1 The operation and importance of the hydrological cycle

What are the processes operating within the hydrological cycle from global to local scale?
By the end of this chapter you will:

- understand the importance of the hydrological cycle in supporting life on Earth and how it operates at a range of spatial and temporal scales
- know that the global hydrological cycle is a closed system and that the drainage basin, a subsystem within it, is an open system
- understand how inputs, stores, flows and outputs operate within systems
- understand how inputs, stores, flows and outputs contribute to contrasting water budgets, river regimes and storm hydrographs at a more local scale.

1.1 The operation of the hydrological cycle at a global scale

In order to understand the operation of the hydrological cycle (also known as the natural water cycle) a systems approach is useful. Three concepts are key to understanding how water cycling operates:

1. Stores (stocks), which are reservoirs where water is held, such as the oceans.
2. Fluxes, which measure the rate of flow between the stores.
3. Processes, which are the physical mechanisms which drive the fluxes of water between the stores.

Key terms

Systems approach: Systems approaches study hydrological phenomena by looking at the balance of inputs and outputs, and how water is moved between stores by flows.

Stores: Reservoirs where water is held, such as the oceans.

Fluxes: The rate of flow between the stores.

Processes: The physical mechanisms that drive the fluxes of water between the stores.

Cryosphere: Areas of the Earth where water is frozen into snow or ice.

The global hydrological cycle

The global hydrological cycle is an example of a closed system driven by solar energy and gravitational potential energy. In a closed system there is a fixed amount of water in the Earth–atmosphere system (estimated at 1385 million km^3). A closed system does not have any external inputs or outputs, so this total volume of water is constant and finite. However, the water can exist in different states within the closed system (liquid water, water vapour gas and solid ice) and the proportions held in each state can vary for both physical and human reasons.

For example, in the last Ice Age more water was held within the cryosphere in a solid form as snow and ice; as less was held in the oceans, sea levels dropped considerably – over 140 m lower than they are today. Recent climate warming is beginning to reverse this with major losses of ice in Greenland and, more recently, Antarctica, and significant rises in sea level (see page 37 for the impacts of climate warming). At a small scale, humans have built numerous water storage reservoirs to complement natural lakes in order to increase the security of their water supplies.

Figure 1.1 shows how the global hydrological cycle works. Essentially there are four major stores of water, of which the oceans are by far the largest: they contain an estimated 96.5 to 97 per cent of the world's total water. The next largest stores occur in the cryosphere (1.9 per cent), and then shallow groundwater. The atmosphere is by far the smallest of the significant stores.

Table 1.1 shows a recent estimate of the size of these stores.

① In the oceans the vast majority of water is stored in liquid form, with only a minute fraction as icebergs

② In the cryosphere water is largely found in a solid state, with some in liquid form as melt water and lakes.

③ On land the water is stored in rivers, streams, lakes and groundwater in liquid form. It is often known as **blue water**, the visible part of the hydrological cycle. Water can also be stored in vegetation after interception or beneath the surface in the soil. Water stored in the soil and vegetation is often known as **green water**, the invisible part of the hydrological cycle.

④ Water largely exists as vapour in the atmosphere, with the carrying capacity directly linked to temperature. Clouds can contain minute droplets of liquid water or, at a high altitude, ice crystals, both of which are a precursor to rain.

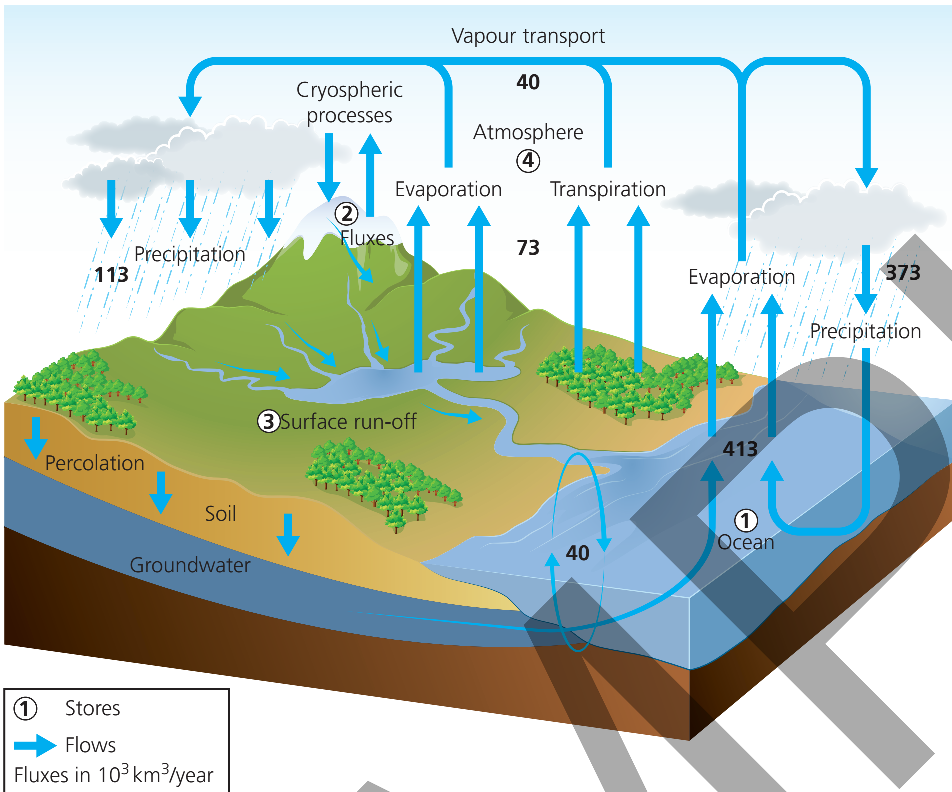


Figure 1.1 The global water cycle

Key terms

Blue water: Water is stored in rivers, streams, lakes and groundwater in liquid form (the visible part of the hydrological cycle).

Green water: Water stored in the soil and vegetation (the invisible part of the hydrological cycle).

Table 1.1 Details of the main global water stores; note that numbers are rounded so the totals may not add up to 100

Store	Volume (10^3 km^3)	Percentage of total water	Percentage of freshwater	Residence time
Oceans	1,335,040	96.9	0	3,600 years
Icecaps	26,350	1.9	68.7	15,000 years depending on size
Groundwater	15,300	1.1	30.1	Up to 10,000 years for deep groundwater; 100–200 years for shallow groundwater
Rivers and lakes	178	0.01	1.2	2 weeks to 10 years; 50 years for very large scale
Soil moisture	122	0.01	0.05	2–50 weeks
Atmospheric moisture	13	0.001	0.04	10 days

Key terms

Precipitation: The movement of water in any form from the atmosphere to the ground.

Evaporation: The change in state of water from a liquid to a gas.

Residence time: The average time a water molecule will spend in a reservoir or store.

Fossil water: Ancient, deep groundwater from former pluvial (wetter) periods.

Transpiration: The diffusion of water from vegetation into the atmosphere, involving a change from a liquid to a gas.

Groundwater flow: The slow transfer of percolated water underground through pervious or porous rocks.

In Figure 1.1 (page 3) the major fluxes are shown, driven by key processes such as **precipitation**, **evaporation**, cryospheric exchange, and run-off generation (both surface and groundwater). These fluxes have been quantified, with the most important being evaporation from the oceans and precipitation on to land and the oceans.

Table 1.1 (page 3) allows you to compare **residence times**. These are the estimates of the average times a water molecule will spend in that reservoir or store. Residence times impact on turnover within the water cycle system. Groundwater, if it is deep seated, can spend over 10,000 years beneath the Earth's surface. Some ancient groundwater, such as that found deep below the Sahara Desert – the result of former pluvial (wetter) periods – is termed **fossil water** and is not renewable or reachable for human use. Major ice sheets too (such as Antarctica and Greenland) store water as ice for very long periods, so the figures in the table represent an average. Ice core dating has suggested that the residence time of some water in Antarctic ice is over 800,000 years.

Conversely, some very accessible stores, such as soil moisture, and small lakes and rivers, have much shorter residence times. Water stored in the soil, for example, remains there very briefly as it is spread very thinly across the Earth. Because of its accessibility it is easily lost to other stores by evaporation, **transpiration**, **groundwater flow** or recharge.

Atmospheric water has the shortest residence time of all, about ten days, as it soon evaporates, condenses and falls to the Earth as precipitation. There is a strong link between residence times and levels of water pollution: stores with a slower turnover tend to be more easily polluted as the water is *in situ* for a longer length of time.

Accessible water for human life support

Figure 1.2a–c summarises where the Earth's total global water is stored, with an overwhelming 96 to 97 per cent stored in the oceans – only around 2.5 per cent occurs as freshwater.

Figure 1.2b looks at the Earth's freshwater supply. Around 69 per cent is locked up in snowflakes, ice sheets, ice caps and glaciers found in high latitudes and high-altitude locations. This water supply is largely inaccessible for human use, although some

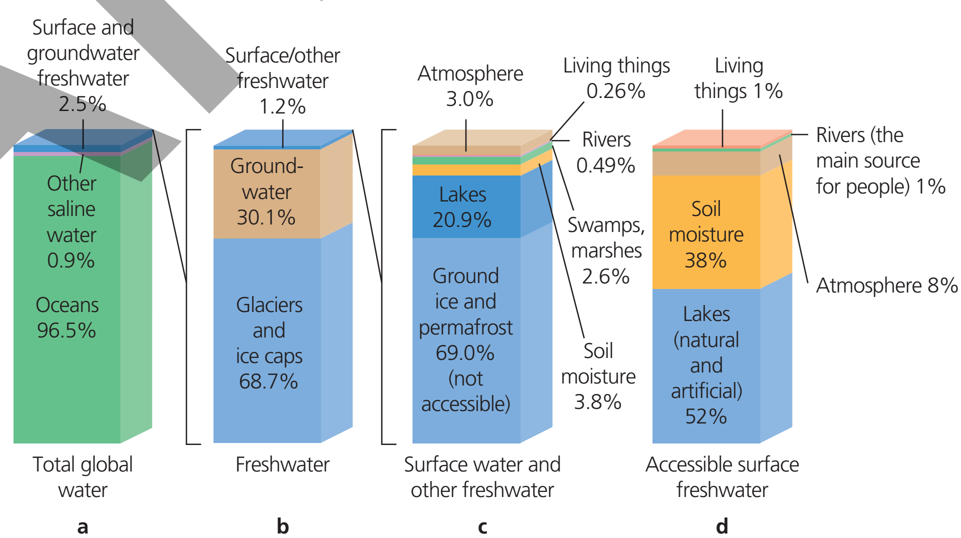


Figure 1.2 Where is the Earth's water? (Source: Adapted from Igor Shiklomanov's 'World freshwater resources' in Peter Gleick (editor), 1993, *Water in Crisis: A Guide to the World's Freshwater Resources*)

streams in mountain areas are 'fed' from ice and snow as melt water. Another 30 per cent occurs as groundwater, some of which is very deep seated as fossil water and, therefore, also inaccessible. This leaves only around one per cent of freshwater which is easily accessible for human use.

Figure 1.2c includes all sources of surface water, including ground ice and permafrost, which are very difficult to access.

Figure 1.2d shows only freshwater that is accessible to humans with current levels of technology – note the importance of lakes and soil moisture. Rivers, which are currently the main source of surface water for humans, constitute only 0.007 per cent of *total* water. It is not surprising that there are so many concerns and disputes about the usage of this tiny, precious fraction. As with any global overview, the differences between places are masked and, in terms of availability of water, it is a very unequal world. It is also notable that technology is being used widely to extend the availability of freshwater supplies, for example, by desalination of ocean water.

1.2 The operation of the drainage basin as an open system

The drainage basin water cycle

On a smaller scale (variable from regional to local, depending on the size of the drainage basin) the drainage basin is a subsystem within the global hydrological cycle. It is an open system as it has external inputs and outputs that cause the amount of water in the basin to vary over time. These variations can occur at different temporal scales, from short-term hourly through to daily, seasonal and annual (Figure 1.3).

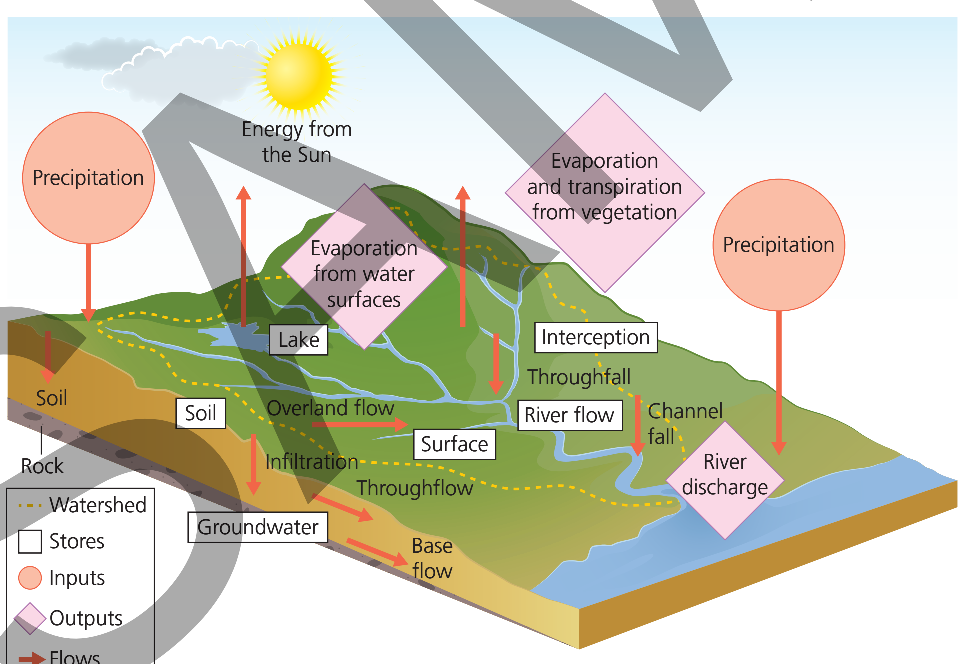


Figure 1.3 The drainage basin cycle

Key terms

Catchment: The area of land drained by a river and its tributaries.

Watershed: The high land which divides and separates waters flowing to different rivers.

Condensation: The change from a gas to a liquid, such as when water vapour changes into water droplets.

Dew point: The temperature at which dew forms; it is a measure of atmospheric moisture.

A drainage basin can be defined as the area of land drained by a river and its tributaries, and is frequently referred to as a river **catchment**. The boundary of a drainage basin is defined by the **watershed**, which is usually a ridge of high land which divides and separates waters flowing to different rivers.

Drainage basins can be of any size, from that of a small stream possibly without tributaries up to a major international river flowing across borders of several countries.

Figure 1.4 shows how a drainage basin works. It has the advantage of showing the inter-linkages between components of the system.

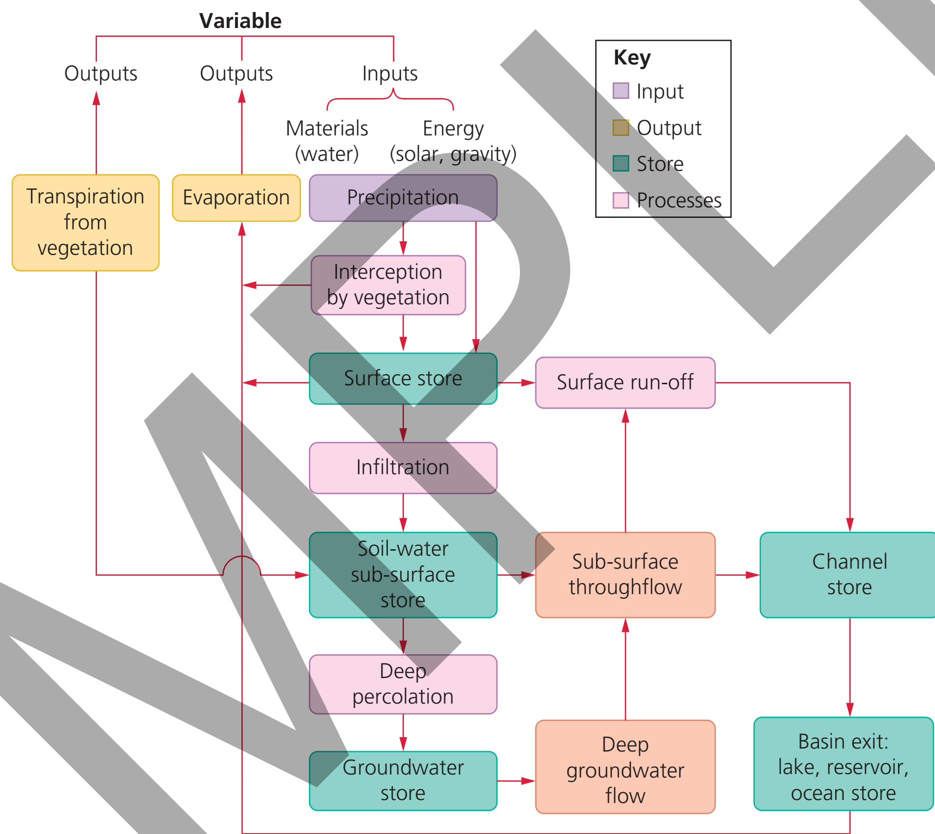


Figure 1.4 A drainage basin as a hydrological system

Drainage basin system inputs

Precipitation

For precipitation (rain, snow, hail) to form, certain conditions are needed:

- air cooled to saturation point with a relative humidity of 100 per cent
- **condensation** nuclei, such as dust particles, to facilitate the growth of droplets in clouds
- a temperature below **dew point**.

There are three main triggers for the development of rainfall, all of which involve uplift and cooling and condensation (Figure 1.5).

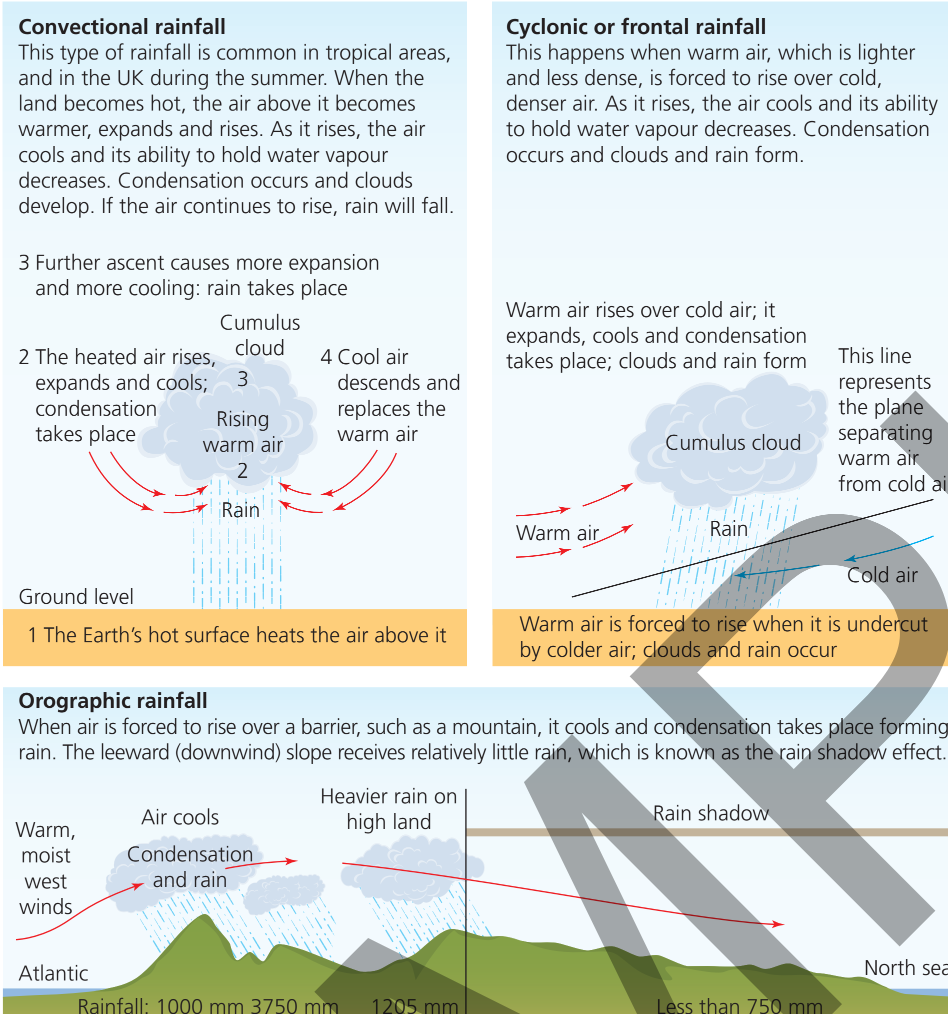


Figure 1.5 The three types of rainfall

As far as the impacts on the drainage basin hydrological system are concerned, there are six key influencing factors:

1. The amount of precipitation, which can have a direct impact on drainage discharge: as a general rule, the higher the amount the less variability in its pattern.
2. The type of precipitation (rain, snow or hail): the formation of snow, for example, can act as a temporary store and large fluxes (flows) of water can be released into the system after a period of rapid melting resulting from a thaw.
3. Seasonality. In some climates, such as monsoon, Mediterranean or continental climates, strong seasonal patterns of rainfall or snowfall will have a major impact on the physical processes operating in the drainage basin system.
4. Intensity of precipitation is also a key factor as it has a major impact on flows on or below the surface. It is difficult for rainfall to infiltrate if it is very intense, as the soil capacity is exceeded.

Precipitation data

It is important to recognise that data on precipitation may not always be reliable. In the UK, 200 automated weather stations spaced about 40 km apart continuously collect precipitation data. In the semi-arid Sahel countries of Mali, Chad and Burkina Faso roughly 35 weather stations collect data across an area of 2.8 million km² (more than 10 times the area of the UK). Major storms can easily fall between these weather stations because rainfall is geographically patchy, especially when it is non-frontal. Understanding rainfall patterns and trends is critical in semi-arid areas (see page 27) but data reliability in these regions is often low.

Rain shadow

A rain shadow is a dry area on the leeward (downwind) side of the mountain. It receives little rainfall as the mountains shelter it from rain-producing weather systems. As the moist air is forced to rise on the windward side of the mountain, rainfall occurs as a result of adiabatic cooling (when the volume or air increases but there is no addition of heat), and condensation to dew point. The air, without much water left in it, is then drawn over the mountains where it descends and is adiabatically warmed by compression. This leads to a very dry 'shadow' area, for example, the Owens Valley is in the rain shadow of the Sierra Nevada range in California.

Key terms

Convectional rainfall: Often associated with intense thunderstorms, which occur widely in areas with ground heating such as the Tropics and continental interiors.

Cyclonic or frontal rainfall: A period of sustained, moderately intensive rain; it is associated with the passage of depressions.

Orographic rainfall: Concentrated on the windward slopes and summits of mountains.

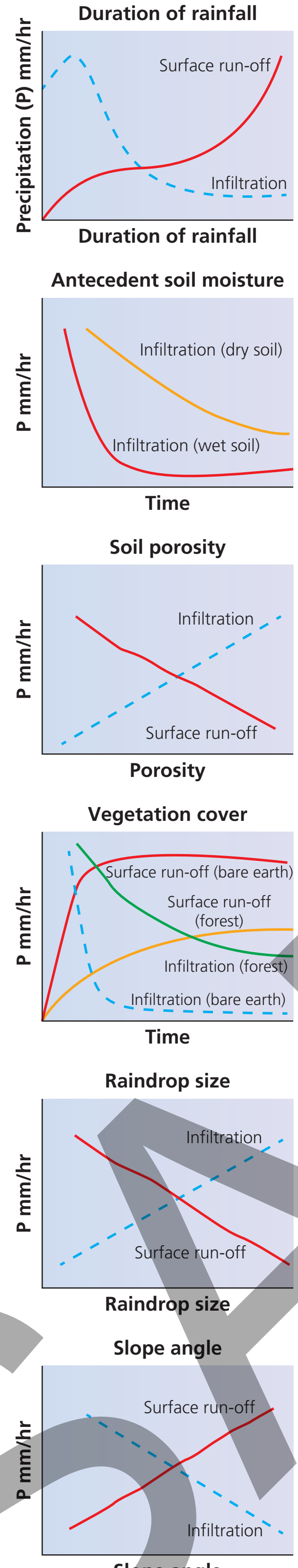


Figure 1.6 Some of the factors influencing the rate of infiltration

5 Variability can be seen in three ways:
- Secular variability happens long term, for example, as a result of climate change trends.
- Periodic variability happens in an annual, seasonal, monthly or diurnal context.
- Stochastic variability results from random factors, for example, in the localisation of a thunderstorm within a basin.

6 The distribution of precipitation within a basin. The impact is particularly noticeable in very large basins such as the Rhone or the Nile, where tributaries start in different climatic zones. At a local scale and shorter time scale the location of a thunderstorm within a small river basin can have a major impact temporarily as inputs will vary, with contrasting storm hydrographs for different stream tributaries.

Fluxes (flows) in the drainage basin

Interception

Interception is the process by which water is stored in the vegetation. It has three main components: interception loss, throughfall and stem flow.

Interception loss from the vegetation is usually greatest at the start of a storm, especially when it follows a dry period. The interception capacity of the vegetation cover varies considerably with the type of tree, with the dense needles of coniferous forests allowing greater accumulation of water. There are also contrasts between deciduous forests in summer and in winter – interception losses are around 40 per cent in summer for certain Chiltern beech forests, but under twenty per cent in winter. Coniferous forest intercepts 25–35 per cent of annual rainfall, whereas deciduous forest only 15–25 per cent and arable crops 10–15 per cent.

Meteorological conditions also have a major impact. Interception varies by vegetation cover. Wind speeds can decrease interception loss as intercepted rain is dislodged, and they can also increase evaporation rates. The intensity and duration of rainfall is a key factor too. As the amount of rainfall increases, the relative importance of interception losses will decrease: as the tree canopies become saturated, so more excess water will reach the ground. There are also variations for agricultural crops, with interception rates increasing with crop density.

Infiltration

Infiltration is the process by which water soaks into (or is absorbed by) the soil. The infiltration capacity is the maximum rate at which rain can be absorbed by a soil in a 'given condition' and is expressed in mm/hr. The rate of infiltration depends on a number of factors, as shown in Figure 1.6.

Key terms

Interception loss: This is water that is retained by plant surfaces and later evaporated or absorbed by the vegetation and transpired. When the rain is light, for example, drizzle, or of short duration, much of the water will never reach the ground and will be recycled by this process (it's the reason you can stand under trees when it is raining and not get wet).

Throughfall: This is when the rainfall persists or is relatively intense, and the water drops from the leaves, twigs, needles, etc.

Stem flow: This is when water trickles along twigs and branches and then down the trunk.

Infiltration: The movement of water from the ground surface into the soil.

Infiltration capacity: The maximum rate at which rain can be absorbed by a soil.

Fieldwork opportunity

Infiltration rates can be measured fairly cheaply and easily using home-made equipment (Figure 1.7). Sink a bottomless container made from a plastic pipe (a diameter of 20 cm is ideal) 10 cm into the ground. Fill the container with water until the water measures 15 cm above the ground. Record the time it takes for the water level to drop by 5 cm. Keep topping up the water and record the times until they are constant for three successive periods. Calculate the results in mm/second:

$$\text{Infiltration rate} = \frac{\text{difference in levels at 5 cm}}{\text{time taken for water level to be reached}}$$

The factors you can usually test for by sampling a comparatively small area include: type of surface cover, soil moisture (using a probe), soil texture (mechanical analysis), angle of slope (using a clinometer), soil compaction and rainfall pattern over a given time (rain gauge, etc.). You can also use a geology map to look at the impact of underlying geology.

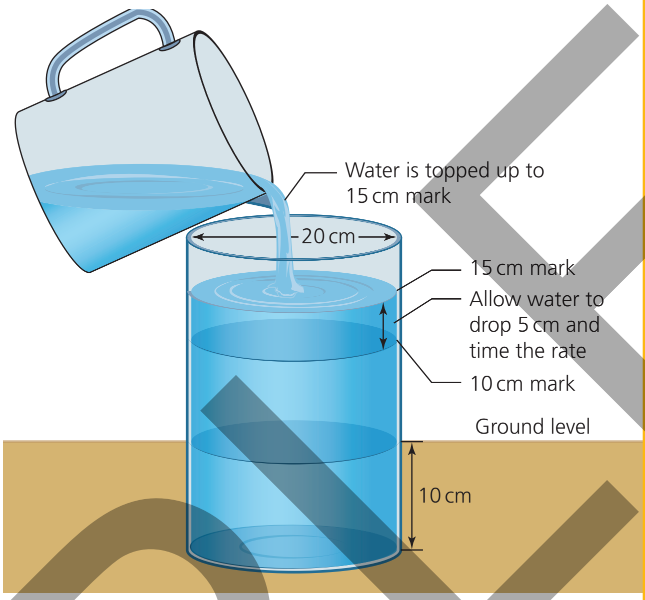


Figure 1.7 Measuring infiltration rates

- Infiltration capacity decreases with time through a period of rainfall until a more or less constant low value is reached.
- The rate of infiltration also depends on the amount of water already in the soil (antecedent soil moisture) as surface or overland flow will take place when the soil is saturated.
- Soil texture – whether sand, silt, loam or clay – also influences soil porosity, with sandy soils having an infiltration capacity of 3–12 mm/hr and less permeable clays 0–4 mm/hr.
- The type, amount and seasonal changes in vegetation cover are a key factor, with infiltration far more significant in land covered by forests (50 mm/hour) or moorland (42 mm/hour), hence the recent drive to vegetate upland catchments that flow into areas liable to flooding. Permanent pasture has infiltration rates of 13–23 mm/hour depending on grazing density and soil type.
- The nature of the soil surface and structure is also important. Compacted surfaces inhibit infiltration (around 10 mm/hour), especially when rain splash impact occurs.
- Slope angle can also be significant: very steep slopes tend to encourage overland run-off, with shallower slopes promoting infiltration.

As Figure 1.6 shows, infiltration is inversely related to **surface run-off** (overland flow), which is also influenced by similar factors.

Key term

Surface run-off: The movement of water that is unconfined by a channel across the surface of the ground. Also known as overland flow.

Flows and transfers (see Figure 1.8)

1 Overland flow (variously known as surface run-off or direct overland flow on account of its rapidity in reaching the river channel) is a concept developed by Horton. He saw this flow as the main way that rainwater was transferred to the river channel. For this type of flow to occur, precipitation intensity must exceed the infiltration rate. Circumstances include an intense torrential storm, persistently high levels of precipitation over a longer period, or the release of very large quantities of

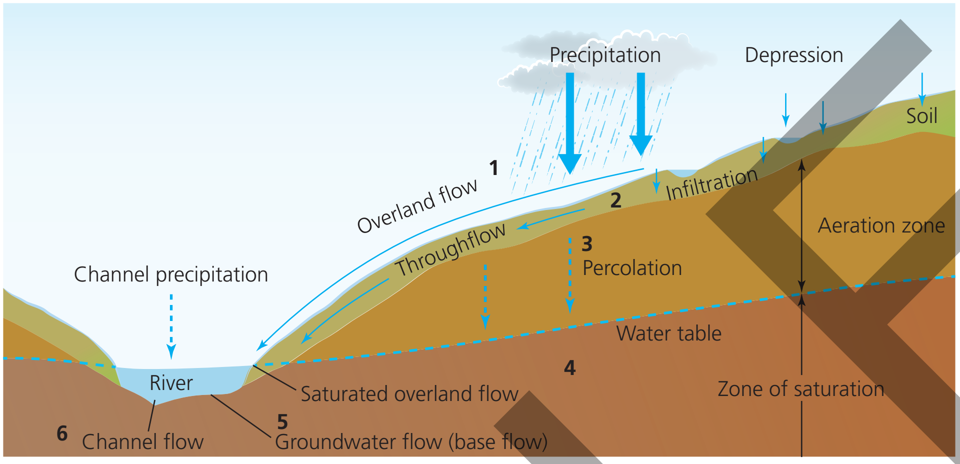


Figure 1.8 How the various flows operate within the drainage basin system

melt water from the rapid melting of snow. Alternatively, bare, 'baked' unvegetated surfaces, which commonly occur in arid or semi-arid regions, also lend themselves to overland flow as this type of ground has very limited infiltration capacity. This type of flow is the primary agent of soil erosion as sediment is removed by a range of erosive processes: rain splash, sheet, rill and gully erosion. Direct overland flow occurs once depression storage capacity in puddles has been exceeded. Overland flow is also a feature of many urban areas (see page 18), especially when the capacity of storm drains and sewers has been exceeded.

2 **Throughflow** refers to the lateral transfer of water down slope through the soil via natural pipes and **percolines** (lines of concentrated water flow between soil horizons to the river channel). While slower than direct overland flow, this shallow transfer can occur quite rapidly in porous, sandy soils.

3 **Percolation** can be regarded as a continuation of the infiltration process; it is the deep transfer of water into permeable rocks – those with joints (pervious rocks such as carboniferous limestone) or those with pores (porous rocks such as chalk and sandstone). The throughflow percolation route is much more likely to be associated with humid climates with vegetated slopes.

4 **Saturated overland flow** is a much slower transfer process as it results from the upward movement of the water table into the evaporation zone. After a succession of winter storms (for example, in the UK during the winters of 2015 or 2019) the water table rises to the surface in depressions and at the base of hill sides. This leads to saturated overland flow making a major contribution to **channel flow** and is a component of flooding.

5 Groundwater flow (also known as base flow or interflow) is the very slow transfer of percolated water through pervious or porous rocks. It is a vital regulatory component in maintaining a steady level of channel flow in droughts and other varying weather conditions.

6 Channel flow takes place in the river once water from the three transfer processes – overland flow, throughflow or groundwater flow – reaches it. Direct channel precipitation is added to **channel storage**.

Key terms

Throughflow: The lateral transfer of water down slope through the soil via natural pipes and percolines.

Percolines: Lines of concentrated water flow between soil horizons to the river channel.

Percolation: The transfer of water from the surface or from the soil into the bedrock beneath.

Saturated overland flow: The upward movement of the water table into the evaporation zone.

Channel flow: The flow of water in streams or rivers.

Channel storage: The storage of water in streams or rivers.

Drainage basin system outputs

Evaporation

Evaporation is the physical process by which moisture is lost directly into the atmosphere from water surfaces (the largest transfer) and soil. Evaporation results from the effects of the Sun's heating and air movement, so rates increase in warm, windy and dry conditions. Climatic factors influencing evaporation rates include temperature, hours of sunshine, humidity and wind speed, although temperature is the most important factor. Other factors include the size of the water body, depth of water, water quality, type of vegetation cover and the colour of the surface (which determines the albedo or reflectivity of the surface).

Transpiration

Transpiration is a biological process by which water is lost from plants through minute pores (stomata) and transferred to the atmosphere. Transpiration rates depend on the time of year, the type and amount of vegetation cover, the degree of availability of moisture in the atmosphere and the length of growing season.

Evapotranspiration (EVT) is the combined effect of evaporation and transpiration. EVT represents the most important aspect of water loss to the atmosphere, accounting for the removal of nearly 100 per cent of the annual precipitation in arid and semi-arid areas, and around 75 per cent in humid areas. Obviously over ice/snow fields, bare rock slopes and soils, desert areas and the majority of water surfaces, the losses are purely evaporative.

Potential evapotranspiration (PEVT) is the water loss that would occur if there was an unlimited supply of water in the soil for use by vegetation. Therefore, the difference between PEVT and EVT is much greater in arid areas than in humid areas.

Key terms

Albedo: A measure of the proportion of the incoming solar radiation that is reflected by the surface back into the atmosphere and space.

Evapotranspiration (ET or EVT): The combined effect of evaporation and transpiration.

Potential evapotranspiration (PET or PEVT): The water loss that would occur if there was an unlimited supply of water in the soil for use by vegetation.

Physical factors that influence the drainage basin cycle

As can be seen when studying the inputs, flows and outputs within the drainage basin system, their relative importance is determined by a number of physical factors. Table 1.2 summarises some of these key influences.

Table 1.2 Physical factors within the drainage basin system and effect on inputs, flows and outputs

Climate	Climate has a role in influencing the type and amount of precipitation overall and the amount of evaporation, i.e. the major inputs and outputs. Climate also has an indirect impact on the vegetation type.
Soils	Soils determine the amount of infiltration and throughflow and, indirectly, the type of vegetation.
Geology	Geology can impact on subsurface processes such as percolation and groundwater flow (and, therefore, on aquifers). Indirectly, geology alters soil formation.
Relief	Altitude can impact on precipitation totals. Slopes can affect the amount of run-off.
Vegetation	The presence or absence of vegetation has a major impact on the amount of interception, infiltration and occurrence of overland flow, as well as on transpiration rates.

Figure 1.9a and Figure 1.9b show contrasting hydrological cycles in two different areas with completely different physical factors. This leads to contrasting inputs, stores, flows and outputs.

- Area A is a semi-arid area, for example, on the fringe of the Atacama Desert in northern Chile. It has a low level of water security as there is very little storage potential, and outputs exceed inputs. Other sources are not accessible (fossil water, melt water from the cryosphere).

Skills focus: Analysing contrasting hydrological cycles

Explain how physical factors have led to contrasts in the hydrological cycles shown in Figure 1.9.

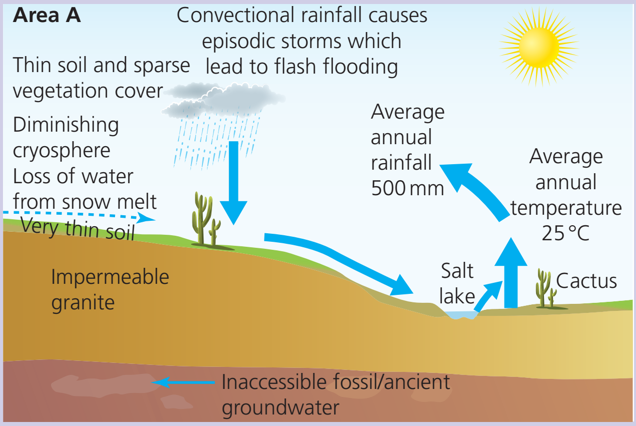


Figure 1.9a The impact of physical factors on two contrasting hydrological cycles (Area A)

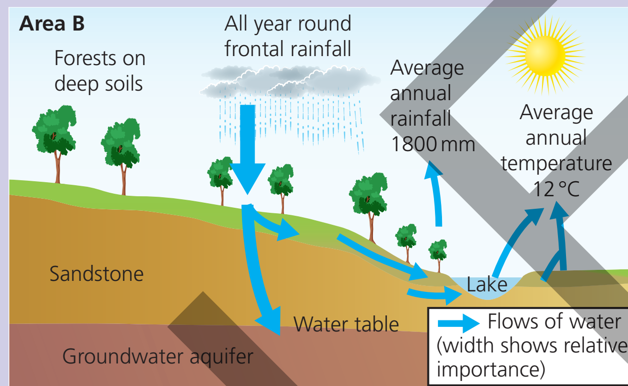


Figure 1.9b The impact of physical factors on two contrasting hydrological cycles (Area B)

- Area B is a temperate rainforest area in southern Chile with a high level of water security; inputs of precipitation exceed outputs and there is also abundant groundwater storage.

Key terms

Deforestation: The cutting down and removal of all or most of the trees in a forested area.

Afforestation: The planting of trees in an area that has not been forested in recent times.

Human factors that influence the drainage basin system

Human impact on precipitation

Human activity can affect precipitation by cloud seeding: the introduction of silver iodide pellets, or ammonium nitrate, to act as condensation nuclei to attract water droplets. The aim is to increase rainfall in drought-stricken areas. It has variable results. Pollution also provides condensation nuclei.

Human impact on evaporation and evapotranspiration

Changes in global land use, for example, deforestation, are a key influence. Also important is the increased evaporation potential resulting from the enormous artificial reservoirs behind mega dams, for example, the Aswan Dam and Lake Nasser in southern Egypt. Conversely, the channelisation of rivers in urban areas into conduits cuts down surface storage and, therefore, evaporation.

Human impact on interception

As interception is largely determined by vegetation type and density, deforestation and afforestation both have significant impacts.

Deforestation leads to a reduction in evapotranspiration and an increase in surface run-off. This increases flooding potential, leads to a decline of surface storage and a decrease in the lag time between peak rainfall and peak discharge. In other words, it speeds up the cycle.

Research on deforestation in Nepal shows a range of negative impacts that have been linked to deforestation, including increases in the sediment load downstream in northern Nepal. Figure 1.10 summarises possible impacts of deforestation in the Himalayas in Nepal.

In theory, afforestation should have the reverse impact by trapping silt and slowing up the hydrological cycle by lengthening lag times. However, as a recent research project in the Plynlimon area of the catchment of the River Severn in Mid Wales showed, there is a period of time just after the planting of young trees where there is an increase in run-off and sediment loss as a result of compaction of soil by tractors and planting equipment, which only stops after 30 years when the trees are more fully grown.

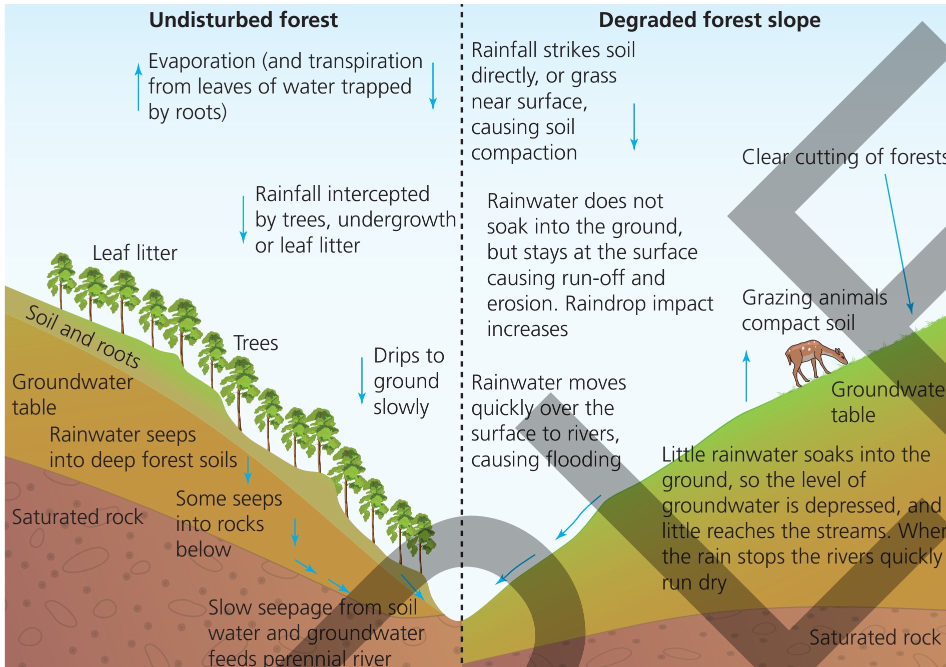


Figure 1.10 The possible impacts of deforestation in the Himalayan foothills of Nepal

Human impact on infiltration and soil water

Human impacts on infiltration largely result from a change in land use. Infiltration is up to five times greater under forests when compared with grassland. With conversion to farmland there is reduced interception, increased soil compaction and more overland flow. This impact is summarised in Figure 1.11. Land-use practices are also important: while grazing cows leads to soil compaction by the trampling of animals, ploughing increases infiltration by loosening and aerating the soil. Waterlogging and salinisation are common if there is poor drainage, so installing drainage mitigates these problems.

Deforestation issues in Amazonia

The environmental impacts are likely to be severe because of the sheer scale of the deforestation in Amazonia. Over twenty per cent of the forest has been destroyed, at an accelerating rate in the last 50 years, by a combination of cattle ranching, large-scale commercial agriculture for biofuels and soya beans, general development of towns and roads, as well as legal and illegal logging. Most recently the Brazilian government has encouraged these activities.

As the Amazon forests contain 60 per cent of the world's rainforests, the environmental impact on global life support systems is bound to be highly significant. The trees act as 'green lungs' by removing CO_2 as they photosynthesise and act as carbon sinks. Destruction of forests reduces this capacity, so adding to the global greenhouse gas emissions, especially in times of drought.

There is also an enormous impact on water cycling. In a forest environment 75 per cent of intercepted water is returned by EVT to the atmosphere, which reduces to around 25 per cent when the forest is cleared. Ultimately, the drier climate can lead to desiccation and further rainforest degradation. The El Niño–Southern Oscillation (ENSO) (see page 26) can lead to significant occurrence of droughts in Amazonia, which can exacerbate forest fires and further destruction.

The sheer scale of Amazonian destruction can have a very significant impact on the water cycle. As more water runs off into the Amazon drainage system, not only does this exacerbate the possibility of severe flooding and mudslides, it also leads to aquifer depletion, as less water infiltrates to recharge them. Overland flow also increases the amount of soil erosion and degradation as nutrients are 'washed away'.

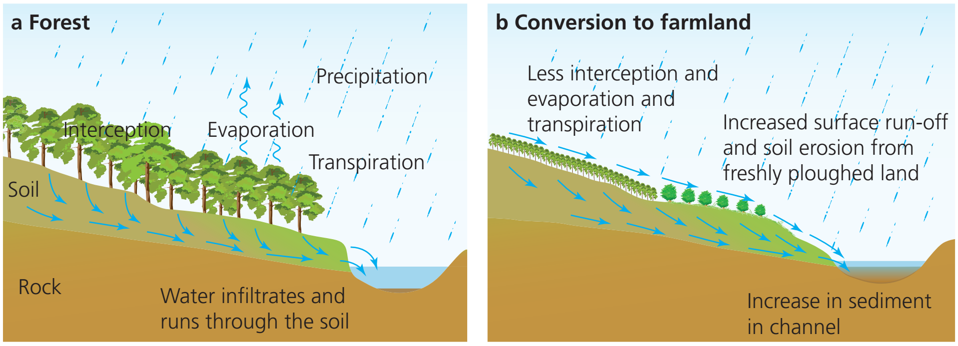


Figure 1.11 The effect on the drainage cycle basin of converting land from forest to farmland

Human impact on groundwater

Human use of irrigation for extensive cereal farming has led to declining water table levels in areas such as the Texan aquifers. The Aral Sea, between Kazakhstan and Uzbekistan, is an example of the damaging effects of the overextraction of water. The Aral Sea began shrinking in the 1960s when Soviet irrigation schemes for the growth of cotton took water from the Syr Darya and Amu Darya rivers, which greatly reduced the amount of water reaching the Aral Sea. By 1994, levels had fallen by 16 m, the surface area had declined by 50 per cent, the volume by 75 per cent, and salinity levels had increased by 300 per cent, with major ecological consequences.

In many British cities, including London, recent reductions in water-using manufacturing activity have led to less groundwater being abstracted. As a result groundwater levels have begun to rise, leading to a different set of problems, such as surface water flooding, flooding of cellars and basements in houses, and increased leakage into tunnels such as those used by the London Underground. The water supplies are also more likely to become polluted.

1.3 The operation of the hydrological cycle at contrasting scales

Water budgets

Water budgets, the balance between precipitation, evaporation and run-off, can be useful at global, regional and local scales.

Figure 1.12 depicts the global water balance in ten-degree latitudinal steps. The graph indicates the importance of the distribution of the atmosphere circulation and, to an extent, land and sea bodies. Only two zones – A and B, temperate and tropical equatorial – show a positive balance of run-off; they mark zones of convergence and uplift and subsequent precipitation. Rivers flowing from these zones are vital in supplying zones of deficit (for example, the Nile supplies Egypt's deserts with vital water). Both climate change and human activities such as deforestation have the capacity to modify the situation in the long and short term.

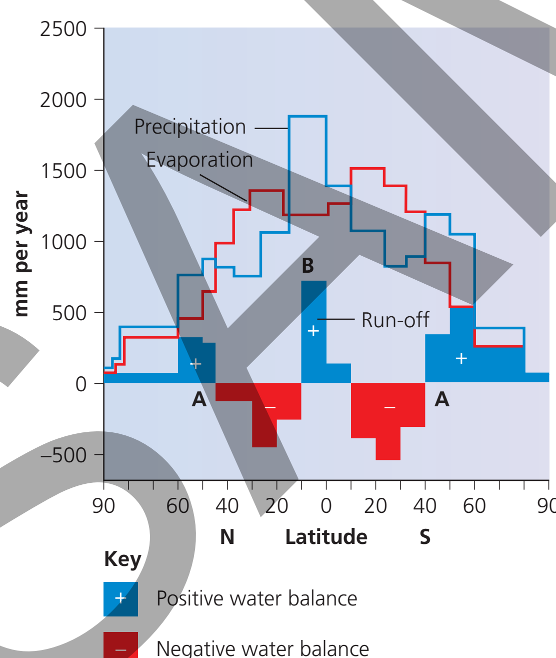


Figure 1.12 The variation of global water budgets with latitude

As you can see in Table 1.3 (page 15), the water balance varies considerably between continents, with South America the most well-endowed continent and Africa the least. Run-off is divided into surface flow and base flow. This is an important distinction because in some places there are severe seasonal differences in surface flow (for example, monsoonal areas):

Table 1.3 Continental scale variation in water balance

Continent	Precipitation (mm/year)	Evapotranspiration (mm/year)	Difference (mm/year)	Run-off (mm/year)	
				Surface	Base flow
Europe	657	375	283	185	97
Asia	696	420	276	205	71
Africa	696	582	114	74	40
Australia (and Oceania)	803	534	269	205	64
North America	645	403	242	171	71
South America	1,564	946	618	395	223

at certain times of the year there may be a shortage of water but at other times a surplus. The base flow represents the usually available water. Although very generalised, Table 1.3 does point to water supply problems on some continents; for example, in Africa precipitation and evapotranspiration are very similar, leaving little water to enter rivers as surface run-off. In contrast, South America has a large precipitation/evapotranspiration difference leading to high surface run-off. Water budgets at a country or regional scale provide a more useful indication of available water supplies (see page 56, Water Poverty Index).

At a more local scale, water budgets show the annual balance between inputs (precipitation) and outputs (EVT), and how this can impact on soil water availability.

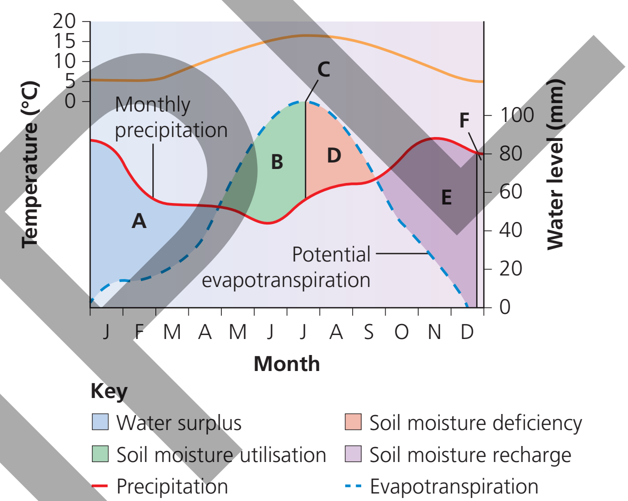
The soil moisture budget is a subsystem of the catchment water balance and is of vital importance to agriculturalists. Drainage basin water budgets are usually called water balances and are usually expressed using the following formula:

$$P = Q + E \pm S$$

Where:

P = precipitation
Q = discharge (stream flow)
E = evapotranspiration
S = changes in storage

Figure 1.13 shows a water budget for southern England. In the UK, the annual precipitation exceeds evaporation in most years and in most places. Therefore, precipitation inputs exceed evaporation losses, so there will be a positive water balance. However, in some years of drought (for example, 1975–6 and 1995–6), and in some summer months, England has a temporary negative water balance.



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

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

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

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

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

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

Figure 1.13 A water budget graph for southern England showing soil moisture status

Fieldwork opportunity

Use the following method to measure water balances within a catchment:

1. Measure stream discharge at a number of points (cross-sectional area × velocity) or make use of a discharge flume within a defined drainage basin to calculate run-off.
2. Use multiple rain gauges located next to discharge sites to measure the spatial variation of rainfall over a given time.
3. Use secondary rainfall and run-off data (if available) for your chosen catchment, and correlate this with the primary results. There are often many differences to explain in a climate as variable as that of the UK.
4. Obtain evapotranspiration measurements as secondary data (possibly available from the Met Office).

Primary measurement of evaporation can be measured using open saucers or pans located across your chosen catchment area. If it is possible to co-operate with a university department or field study research centre, you may be able to borrow a lysometer, which measures EVT.

River regimes

A **river regime** can be defined as the annual variation in discharge or flow of a river at a particular point or gauging station, usually measured in cumecs. Much of this river flow is not from immediate precipitation or run-off, but is supplied from groundwater between periods of rain, which feeds steadily into the river system from base water flow. This masks the fluctuations in stream flow caused by immediate precipitation. British rivers flowing over chalk, for example, the River Kennet, show this feature as well, as they maintain their flow even in very dry conditions, which is a result of base flow from the chalk aquifers.

The character of a regime of the resulting stream or river is influenced by several variable factors:

- The size of the river and where measurements are taken in the basin: many large rivers have very complex regimes resulting from varied catchments.
- The amount, pattern and intensity of the precipitation: regimes often reflect rainfall seasonal maxima or when the snow fields or glaciers melt (for snow the peak period is in spring, for glaciers it is early summer).
- The temperatures experienced: evaporation will be marked in summer as the temperatures are warmer.
- The geology and overlying soils, especially their permeability and porosity: water is stored as groundwater in permeable rocks and is gradually released into the river as base flow, which tends to regulate the flow during dry periods.
- The amount and type of vegetation cover: wetlands can hold the water and release it very slowly into the system.
- Human activities, such as dam building, which can regulate the flow.

Overall the most important factor determining stream flow is climate. Figure 1.14 (page 17) shows how these factors lead to a variety of regimes.

Key terms

River regime: The annual variation in discharge or flow of a river at a particular point or gauging station, usually measured in cumecs.

Rising limb: The part of a storm hydrograph in which the discharge starts to rise.

Peak discharge: The time when the river reaches its highest flow.

Storm hydrographs

Storm hydrographs show the variation of discharge within a short period of time, normally an individual storm or a group of storms not more than a few days in length. Before the storm starts the main supply of water to the river or stream is through groundwater or base flow but, as the storm develops, water comes to the stream by a number of routes. Some water infiltrates into the soil and becomes throughflow, while some flows over the surface as overland flow. This water reaches the river in a comparatively short time so is known as quick flow. The storm hydrograph records the changing discharge of a river or stream in response to a specific input of precipitation.

Figure 1.15 (page 17) shows the main features of a storm hydrograph.

- Once the rainfall input begins the discharge starts to rise; this is shown on the **rising limb**.
- **Peak discharge** is eventually reached some time after the peak rainfall because the water takes time to move through the system to the gauging station of the basin.
- The time interval between peak rainfall and peak discharge is known as **lag time**.
- Once the storm input has ceased the amount of water in the river starts to decrease; this is shown by the **falling or recessional limb**.
- Eventually the discharge returns to its normal level or **base flow**.

The shape of a storm hydrograph may vary from event to event on the same river (temporal variation), usually closely linked to the pattern of the storm event, or from one river to another (spatial variation – often related to basin characteristics) (Table 1.4, page 18). Some hydrographs have very steep limbs, especially rising limbs with a high peak discharge and a very short lag time – usually called 'flashy' hydrographs. At the other end of the spectrum, some storm hydrographs have a very gentle rising limb, a lower peak discharge and a long lag time – usually called delayed or attenuated hydrographs.

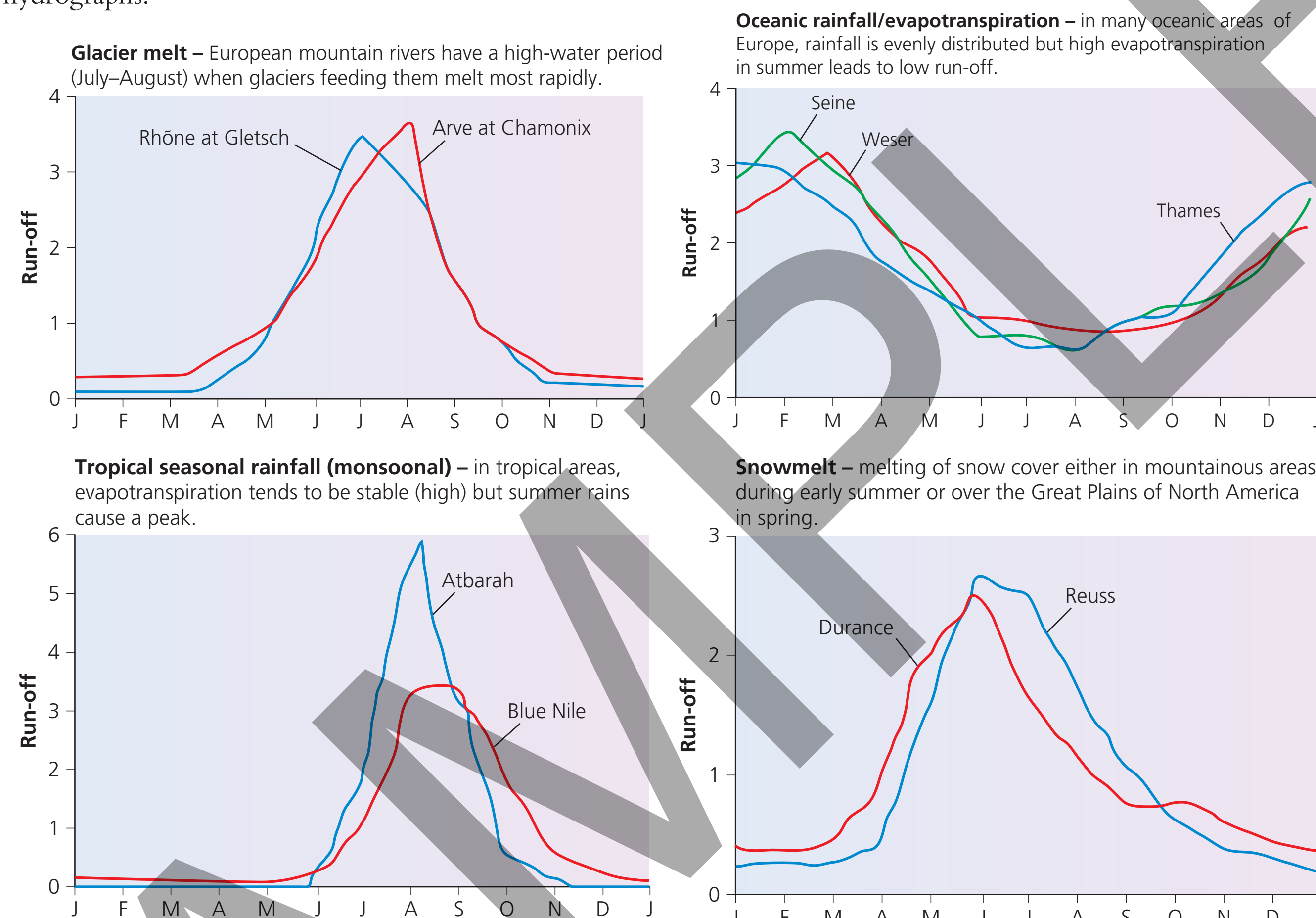


Figure 1.14 River regimes in four climate zones

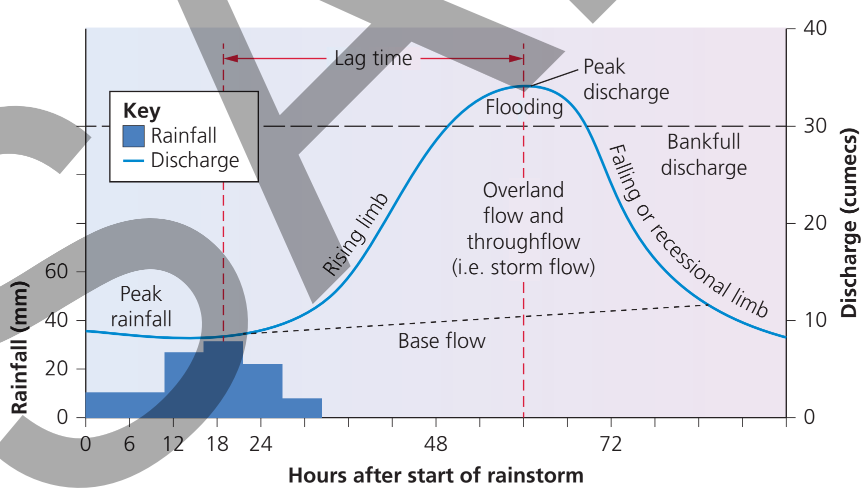


Figure 1.15 Features of a storm hydrograph

Key terms

Lag time: The time interval between peak rainfall and peak discharge.

Falling or recessional limb: The part of a storm hydrograph in which the discharge starts to decrease.

Base flow: The normal, day-to-day discharge of the river.

Fieldwork opportunity

Investigate the impact of a storm on a small stream:

- Use the weather forecast to identify the likely occurrence of a storm in your local area, having researched an accessible stream of 2–3 km in length.
- Develop a sampling strategy for ten to fifteen measuring points from source to mouth.
- Before the storm arrives, develop a set of baseline results for width, depth, velocity, cross-sectional area (CSA), discharge, stone shape and size.
- Once the storm starts, set up a series of homemade rain gauges to record rainfall at key intervals. Try to calculate intensity per 30 minutes.
- Try to carry out depth, CSA, velocity and discharge measurements during the storm at three key stations to create storm hydrographs.
- After the storm ends, and one day later, redo all the measurements at all your chosen stations on the stream.

Support your primary investigation with secondary data from the Met Office on the storm, and also any measurements of discharge in neighbouring rivers and streams.

There is little control over the physical factors; however, effective planning and management can help to mitigate catchment flooding.

The impact of urbanisation on hydrological processes

Urbanisation is probably the most significant human factor that leads to increased flood risk. Figure 1.16 summarises the effect of urbanisation on hydrological processes.

- Building activity leads to clearing of vegetation, which exposes soil and increases overland flow. Piles of disturbed and dumped soil increase erodability. Eventually the bare soil is replaced by a covering of concrete and tarmac, both of which are impermeable.
- The high density of buildings means that rain falls on to roofs and is then swiftly dispatched into drains by gutters and pipes.

Table 1.4 The range of factors that interact to determine the shape of a storm hydrograph

Factor	'Flashy' river	'Flat' river
Description of hydrograph	Short lag time, high peak, steep rising limb	Long lag time, low peak, gently sloping rising limb
Weather/ climate	Intense storm which exceeds the infiltration capacity of the soil Rapid snow melt as temperatures suddenly rise above zero Low evaporation rates due to low temperatures	Steady rainfall which is less than the infiltration capacity of the soil Slow snow melt as temperatures gradually rise above zero High evaporation rates due to high temperatures
Rock type	Impermeable rocks, such as granite, which restrict percolation and encourage rapid surface run-off	Permeable rocks, such as limestone, which allow percolation and so limit rapid surface run-off
Soils	Low infiltration rate, such as clay soils (0–4 mm/h)	High infiltration rate, such as sandy soils (3–12 mm/h)
Relief	High, steep slopes that promote surface run-off	Low, gentle slopes that allow infiltration and percolation
Basin size	Small basins tend to have more flashy hydrographs	Larger basins have more delayed hydrographs; it takes time for water to reach gauging stations
Shape	Circular basins have shorter lag times	Elongated basins tend to have delayed or attenuated hydrographs
Drainage density	High drainage density means more streams and rivers per unit area, so water will move quickly to the measuring point	Low drainage density means few streams and rivers per unit area, so water is more likely to enter the ground and move slowly through the basin
Vegetation	Bare/low density, deciduous in winter, means low levels of interception and more rapid movement through the system	Dense, deciduous in summer, means high levels of interception and a slower passage through the system; more water lost to evaporation from vegetation surfaces
Pre-existing (antecedent) conditions	Basin already wet from previous rain, water table high, soil saturated so low infiltration/percolation	Basin dry, low water table, unsaturated soils, so high infiltration/percolation
Human activity	Urbanisation producing impermeable concrete and tarmac surfaces Deforestation reduces interception Arable land, downslope ploughing	Low population density, few artificial impermeable surfaces Reforestation increases interception Pastoral, moorland and forested land

- Drains and sewers are built, which reduce the distance that storm water must travel before reaching a channel. The increase in the velocity occurs because sewers generate less friction than natural pathways: sewers are designed to drain water quickly.
- Urban rivers tend to be channelised with embankments to guard against flooding. When floods occur they can be more devastating as the river overtops defences in a very confined space.
- Bridges can restrain the free discharge of floodwaters and act as local dams for upstream floods.
- In extreme weather events, urban areas such as Manchester, Leeds and York are highly vulnerable. They have to manage flood control problems with a higher, quicker peak discharge, as well as pollution problems from the storm water which washes off the roads, containing toxic substances.

Figure 1.17 (page 20) shows that as urbanisation intensifies, it has a major impact on the working of the hydrological cycle. Decision makers and planners therefore have a number of options that involve managing the catchment as a whole, for example, developing appropriate land use, such as forestry and moorlands, in the upper areas, and managing development in the lower part of catchments by land use zoning, and by limiting building on the floodplains so ‘making space for water to flood’. At the same time they have to defend high-value properties and installations against agreed flood recurrence levels. There are also a number of grants for comparatively low-cost strategies that can be used to lower flood risks, such as semi-permeable surfaces for car parks and high level wiring systems in houses, as well as the government developing affordable insurance (Flood Re). Additionally, building regulations can be tightened to ensure flood-proof property designs.

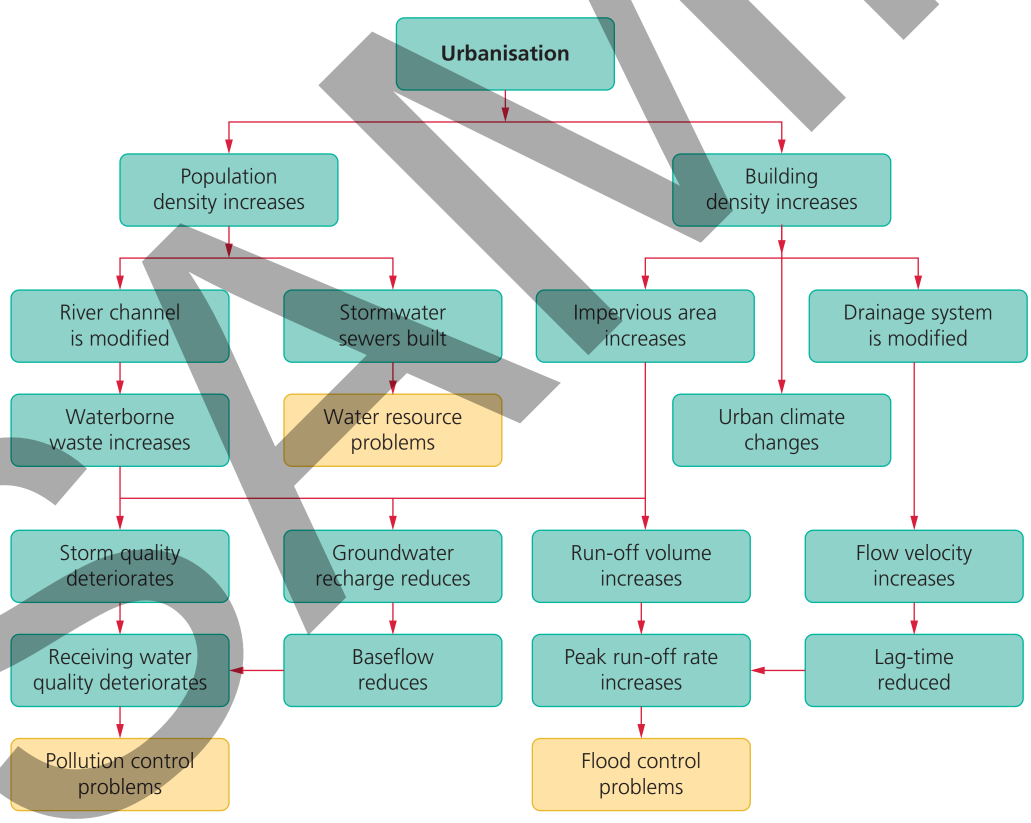


Figure 1.16 The impact of urbanisation on hydrological processes

> **Synoptic themes:**
>
> **Players**
>
> Environmental managers and planners increasingly look at catchment management both upstream (e.g. afforestation) and in the lower course (e.g. flood defences) in order to manage the impacts of urbanisation and changes in land use which have exacerbated flood risk.

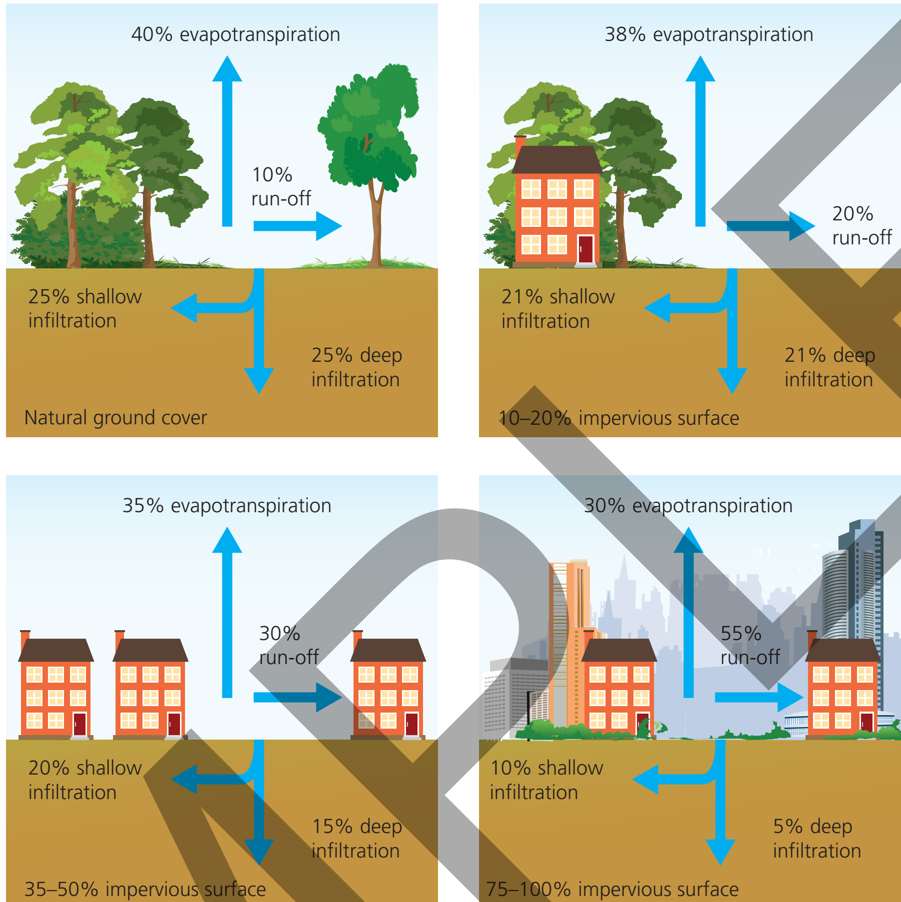


Figure 1.17 The impact of the intensity of urbanisation on hydrological processes (Source: US Department of Agriculture)

Skills focus: Regimes and storm hydrographs

1 Using data from Table 1.5, draw two graphs to compare rainfall and run-off in the two neighbouring catchments of Austwick Beck and Clapham Beck in North Yorkshire.

Table 1.5 Yearly figures for two drainage basins

	Austwick Beck		Clapham Beck	
	Rainfall (mm)	Channel run-off or stream flow (mm)	Rainfall (mm)	Channel run-off or stream flow (mm)
Oct	74	6	66	22
Nov	88	6	96	22
Dec	170	18	136	26
Jan	148	102	176	38
Feb	12	30	16	26
Mar	122	42	122	36
Apr	90	34	90	28
May	136	24	100	26
Jun	168	16	130	20
Jul	208	44	182	22
Aug	92	24	114	20
Sep	204	26	210	22
TOTAL	1,512	372	1,408	306

2 Study the map in Figure 1.18. Using your own knowledge, describe and suggest reasons for any differences shown on your graphs from Question 1.

3 Describe the differences in the storm hydrographs shown in Figure 1.18. They are both for the same storm.

4 Suggest reasons for the differences you have described. You should refer back to page 16 (river regimes and storm hydrographs).

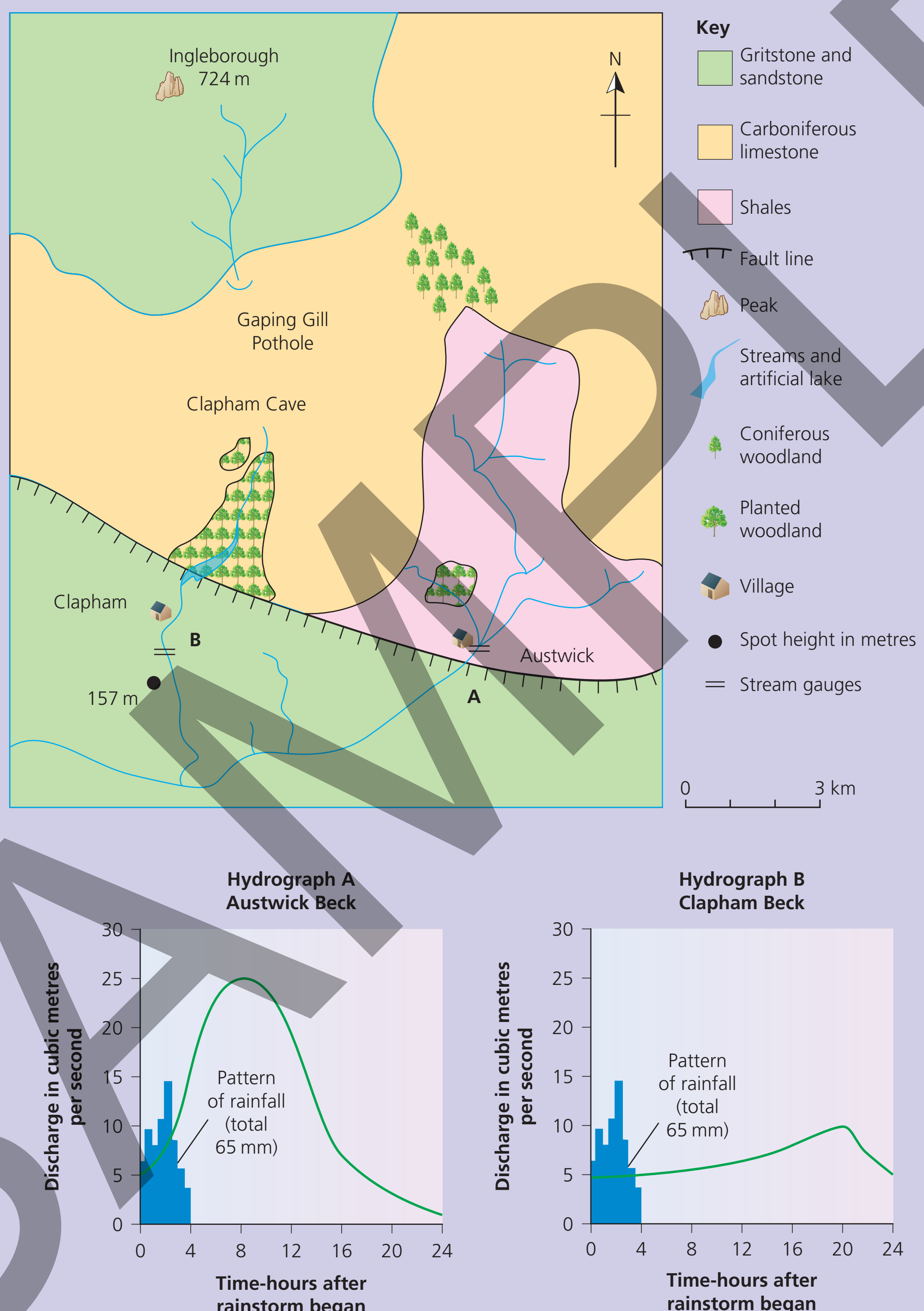


Figure 1.18 Contrasting catchments in North Yorkshire

Review questions

1 Using Figure 1.19 as a framework, use Figure 1.1 on page 3 to annotate the transfers between stores with the correct flux measurements.

Provide a brief commentary on your annotations.

2 Study Table 1.6 below, showing changes in run-off and soil erosion after deforestation. Comment on the impact of different land uses on run-off and erosion rates. Are similar changes apparent in all five locations, or do slope and rainfall totals also play a part?

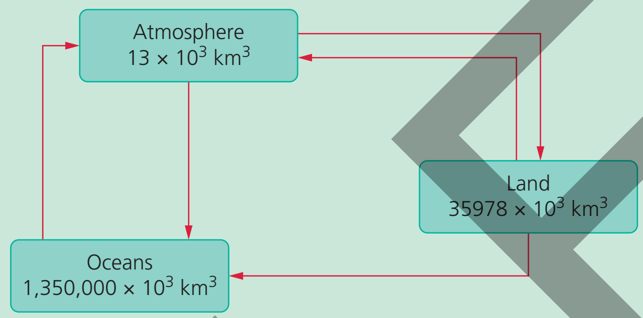


Figure 1.19 The global hydrological system

Table 1.6 Changes in run-off and erosion after deforestation; A = forest or ungrazed thicket, B = crops, C = barren soil

Location	Average annual rainfall (mm)	Slope (%)	Annual run-off (%)			Erosion (tonnes per hectare per year)		
			A	B	C	A	B	C
Ouagadougou, Burkina Faso	850	0.5	2.5	2–32	40–60	0.1	0.6–0.8	10–20
Sefa, Senegal	1300	1.2	1.0	21.2	39.5	0.2	7.3	21.3
Bouaké, Ivory Coast	1200	4.0	0.3	0.1–26	15–30	0.1	1–26	18–30
Abidjan, Ivory Coast	2100	7.0	0.4	0.5–20	38	0.03	0.1–90	108–170
Mbapwa, Tanzania	c570	6.0	0.4	26.0	50.4	0	78	146

3 Carry out further research and write a short scientific article to assess the impact of deforestation in Nepal and the rivers Indus and Brahmaputra. You should weigh up the range of evidence on the scale of the issue.

4 Figure 1.20 (page 23) shows the classification of river regimes across the world. Use this, and the article by Haines, Finlayson and McMahon (https://www.researchgate.net/publication/ 223497649_A_Global_Classification _of_River_Regimes) to research the regimes of the following rivers:
- the Yukon
- the Amazon
- the Indus

Draw annotated sketch diagrams to explain their patterns.

5 Explain the changes in the hydrological processes during a storm shown in Figure 1.21 (page 23).

6 Select a Catchment Management Plan or River Basin Management Plan for any UK river from the following website: www.gov.uk/government/collections/catchment-flood-management-plans. Summarise the key features of the plan and explain how decision makers are working to manage its problems.

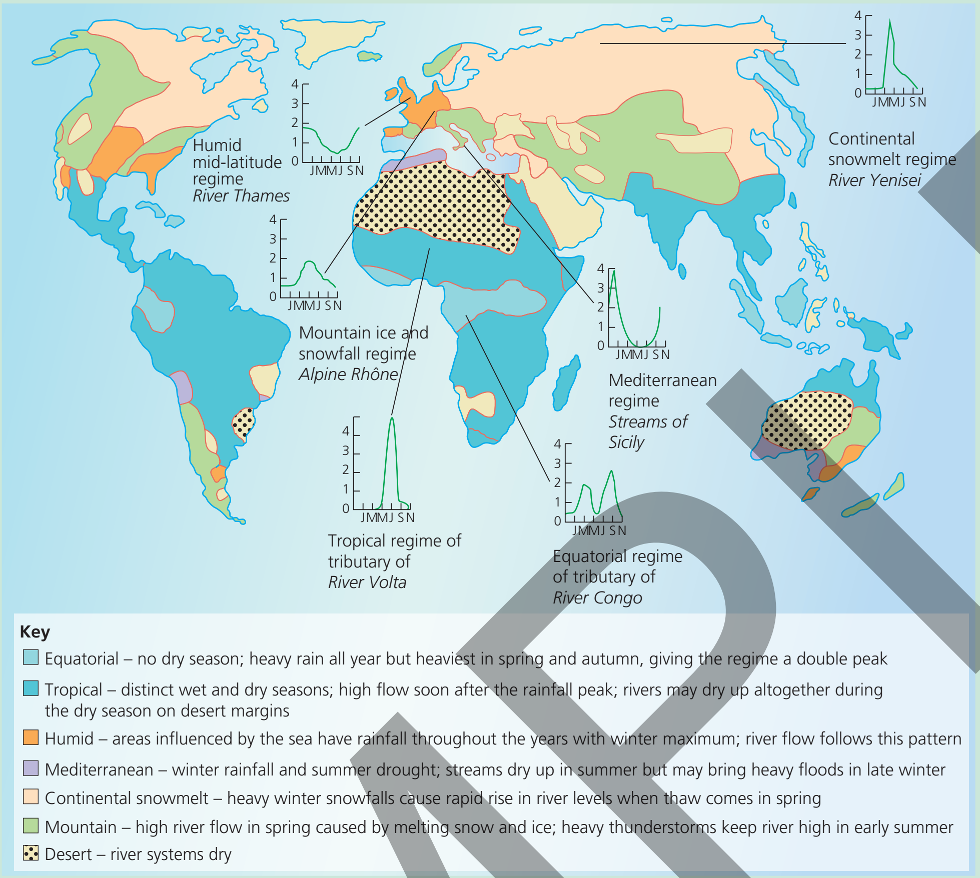


Figure 1.20 Classification of river regimes

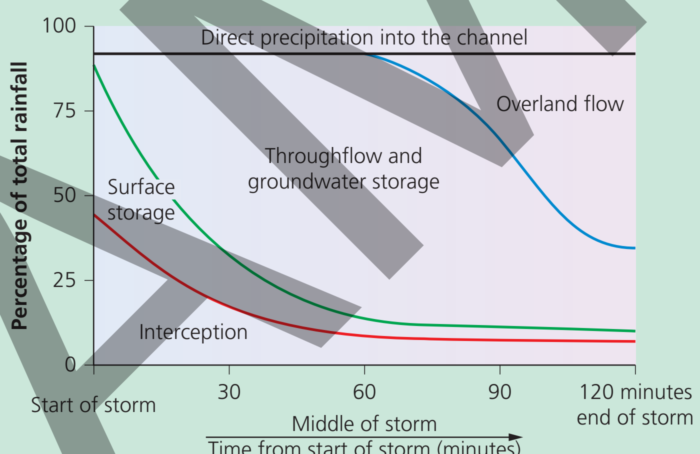


Figure 1.21 The changes in hydrological processes during a storm

Further research

Find out more about the hydrological system:
http://www.water-research.net
http://water.usgs.gov/edu/watercycle.html