River morphodynamics

Part 3: Sediment transport

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Sediments classification

Canonical definition of sediment grain sizes as defined by geologist Chester K. Wentworth in a 1922 article in The Journal of Geology: "A Scale of Grade and Class Terms for Clastic Sediments"

Millimeters (mm)		Micrometers (µm)	Phi (φ)	Wentworth size class	
	4096		-12.0		
				Boulder	Gravel
	256		-8.0		
				Cobble	
	64		-6.0		
				Pebble	
	4		-2.0		
				Granule	
	2.00		-1.0		
				Very coarse sand	Sand
	1.00		0.0		
				Coarse sand	
1/2	0.50	500	1.0		
				Medium sand	
1/4	0.25	250	2.0		
				Fine sand	
1/8	0.125	125	3.0		
				Very fine sand	
1/16	0.0625	63	4.0		
				Coarse silt	Silt
1/32	0.031	31	5.0		
				Medium silt	
1/64	0.0156	15.6	6.0		
				Fine silt	
1/128	0.0078	7.8	7.0		
				Very fine silt	
1/256	0.0039	3.9	8.0		
				Clay	Mud
	0.00006	0.06	14.0		

The sediment journey

Hydrology

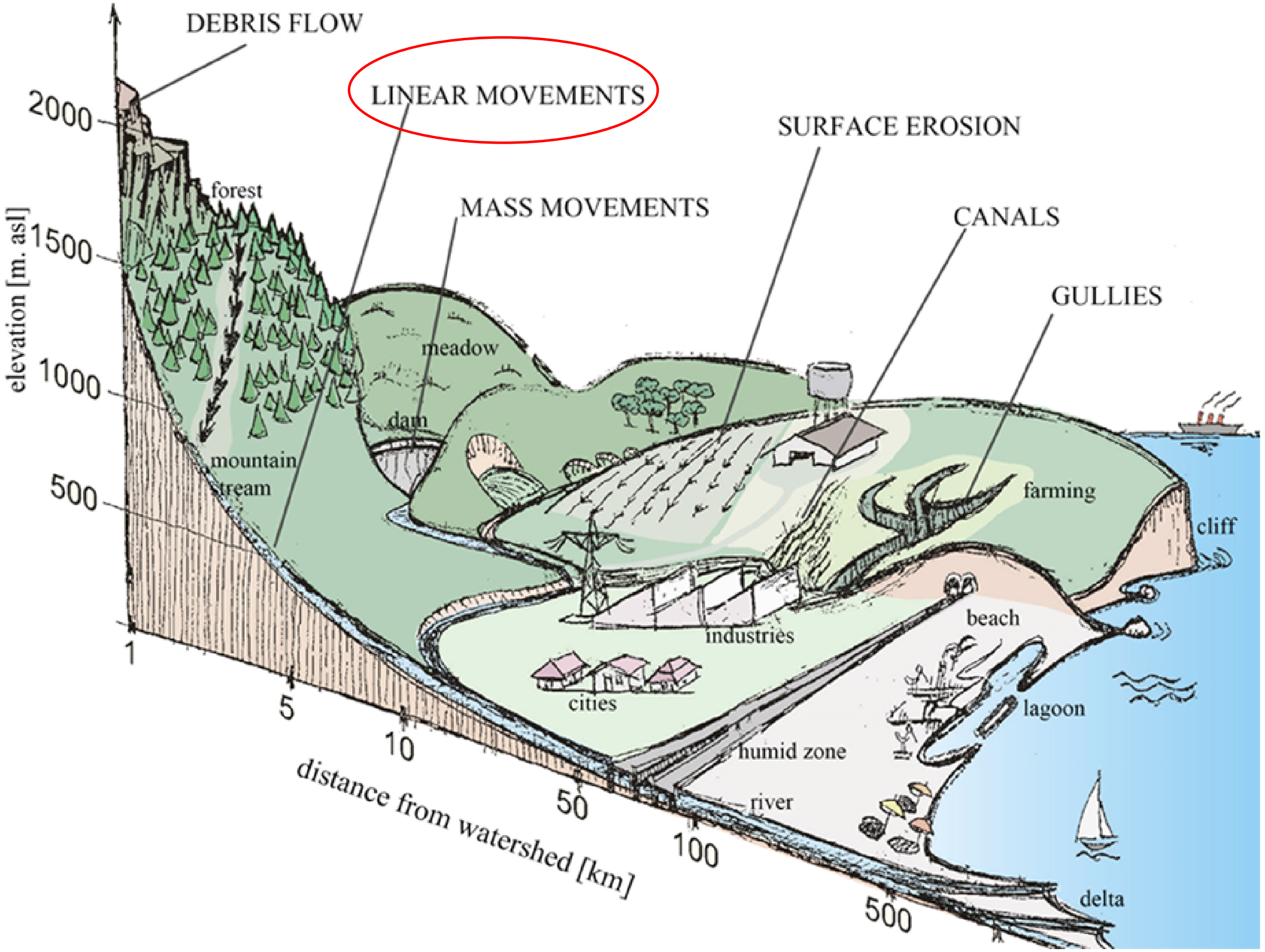
Rainfall
Discharge

Sediments

Mobilisation
Transport
Deposition

- Linear movements
- Surface movements
- Volume movements

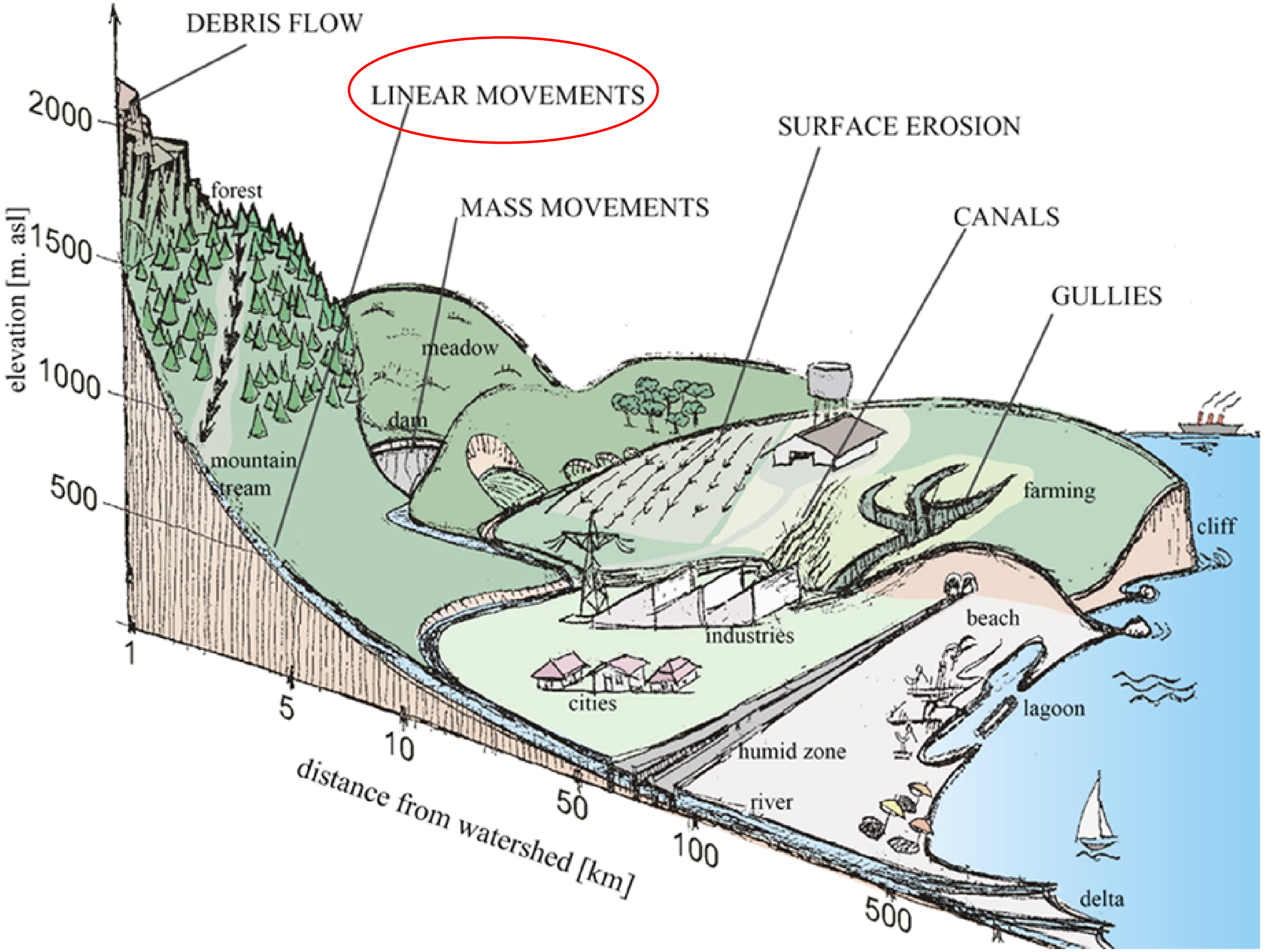
Sedimentary systems: main sediment motions type (Di Silvio, 2006)



The sediment journey

Linear movements: river transport, rills	Surface movements: soil creep, gully erosion	Mass movements: landslides, debris-flows

Sedimentary systems: main sediment motions type (Di Silvio, 2006)



Mass movements

Landslides and **debris flow** can be triggered by

Typical return period = 50-100 years

- intense hydrological events (floods)
- extreme environmental happenings (earthquakes)

overfeed the plain, rapidly creating a large deposition → **overaggradation**

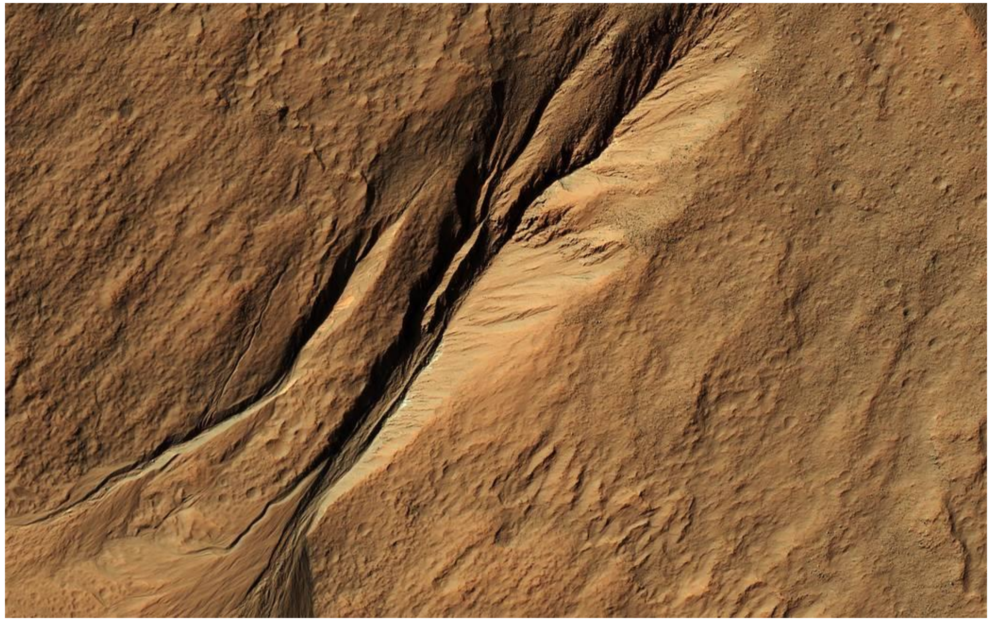
Surface movements

Soil creep: gradual, non-catastrophic downslope movement of weathered material under the influence of gravity

Typical return period = 0.1-1 years

Soil loss: diffuse (sheet) erosion of cultivated and natural slopes

→ is typically computed with an USLE-like formulation



Rills and gullies on Mars surface (NASA, 2018)

Erosion is related to:

- rainfall intensity and duration
- vegetation cover (bare soil, grass, bushes, etc.)
- type of soil
- topography of the basin (steep or flat)
- use of the land (crop, parking, arable, etc.)

Surface movements

Universal Soil Loss Equation

- firstly developed by the U.S. Dept. of Agriculture (Wischmeier& Smith, 1978)

- information on soil loss per unit area per event [tons/acre/event]

slope-length factor (topography)

slope-steepness factor (topography)

soil loss (erosion)

support practice factor (conservation)

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

rainfall and runoff factor (erosivity)

soil factor (erodibility)

cover and management factor (vegetation)

Surface movements: U.S.L.E.

Erosivity

- intensity of rainfall and velocity/dimension of the drops

Erodibility

- soil properties like grainsize, cohesion, permeability, thickness of the humus stratum, organic matter, etc.)

Topography

- length and slope of the area, presence of terraces, etc.

Vegetation cover

- soil surface cover (bare soil, vegetation, concrete, etc.)

Conservation

- management strategies (crop rotation, tillage etc.)

Linear movements

In rivers, gullies and rills

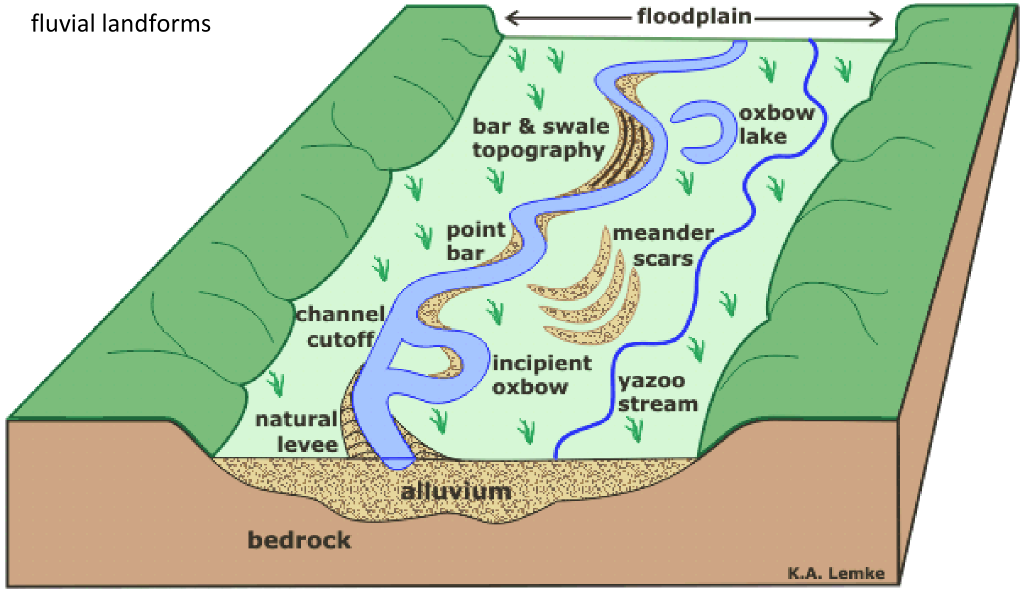
Typical return period = 1-2 years

- erosion/aggradation along the stream and on the floodplains → sedimentary patterns

- sediment transport in rivers → sediment transport formulae

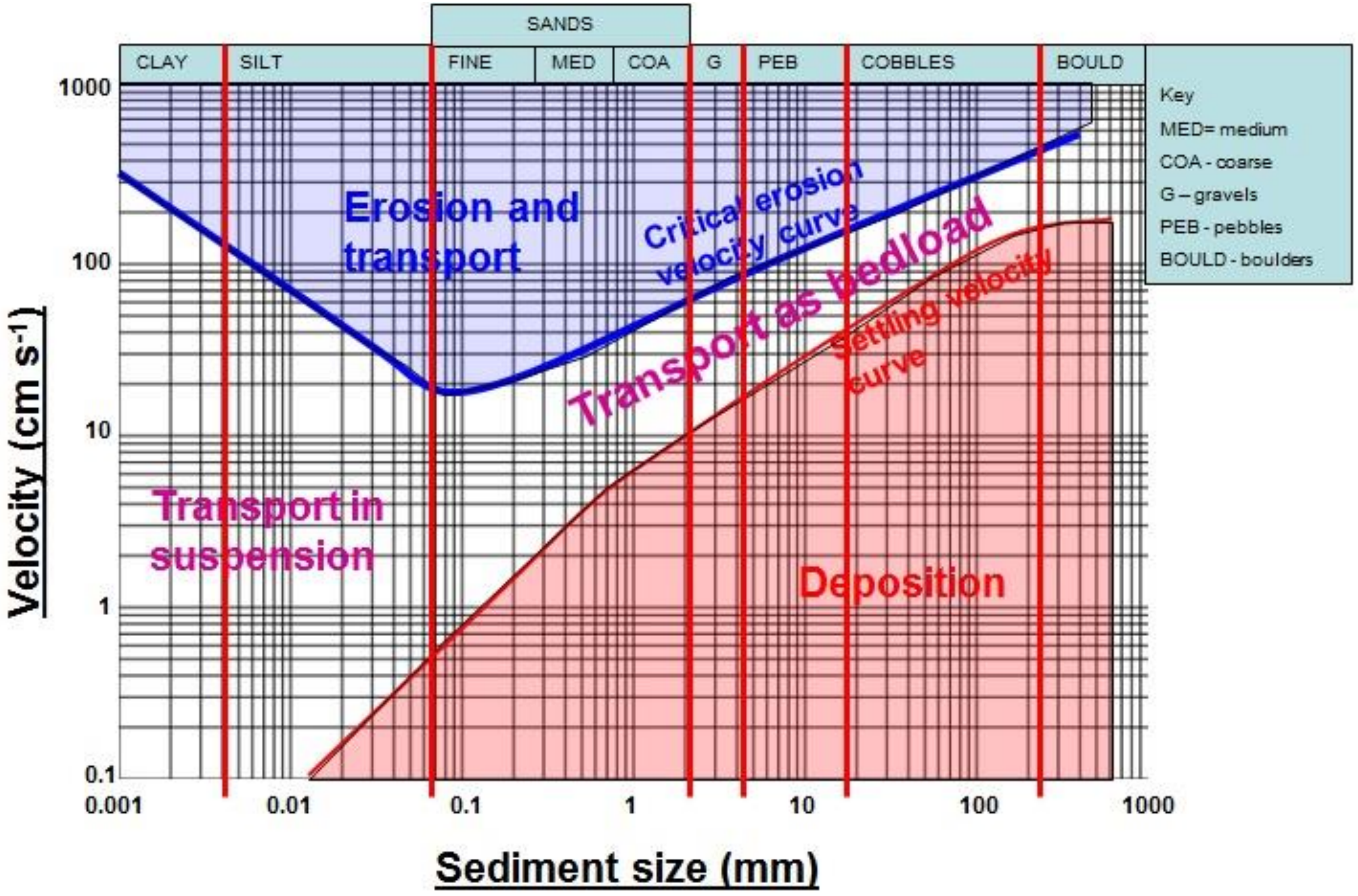
Cecina River, Italy

fluvial landforms



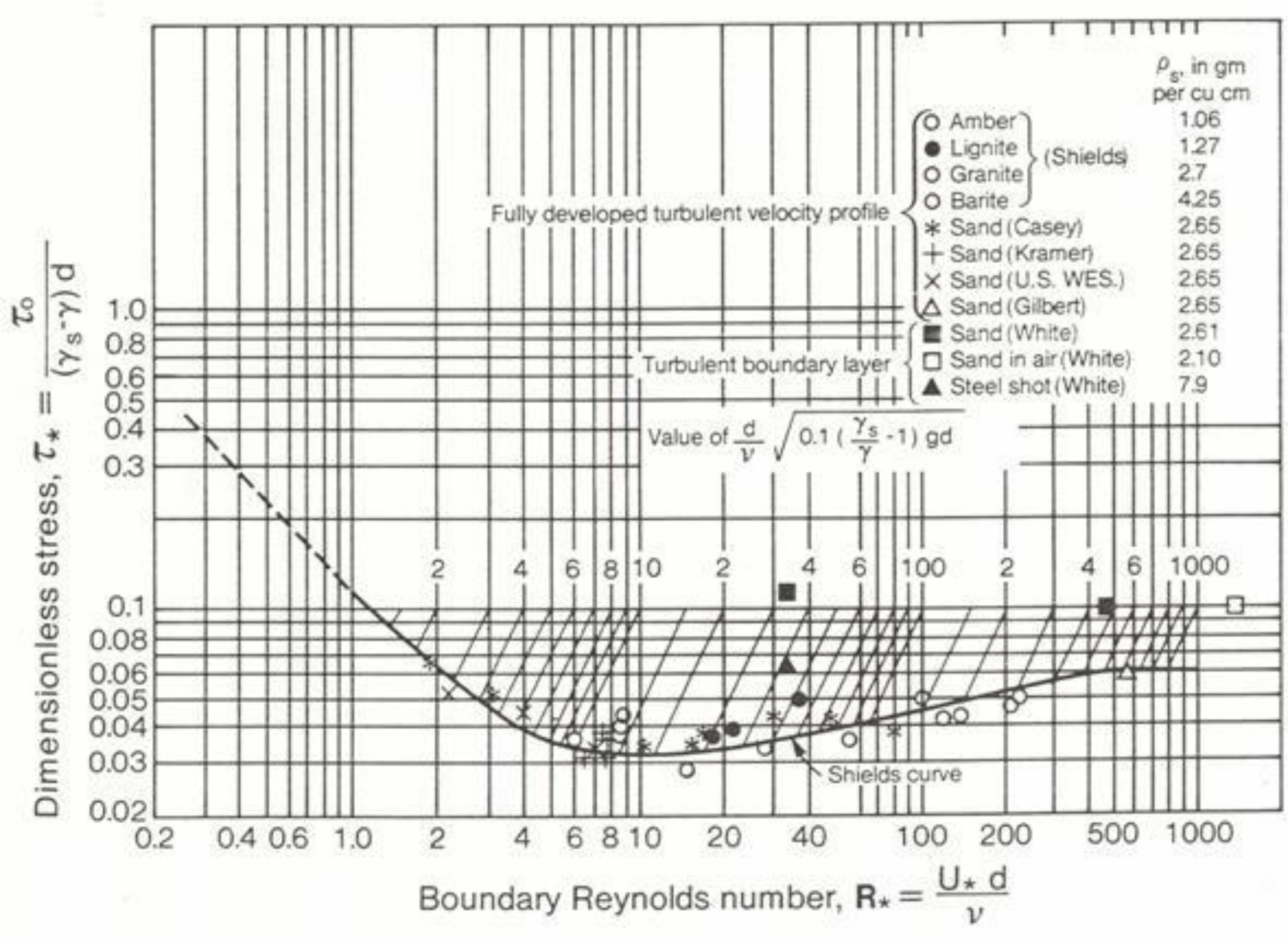
Linear movements

Hjulström curve



Linear movements

Shields curve



Sediments and river landscapes

Alluvial channels

Class of channels forming the vast majority of rivers on the earth's surface.

Alluvial channels are self-formed channels in sediments that the river typically has at one time or another transported downstream in the flow.

Channel and floodplains of alluvial rivers are formed by erosion and deposition of sediments.

Erosion

Removal and transport of sediment (mainly from the boundary, but also from the bed).

Deposition

Transport and placement of sediment (mainly on river boundaries, but also on the bed).

Some definitions

Competence

Competence refers to the largest size (diameter) of sediment particle or grain that the flow is capable of moving; it is a hydraulic limitation.

If a river flows very slowly has no power to mobilize and transport sediment of a given size even though such sediment is available to transport. A river may be competent or incompetent with respect to a given grain size.

Capacity

Capacity refers to the maximum amount of sediment of a given size that a stream can transport as bedload. Given a supply of sediment, capacity depends on channel gradient, discharge and sediment composition.

Capacity transport is the competence-limited sediment transport (mass per unit time) predicted by all the sediment-transport equations, and occurs only when sediment supply is abundant (non-limiting).

Sediment supply

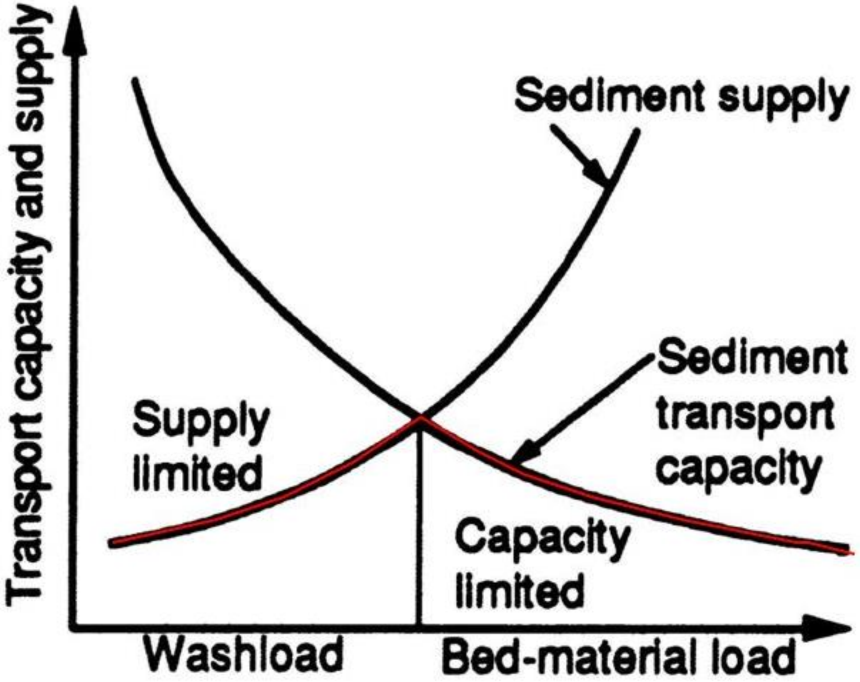
Sediment supply refers to the amount and size of sediment available for sediment transport.

Supply-limited and capacity-limited transport

Because of these two different potential constraints (hydraulics and sediment supply) distinction is often made between **supply-limited** (most of present alluvial rivers) and **capacity-limited** transport.

Much of the material supplied to a stream is very fine (silt and clay) and, provided it can be carried in suspension, almost any flow will transport it. Although there must be an upper limit to the capacity of the stream to transport such fines, it is probably never reached in natural channels and the amount moved is limited by supply.

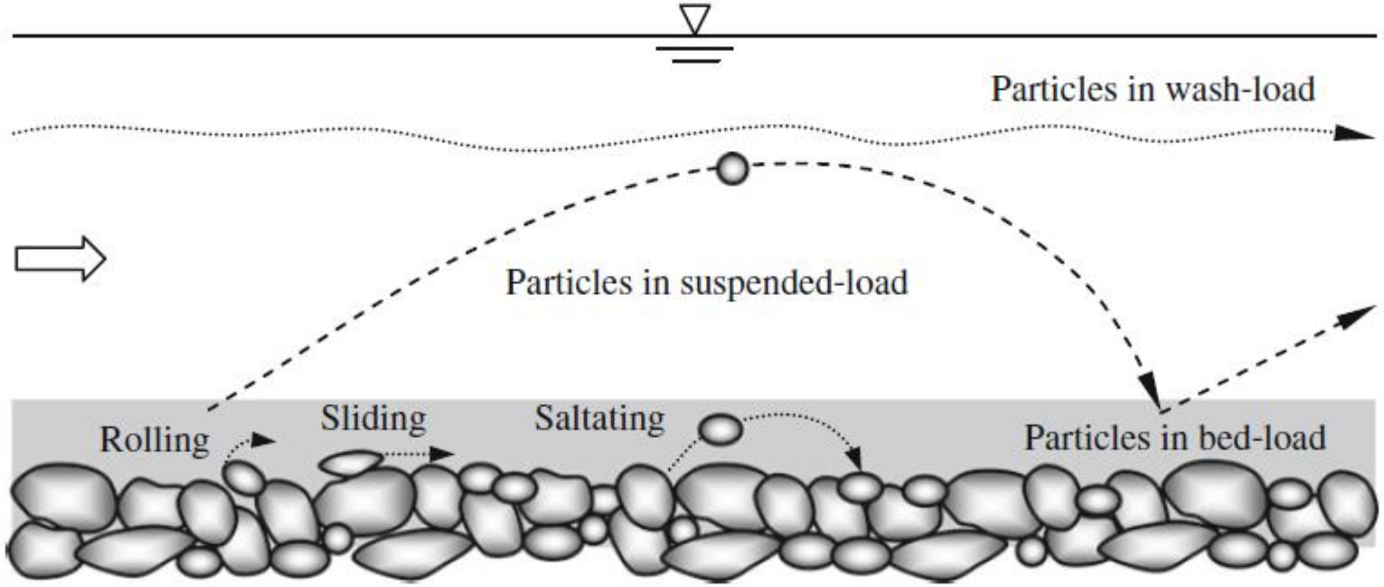
In contrast, transport of coarser material (coarser sand and gravel) is largely capacity-limited.



River sediment transport

There are three basic classes of load:

- **Bed load**: sediment rolling, bouncing, and creeping along the river bed
- **Suspended load**: sediment that is fine enough to remain in suspension in stream (size depends on velocity and turbulence)
- **Dissolved load**: the invisible load of dissolved ions (e.g. Ca, Mg, K, HCO3)



Schematic of different modes of sediment transport (from Dey, 2018)

Sediment transport modes

Dissolved load

It is material that has gone into solution and is part of the fluid moving through the channel.

The amount of material in solution depends on supply of a solute and the saturation point for the fluid.

The dissolved load is very sensitive to water temperature (e.g., tropical rivers carry larger dissolved loads than those in temperate environments).

In many regions most of the sediment is removed from the hillslopes in solution as dissolved load and must be accounted for in estimating the erosion rate (surface erosion).

water discharge [m³/s]

total dissolved transport [kg/s]

$$\boldsymbol{Q_{s,d} = CQ}$$

dissolved load concentration [kg/m³]

Sediment transport modes

Washload

It is part of the suspended-sediment load, but composed by very fine particles (clay and minerals).

Unlike most suspended-sediment load, wash load does not rely on the force of mechanical turbulence generated by flowing water to keep it in suspension. It is kept in suspension by thermal molecular agitation (Brownian motion).

It tends to be uniformly distributed throughout the water column: it does not vary with the height above the bed.

Wash load is that component of the particulate or clastic load that is “washed” through the river system, without shaping its bed.

Wash load represents the cohesive part of the transported material, and usually (alluvial) river dynamics are not affected by this.

Sediment transport modes

Suspended load

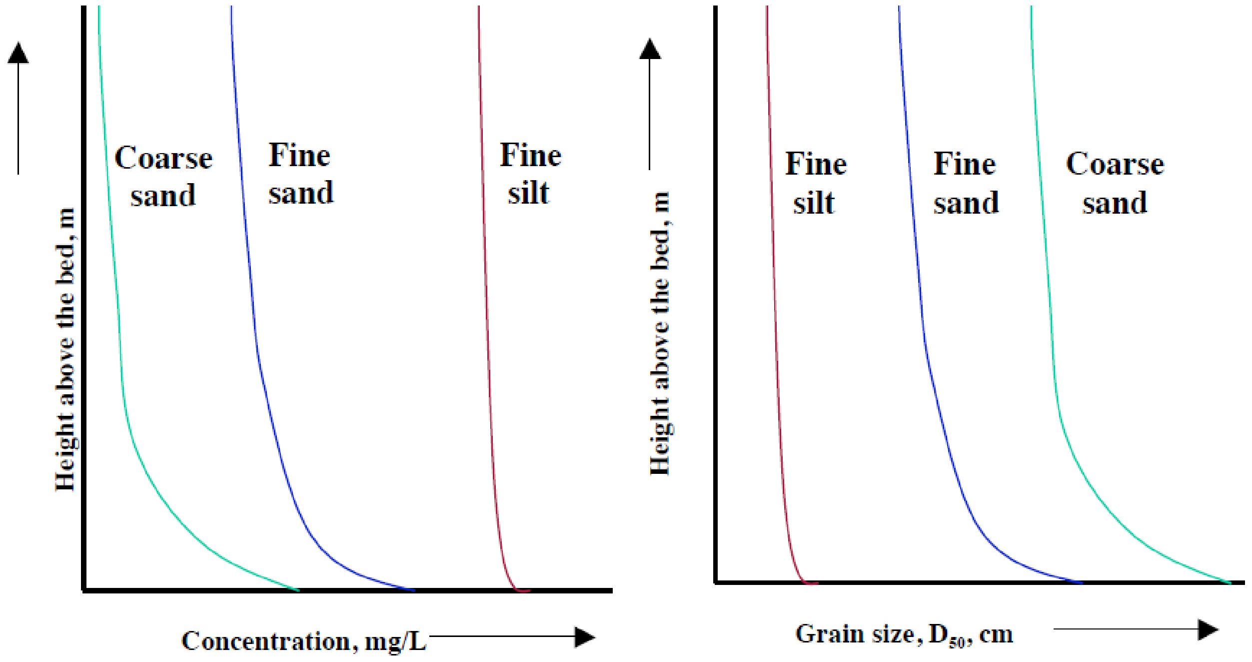
Suspended-sediment load concerns material that moves through the channel in the water column.

These materials, mainly silt and sand, are kept in suspension by the upward flux of turbulence generated at the bed of the channel.

The upward currents must equal or exceed the particle fall-velocity for suspended-sediment load to be sustained.

Suspended-sediment concentration and grain size of suspended sediments typically appear distributed in the vertical water column.

Suspended sediment vertical distribution (from Higgis, 2016)



Sediment transport modes

Bedload

Bed load is the material that moves through the channel fully supported by the channel bed itself.

These materials, mainly sand and gravel, are kept in motion (rolling and sliding) by the shear stress acting at the boundary.

Unlike the suspended load, the bed load is capacity-limited (function of hydraulics rather than supply).

A distinction is often made between the bed-material load and the bed load.

Bed-material load is that part of the sediment load found in appreciable quantities in the bed and collected in bedload samplers. That is, the bed material is the source of this load component and it includes particles that slide and roll along the bed (bed load transport) but also those near the bed transported in saltation or suspension.

Bed load, strictly defined, is just that component of the moving sediment that is supported by the bed and not by the flow.

The term bed load refers to a mode of transport and not to a source.

Sediment transport modelling

Many (empirical) sediment transport formulae are available and are adopted by numerical codes.

What formula to use is a matter of validity field and calibration.

Most models solve the Exner equation (sediment continuity eq.) and compute the quantity of sediment eroded/deposited in a control volume, by making a difference between how much sediment enters and leaves from the volume.

Sediment is stored in a multi-phase mixture with water: the porosity translates mass change into volume changes:

channel width [m]

channel bed elevation [m]

$$(1-\lambda)B\frac{\partial n}{\partial t} = -\frac{\partial Q_s}{\partial x}$$

total transported sediment load [m^3/s m]

active layer porosity [-]

transport capacity > sediment supply → erosion

transport capacity < sediment supply → deposition

Sediment transport modelling

Bed roughness

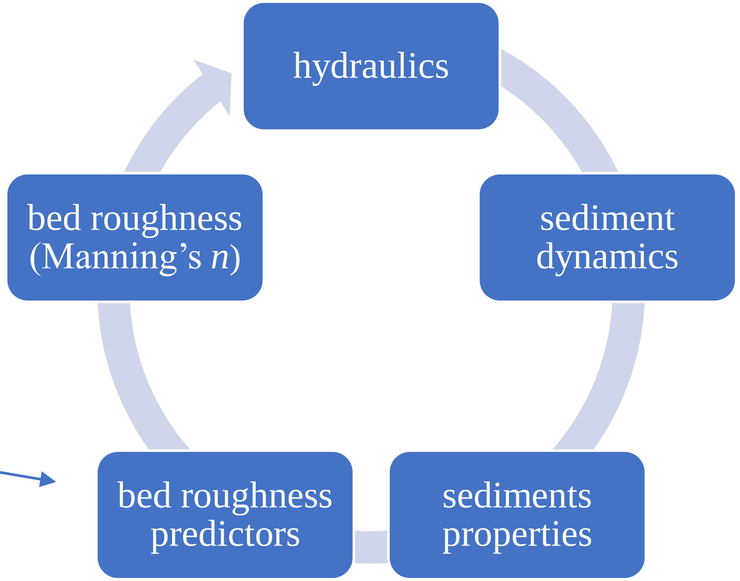
The bed roughness is a dynamic properties, changing based on the sediment dynamics.

Mobile bed models simulate changes in bed elevation and gradation. The latter are used by the code to compute:

- bed roughness

- feedbacks between bed roughness and sediment transport

equations and algorithms that relate roughness to hydraulics and sediment properties



Sediment transport modelling

Transport capacity

Sediment transport formulas compute the transport potential (the maximum sediment load possibly transported)

The transport capacity for each grain size is the transport potential multiplied by the presence percentage of each grain size in the bed

→ continuity eq. is applied for each grain size

presence percentage [-]

number of grain size classes [-]

$$T_c = \sum_{j=1}^{n} \beta_j T_j$$

transport capacity of each grain size [m^3/s]

total transport capacity [m^3/s]

Stream power

The power of a river or stream is characterized by the product of its discharge and slope

$$W = \rho g Q S$$

The power per unit area of a riverbed is called the unit stream power, and is derived by dividing the product of its discharge and slope by the channel width

$$w = \rho g Q S / W$$

The ability of a river to cut down into bedrock is generally taken to be a function of its stream power (or unit stream power).

Dominant discharge

The dominant discharge is the flood that does the most geomorphological work

- Large floods - have most potential to erode and transport
- Medium sized floods occur more frequently do more geomorphological work in the long-term
- Small floods - cannot mobilize coarse sediment

Conventional wisdom holds that most sediment transport by floods corresponding to the bankfull discharge.

Flood, over the bankfull
(from Nones, 2018)

Floodplain and return periods
(from Montgomery, 2012)