with Twitter updates for each one.

Find your nearest river gauge and monitor it for the time that you are learning this topic.

- 1 What changes do you notice?
- 2 How does the river respond to any rainfall events during this time?
- 3 How does it compare to other gauge locations which may be further up or down the river channel? Can any aspects of the drainage basin be deduced from changes in the flow at particular gauges?



Look on **Cambridge Elevate** to access the GaugeMap (www.cambridge.org/links/gase6001).



Look on **Cambridge Elevate** for rivers in Wales. Go to Natural Resources Wales (www.cambridge.org/links/gase6002).

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larger scale, such as the shifting of rainfall patterns over the longer term. Many desert regions, for example, have previously had a wetter climatic pattern which may have formed some of the relict landforms that are found there. These factors influence the working of the natural drainage basin system.

Geology (and soils)	Impermeable rocks (and clay soils) result in a rapid rise in discharge, whereas permeable or porous rocks may store water for a period, along with sandy soils which allow water to enter them (a high infiltration capacity).
Relief	Steep slopes cause rapid water movement in upland areas, whereas gentle slopes transfer water more slowly.
Drainage density	This refers to the average length of stream channels per square kilometre – higher values increase discharge levels more rapidly.
Vegetation	Vegetation intercepts precipitation, which may then be lost by evapotranspiration. Well-vegetated catchments delay rises in river discharge as the water is caught up on leaves or taken up by plants. In areas with deciduous trees there may also be seasonal variations in drainage as tree cover grows in spring and leaves are shed in autumn.
Antecedent soil moisture	Previous rainfall may have caused soil storage to be at, or close to, saturation, and discharge may be higher.
Precipitation type	Snow will release water once it melts, which may be weeks or months after it has fallen, and result in raised river levels after warm weather.
Precipitation intensity	Thunderstorms may provide rainfall which exceeds the infiltration capacity of the soil and lead to flash flooding. These are more common in summer than at other times of year.

Table 1.2 Physical factors affecting river discharge.

Land use	Catchment that has stopped being natural will tend to offer an impermeable surface to rainfall and speed drainage. This is particularly the case where there is additional drainage installed. This would speed up the flow of water into the river channel, and there could also be problems if the drains are blocked by storm debris.
Agriculture	Some farming practices may result in extra surface drainage. Livestock can compress the surface soil with their hooves, and loose soil may also be washed away. This not only affects water quality in the river but also potentially increases the risk of flooding. Water may also be abstracted from the river for use in irrigation during dry periods. This will be done under licence.
Construction	Some construction may restrict the channel. Water may flow faster through bridges, which may also become blocked by floating debris during high flow and form temporary debris dams. There may also be reservoirs, which hold back water, and delay its arrival into the lower channel. Any levees or raised riverbanks ultimately increase the channel capacity and may change the efficiency of the channel (its ability to transfer water). In places like Boscastle in Cornwall, which have experienced flash flooding, local river channels are often placed in larger artificial courses, and bridge levels are raised.

Table 1.3 Human factors affecting river discharge.

**Tip**

Although the term 'infiltration capacity' sounds like it is an amount of water that the soil can hold, it is actually a rate (measured in mm/hour).

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Excerpt

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1 Water and carbon cycles



Making connections

Flooding is a significant hazard, and the location of many cities increases their flood risk. This is explored in section 9.5 Urban drainage.



Watch a video on **Cambridge Elevate** about the effects of flooding in Tewkesbury, UK.

Changes in the water cycle over time

All drainage basins will undergo natural variations over time, which will influence the water cycle. These vary in scale and also through the year. There will be seasonal changes.

Storm events will occur during the year. Some individual storms may be significant enough to result in major changes, such as the record rainfall that fell in parts of Cumbria in December 2015. Water may also be abstracted at certain times of year for irrigation, which may result in a lowering of the water levels. If oxygen levels in the river drop as a result, fish are threatened. For this reason, abstraction of water on a large scale requires a license.

Catchments are also subject to change as a result of human activities which influence the way they are managed and used. Management of the river for water supply, construction along its course and the seasonal changes in weather and vegetation cover will also influence the way that water moves through the drainage basin.

Typical changes

Typical changes which might be observed include:

- the removal of vegetation, such as deforestation (removal of trees) for construction
- impermeable surfaces such as concrete and tarmac replacing permeable ones as houses and roads are built as a result of urbanisation (Figure 1.8)
- changing land-use practices by farmers, such as drainage, or changes in cropping.

Each of these changes would change the balance of transfers between the different stores, and the overall water balance at the end of each year. This may affect the availability of soil moisture and the flow in river channels. The water cycle will continue, but the relative importance of certain stores, and the rate of movement through the cycle, will also vary.



Figure 1.8 House construction changes the drainage basin's response to rainfall.

ACTIVITY 1.3

- 1 Use Ordnance Survey maps of different ages to explore the changes that have taken place in a selected 5 km stretch of river. Produce an annotated map or sketch map to show the changes that you identify.



Tip

Access Ordnance Survey maps of different ages to explore the changes that have taken place in your local area, *particularly on the urban–rural fringe of settlements, where the rate of change has often been fastest*. These can be accessed online if you do not have paper copies.