Origin and propagation of coarse alluvial bedload

Coarse bedload is transported by rolling along the bottom. It is made up of grains generally larger than sand, however, in certain rivers with a low unit stream power (e.g. the lower Loire River), sand may be included in the bedload.

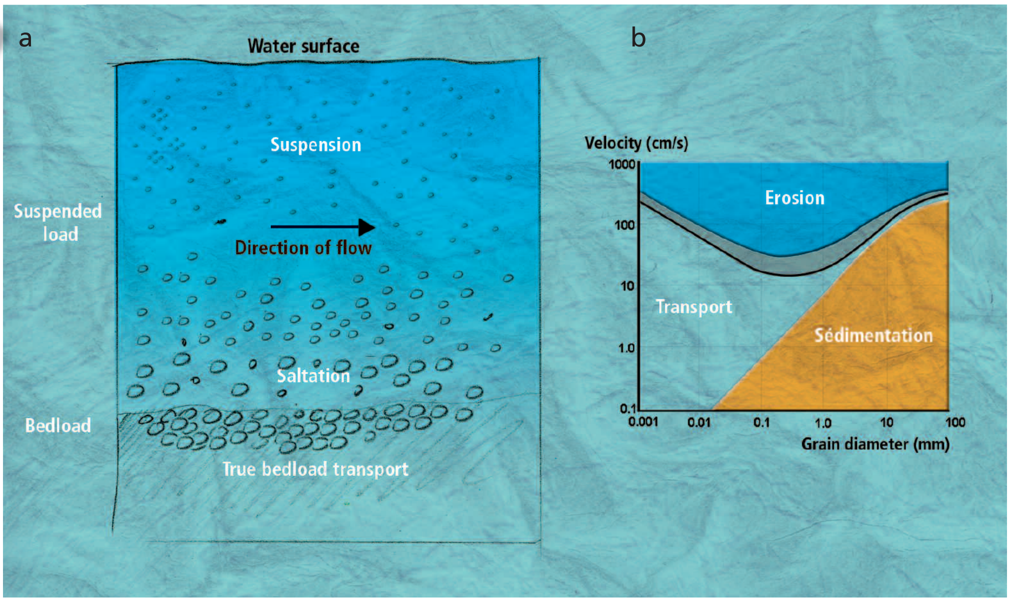
Suspended load and bedload

It is acknowledged that sediment transport in rivers takes place in two manners (see Figure 14a): :

- **bedload transport** along the bottom when the grain size exceeds a certain diameter and the current cannot suspend the transported matter;
- **suspended load** when the sediment is fine and the current is strong enough to carry the particles in the water column.

NB The term **saltation** is occasionally used for an intermediate type of transport that takes place slightly above "true" bedload transport in the water column. The particles advance by "leaping" rather than by sliding or rolling, generally in continuous contact along the bottom.

Figure 14



(a) Suspended load and bedload. The term "saltation", designating an intermediate type of sediment transport, is not commonly used today. (b) The Hjulström curve (1935).

The Hjulström curve (1935, Figure 14b) shows a fairly clear limit for a grain diameter of 0.5 mm and a velocity of 20 cm/s, that is interpreted by some researchers as the limit between bedload and suspended load. It should be noted however that grains of sand 0.5 mm in diameter can be suspended at higher flow velocities (see above). **Sand in general constitutes an intermediate class of sediment that can be transported as bedload or suspended,** depending on the flow velocities and the turbulence. The curve also makes clear the "temporary" nature of bedload transport. Above the 0.5 mm diameter size, a grain put into motion at a certain flow velocity will rapidly cease moving at a velocity even slightly lower, whereas grains of silt, once in motion, travel downstream at essentially the same velocity as the water and do not settle until they encounter virtually stagnant hydraulic conditions.

Origin of bedload

The concepts pertaining to power have been well defined, however, the same cannot be said for those addressing sediment load, the second major factor in the geodynamic equilibrium of rivers. In this section, we will present only the processes involved in bedload production and transport, not those involved in the entrainment and transport of finer sediment (suspended load and washload).

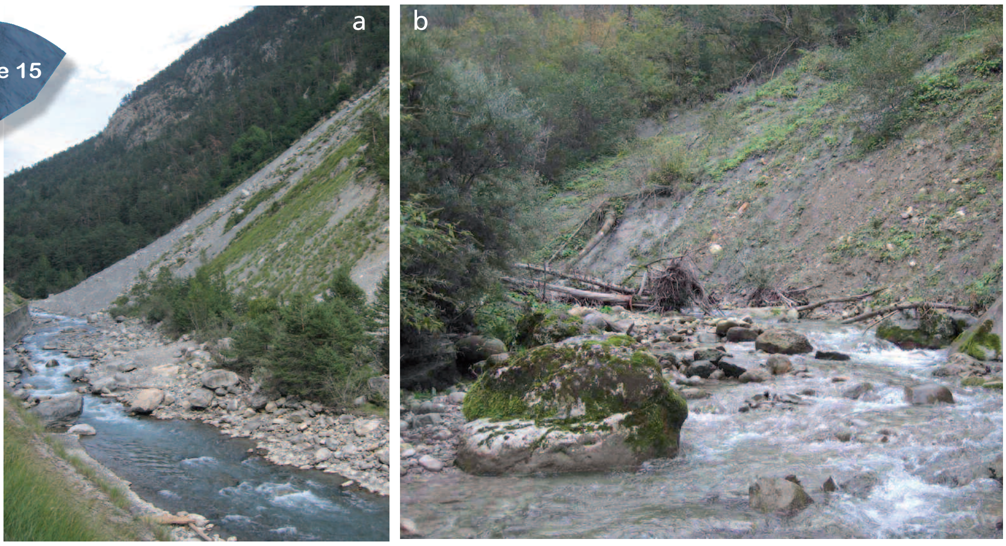
External sources

As the name indicates, these loads come from outside the river and its alluvial plain.

■ Primary production

This consists of the coarse sediment that virtually falls into the river. In mountain regions, it is produced by the erosion of moraines, scree and avalanche fans, landslides, torrents, rock deposits on slopes, etc.

Figure 15

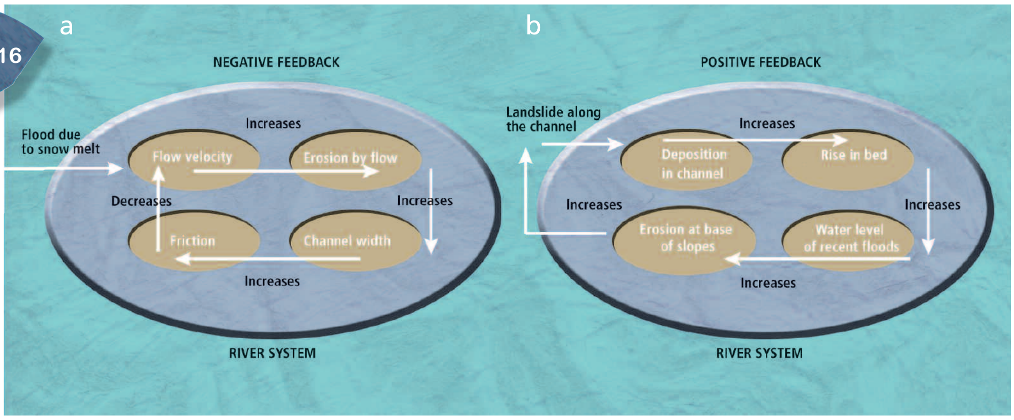


a- b- © J.R. Malavoi

Examples of primary production of external sources. (a) Avalanche residue and scree drawn downward by gravity. (b) Erosion of an avalanche fan by a torrent, with rocks from scree deposits and moraines.

This type of primary production may be found only under special conditions, i.e. at the head of mountain river basins having little or no vegetation and steep valleys with slopes arriving very near the river. These primary sources currently produce less and less in European mountains due in part to reforestation of mountain slopes, itself due to global warming following the erosive crisis of the Little Ice Age, and in large part to numerous human efforts to limit external sources of sediment load (planting of slopes to enhance their stability, weirs, deposit zones for torrents, etc.).

Figure 16 (next page) explains the relations between channel dynamics and slope bottoms.



Examples of relations between channel dynamics and slope bottoms. (a) A flood adjusts the configuration of the channel to its characteristics (increased width) such that the resulting greater friction contributes to reducing erosive processes (negative feedback). (b) The bottom of the valley slope is destabilised by an increase in the width of the channel and/or a major flood. The sediment entering the channel raises the bed and the water level, thus contributing to further erosion at the base of the slope (positive feedback) (Marston, 1993).

■ Secondary production

Secondary production is that arriving from tributary rivers, comprising sediment from both internal and external sources.

Figure 17

a- b © J.R. Malavoi

Examples of secondary, external sources. (a) Torrent with coarse sediment. (b) Input of rocky bedload via a tributary depositing its alluvial fan in the main river.

Internal sources

Theoretically speaking, the internal sources are those drawn from the river itself or from its floodplain. Another term commonly used is "internal stored alluvium".

This stored volume is present in two forms:

- **the stored alluvium available in the riverbed itself;**
- **the alluvium stored on the floodplain and the terraces,** deposited during active climatic periods, notably during the Quaternary glaciations (this is called "fossil" alluvium), and gradually reinjected in rivers through lateral erosion.

■ Alluvium stored in the riverbed

There are two types of alluvium stored in riverbeds.

Alluvial macroforms

Alluvial macroforms consist of large quantities of sediment deposited by bedload transport during floods and that migrate more or less rapidly downstream. They are fairly easy to identify in the field or using aerial photographs because they are generally discrete units with recognisable shapes.

Figure 18

Examples of macroforms in transit. (a) Numerous mid-stream bars in a riverbed with banks that are only slightly erodible. Their three-dimensional shape, with a stoss face on the upstream side, is similar to that of sand dunes.
(b) Numerous bars forming in a river with non-cohesive banks. Braiding develops.

Their quantity (frequency), shape and spatial distribution all depend on the quantity of the internal and external volumes of sediment. When large volumes are available, the riverbed may become a succession of macroforms (Figure 18a). If even larger quantities are input and the banks are highly erodible, a braiding pattern may develop (Figure 18b).

These macroforms comprise a majority of the observable and measurable sediment discharge. They may simply pass through without any mixing of the underlying sediment, notably if the river bottom is protected by an armour of large-grain sediment (see box) or by vegetation (Figure 19).

Figure 19

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(a) Downstream side of an active dune in the sand-bed section of the Loire River (upstream to the right). (b) Active gravel dune in the Doubs River (upstream to the right). In both cases, the dune moves without any interaction with the existing stored alluvium, which is protected by the vegetation.

The bottom of the riverbed

In addition to macroforms, which are both storage zones and means of transport for river alluvium, part of the bedload can be entrained directly on the bottom of the riverbed, if the bottom is alluvial and not paved.

When the bed materials drawn from the bottom are not replaced with material from upstream, the riverbed is degraded. If this process continues over time, e.g. following the creation of a dam or trapping of upstream material in an old gravel pit, the imbalance that was initially temporary may become long term.

■ Alluvium stored on the floodplain and the terraces

In temperate zones, most of the coarse alluvium potentially available for transport may now be found on the terraces at the bottom of valleys. Only a limited number of upper reaches in mountain river basins still contain large quantities of sediment representing primary, external inputs.

The terraces comprise tremendous volumes of alluvium deposited by rivers during the Pleistocene, i.e. essentially during cold periods, and that are identified on BRGM geological maps by the codes Fyz and Fy for terraces formed during the Würm glaciation and codes Fx to Fu for older Quaternary formations.

The Fz code signals Holocene alluvial plains that were formed since the end of the last glaciation approximately 15 000 years ago.

All these formations, particularly Fy to Fz, may represent available stored volumes if they are located close enough to the active riverbed to be subject to lateral erosion, in which case this "fossil" alluvium may be reinjected into the river.

Armouring and paving

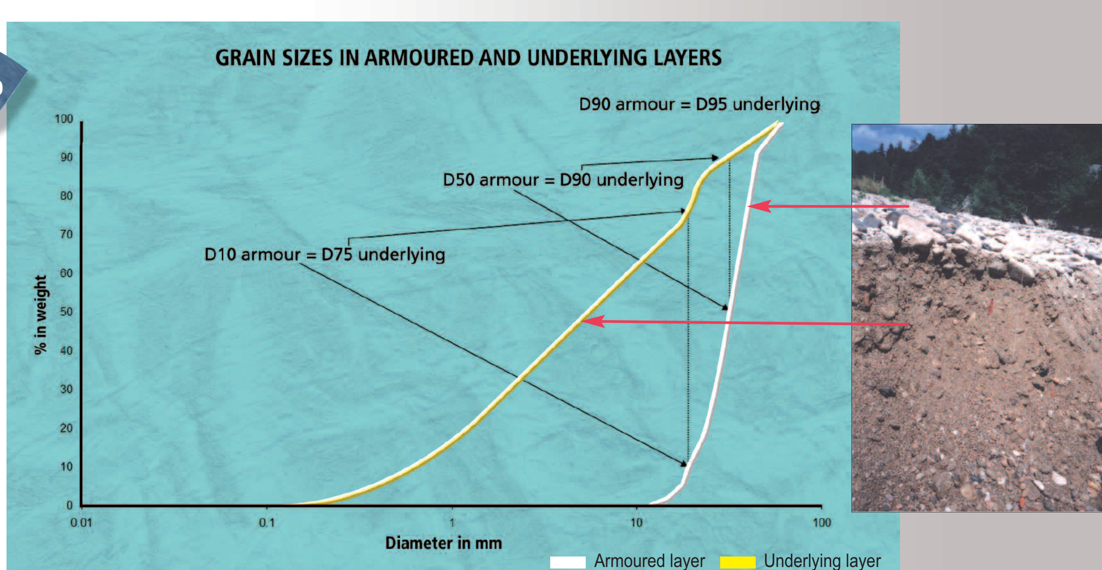
River alluvium is generally made up of materials having different grain sizes, often ranging from sand to cobble stones. When this sediment is subjected to certain flow velocities, the finer to mid-sized elements are carried off while the larger elements remain in place. If this sorting process lasts long enough, a high concentration of coarse elements will remain at the surface of the riverbed. This stable accumulation of larger elements that temporarily protects the underlying layers is called armouring. If continued even further, the process results in riverbed paving, which is a much more stable result over time.
The definitions below were proposed by Bray and Church (1980).

- An **armour** layer is a coarse surface layer produced by the removal of the finer elements during and after each event moving all or part of the various grain sizes available for transport. The layer is thus restructured by episodic events transporting bedload during which all grain sizes are mobilised. A majority of researchers are of the opinion that restructuring of the surface layer is a frequent event occurring at least several days per year.
- In the case of **paving**, the elements making up the surface layer are mobilised only during exceptional hydrological events (major floods), if at all (the current hydrological regime may not be capable of restructuring the layer). This is the same sorting process as armouring, but more extreme due to particular conditions:

  - blocking of all new bedload from upstream by dams or natural obstacles;
  - reduced flood discharges that can no longer restructure the substratum;
  - incision of the riverbed to reveal much older layers comprising larger elements exceeding the current transport capacity of the river (i.e. that were transported during periods of higher transport capacity).

The sorting process resulting in armouring and, in extreme cases, paving thus produces layers having different grain-size compositions, the armoured top layer and the underlying layer. A majority of researchers think that the **grain-size distribution of the bedload** (subject to bedload transport, i.e. not suspended) corresponds to that of the **underlying layer** and not that of the armoured layer.

Figure 20



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Grain-size distribution curve of an armoured layer and an underlying layer. Note that the distribution is much tighter for the armoured layer, which is logical because it is created by a process that removes a large percentage of the smaller grains sizes, thus significantly reducing the standard deviation.

Propagation of bedload

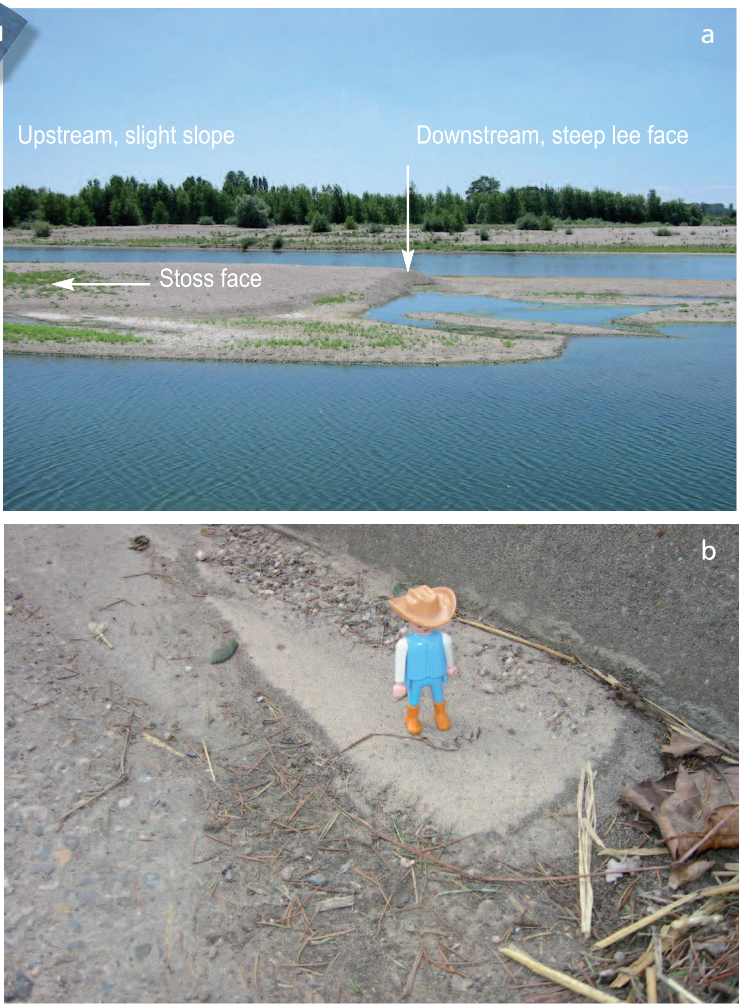
Once injected into the river, bedload propagates more or less rapidly, depending on the local geomorphological conditions (changes in slope, widening of the bed, structures modifying the flow conditions, etc.) and discharge levels capable of entraining it.

Landforms produced by bedload propagation

The most frequent landform produced by bedload transport is a sediment macroform called a bar or a dune[1]. It has a characteristic, **three-dimensional configuration** that can be identified and located. The perimeter and volumes may be drawn. Most often, there is a stoss face on the upstream side and an active front facing downstream (progradation front or lee face) with a steep slope, close to the steady slope for granular materials (40 to 45°).

It should be noted, however, that there also exists a type of propagation on plane beds when flows become torrential (Fr ≥ 1) in sand-bed rivers.

Figure 21



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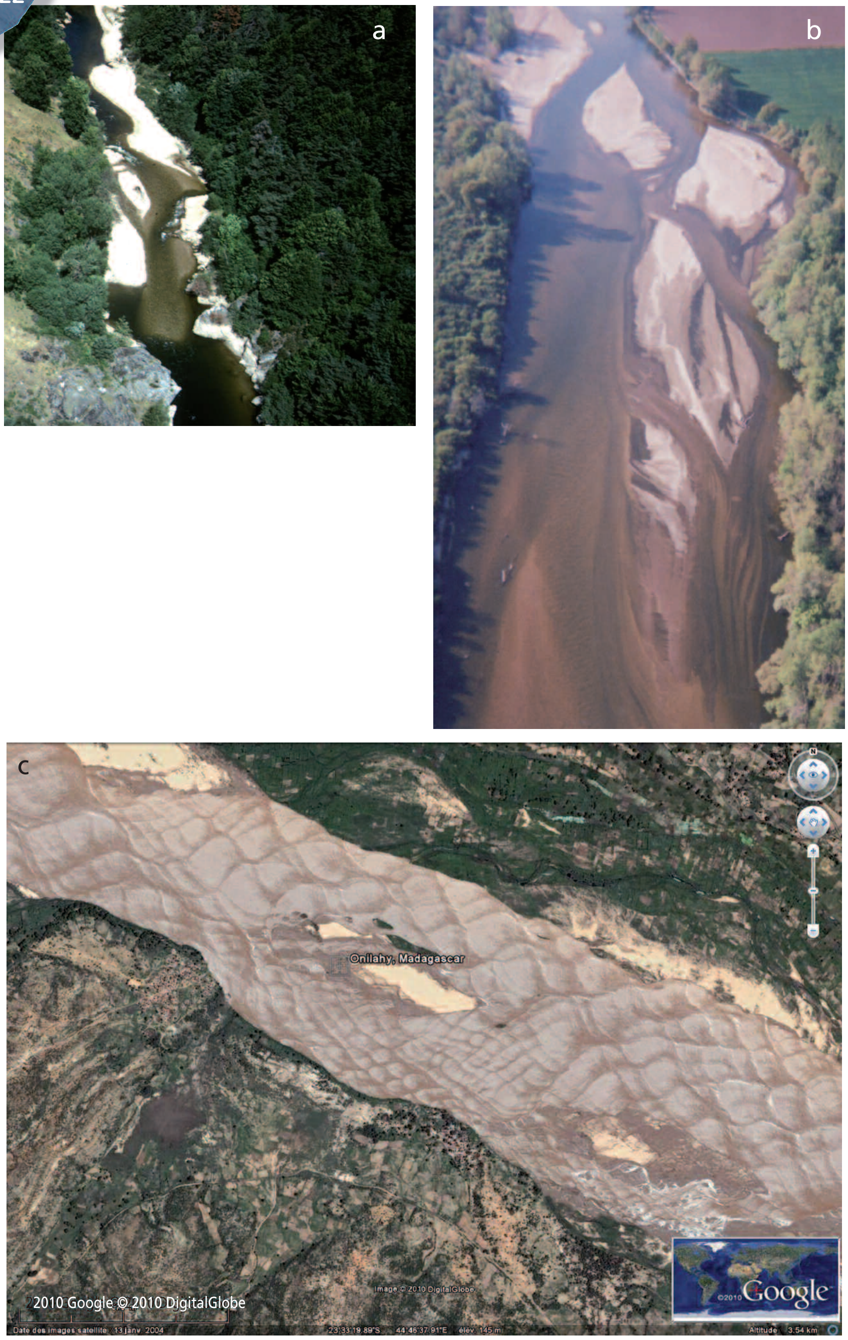
Examples of migrating dunes/bars. (a) In the lower Doubs River. (b) In a drain channel. The processes and the resulting forms are identical.

[1] There is currently some uncertainty concerning these two terms. For some authors (notably Yalin and Silva, 2001), dunes are macroforms whose size and wavelength are proportional to the depth, whereas bars have a size and wavelength proportional to the bankfull width. The macroturbulences creating dunes are thought to be vortexes with a horizontal axis and those creating bars are thought to be vortexes with a vertical axis.

If the sediment load is high in volume, the macroforms may be joined, i.e. the front of each dune crawls onto the tail of the preceding dune, which itself is progressing downstream (see Figure 22). The result is similar to a braided pattern.

Figure 22



(a) Set of stone dunes in the upper Allier River.
(b) Set of sand dunes in the lower Allier River.
(c) Gigantic series of dunes in a braided river in Madagascar.

a- b- © J.R. Malavoi

Conversely, if there is little sediment in transit, isolated macroforms migrate down the river and are all the easier to locate and measure (see Figure 23). Of course, all the intermediate situations between these two extremes also exist.

Figure 23

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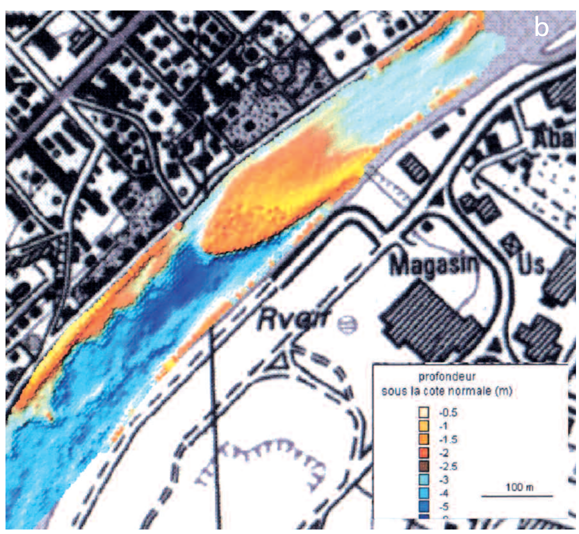
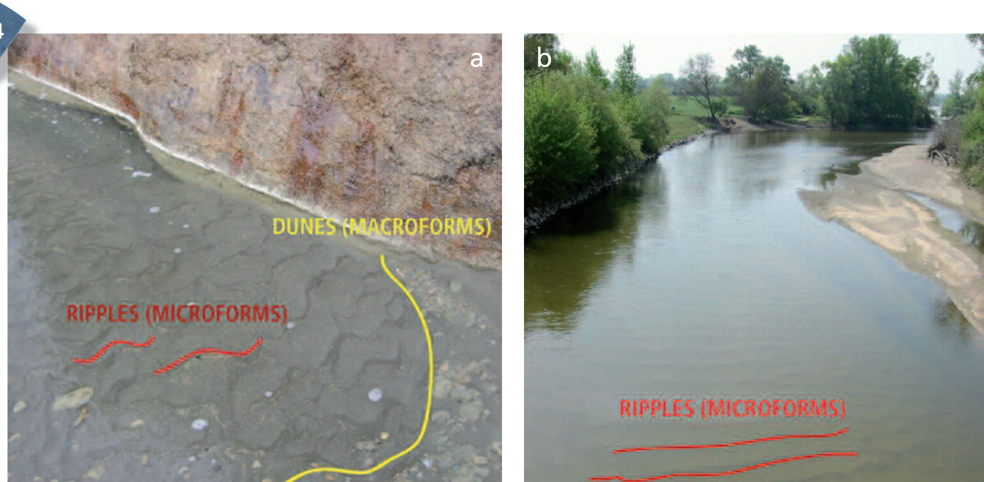


Fond SCAN 25®. © IGN 2010.

(a) Stone bar migrating down the Tarn River (upstream to the left).
(b) Isolated stone bar in the Doubs riverbed, just downstream of the town of Dole (bathymetric measurements by the Rhône-Saône Navigation Service). (Upstream to the right.)

NB Ripples are sediment microforms that are driven slowly across the surface of alluvial macroforms by low-velocity currents (a few dozen centimetres per second). They are generally found in rivers with sand beds or having sand deposits.

Figure 24



a-b- © J.R. Malavoi

Ripples are alluvial microforms that develop on the surface of macroforms (dunes).

Shingling

Individual elements of the bedload travel with the flow in different manners, depending on their morphology, which itself depends on their geology. Material from stratified, sedimentary rock, which generally has potential weak points or strata, are often flat in shape. Travel downstream generally occurs through rotation around their longest dimension (axis a), in which case an armoured layer would appear to be "shingled" (see Figure 25).
On the other hand, coarse alluvium from eruptive rock (basalt, granite) or metamorphic rock (e.g. quartzite) is generally very rounded and does not fall into a shingled pattern.
Shingled armoured layers would appear to be less resistant to erosion than equivalently sized stones resting flat on the bed and more tightly imbricated with the surrounding stones.

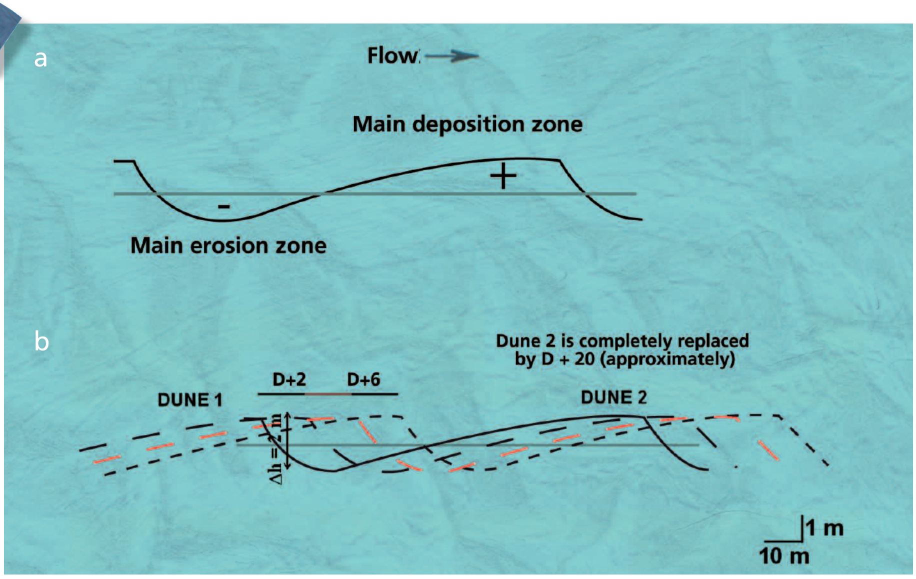
Figure 25

Shingled pattern of transiting sediment on an alluvial bar in the Durance River. (Upstream to the upper left.)

Bedload propagation

The theory behind the migration of macroforms (dunes or bars) is presented in Figure 26.
In a context of dynamic equilibrium, the dune propagates downstream due to erosion of its upstream section (the stoss face) and migration of the entrained grains along the surface of the form until they fall down the lee face. The stoss face and the steep lee face resemble the shape of dunes formed by the wind. They are caused by the roughness of the bed that slows dune transit and provokes the mechanical "compression" effect.

Figure 26



(a) Long profile of theoretical dune propagation (according to Yalin and Silva, 2001). (b) Theoretical example showing the replacement of a dune by another arriving from upstream, after x number of days.

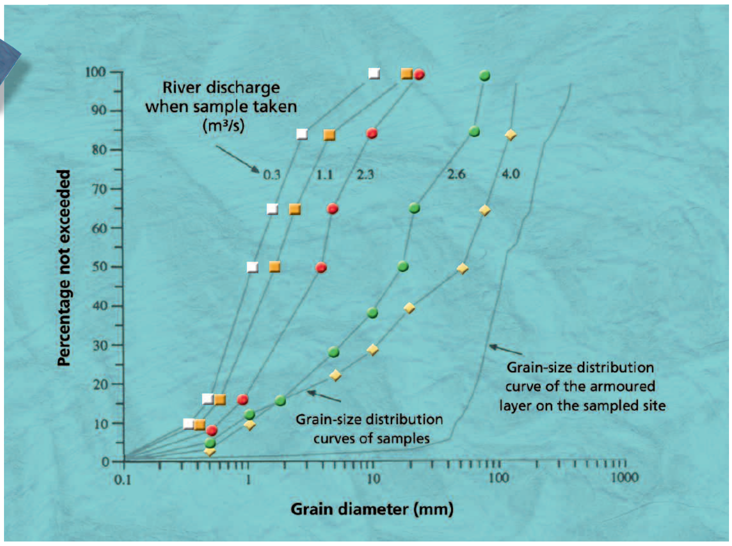
This process is theoretical because erosion at the apex of the dune (with the + sign) is often observed.

Composition of bedload

Even though it is generally acknowledged that during floods, bedload transport involves most of the sediment range or spectrum of grain sizes available for transport, it is also clear that the grain-size distribution of the transported material differs significantly depending on the water discharge. The discharge level determines the stream transport capacity in conjunction with the tractive force[2].

This phenomena is clearly illustrated in Figure 27. The higher the discharge (and the tractive force), the larger the average size of the transported material (D50 = 1 mm at 0.3 m^3/s and 50 mm at 4 m^3/s). The range of grain sizes increases for the same reasons, i.e. increasingly larger sizes are entrained. It is also interesting to note that, in this example, the grain-size distribution curve of even the highest discharge does not equal the grain-size distribution curve of the armoured layer along the river bottom (curve the farthest to the right in the graph).

Figure 27



Change in grain-size distribution of sediment as a function of the discharge. Bedload samples drawn during a single flood (according to Bathurst, 1987).

[2] Tractive force τ is the product of the slope x depth of water x density of water. It is generally expressed as N/m².
τ is calculated as $\tau = \gamma hJ$ (in N/m²)
where γ is the density of water (9 810 N/m³), h the depth of water (m), J the hydraulic gradient in m/m.

This explains why, given the local flood levels and geomorphological conditions, the grain-size distribution of macroforms may differ, both spatially and temporally.

For example, it is occasionally possible to see a gravel macroform migrating over another macroform with pebbles on its surface. This means that the last flood had enough transport capacity to transport gravel from upstream, from banks, tributaries, etc., but not enough to break up the armoured layer of pebbles on the underlying macroform (see Figure 28).

Figure 28

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A gravel dune migrating over the coarser substratum located at the bottom of the image.

Bedload propagation velocity

It is very difficult to measure and even harder to predict the propagation velocity of alluvial bedload. This parameter is, however, an essential factor in managing sediment transport.

Some data, similar to those shown in Table 1, have been published in scientific journals or in reports by engineering firms. The data often consist of velocity measurements on individual elements when it would be much more useful in terms of sediment management to know the propagation velocity of macroforms.

Table 1 *Some data on the propagation velocities of coarse alluvium.*

River	Grain size	Q conditions	Q duration	Distance covered	Author	Year
Agly	pebbles	Q1.5/year)	1.5 hours	120 m	BRL	1988
Agly	pebbles	Q2.4/year)	5 hours	310 m	BRL	1988
Verdouble	pebbles	several floods, including Q5, Q2, Q4		850 m	Anguenot	1972
				max. 1 800 m		
				10 km/century on average		
Ardennes	30 to 80 mm			3 km/century on average	Petit	1997
Hérault	pebbles			20 km/century	Tricart and Vogt	1967
Isère	pebbles			10 km/century	Salvador	1991

A recent publication by Katolikov and Kopaliani (2001) filled out this data with information on the propagation of side bars. They noted values between approximately 50 and 500 metres per year, which is roughly similar to the values in Table 2 (3 to 20 kilometres per century).

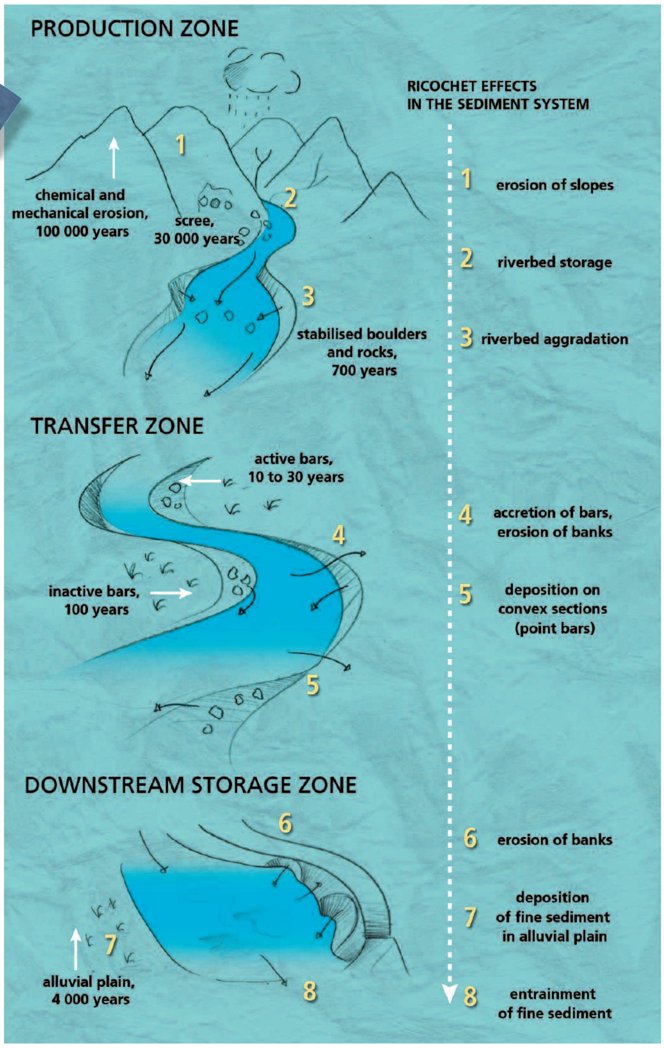
Table 2 *Propagation velocity of side bars (drawn from Katolikov and Kopaliani, 2001).*

River	Velocity (m/year)	Author	Remarks
Garonne	20 - 30	Baumharten, 1848	
Rhine	270	Popov, 1969	
Downstream of Strasbourg	500	Yasmund, 1930	209 side bars between Basel and Sonderheim
Mur (Austria)	100 - 200 (over 8 months)	Eksner, 1924	Channelised section, 7 km long. Length of alternating bars = 5 to 6 times the bankfull width
Volga	100 - 200	Popov, 1969	
Amour	200 - 600	Bashkirov, 1956	
Danube	200	Polyakov, 1951	
Vistula	100	Popov, 1969	

Temporary storage of bedload

Transiting bedload may be stored for more or less long periods during its transport downstream. The general idea is shown in figure 29.

Figure 29



Production, transfer and storage of bedload (according to Sear and Newson, 1993). The storage durations are rough approximations intended to provide a general idea .

■ Natural storage

The most obvious case of natural storage of transiting alluvium is in the form of bars and dunes, particularly point bars along convex banks (both active and inactive bars shown in Figure 29).

In the active section of the bars, storage is temporary (a few months or years) and the material is frequently restructured and carried further along downstream by the sediment-transport processes discussed above. In the inactive section of bars (behind the active section), vegetation gradually develops in step with the erosion of the concave bar opposite and with the lateral and downstream migration of the meander. This increase in vegetation and the gradually increasing distance to the high-velocity zones limit the sediment-transport processes. The more or less vegetated sediment is consequently stored for a period of a few years to a few dozen years, until the upstream meander translates downstream and picks up the stored material (lateral erosion) (see Figure 30) or until the meander is cut off (chute cutoff).

The more active the river, the shorter the storage duration because translation of the meanders downstream rapidly entrains (lateral erosion) the vegetated sections of the bars (Figures 30a and 30b).

These parameters determining shorter or longer storage durations are also applicable to braided rivers in which the effect of macroform vegetation on long-term storage processes is also significant (see Figure 30).

Figure 30

Examples of natural storage of coarse alluvium during transit. (a) Point bars. (b) Vegetated section of a braided riverbed.

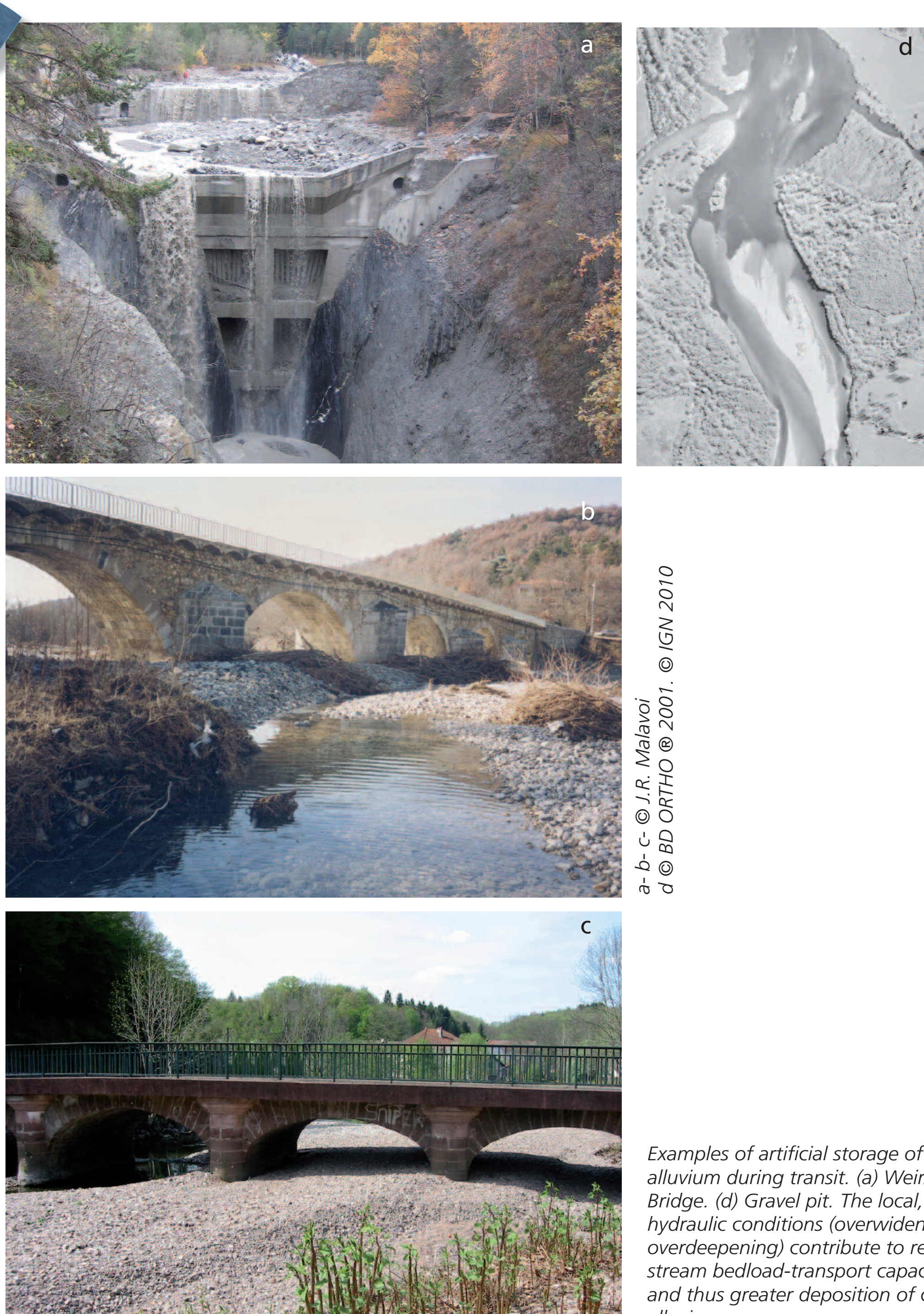
■ Artificial storage

It is acknowledged that tall dams block bedload completely and sometimes definitively, unless they are equipped with functional flushing gates, which is rare.

Storage over more or less long periods may also occur upstream of low installations (weirs, Figure 31a), of installations crossing rivers (bridges and areas just upstream of bridges, Figures 31b and 31c), generally with over-sized cross-sections, and in old gravel pits in the riverbed (Figure 31d). These types of storage, caused by installations or civil work, greatly exceed the "normal" storage durations that occur under natural flow conditions.

NB Storage caused by a weir may extend far upstream of the installation (several kilometres) due to upstream sediment deposition.

Figure 31



Examples of artificial storage of coarse alluvium during transit. (a) Weir. (b, c) Bridge. (d) Gravel pit. The local, hydraulic conditions (overwidening, overdeepening) contribute to reducing stream bedload-transport capacity and thus greater deposition of coarse alluvium.

Control factors and geodynamic ranking