Cambridge AS & A Level · Geography 9696 · Notes

Hydrology and fluvial geomorphology AS

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What you need to know

By the end of this topic you should be able to:

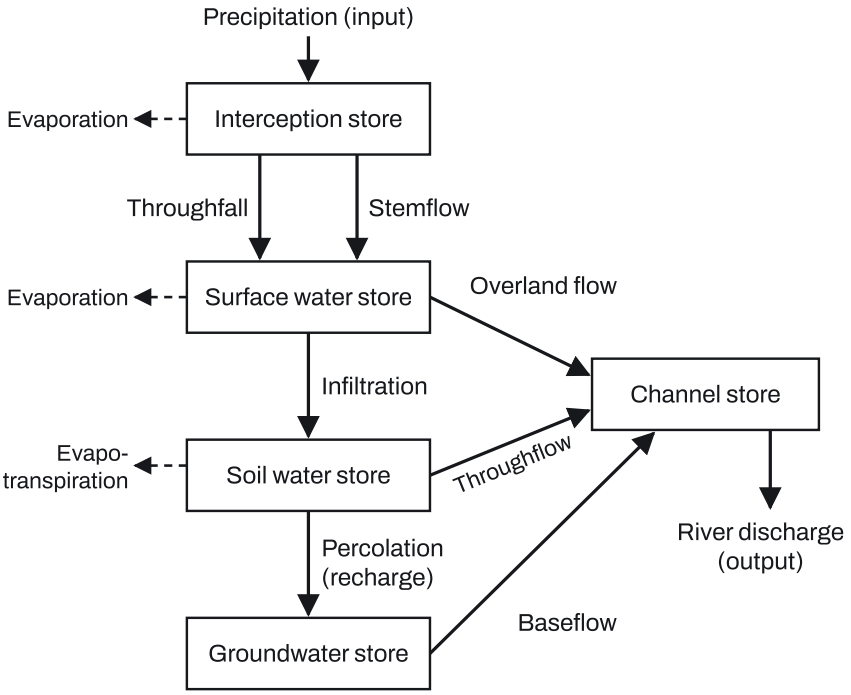
1. **Explain the drainage basin system.** Its outputs (evaporation, evapotranspiration, river discharge), its stores (interception, soil water, surface water, groundwater, channel storage) and its flows, above ground (throughfall, stemflow, overland flow, channel flow) and below ground (infiltration, percolation, throughflow, groundwater flow, baseflow). Explain underground water: the **water table**, groundwater, **recharge** and **springs**.
2. **Read and explain hydrographs.** Name the parts of a **storm hydrograph** and an **annual hydrograph**, and explain how climate (precipitation type and intensity, temperature, evaporation, transpiration, evapotranspiration, antecedent moisture) and drainage basin characteristics (size and shape, drainage density, soil porosity and permeability, rock type, slopes, vegetation type, land use) change them.
3. **Explain channel processes.** Erosion (abrasion or corrasion, solution, cavitation, hydraulic action), transport (traction, saltation, suspension, solution), deposition using the **Hjulström curve**, and river flow: velocity, discharge, laminar, turbulent and helicoidal flow, and the **thalweg**.
4. **Explain channel types and landforms.** Straight, braided and meandering channels; meanders with river cliffs, point bars and oxbow lakes; riffle and pool sequences, waterfalls, gorges, bluffs, floodplains, levées and deltas.
5. **Explain the human impact.** How land-use change (deforestation, afforestation, urbanisation), abstraction and water storage change flows and stores; the causes and impacts of river floods; how flood risk is predicted with **recurrence intervals**; and how floods are prevented or their effects reduced by forecasts and warnings, **hard engineering** (dams, straightening, levées, diversion spillways) and **soft engineering** (floodplain and drainage basin management, wetland and riverbank conservation, river restoration).
6. **Use a flood case study.** One recent river flood: its causes, its impacts on people and on the environment, and how well the attempts to reduce its impact worked.

It is examined in Paper 1: a compulsory 10-mark resource question (Question 1) and an optional 30-mark structured question (Question 4).

Understand it

The drainage basin system

A **drainage basin** (catchment) is the area of land drained by a river and its tributaries. Its edge is the **watershed**, the high ground that separates it from the next basin. Treat the basin as an open system: precipitation comes in, water is held in **stores**, moves between stores by **flows**, and leaves as **outputs**.



Follow the rain. Leaves and stems catch some of it (**interception**); part of that evaporates straight back from the leaves. The rest reaches the ground by dripping off leaves (**throughfall**) or running down twigs and trunks (**stemflow**). At the surface, water either soaks in (**infiltration**) or, if it cannot, collects in hollows (**surface water** store) and runs across the ground (**overland flow**). Water in the soil moves sideways downslope through it (**throughflow**) or seeps down into the rock (**percolation**), refilling the groundwater store. **Groundwater flow** moves very slowly through the rock and seeps into the river as **baseflow**. In the channel, water moves as **channel flow** and leaves the basin as **river discharge**. Water also leaves by **evaporation** and by **transpiration** from plant leaves; together these are **evapotranspiration**.

Overland flow starts in two ways:

- rain falls faster than the soil's **infiltration capacity** (the fastest rate it can absorb water), as in a cloudburst or on bare, compacted or paved ground;
- the soil is already **saturated**, so even gentle rain cannot soak in, as after a long wet spell or at the foot of a slope.

Underground water

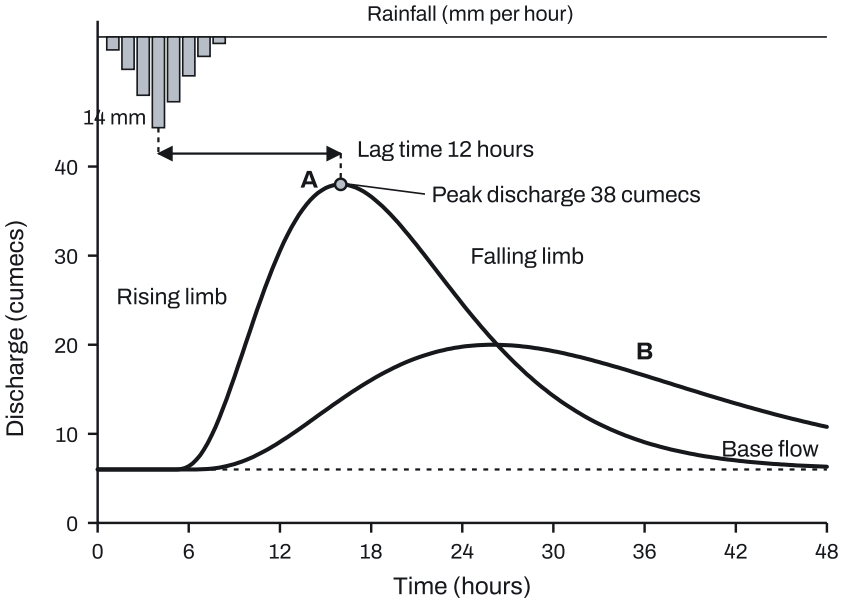
Below a certain depth every pore and crack in the rock is full of water: this is **groundwater**, and the top of this saturated zone is the **water table**. A rock that stores water and lets it pass (porous sandstone, jointed limestone or chalk) is an **aquifer**. The water table rises when **recharge** (water percolating down to refill the groundwater store) is greater than the water leaving, and falls in a dry, hot season or when people **abstract** (pump out) water faster than it is replaced.

A **spring** is a place where groundwater comes out at the surface on its own:

- where the water table meets the ground, often at the foot of a slope, and more so when the water table rises in a wet season;
- where permeable rock lies on top of an impermeable layer such as clay: water percolating down is stopped, moves sideways along the top of the impermeable layer and emerges where that boundary meets the slope, often as a line of springs.

Storm hydrographs

A **hydrograph** shows a river's **discharge** over time. Discharge is the volume of water passing a point each second, in **cumecs** (cubic metres per second). A **storm hydrograph** shows how a river responds to one storm, with the rainfall drawn as bars.



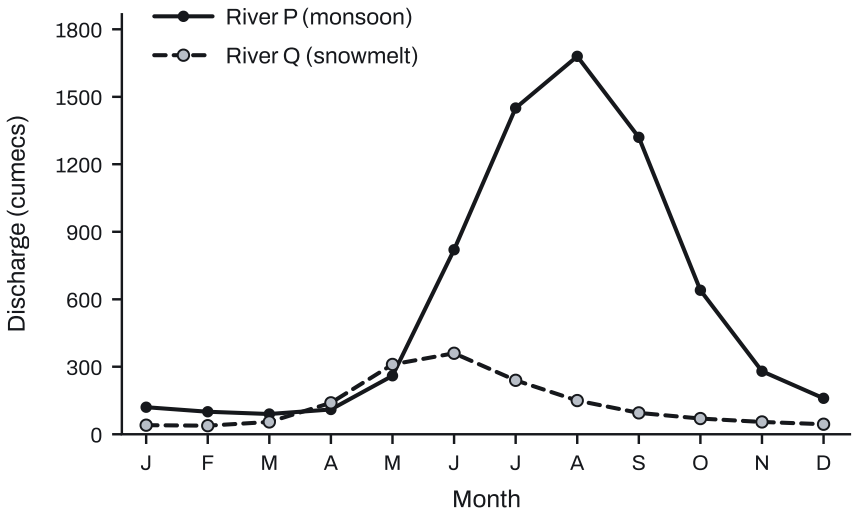
- **Base flow**: the normal flow before the storm, fed mainly by groundwater.
- **Rising limb**: discharge increasing as storm water arrives.
- **Peak discharge**: the highest discharge.
- **Lag time**: the time from peak rainfall to peak discharge.
- **Falling (recession) limb**: discharge decreasing. It is usually gentler than the rising limb, because water arriving by throughflow and groundwater flow keeps coming after the overland flow has gone.
- **Quickflow (storm flow)**: the water above base flow, arriving quickly by overland flow and fast throughflow.

- **Bankfull discharge**: the discharge that just fills the channel. Above it, the river floods.

In the diagram, A rises from 6 cumecs at hour 5 to 38 cumecs at hour 16. The heaviest rain (14 mm) fell in hour 4, so the lag time is $16 - 4 = 12$ hours. A is **flashy**: short lag time, high peak, steep limbs. B, a basin that had the same storm, peaks at only 20 cumecs at hour 26 (lag time 22 hours) but stays above base flow much longer: it is **subdued**.

Annual hydrographs

An **annual hydrograph** (the river's **regime**) shows discharge through a year, often as monthly means. Its pattern follows the climate: when rain falls, when snow and ice melt, and how much water evaporates.



River P peaks at 1680 cumecs in August, about 19 times its March low, because the monsoon brings most of the year's rain in a few months. River Q peaks in June, when the winter's snow melts; in winter precipitation is stored as snow, so discharge stays low.

The annual hydrograph of the same river also changes **from year to year**, because of things that change over months and years:

- the amount, timing and intensity of rainfall (a weak or late wet season, a drought, a very wet year that leaves soils saturated);
- temperature: a hot year raises evaporation and lowers discharge, and an early or rapid snow or glacier melt brings the peak forward and raises it;
- land use: crops harvested leave bare soil for part of the year, and deforestation or urbanisation add runoff;
- people: dams store wet-season water and release it in the dry season, and abstraction for irrigation lowers flows.

Rock type, soils and relief explain why two rivers differ, but they hardly change from one year to the next.

What controls the shape of a storm hydrograph

Every factor works through two questions: **how much** rain reaches the channel, and **how fast**. Fast routes (overland flow) give a short lag time, a high peak and a steep rising limb. Slow routes (infiltration, throughflow, percolation, then baseflow) give a long lag time, a low peak and gentle limbs, but a higher base flow afterwards.

Factor	Flashier hydrograph	More subdued hydrograph
Precipitation intensity	Intense rain exceeds infiltration capacity, and heavy drops pack bare soil	Gentle rain soaks in
Precipitation amount	Long, heavy rain saturates the soil, so more water runs off	Small totals are held in stores
Precipitation type	Rain on frozen ground; a sudden thaw	Snow is stored until it melts, giving a long lag
Temperature, evaporation, transpiration	Cool weather, plants dormant: little water lost	Hot weather, plants growing: more water lost
Antecedent moisture (how wet the basin is from earlier rain)	Wet, saturated soil	Dry soil absorbs the rain
Basin size	Small: water travels a short way, so the lag is short	Large: longer lag, though a larger total volume
Basin shape	Circular: tributaries' water reaches the main channel at about the same time	Elongated: water arrives in turn, so the peak is lower and later
Drainage density	High: water soon reaches a channel	Low
Soils	Clay: tiny pores, so low permeability	Sandy: large connected pores, so high permeability
Rock type	Impermeable (granite, shale): little percolation	Permeable (limestone, chalk, sandstone): water is stored as groundwater
Slopes	Steep, convex	Gentle, concave
Vegetation	Sparse cover, bare soil, deciduous trees in winter	Dense forest: interception, stemflow, roots that open the soil, transpiration
Land use	Towns, drains, soil compacted by machines or livestock	Forest, wetland, well-covered pasture

Porosity is how much pore space a soil or rock has (how much it can store); **permeability** is how easily water passes through it. Clay is porous but its pores are tiny, so it is almost impermeable.

Drainage density is the total length of streams divided by the basin's area (km per km²). It is high where rock and soil are impermeable, rain is heavy, slopes are steep and vegetation is sparse, and low on permeable rock, where water goes underground. It depends on these conditions, not on how big the basin is.

River flow

Velocity is the speed of the water (m/s); **discharge** = cross-sectional area × mean velocity. Friction with the bed and banks (the **wetted perimeter**) slows the water, so a channel's efficiency is its **hydraulic radius** = cross-sectional area ÷ wetted perimeter. A channel 12 m wide and 1.5 m deep has area 18 m², wetted perimeter $12 + 2 \times 1.5 = 15$ m and hydraulic radius 1.2 m; at 0.8 m/s its discharge is $18 \times 0.8 = 14.4$ cumecs. A channel 30 m wide and 0.6 m deep has the same area but a hydraulic radius of about 0.58 m, so it loses more energy to friction.

Downstream the gradient falls, but **mean velocity usually rises**: tributaries add water, and the channel becomes deeper and smoother, so less energy is lost to friction. Mountain streams only look fast because the water is broken by boulders.

- **Laminar flow**: smooth flow in sheets (layers) parallel to the bed, with no eddies. It is rare, found only in shallow, slow water over a smooth bed.
- **Turbulent flow**: irregular, swirling flow with eddies moving up and down. It is the normal flow in rivers, caused by rough beds and high velocity. It lifts fine sediment, and with that sediment it erodes the bed and banks.
- **Helicoidal flow**: a spiral flow round a bend. Surface water moves across to the outer bank, plunges down it, returns across the bed to the inner bank and rises again, all while moving downstream. It is a flow across the whole channel, not a thin corkscrew down the middle.
- **Thalweg**: the line of fastest flow, along the deepest part of the channel. It swings towards the outer bank on bends and crosses the channel between bends.

Erosion, transport and deposition

A river's energy comes from its mass of water and its velocity; most is used up in friction, and what is left erodes and carries sediment (the **load**). When velocity or discharge falls, the river drops its load.

Erosion (of the bed and banks):

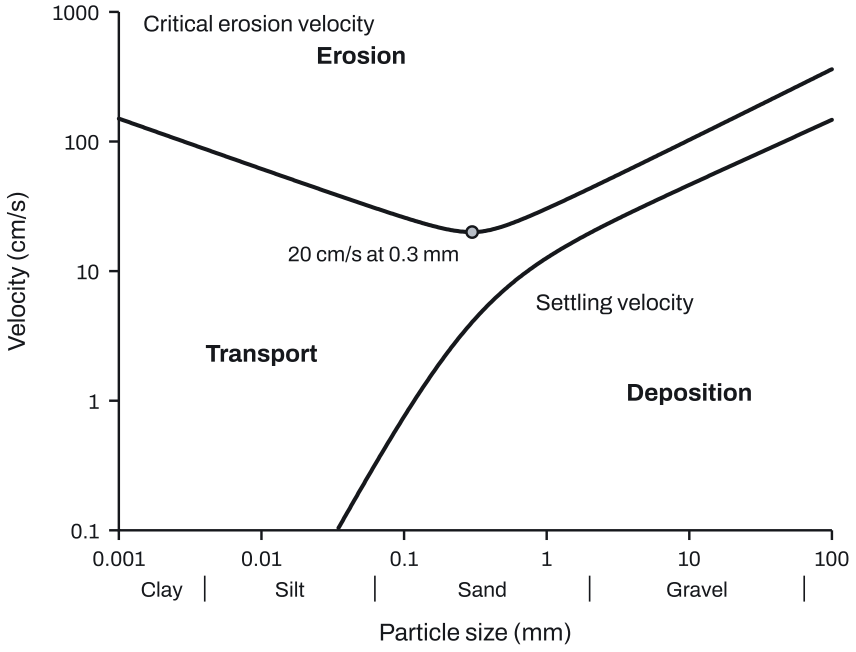
- **Abrasion (corrasion)**: the load scrapes and is thrown against the bed and banks. It is fastest when the water is fast, the load large, hard and plentiful (as in floods) and the bed soft.
- **Hydraulic action**: the force of the water, plus air squeezed into cracks, loosens and removes material; strongest where flow is fast and turbulent (outer bends, plunge pools).
- **Cavitation**: air bubbles in very fast water implode, and the shock waves, repeated many times, weaken the bed and banks; mainly at rapids and waterfalls.
- **Solution (corrosion)**: slightly acidic water (carbonic or organic acids) dissolves rock such as limestone and chalk, whatever the velocity.

- **Attrition** is also credited: particles knock together and become smaller and rounder downstream. It wears down the load, not the channel.

Transport:

- **Traction**: the largest particles (boulders) roll, slide or are dragged along the bed, always touching it, mainly at high discharge.
- **Saltation**: medium particles (coarse sand, small gravel) bounce along the bed: turbulence lifts them and they fall back a short way downstream.
- **Suspension**: fine particles (clay, silt) are held up in the water by turbulence and carried without touching the bed.
- **Solution**: dissolved minerals are carried invisibly. Solution is both an erosion and a transport process.

The Hjulström curve shows, for each particle size, the velocity needed to pick it up and the velocity at which it is dropped. Both axes are logarithmic.



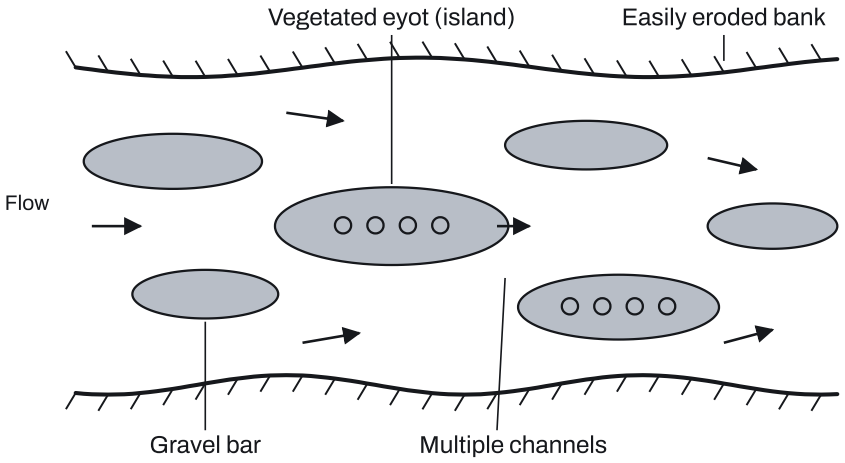
- The **upper curve** (critical erosion velocity) is the speed needed to lift a particle off the bed. "Erosion" on this graph means picking up (entrainment), not abrasion.
- **Sand of about 0.3 mm is easiest to pick up**, at about 20 cm/s. Bigger particles need more, because they are heavier: about 100 cm/s for 10 mm gravel.
- **Clay and silt also need high velocities** (about 60 cm/s at 0.01 mm, about 150 cm/s at 0.001 mm), because the particles are cohesive (they stick together) and lie in a smooth bed that the current barely disturbs.
- The **lower curve** (settling velocity) is where particles drop out. Once moving, a particle is carried at velocities well below the one needed to pick it up. Clay stays in suspension even when the water is almost still; it settles only in still water, or when it **flocculates** (clumps into heavier flakes) in salt water.

- As velocity falls, the **largest particles are deposited first**: 10 mm gravel below about 46 cm/s, 1 mm sand below about 13 cm/s, finer material later. So deposits are sorted by size.

In a channel this explains erosion on fast outer bends, deposition on slow inner bends, and deposition where a river slows at its mouth or on its floodplain. Its limits: it was drawn for uniform grains in experiments, while real beds mix sizes and shapes; turbulence and solution matter too; and the velocity at the bed is not the mean velocity.

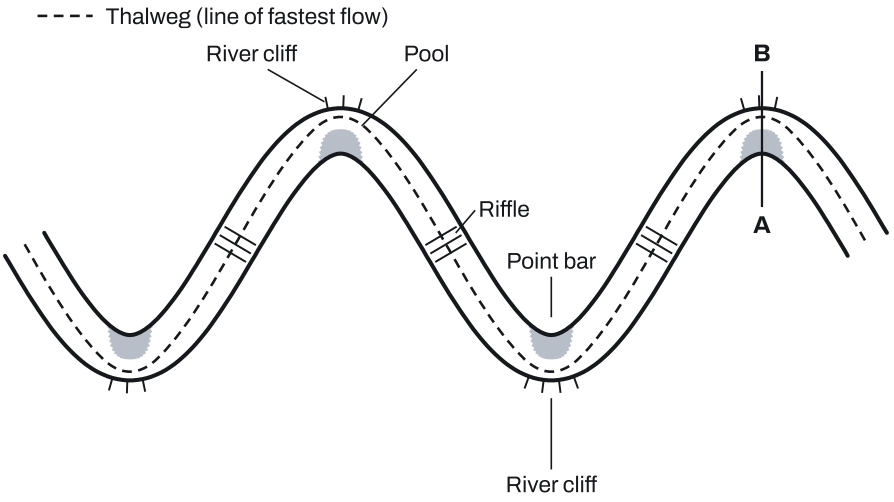
Channel types

- **Straight** channels are rare and short. Even in them the thalweg swings from side to side and riffles and pools form, the start of a meander.
- **Braided** channels: one wide, shallow channel split into many smaller channels by bars of gravel and sand and by islands (**eyots**), some vegetated; the channels divide and rejoin and shift after every flood. Braiding needs a **large load of coarse sediment** (glacial meltwater, steep mountain catchments, easily eroded rock), a **discharge that varies a lot** (seasonal snowmelt, flash floods), so that as flow falls the river drops its load as bars and splits around them, **easily eroded banks** that let the channel widen, and often a steep gradient. Vegetation that grows on the bars holds them in place as islands. The Rakaia River on New Zealand's Canterbury Plains and the Brahmaputra in Bangladesh are braided.

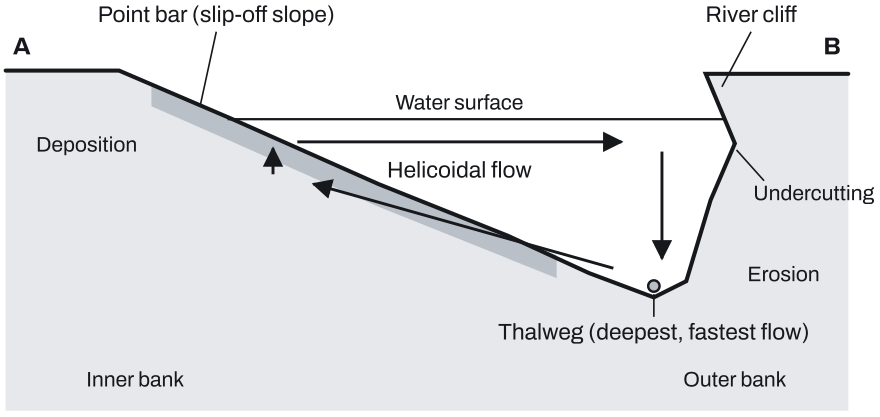


- **Meandering** channels: a single channel winding in loops, usually with a gentler gradient, finer load and steadier discharge than a braided one.

Meanders: riffles, pools, river cliffs, point bars and oxbow lakes

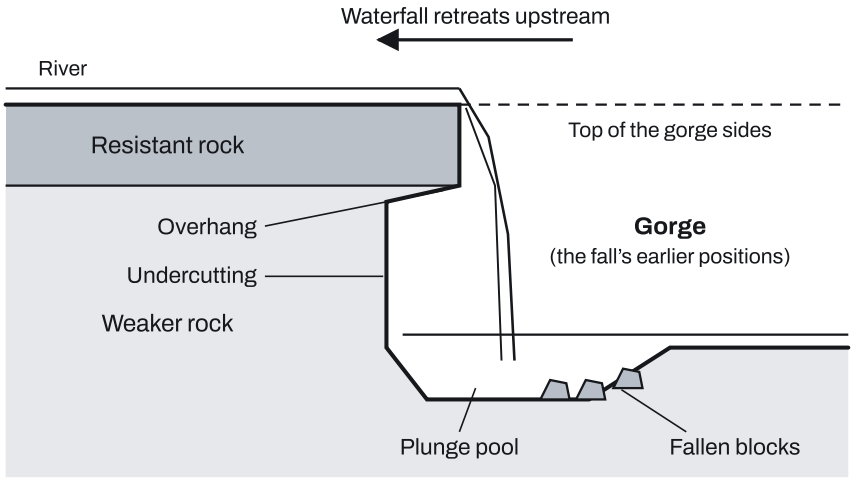


1. **Riffles and pools.** Even in a fairly straight channel, coarse sediment builds shallow bars (**riffles**) about 5 to 7 channel widths apart, with deeper, smoother **pools** between them. Riffles sit where the flow crosses between bends; pools sit at the bends.
2. **Bends grow.** The thalweg swings from bank to bank, so each bank in turn takes the fastest water.
3. **Helicoidal flow** carries water to the outer bank at the surface and back along the bed to the inner bank, taking eroded sediment with it.
4. **River cliff.** On the outer bank the water is fast and deep. Hydraulic action and abrasion undercut the bank until it collapses, leaving a steep **river cliff**.
5. **Point bar.** On the inner bank the water is slow and shallow, so sediment is deposited as a gently sloping, crescent-shaped **point bar** (**slip-off slope**).
6. The meander migrates sideways and downstream, widening the valley floor.



Oxbow lakes. Erosion on the outer banks makes the bends more **sinuous**, and the **neck** between two bends narrows. In a flood, at high discharge, the river cuts through the neck, a shorter, steeper route. Deposition seals the ends of the old bend, leaving an **oxbow lake**, which slowly fills with sediment and plants and becomes a **meander scar**.

Waterfalls, gorges and bluffs



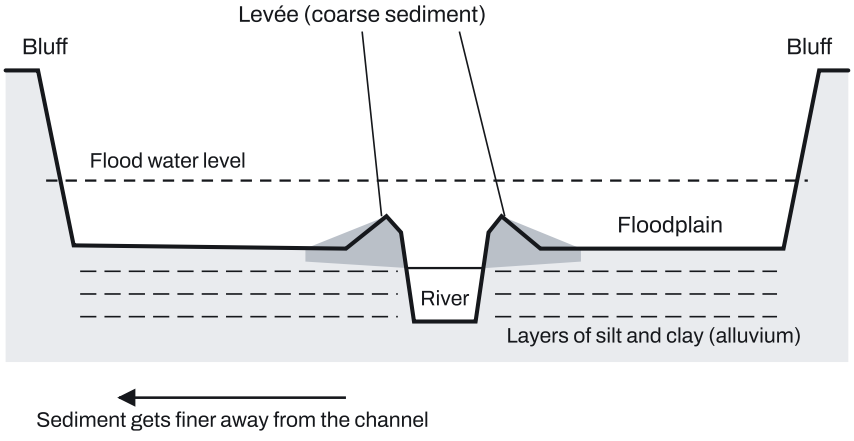
A **waterfall** forms where resistant rock lies on top of (or upstream of) weaker rock. The river erodes the weaker rock faster (**differential erosion**), making a step. Falling water scours a deep **plunge pool** by hydraulic action and abrasion from swirling boulders, and undercuts the weak rock behind the fall, leaving an **overhang** of hard rock that eventually collapses; the fallen blocks add to the abrasion. As this repeats, the waterfall **retreats upstream** (headward erosion). Falls also form at **knickpoints** after a fall in base level, at faults, and below glaciated hanging valleys. **Example:** Niagara Falls, on the USA–Canada border, where hard dolostone lies over weaker shale, has retreated about 11 km upstream, leaving the Niagara Gorge.

A **gorge** is a narrow, steep-sided valley where the river cuts down much faster than the sides are worn back. It forms:

- behind a **retreating waterfall**, as above, with rockfalls keeping the sides steep;
- by **rejuvenation**: tectonic uplift or a fall in sea level gives the river new energy, and it cuts down rapidly to its new base level, as the Colorado River did into the uplifted plateau of the Grand Canyon;
- by powerful glacial **meltwater** in the past.

A **bluff** is the steep slope at the edge of a floodplain, where migrating meanders have cut into the valley side.

Floodplains and levées

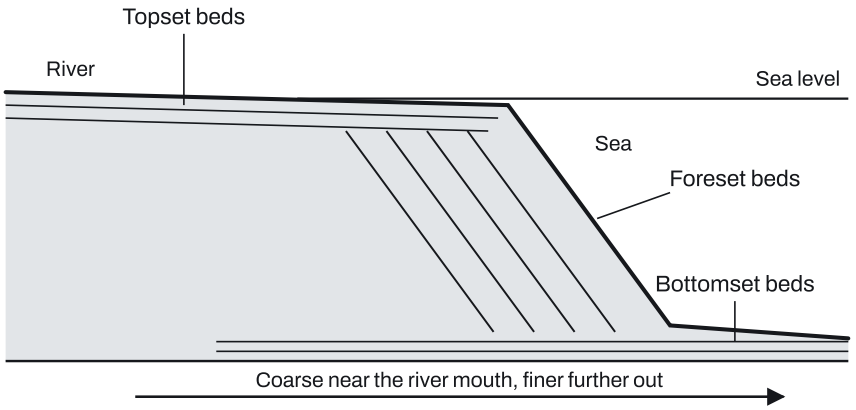


A **floodplain** is the wide, flat valley floor either side of a river that is covered when it floods. It is built by meanders migrating sideways (eroding the valley sides back to the bluffs and leaving point-bar deposits behind) and by floods: when discharge exceeds bankfull, water spreads over the land, slows down and drops layers of fine silt and clay (**alluvium**).

Levées are natural raised banks along the channel. When the river overtops its banks, the water leaving the channel loses velocity at once, because it becomes shallow and meets the friction of the floodplain. The **coarsest sediment is dropped first**, right beside the channel; finer material is carried further across the floodplain. Repeated floods build the banks up into levées. Between floods, deposition on the bed can raise the river above its own floodplain.

Deltas

A **delta** is a landform of deposited sediment where a river enters a sea or lake and drops its load faster than waves, tides and currents can remove it. It needs a large sediment load, a calm sea with a small tidal range, and shallow water offshore.



1. Entering still water, the river loses velocity and deposits its load, coarsest first. In salt water, clay particles **flocculate** and sink.
2. **Bottomset beds**: the finest clay, carried furthest out, settles in thin horizontal layers on the sea floor.
3. **Foreset beds**: coarser sediment builds the steep advancing front in inclined layers, most of the delta's bulk.
4. **Topset beds**: near-horizontal layers laid over the top by the river, extending its floodplain.
5. As the delta grows seaward, each set is laid over the last, and deposits split the river into **distributaries**.

The **shape** depends on the balance between river and sea:

- **Arcuate** (fan-shaped): many distributaries, with waves and longshore drift smoothing the front into a curve. Nile.
- **Cuspate** (pointed like a tooth): waves from opposite directions push the sediment of one main channel into a point. Tiber, Ebro.
- **Bird's foot**: a powerful river carrying much fine sediment into a sea with weak waves and tides builds long fingers of land along its distributaries. Mississippi.

Deltas grow larger where discharge and load are high, the water is shallow, marine processes are weak, and vegetation such as mangroves holds the sediment.

How people change flows and stores

- **Deforestation** removes interception, stemflow and transpiration, exposes and compacts the soil, and lowers infiltration. So overland flow rises: shorter lag time, higher peak, more total discharge. Less recharge means lower baseflow in the dry season, and soil erosion adds sediment to channels.
- **Afforestation** does the reverse: more interception, transpiration and infiltration, so less channel flow and a longer lag time. The drainage ditches dug for new plantations can speed runoff for the first few years.
- **Urbanisation** covers soil with concrete, tarmac and roofs, so infiltration falls and overland flow rises; gutters and drains deliver it fast. Hydrographs become flashier, and less recharge lowers the water table. But leaking water pipes and sewage add to channel flow, and water used in a town may be taken from, or returned to, a different river.
- **Farming**: ploughing up and down slopes makes channels for runoff; machinery and livestock compact the soil; land is bare after harvest; field drains speed runoff. Terracing and contour ploughing slow it.
- **Abstraction**: pumping water from rivers or aquifers for drinking, industry and irrigation lowers channel flow and the water table, and can dry up springs and wells.
- **Water storage**: a reservoir is a large new store. It holds back flood peaks and releases water steadily, so the river below has lower peaks and higher low flows, but more water evaporates from the lake and the dam traps sediment. The Aswan High Dam ended the Nile's yearly flood, and with its sediment trapped, the Nile delta's coast is now eroding.

So land-use change does **not always increase** channel flow: afforestation, restoring wetlands, reservoirs and abstraction all reduce it.

River floods: causes, impacts and prediction

A river floods when its discharge exceeds bankfull, so water overtops the banks onto the floodplain.

- **Physical causes**: long periods of heavy rain (a monsoon, a slow-moving depression), short intense rain (a thunderstorm, giving a flash flood), rapid snowmelt, rain on frozen or saturated ground, all made worse by the basin factors above.
- **Human causes**: urbanisation and deforestation upstream, building on floodplains, straightening channels upstream (which sends water downstream faster), soil erosion that raises river beds, and defences that fail.

The cause is often far **upstream** of the place that floods.

- **Impacts on people**: deaths, homes lost, disease (cholera from dirty water, malaria from standing water), roads, power and water supplies cut, crops and livestock lost, people displaced. Poorer countries usually suffer more deaths, richer ones larger money losses.

- **Impacts on the environment**: bank collapse and landslides, channels changing course, pollution spread, habitats destroyed; but also fresh fertile silt, recharged wetlands and groundwater, and breeding grounds for fish.

Recurrence intervals. Take the highest discharge of each year for n years of records, rank them with the largest as rank 1, and work out the **recurrence interval** (return period) $T = \frac{n+1}{m}$ for a flood of rank m. The **probability** that a flood at least that big happens in any one year is $\frac{1}{T}$. With 39 years of records, the 4th largest flood has $T = \frac{39+1}{4} = 10$ years: a 10% chance each year. Plotting discharge against recurrence interval shows the **magnitude–frequency** relationship: the bigger the flood, the rarer it is.

A "1 in 100-year flood" is **not** one that comes every 100 years: it has a 1% chance **every** year, so two can come close together. Over 30 years, the chance of at least one is $1 - 0.99^{30} \approx 26\%$.

Planners use them to map flood risk, zone land, design defences to a standard (such as the 1 in 100-year flood), set insurance and plan emergencies. Their limits: they are only as good as the records (40 years says little about a 200-year flood), and they assume the future is like the past, while climate change, urbanisation and new defences change the basin.

Reducing the impact of floods

Some methods **prevent** flooding (stop the water reaching people); others **reduce the impact** when it comes.

Forecasts and warnings use rain radar, river gauges and computer models to predict river levels hours or days ahead, so people can move belongings, evacuate and close roads. They are cheap and save lives, but do not stop damage, must reach people who trust them, and give little time before flash floods. In Germany in July 2021, forecasters warned of extreme flooding days ahead, but local warnings and evacuations came too late in places and more than 180 people died. Forecasting is **not** soft engineering; it is a separate approach.

Hard engineering builds structures to control the river:

Method	How it reduces flooding	Drawbacks
Dams and reservoirs	Store floodwater and release it slowly, controlling discharge downstream	Very costly; people displaced; sediment trapped; can fail; a reservoir already full gives no protection
Straightening	Cuts through meanders, so water flows faster out of the area at risk	Sends the flood downstream faster; habitats lost
Levées and flood walls	Raise the banks so the channel holds more water	If overtopped or breached, flooding is sudden and deep; encourage building behind them
Diversion spillways and relief channels	Take surplus water out of the main channel, around a town or into storage	Costly; flood land elsewhere
Dredging	Deepens the channel so it carries more water	Must be repeated; disturbs habitats

Examples: China's Three Gorges Dam stores Yangtze floodwater; the Bonnet Carré Spillway diverts Mississippi floodwater away from New Orleans into a lake; during the 1993 Mississippi floods many levées were overtopped or breached.

Soft engineering works with natural processes:

- **Floodplain management (land-use zoning)**: keep homes off high-risk land and use it for parks, pasture or washlands that store floodwater. Cheap, but hard where towns already stand there.
- **Drainage basin management**: tree planting, small "leaky" dams, ponds and contour ploughing slow water upstream. In Pickering, England, the "Slowing the Flow" scheme of leaky dams, trees and a storage bund is credited with helping the town avoid flooding in the winter of 2015–16.
- **Wetland and riverbank conservation**: wetlands store water like a sponge and release it slowly; planted banks resist erosion and slow the flow.
- **River restoration**: restore meanders and reconnect the river to its floodplain, so it floods where little harm is done. The Netherlands' Room for the River programme lowered floodplains and moved dykes back, as at Nijmegen on the River Waal.

Weighing them up. Soft methods are cheaper, sustainable and good for wildlife, but reduce rather than prevent flooding, work best against small and moderate floods, and take years; in an extreme flood every store is full. Hard methods protect particular places to a design standard, but are costly, often unsightly, move the risk elsewhere and can fail catastrophically; as climate change makes large floods more frequent, defences built to past standards are overtopped more often. Most places now combine both with forecasting and insurance.

Case study: Pakistan floods, 2022

- **Causes**: an exceptionally heavy monsoon from mid-June to late August, with August rainfall in Sindh and Balochistan several times its normal amount; a spring heatwave had also added glacier meltwater in the north. The flat, densely farmed Indus plain drained slowly, embankments failed, and many homes stood on the floodplain.
- **Impacts on people**: more than 1,700 deaths; about 33 million people affected; homes, roads, bridges and schools destroyed; damage and losses estimated at about US$30 billion; outbreaks of malaria and waterborne disease from standing water.
- **Impacts on the environment**: farmland under water for months; crops such as cotton and rice destroyed and around a million livestock killed; water and soil polluted; new silt spread across the plain.
- **Attempts to reduce the impact**: warnings, rescues, relief camps and international aid; embankments and barrages on the Indus. Officials cut the embankment of Manchar Lake to protect the town of Sehwan, which flooded surrounding villages instead.
- **Evaluation**: warnings reached many rural people late or not at all, defences were built for smaller floods, and poverty slowed recovery; the response saved lives but the flood outstripped every plan. Floodplain zoning, warnings that reach villages and well-kept embankments would reduce the impact next time.

Key facts and formulas

There is no formula list in Paper 1, so learn all of these.

Formula	Status
Discharge (cumecs) = cross-sectional area (m^2) × mean velocity (m/s)	Learn it
Lag time = time of peak discharge – time of peak rainfall	Learn it
Drainage density = total stream length (km) ÷ basin area (km^2)	Learn it
Hydraulic radius = cross-sectional area ÷ wetted perimeter (higher = more efficient channel)	Learn it
Recurrence interval $T = \frac{n+1}{m}$ (n = years of records, m = rank of the flood, largest = 1)	Learn it
Chance of a flood at least that big in any one year $= \frac{1}{T}$ (1 in 100 years = 1%)	Learn it
Percentage of precipitation following a route = route ÷ total precipitation × 100	Learn it

Term and meaning	Status
Interception: precipitation caught and held by leaves and branches before it reaches the ground	Learn it
Throughfall: water dripping from or falling through vegetation to the ground; **stemflow**: water running down stems and trunks	Learn it
Infiltration: water soaking into the soil surface; **percolation**: water moving down from the soil into the rock below	Learn it
Throughflow: water moving downslope through the soil, roughly parallel to the surface	Learn it
Overland flow: water flowing across the surface when infiltration capacity is exceeded or the soil is saturated	Learn it
Baseflow: groundwater seeping into the channel from the rock; it keeps rivers flowing between storms	Learn it
Recharge: water that percolates down and refills the groundwater store	Learn it
Evapotranspiration: evaporation from surfaces plus transpiration through the stomata of leaves	Learn it
Abrasion (corrasion): the load wearing away the bed and banks; **hydraulic action**: the force of the water and compressed air loosening material	Learn it
Cavitation: imploding air bubbles in fast water sending shock waves that weaken the bed and banks	Learn it
Traction: large particles rolled or dragged along the bed; **saltation**: particles bouncing along the bed	Learn it

Term and meaning	Status
Suspension: fine particles held up and carried in the water; **solution**: minerals dissolved and carried	Learn it
Laminar flow: smooth flow in sheets parallel to the bed, no eddies; **turbulent flow**: swirling flow with eddies	Learn it
Thalweg: the line of fastest flow along the deepest part of the channel	Learn it

How to do it

We have tagged 60 questions for this topic (2021–2025, all from Paper 1), 54 different (Papers 12 and 13 were the same in June 2022, 2023 and 2024). Every one is a multi-part Question 1 or Question 4, so all 60 mix types and the counts add up to more than 60.

Question type	Questions
Explain how a river landform or channel type forms	30
Describe or compare what a figure, photo or table shows	23
Evaluate a statement about what controls flows, hydrographs, floods or river processes (15-mark essay)	19
Read, state or calculate a value from a figure	18
Define two fluvial or hydrological terms	16
Explain how weather, land use or people change hydrographs, flows, stores or flooding	16
Explain how drainage basin characteristics affect the storm hydrograph, discharge or stores	15
Name or identify a feature, channel type or flow on a resource	14
Describe or briefly explain a drainage basin flow or hydrological idea	12
Evaluate flood management (15-mark essay)	11
Explain flood risk, prediction, impacts or management (short or 8-mark)	9
Explain erosion, transport and deposition using velocity and flow (Hjulström, flow patterns)	9
Describe or explain an erosion or transport process	8
Describe the features of a landform or channel type	6
Draw a labelled sketch map or cross-section	4

Short parts (3–5 marks) give 1 mark for a simple point and 2 (sometimes 3) for a developed one. The 8-mark (b) parts are marked in levels (Level 3, 6–8 marks), and the 15-mark (c) essays in four levels (Level 4, 12–15 marks).

1. Explain how a river landform or channel type forms (30 questions)

1. **Start with the conditions**: where the landform is and what the river is doing there (velocity, discharge, load, rock).
2. **Give the processes in order**, each linked to the next with "so" or "because": velocity or energy changes → erosion or deposition → the shape that results.
3. **Name the processes precisely** (hydraulic action, helicoidal flow, flocculation), and finish with how the landform changes over time.
4. **Add a labelled diagram** where it helps; diagrams are credited.

For a pair ("waterfalls and gorges", "river cliffs and point bars"), cover both: one alone is capped (often at Level 2). Use the cause chains in "Understand it".

Variation: "suggest how the channel may change over time" from a photo: meanders migrate and become more sinuous, necks are cut through to form oxbow lakes and meander scars, lateral erosion widens the channel, levées grow, and people may straighten or dredge it.

2. Describe or compare what a figure, photo or table shows (23 questions)

1. **Describe the overall pattern first** (rises, falls, peaks, highest, lowest, where).
2. **Quote data with units** for at least one point: a mark is usually kept for data.
3. **Only describe**: no reasons unless the question asks "why".

For **compare**, write linking sentences ("whereas", "both", "higher than"); two separate descriptions are capped at about 2 marks. If asked for similarities and differences, give both. For River P above: "Discharge is lowest at 90 cumecs in March, rises sharply from May to a peak of 1680 cumecs in August, about 19 times the March flow, then falls from September."

3. Evaluate a statement about what controls flows, hydrographs, floods or river processes (15-mark essay) (19 questions)

The statements are "X is the most important factor in..." or "Y always...". Plan:

1. **Introduction**: define the key terms and say what the question is really asking.
2. **Explain the named factor fully**: how it changes lag time, peak, limbs and base flow, or the flows and stores asked about.
3. **Weigh at least three other factors** (antecedent moisture, rock and soil, slopes, basin size and shape, vegetation, land use, dams, abstraction), saying when each matters more or less.
4. **Use real examples** throughout: with none, the maximum is 6.
5. **Conclude with a judgement** on "how far": for example, precipitation is the input that the other factors modify, so it sets the size of the response, but the basin decides its shape.

Pick out every key word: "intensity" as well as "amount", "most", "always", "shape", "channel flow". For "land use always increases channel flow", give changes that reduce it too (afforestation, wetland restoration, reservoirs, abstraction).

4. Read, state or calculate a value from a figure (18 questions)

1. **Read the axis carefully**, including log scales and which graph or line the question names.
2. **Show working** for a difference, range or percentage: "4800 – 1900 = 2900 cumecs".
3. **Give units every time** (cumecs, hours, days, m, cm/s, %): without them the mark is lost.

Lag time is peak rainfall to peak discharge, not the start of the rain. On a Hjulström curve, find the size on the bottom axis, go up to the curve, and read across.

5. Define two fluvial or hydrological terms (16 questions)

Two marks each: say **what kind of thing** it is (a flow, a store, an erosion process, a transport process) **(1)**, then **how or where** it happens **(1)**. Learn the definitions in "Key facts and formulas" exactly. For percolation, say **downward** and **after infiltration**; for laminar flow, say **in sheets** and **parallel to the bed**; for evapotranspiration, mention **transpiration from leaves**; for recharge, say it refills the **groundwater store**.

6. Explain how weather, land use or people change hydrographs, flows, stores or flooding (16 questions)

1. **Name the factor** (seasonal rainfall, snowmelt, deforestation, a dam).
2. **Say what it does to the water**: more or less of it, faster or slower to the channel, which flow or store changes.
3. **Say what happens on the graph**: earlier or higher peak, shorter lag time, lower dry-season flow.

A bare factor scores nothing. "Explain two reasons" needs both developed. Use clues in the resource (latitude, snow, monsoon, basin size).

7. Explain how drainage basin characteristics affect the storm hydrograph, discharge or stores (15 questions)

1. For each characteristic, **contrast its two extremes**: permeable and impermeable, circular and elongated, steep and gentle.
2. **Link each to infiltration and overland flow**, then to each part of the hydrograph: lag time, peak discharge, rising and falling limbs, base flow.
3. In an 8-mark answer **cover both named factors**: one alone is capped at 4 marks.

For **stores**, go store by store (interception, surface, soil, groundwater, channel) and say which factors (soils, rock, relief, vegetation, climate, people) fill or empty each.

8. Name or identify a feature, channel type or flow on a resource (14 questions)

Give the precise term, one answer only: floodplain, distributary (not "river channel"), meander, braided channel, eyot, point bar, river cliff, levée, bluff, the Hjulström curve, a named flow (for example infiltration + percolation for water entering the ground).

9. Describe or briefly explain a drainage basin flow or hydrological idea (12 questions)

Usually 3 marks, one per step: where the water comes from → how and which way it moves → where it goes, plus what speeds it up. For throughflow: after infiltration (1), water moves downslope through the soil parallel to the surface (1) under gravity, faster in sandy soil and on steep slopes (1). Precipitation may not reach a channel because it is intercepted and evaporated, transpired, held in soil, groundwater or snow, or abstracted; and water that has infiltrated can still reach it by throughflow. Drainage density: total stream length (1) ÷ basin area (1), in km per km^2 (1).

10. Evaluate flood management (15-mark essay) (11 questions)

1. **Define** hard and soft engineering (and prevention against reducing impact, if relevant).
2. **Explain how each method works**, then judge it: cost, side effects, how big a flood it copes with, who gains and who loses.
3. **Use located examples** (Three Gorges, Room for the River, Pickering, your case study).
4. **Judge the statement**: soft methods cope with frequent small floods but not the 1 in 100-year flood; hard methods protect towns, at a cost and with risk if they fail; the best approach combines them with forecasting.

For "with the aid of a case study, evaluate the attempts...", outline the causes and impacts, then judge each response against the impacts on people **and** the environment.

11. Explain flood risk, prediction, impacts or management (short or 8-mark) (9 questions)

- **One method, 3 marks**: name it (1), how it works (1), the result (1): "Levées (1) make the banks higher (1), so a larger discharge fits in the channel before water spills out (1)."
- **How a flood map helps**: shows where to send warnings, where to zone or restrict building, where defences are needed.
- **Recurrence intervals in prediction (8 marks)**: what they are and how they are calculated, both **magnitude and frequency**, their uses in planning, and their limits (short records, a changing climate and basin).
- **Impacts**: explain why each happens rather than listing them; include benefits.

12. Explain erosion, transport and deposition using velocity and flow (Hjulström, flow patterns) (9 questions)

1. **Describe the curves** with data: sand easiest (about 20 cm/s), high velocities for cohesive clay and silt and for heavy gravel.
2. **Explain each part**: weight, cohesion, deposition as velocity falls (largest first), clay in suspension until it flocculates.
3. **Apply it to a real channel** (outer and inner bends, riffles, floodplains, deltas) and **note its limits**.

For "describe" give the trends with data only; for "explain" give the reasons.

13. Describe or explain an erosion or transport process (8 questions)

Say **what** moves or is worn away, **how**, and **when** it is strongest (velocity, discharge, particle size, rock type). For "two processes", develop both: marks split 2/2 or 3/1. For turbulent flow, the eddies lift particles and the **particles** do the eroding. Abrasion varies along a channel with velocity, the amount and size of load, and how erodible the bed is.

14. Describe the features of a landform or channel type (6 questions)

One mark per feature, each with detail (size, shape, position); a bare list such as "pools, riffles" is not enough. **Braided**: many channels dividing and rejoining, eyots (some vegetated), gravel bars, a wide, shallow main channel, steep banks. **Meander**: river cliff, point bar, pools at bends, riffles between. To **contrast** braided and meandering, pair each point (see Quick check 5).

15. Draw a labelled sketch map or cross-section (4 questions)

1. **Draw what is in the photo**, not a textbook meander: the actual bends, bars and channels.
2. **Draw the type asked for**: a sketch map is a plan; a cross-section gets no credit for the sketch when a map is asked.
3. **Label accurately**: point bar, river cliff, floodplain, main and secondary channels, eyots, vegetation. Usually 2 marks for the sketch, 2 for the labels.

Worked examples

Example 1

Use the storm hydrographs in the second diagram of "Understand it". A and B are two basins that received the same storm.

(a) (i) State the peak discharge of hydrograph A. **[1]** (ii) Calculate the lag time of hydrograph A. **[1]**

(b) Describe the shape of hydrograph A. **[3]**

(c) Suggest two reasons why hydrograph B has a lower peak and a longer lag time than A. **[5]**

(a)(i) 38 cumecs **(1)**, with units.

(ii) Peak rainfall at hour 4, peak discharge at hour 16: $16 - 4 = 12$ hours **(1)**.

(b)

- A steep rising limb: discharge rises from 6 cumecs at hour 5 to 38 cumecs at hour 16, about 3 cumecs an hour **(1)**.
- A high, narrow peak: the hydrograph is flashy **(1)**.
- The falling limb is gentler than the rising limb: it takes until about hour 34 to fall back to 10 cumecs **(1)**.

(c)

- **Rock and soil.** Basin B may have permeable rock such as sandstone and sandy soils **(1)**. More rain infiltrates and percolates rather than running off, so it reaches the river slowly as throughflow and baseflow **(1)**, delaying and lowering the peak **(1)**.
- **Vegetation.** Basin B may be forested **(1)**: interception holds rain on leaves, some evaporates, and stemflow and roots slow the water and help it soak in, so less reaches the channel and later **(1)**.

Two developed reasons: **5 marks**.

Example 2

(a) Define the hydrological terms 'throughflow' and 'recharge'. **[4]**

(b) A river gauge has recorded the highest discharge of each year for 39 years. The fourth largest of these was 820 cumecs. Calculate the recurrence interval of this flood and the chance of a flood of at least this size in any one year. **[3]**

(a) Throughflow is the movement of water through the soil **(1)**, downslope and roughly parallel to the ground surface, after infiltration **(1)**. Recharge is the refilling of the groundwater store **(1)** by water percolating down from the soil into the rock **(1)**.

(b) $T = \frac{n+1}{m} = \frac{39+1}{4}$ **(1)** $= 10$ years **(1)**. Chance in any one year $= \frac{1}{10} = 10\%$ **(1)**.

Example 3

Explain how floodplains and levées are formed. **[8]**

A floodplain is the flat land either side of a river that is covered in floods. As meanders migrate across the valley, erosion on their outer banks wears the valley sides back to the bluffs, while point bars are left behind on the inner banks, so the valley floor becomes wide and flat. Each time discharge exceeds bankfull, water spreads over this land; it becomes shallow and meets friction, so it slows and drops layers of silt and clay (alluvium) that build the floodplain up.

Levées form at the edge of the channel during the same floods. The moment water leaves the channel it loses velocity, so it drops its coarsest sediment first, right beside the channel, and carries finer silt further across the floodplain. After many floods, the coarse deposits build raised banks, the levées, which slope gently away from the river. Between floods, deposition on the bed may raise the river so that it flows above the floodplain, as on parts of the Mississippi.

Level 3 (6–8 marks): both landforms explained with the processes in sequence (lateral erosion, overbank flow, loss of velocity, sorting of sediment), and a real example.

Example 4

'Afforestation is the most effective way to reduce river flooding.' With the aid of examples, how far do you agree with this statement? **[15]**

Introduction. Afforestation (planting trees in a drainage basin) is soft engineering. "Effective" means fewer floods and less damage, so compare it with other soft and hard methods.

For. Trees intercept rain, transpire and open up the soil, so more rain infiltrates and less becomes overland flow: lag times lengthen and peaks fall. It is cheap, reduces soil erosion and helps wildlife. At Pickering, tree planting with leaky dams and a storage bund helped the town avoid flooding in 2015–16.

Against. Trees take decades to grow, and help most with small and moderate floods: in a long, extreme storm the soil saturates and most water still runs off. Towns already on a floodplain are protected more reliably by hard engineering, such as the Three Gorges Dam storing Yangtze floodwater or the Bonnet Carré Spillway diverting water from New Orleans. Room for the River shows other soft methods can work faster, and forecasts save lives in floods nothing can stop.

Conclusion. Afforestation works well, in the long term, against frequent smaller floods in upland basins, but not as the most effective method on its own: rare, large floods also need storage, defences and warnings.

Level 4 (12–15 marks): the factor explained, weighed against several alternatives with located examples, and a judgement that answers "how far".

Common mistakes

- **Mixing up throughfall and throughflow.** Throughfall drips through vegetation above ground; throughflow moves through the soil.
- **Vague definitions.** Percolation is the *downward* movement of water *after infiltration*; laminar flow moves *in sheets parallel to the bed*; recharge refills the *groundwater store*; evapotranspiration includes *transpiration through leaves*.
- **Drawing helicoidal flow as a corkscrew down the middle of the channel.** It crosses the whole channel: surface flow to the outer bank, return flow along the bed to the inner bank.
- **Confusing riffles with point bars.** Riffles are shallow bars between bends; point bars are deposits on the inner bank.

- **Thinking velocity always falls downstream.** Mean velocity usually rises, because discharge and channel efficiency increase.
- **Misreading the Hjulström curve.** "Erosion" there means picking particles up; deposition happens when velocity *falls*; and read log axes carefully.
- **Forgetting units**, or reading from the wrong graph.
- **Explaining when asked to describe** (or the reverse), and writing two separate descriptions when asked to compare.
- **Confusing braided and meandering channels**, and forgetting that braiding needs a discharge that varies a lot.
- **Linking drainage density to basin size.** It depends on rock, soil, rainfall, slope and vegetation.
- **Calling forecasting soft engineering**, or muddling which methods are hard and which soft.
- **Blaming a flood on the town that flooded.** The rain, runoff and discharge usually built up upstream.
- **Ignoring key words in essays** ("intensity", "most", "always", "shape", "channel flow").
- **Saying turbulent flow erodes by itself.** The particles it picks up do the abrasion.

How to get the marks

- **Units and working.** Every reading needs units; every calculation shows its working.
- **Develop each point.** In 3–5 mark parts, a simple point earns 1 and a developed point (cause → effect → result) earns 2.
- **Describe** = what it looks like, with data. **Explain** = reasons and processes. **Suggest** = apply what you know to an unfamiliar resource; several sensible reasons are credited. **Compare** = similarities and differences together, with linking words. **Define** = precise meaning: what it is and how it works.
- **Use the resource.** In Question 1, quote figures from it, and use its clues (location, season, basin size) in the explanation part.
- **8-mark (b) parts** are levelled: Level 3 (6–8) needs clear explanation of the whole sequence, covering every part of the question, with examples or a labelled diagram.
- **15-mark essays** are levelled: Level 4 (12–15) needs a thorough, balanced assessment with located examples built into the argument and a clear judgement. With no examples the maximum is 6.
- **Diagrams earn credit** when labelled and annotated with processes, not decorative.

Quick check

1. A drainage basin has an area of 124 km² and its streams have a total length of 186 km. Calculate its drainage density and say what a high value would mean for its storm hydrograph.
2. In a forested basin, 900 mm of precipitation falls in a year. 180 mm is intercepted and evaporated, 90 mm runs off as overland flow and the rest infiltrates. Calculate the percentage of precipitation that enters the ground.

3. Using the Hjulström curve diagram, state the velocity needed to pick up 0.1 mm sand, and the velocity below which 1 mm sand is deposited.
4. A flood has a recurrence interval of 50 years. State its chance of happening in any one year, and calculate the chance of at least one such flood in 20 years.
5. State two differences between a braided channel and a meandering channel.

Answers

1. $186 \div 124 = 1.5$ km per km². A high density means water reaches a channel quickly: a short lag time, a high peak and a steep rising limb.
2. $900 - 180 - 90 = 630$ mm infiltrates. $\frac{630}{900} \times 100 = 70\%$.
3. About 26 cm/s to pick it up; it is deposited when velocity falls below about 13 cm/s.
4. $\frac{1}{50} = 2\%$ each year. Chance of none in 20 years $= 0.98^{20}$, so the chance of at least one $= 1 - 0.98^{20} \approx 33\%$.
5. Any two: several channels divided by bars and eyots, against one channel; wide and shallow, against narrower and deeper; coarse bedload, against finer load; a discharge that varies a lot, against a steadier one.

Past questions to try

- **9696/11/O/N/24 Q4**: throughflow, slopes and hydrographs, gorges, and an essay on soft engineering.
- **9696/13/M/J/23 Q1**: reading and explaining the Hjulström curve.
- **9696/12/O/N/24 Q1**: comparing annual hydrographs and why they vary.
- **9696/13/M/J/24 Q4**: recurrence intervals, and a flood case study.