MANAGEMENT OF NATURAL HAZARDS
IN MOUNTAIN BASINS

Basics of river hydrology and sediment transport

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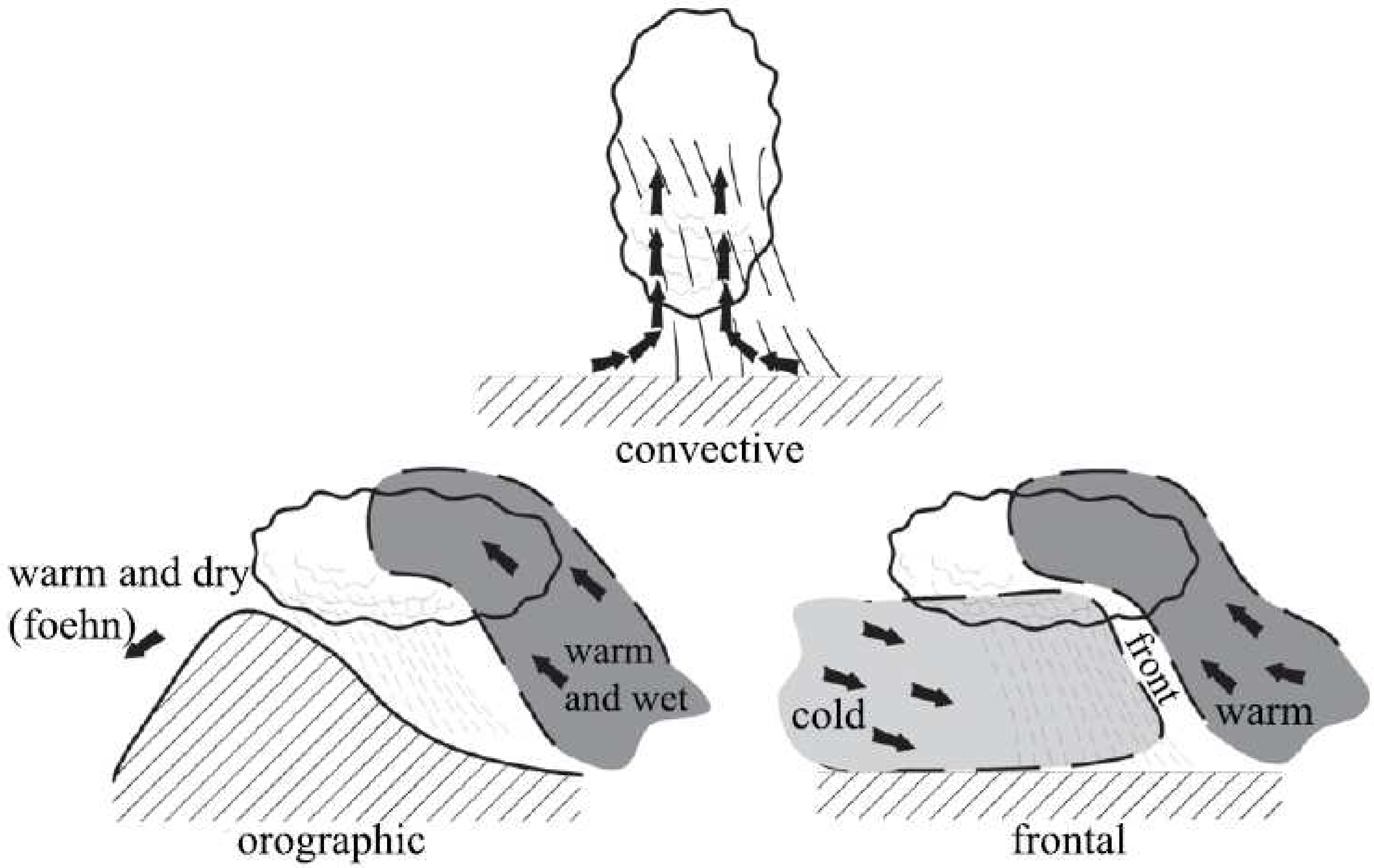
Academic year 2014/2015

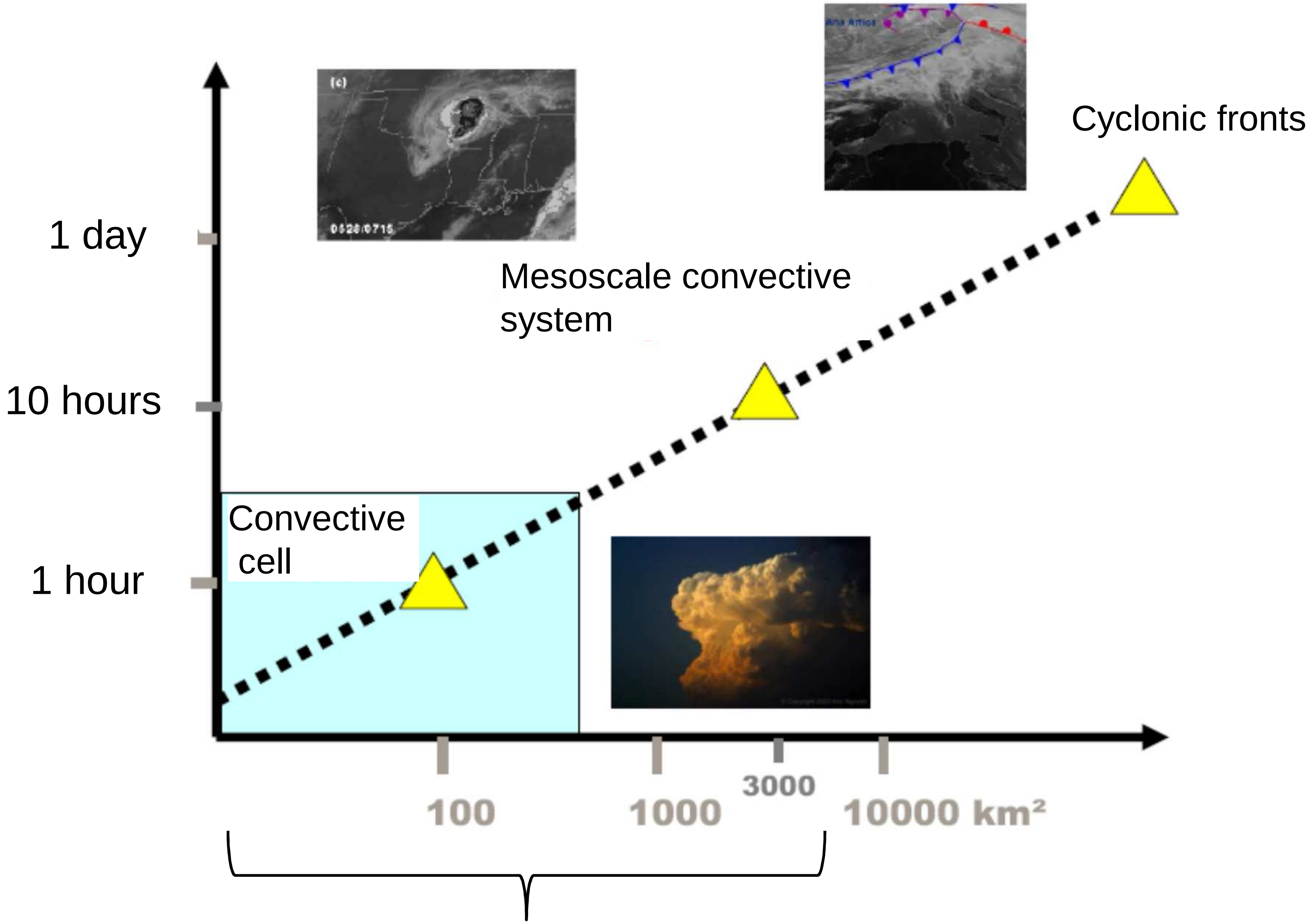
Credits to:
P.R. Bierman, D.R. Montgomery (2014) «Key concepts in Geomorphology»

Types of precipitation events

- Three main meteorological processes determine precipitation

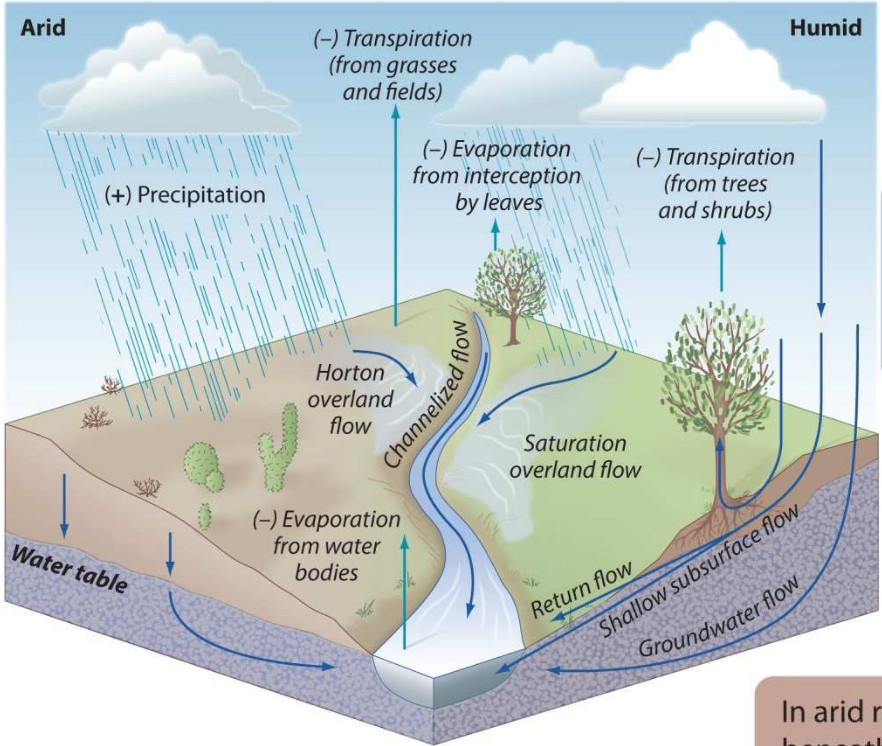


Spatio-temporal scales in precipitation



Most relevant spatial scales for mountain basins

Basic notions of hydrology: runoff generation



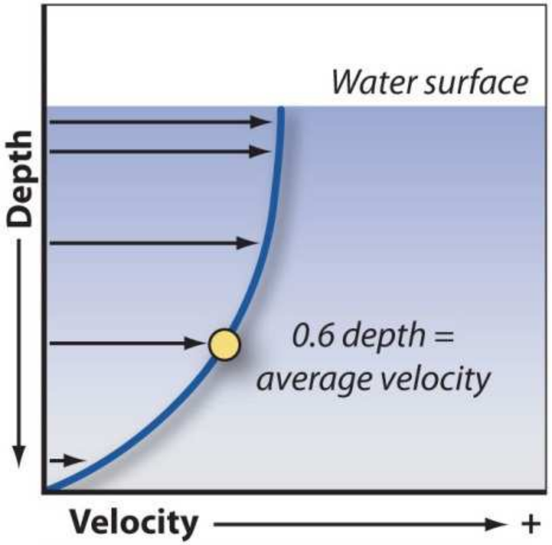
Water, falling as precipitation, takes various paths on, below, and away from Earth's surface. Some precipitation never reaches the ground because it is **intercepted** and evaporates from vegetation. Some water **infiltrates** and flows through the ground, some runs off the land surface, and some is returned to the atmosphere by the pumping action of vegetation, **transpiration.**

In arid regions, the groundwater table beneath hillslopes is deep, and precipitation mainly comes as high-intensity, short-duration storms. Because the dry climate supports scant vegetation, little precipitation is intercepted. **Infiltration rates** can be low, especially for A-horizons composed of wind-blown dust and clay. Large amounts of **Horton overland flow** occur because the rate of precipitation exceeds that of infiltration. Runoff also occurs through direct precipitation onto stream channels.

In humid regions, the water table can be close to the surface. Large amounts of vegetation intercept precipitation, make soil more permeable, and transpire water. Where and when the **water table** intercepts the ground surface, there is **return flow** and rainfall generates **saturation overland flow.** Some precipitation infiltrates and moves through the shallow, permeable, near-surface soil as **shallow subsurface flow** before emerging as return flow and entering streams. Precipitation that infiltrates deeply becomes **groundwater.**

Basic notions of hydrology: channelized runoff

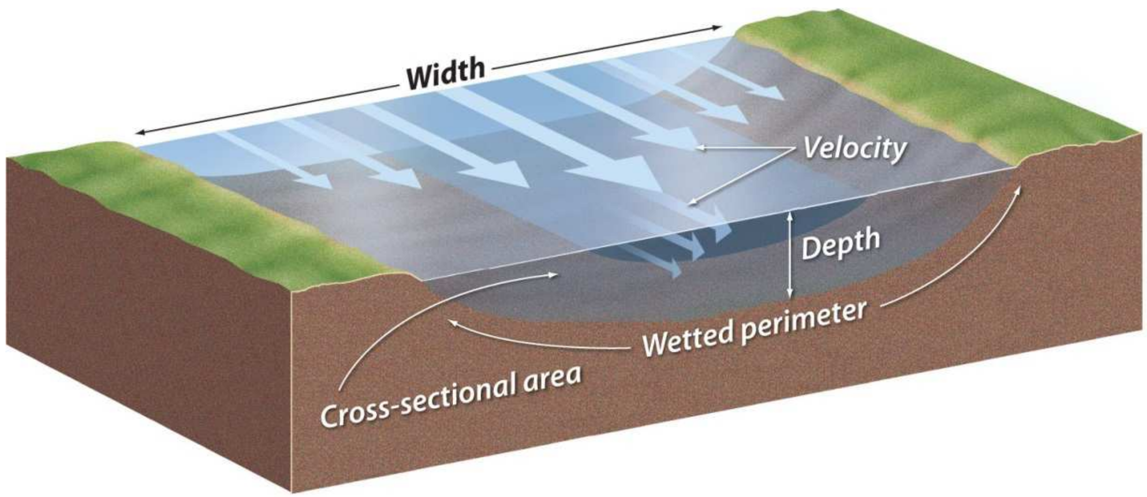
The **discharge** (Q) of a river is equal to the product of the average channel width (W), average depth (D), and average flow speed (U), which is commonly referred to as flow velocity, implicitly meaning the net speed of water flowing downstream. The portion of the channel bed in contact with the flow, and thus providing frictional resistance, is the **wetted perimeter** (P_w), which is approximately equal to the channel width plus twice the flow depth ($P_w = W + 2D$). The channel cross-sectional area is $W \times D$.



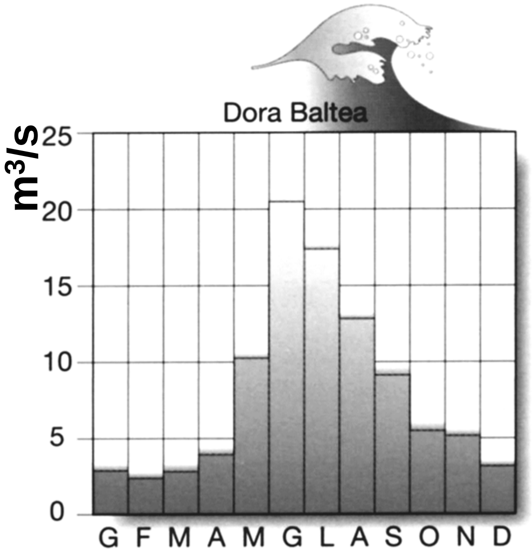
The downstream velocity of water flowing in a river increases in a logarithmic profile from the channel bed toward the surface, with the average downstream velocity at about 0.6 times the total flow depth.

Q = V A

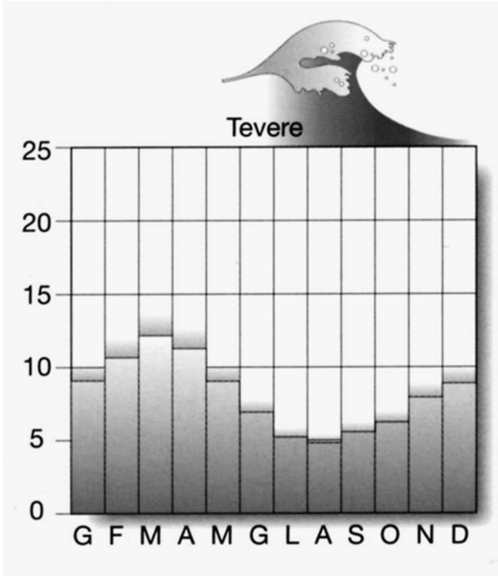
(continuity equation)



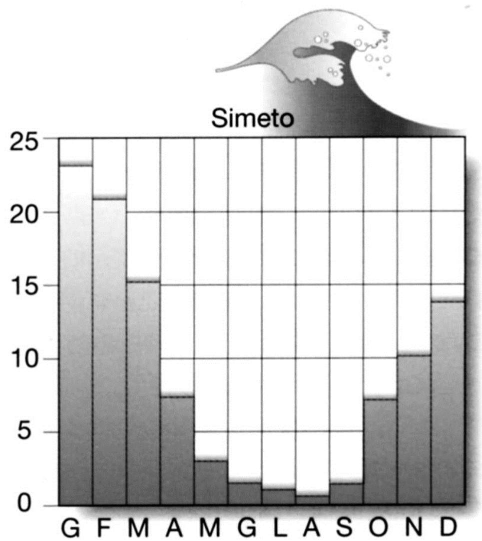
Basic notions of hydrology: runoff regimes



Glacial regime



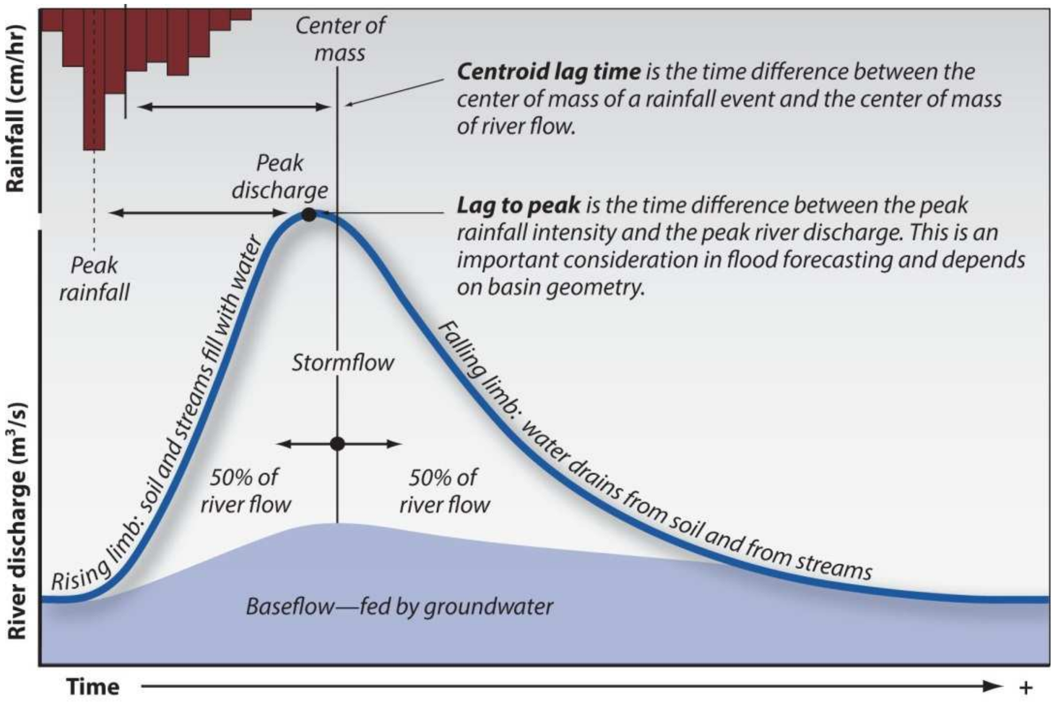
Rainfall-snowmelt regime

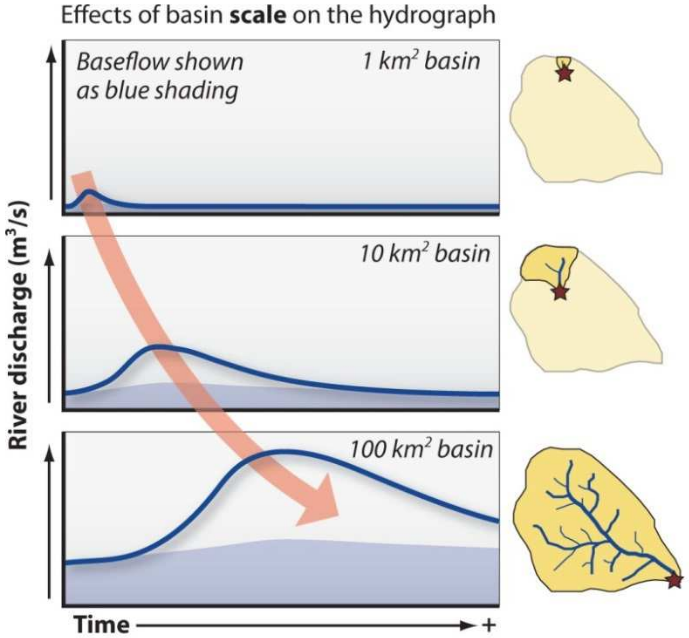


Pluvial (rainfall) regime

- In Alpine basins (as in most high-elevation mountain ranges), a large proportion of the runoff volume takes place in summer (snow and glacier melt !)

Basic notions of hydrology: hydrographs





Rainfall

During a rainfall event, the intensity at which precipitation falls on a landscape is often variable. The **peak rainfall,** a measure of the greatest intensity of rainfall, does not necessa occur in the middle of a rainfall event. Therefore, the peak and the center of mass of rainfal (the point at which half of the total rainfall has fallen) often do not correspond.

In general, river **discharge** increases with basin area. Rivers rise and fall more slowly in large basins than in small basins due to the lag time of water coming from distal locations. The area under the curves increases with basin area as more water runs off from larger basins, especially in humid regions.

Discharge

As precipitation falls across a landscape, some of it infiltrates and some runs off and enters river channels causing **discharge** and **river stage** to rise. As the soil fills with water, more precipitation enters river channels as **runoff,** groundwater flow, and **subsurface stormflow.** This flow moves downstream, entering progressively larger channels, where the water level, or stage, rises until reaching the peak, or maximum discharge resulting from a rainfall event. As water drains from the landscape and from channels, the river stage begins to fall, eventually returning to **baseflow,** which reflects normal groundwater discharge to rivers. Baseflow does not occur in most arid-region streams, because arid-region streams tend to flow ephemerally.

Basic notions of hydrology: frequency analysis

- Hydrologic systems are sometimes impacted by extreme events such as **severe storms, floods, and droughts**.

- Extreme events (with large magnitude) occur less frequently than moderate events (with smaller magnitude).

- The objective of frequency analysis of hydrological data is to relate the magnitude of extreme events to their frequency of occurrence through the use of **probability distributions** (=relation between magnitude and probability).

- It is assumed the events (data) are independent from each other and are generated by a stochastic process.

What has happened and the frequency of events in a record are the best indicators of what can happen and its probability of happening in the future.

Basic notions of hydrology: return period

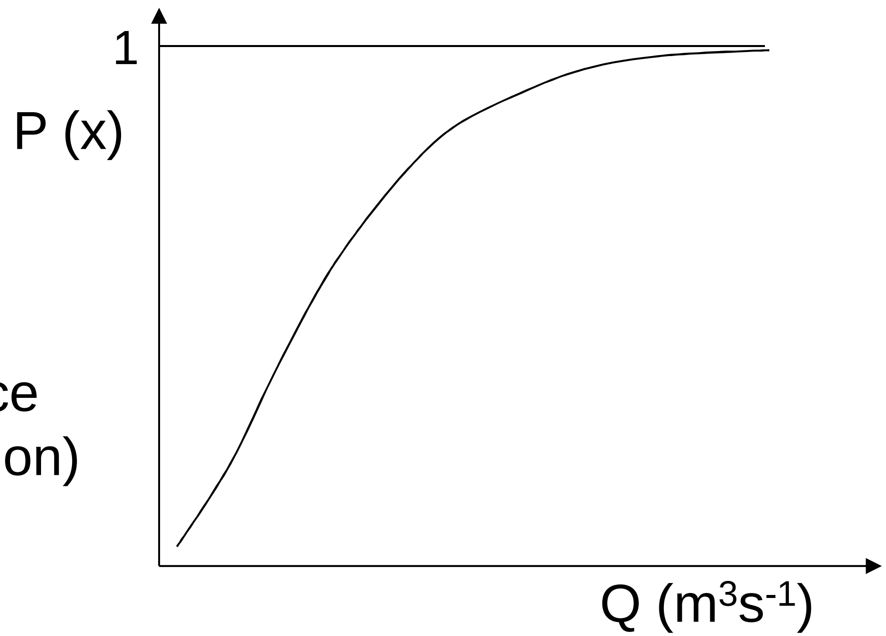
<u>Return period</u> (or recurrence interval) *T:*

➢ number of years for a hydrological variable (rainfall depth, peak flow discharge, low flow discharge) to be equalled or exceeded <u>on average</u> one time

or:

➢the event occurs <u>at least</u> with a certain magnitude once every T years

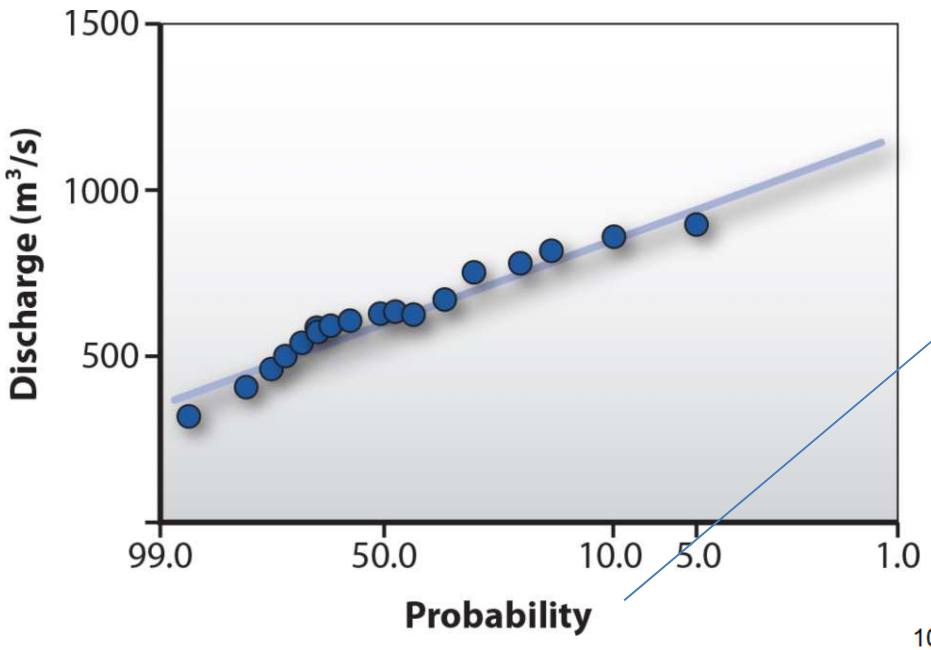
$$T = \frac{1}{F(x)} = \frac{1}{1 - P(x)}$$



F(x) = probability of exceedence
P(x) = probability of non-exceedence
(cumulative distribution function)

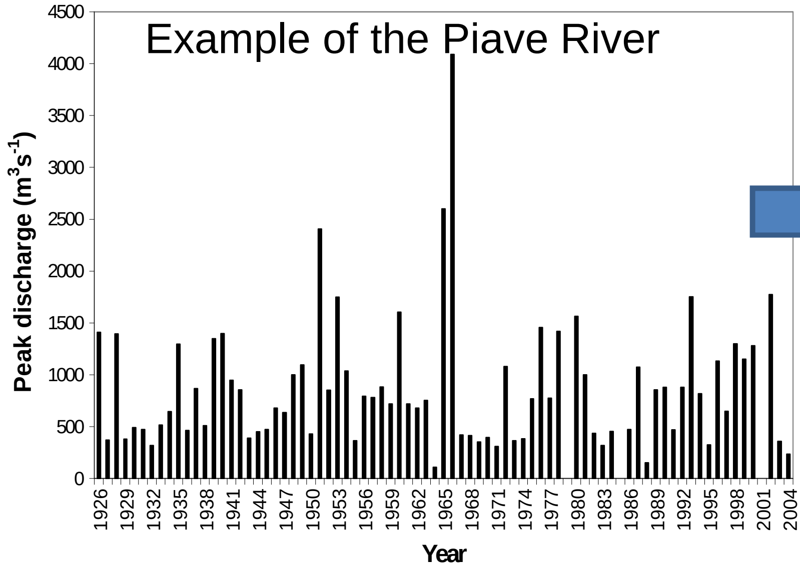
$$1 - P(X < x) = 1/T$$

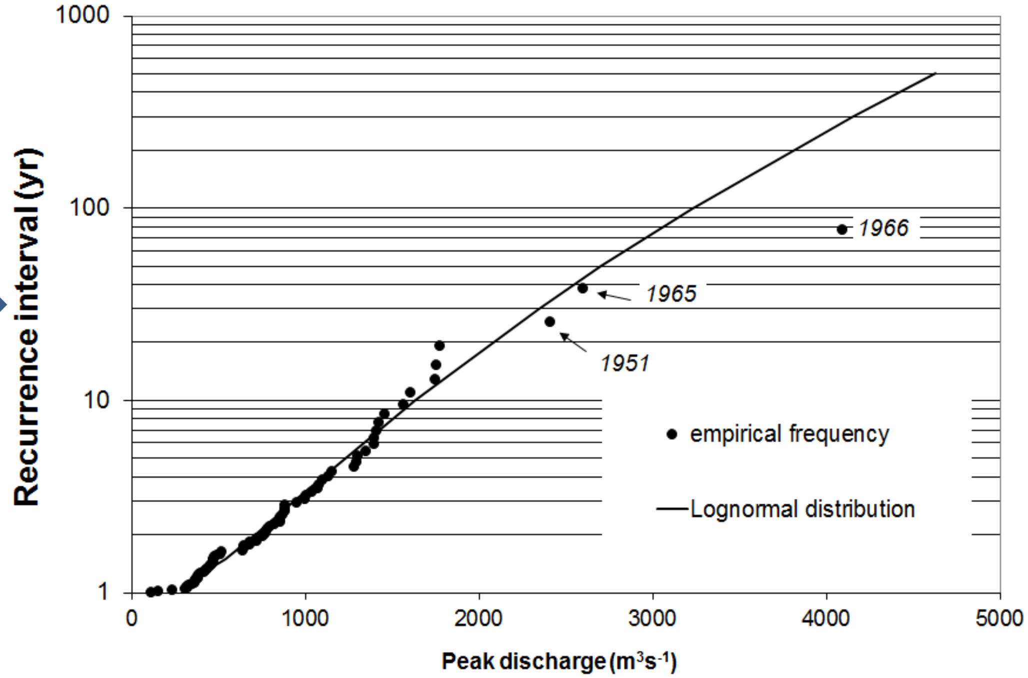
Basic notions of hydrology: return period



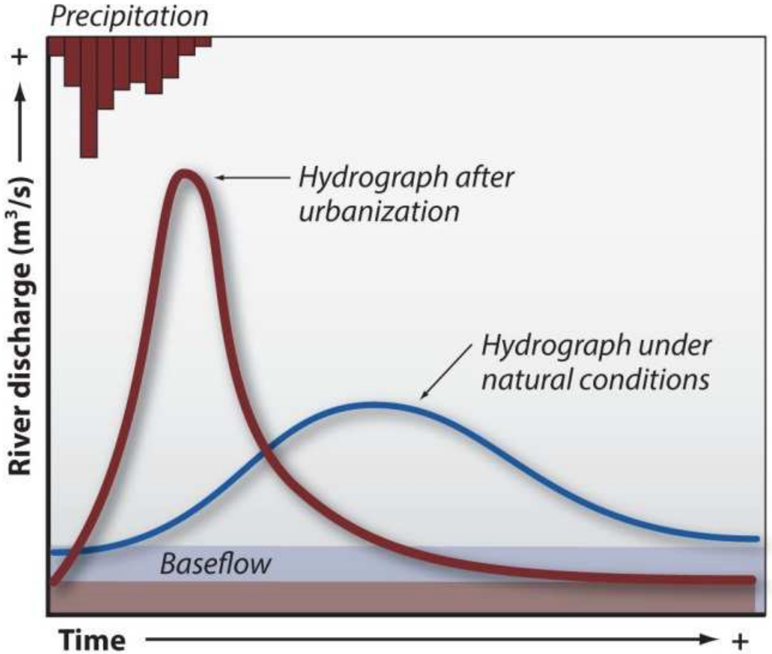
Annual probability of exceedance (1/T)

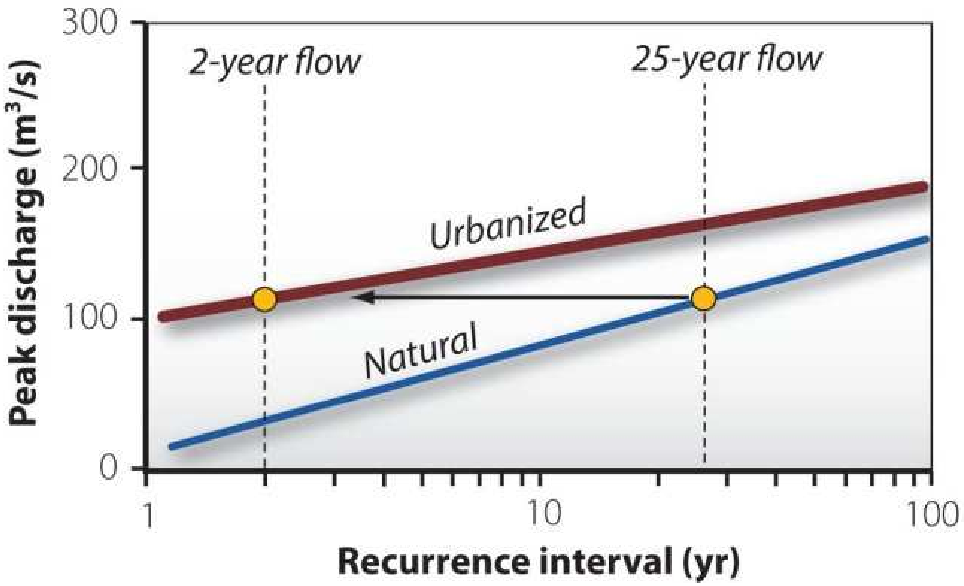
Calculated by applying Gumbel or lognormal probability distributions (see additional optional material available on Moodle to learn more)





Basic notions of hydrology: influence of land use





Under natural conditions, rainfall follows convoluted paths through the landscape. Water is held in **detention storage** by irregular pit and mound topography, infiltrating into organic-rich forest soil, and moving slowly to the channel. The infiltrating water feeds **baseflow** during times when it is not raining. **Flood peaks** are delayed because natural landscape characteristics slow the rising limb of the hydrograph, lower the peak flow, and extend the flood duration.

After urbanization, rainfall moves rapidly to the channel with little chance to infiltrate; thus, baseflow is reduced. Flowing directly off **impervious surfaces,** such as parking lots, and into storm sewers, runoff rapidly enters streams, raising their level quickly. Flood peaks now come sooner and are higher, increasing flood hazards and the tempo of geomorphic change. In the example below, the natural 25-year flow becomes the much more frequent urbanized 2-year flow.

Basic notions of hydrology: peak flood discharge

Flood hydrograh volume and peak discarge depend on:

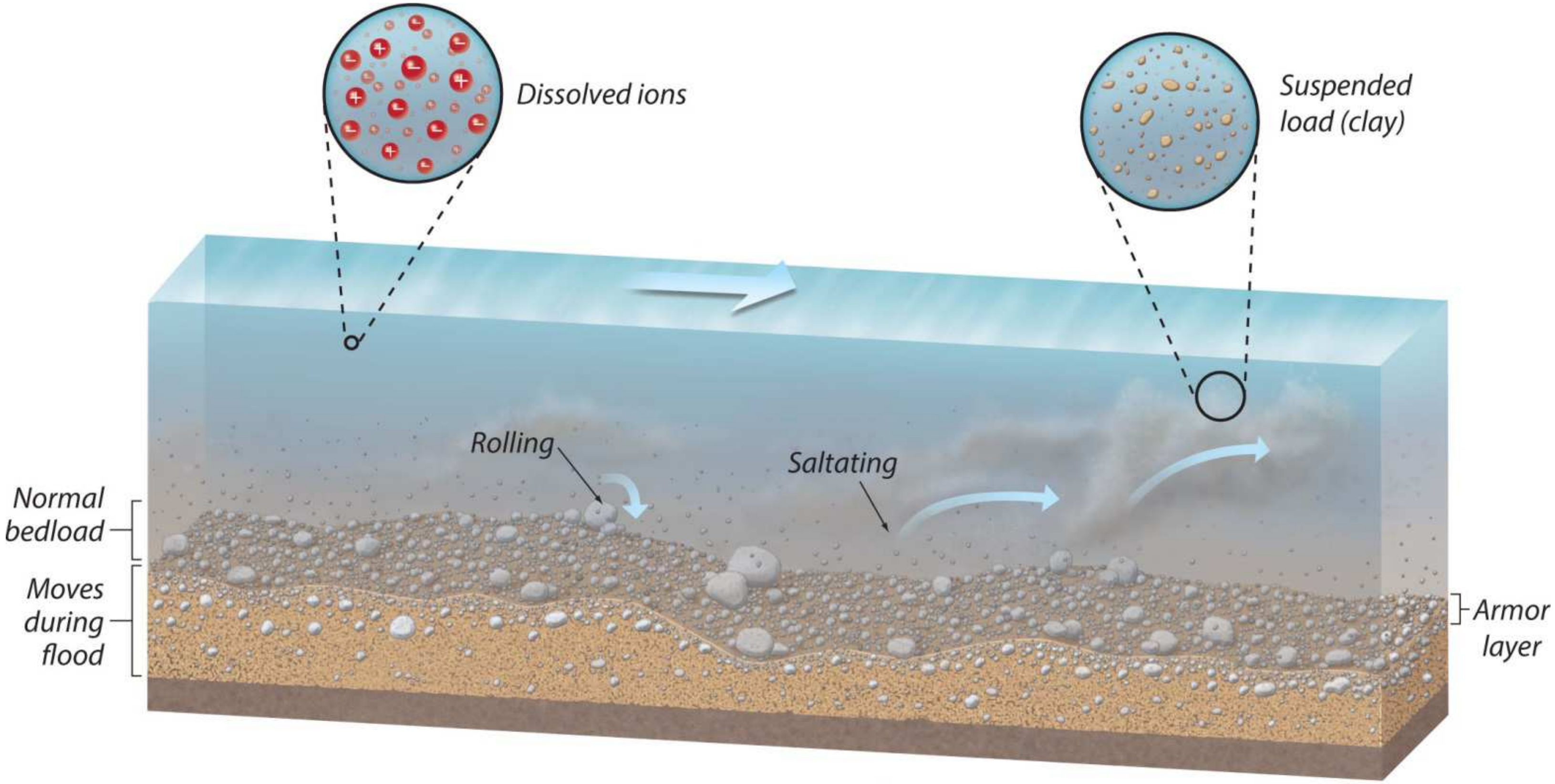
- Basin area
- Basin slope and shape
- Basin geology (degree of permeability of rock substrate)
- Land use (infiltration capacity of soils)
- Rainfall intensity
- Spatial and temporal distribution of rainfall

Sediment transport by fluvial processes

- Sediments are mobilized by forces due to flowing water
- "Newtonian" rheology (linear stress – strain rheology)
- Sediment concentration depends on gradient
- Mostly <5% but up to 10% in volume (transition towards hyperconcentrated)

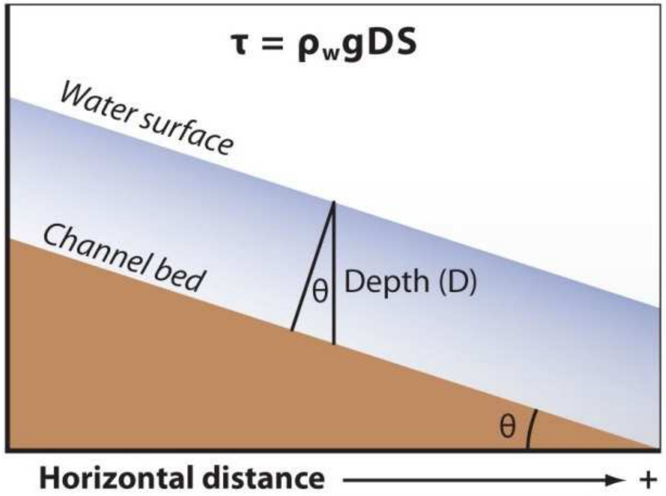
- Density about 1,000 kg m^{-3}
- Velocity <3-5 m s^{-1}

Sediment transport by fluvial processes



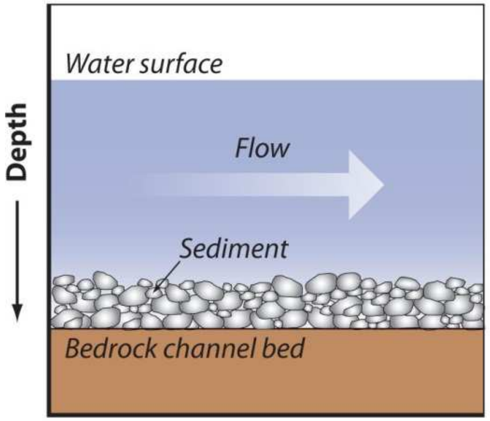
Streams carry material as **dissolved load, suspended load,** and **bedload.** Dissolved load is composed of ions in solution that travel at the speed of the flow. Suspended load (typically silt and clay) is composed of material suspended by turbulence in the flow and moving at the speed of the flow. Bedload moves by rolling or sliding along the channel bed and is typically composed of gravel and cobbles. Sand may travel as either suspended load or bedload, depending on the flow velocity. **Saltating** sediment is swept from the bed, then travels some distance while settling back to the channel bottom. Bedload moves intermittently and thus more slowly than the flow. Streambeds are often **armored** by a layer of large clasts due to winnowing of finer material from the bed.

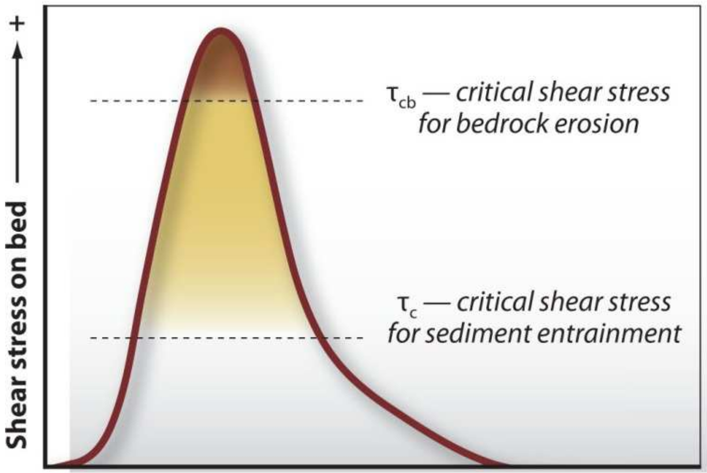
Initiation of sediment motion and bed erosion



The **shear stress** (τ) exerted on the channel bed by the flow is equal to the downslope component of the weight of the overlying water $\tau = \rho_w gDS$, where ρ_w is the density of water and g is the acceleration due to gravity. The small angle approximation, where S ~ sin θ, is often used.

- The driving force is shear stress (τ) (proportional to flow velocity)





During a flood, shear stress on the stream bed increases as the depth and velocity of water increase. The **critical shear stress** above which bedrock erosion occurs (τ_{cb}) is higher than that required to entrain sediment from the channel bed (τ_c). Thus, rare floods, high-stream power events that generate large shear stresses on the bed, are required to erode rock. Often bedrock only erodes significantly during the highest flood peaks.

Also used:

Stream power $\Omega = \gamma Q S$

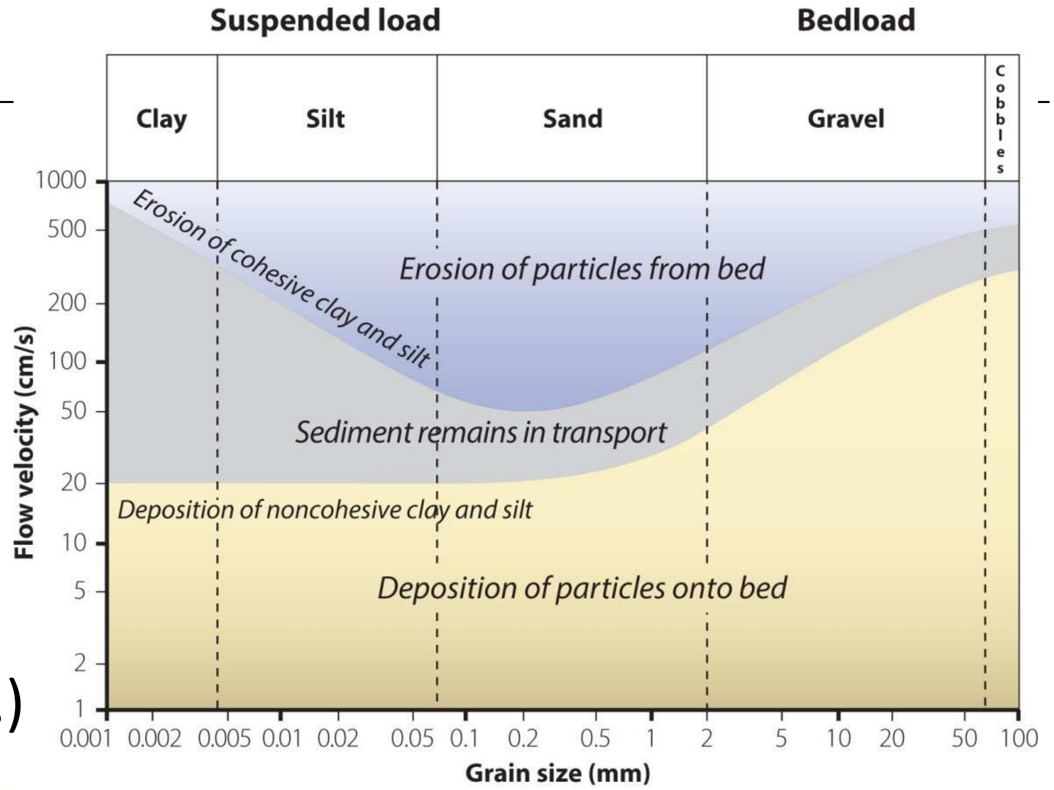
Unit stream power $\omega = \gamma Q/W S$

Initiation of motion

- The main resisting force is given by the weight of sediment particles (proportional to grain size)

Additional factors are:

- cohesion (fine s.)
- particle imbrication (coarse s.)



Erosion: The flow velocity required to erode material from a channel bed is a function of grain size. Sand is eroded at lower flow velocities than both coarser material (gravel and cobbles) and finer-grained material (silt and clay). To erode silt and clay, water must be moving quickly enough to overcome the **cohesive** strength of the material. The greater velocity needed to erode larger particles reflects their greater mass.

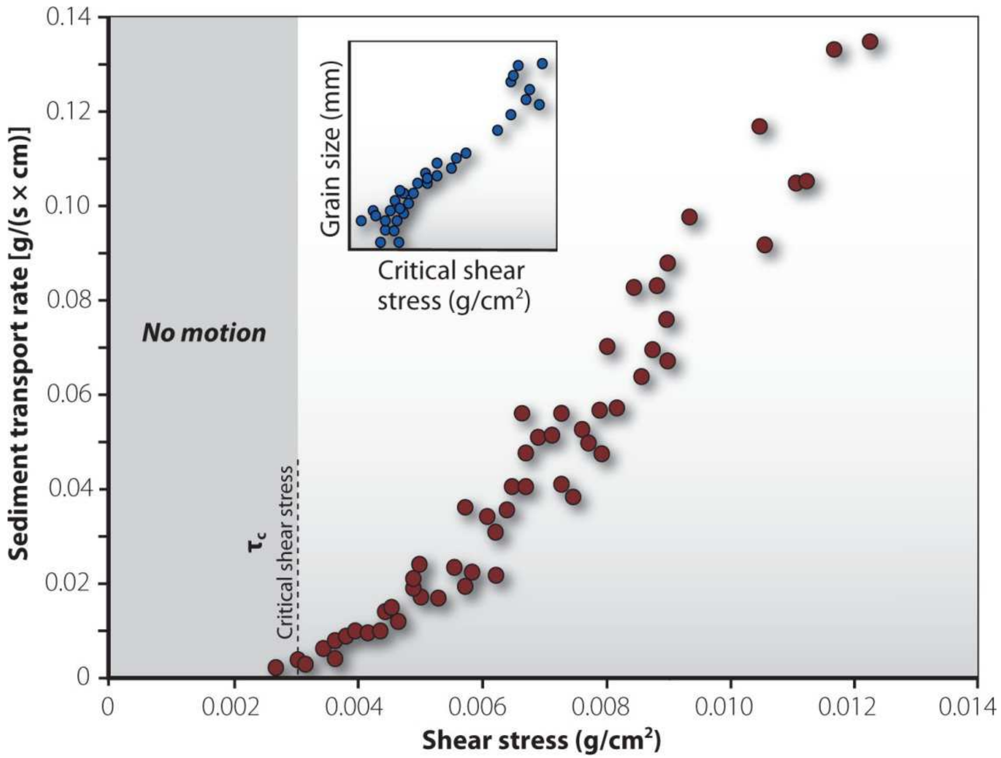
Transport: For large grain sizes that travel as **bedload,** there is little difference in the flow velocity required for erosion and deposition. In contrast, smaller particles that travel as **suspended load** can remain in motion at flow velocities well below those required to erode them.

Deposition: Fine-grained material (silt and clay) settles out in very still water, whereas coarse-grained material settles out even in swift water.

Bedload transport rates: very hard to estimate !

Bedload transport rates depend on:

- Shear stress exceeding the motion threshold value
- Channel slope
- Channel roughness (flow energy dissipation)
- Sediment availability (quantity and size)



Bedload transport **(entrainment)** typically begins at a **critical shear stress (τ_c)**, below which there is no motion and above which sediment transport rates increase with increasing shear stress. The critical shear stress needed to initiate motion increases with grain size (see inset).

To learn more take the 2nd year optional course «Water and sediment management»

Sediment yield at the Earth's scale

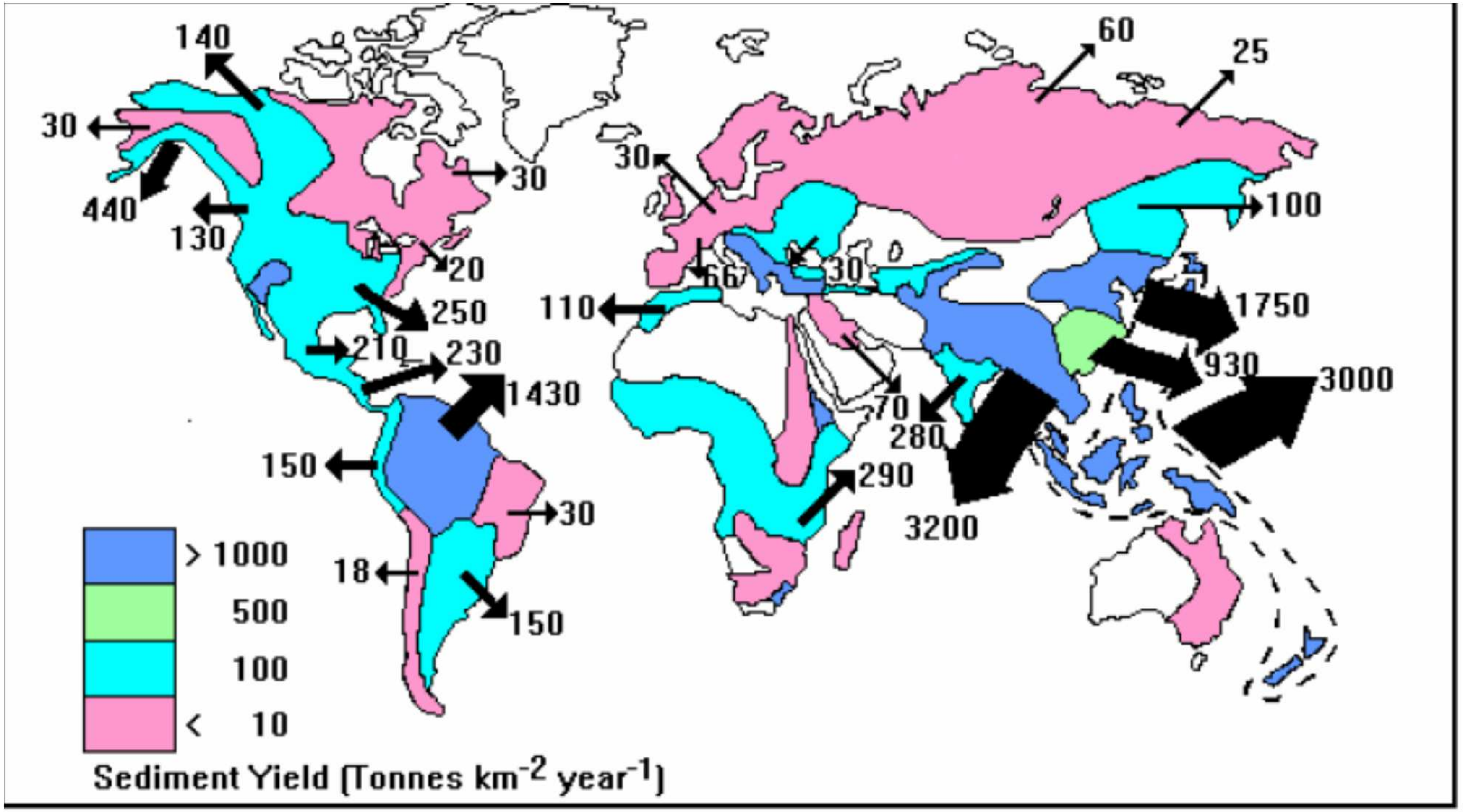


Figure 5 Global pattern of sediment yield, with river output of sediment to the oceans (tonnes x10^{6}) (Ref. 6). (Reproduced by permission)

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