Basic concepts

Initial definition of river hydromorphology

The scientific discipline now called river hydromorphology deals essentially with:

- **physical processes** determining river operation. This is the dynamic side of the discipline. Terms used include "river dynamics" or **"river geodynamics"**;
- the resulting river **configurations.** The term used here is **"river morphology".**

Though the WFD (EU Water framework directive) recently employed the term "river hydromorphology", the name generally used for the scientific discipline is "river geomorphology". Another term that is no longer used, but may still be found in older documents, is "potamology" (M. Pardé), which includes numerous hydrological aspects, notably flooding.

The WFD also includes the operation of the hydrological compartments in the term "hydromorphology". This aspect of hydromorphology will be addressed only in passing in this book, when looking at the role of hydrology in geodynamic processes. The direct ecological impacts of hydrology, due in particular to alterations (minimum discharges, hydropeaking, changes in flood regimes) will not be covered extensively here, indeed they would require a complete book to cover the subject.

Caution. The term **"hydrogeomorphology"** is currently used restrictively in France to designate a special method of determining floodable zones (Masson *et al.*, 1996), based on topographical and geomorphological characteristics of a valley bottom (riverbed, bankfull channel, floodplain below non-floodable river terraces).

River geomorphology did not come into being as a full-fledged scientific discipline until recently, after the initial work to structure the field in the 1950s, notably in the United States. In France, the pioneering work was done by Jean Tricart on the morphologies produced by the torrential flows in rivers in the Cévennes, Languedoc and Catalonia, following the floods in 1957 and 1958. He also launched studies on the geomorphology of rivers in Western Africa. The overall goal in his work was to design territorial planning policies that preserve river environments.

Historically speaking, publications on the topics addressed by river geomorphology may be found in many of the earth sciences, i.e. physical geography, of which geomorphology is a subsection, geology, sedimentology, hydraulics and hydrology. It may be said that this scientific field lies at the intersection of all the above disciplines, from which it draws a number of elements that it incorporates in its own field of study and its own investigative rationale. River geomorphology was also included in the field of river ecology right from the start of the PIREN programmes (multi-disciplinary programmes for environmental research) launched in 1979 by the CNRS (French national scientific research centre) and the Ecology ministry. These programmes worked notably on the Rhône and Garonne rivers, the Alsatian plain and later the Seine river.

River hydrosystems and the role of hydromorphology

It is now widely acknowledged that the physical processes determining river dynamics and, consequently, river morphology and river temporal and spatial evolution also determine, directly or indirectly, the dynamics of the associated ecosystems.

Broadly speaking, the main river environments in valley bottoms constituting the physical support of ecosystems are:

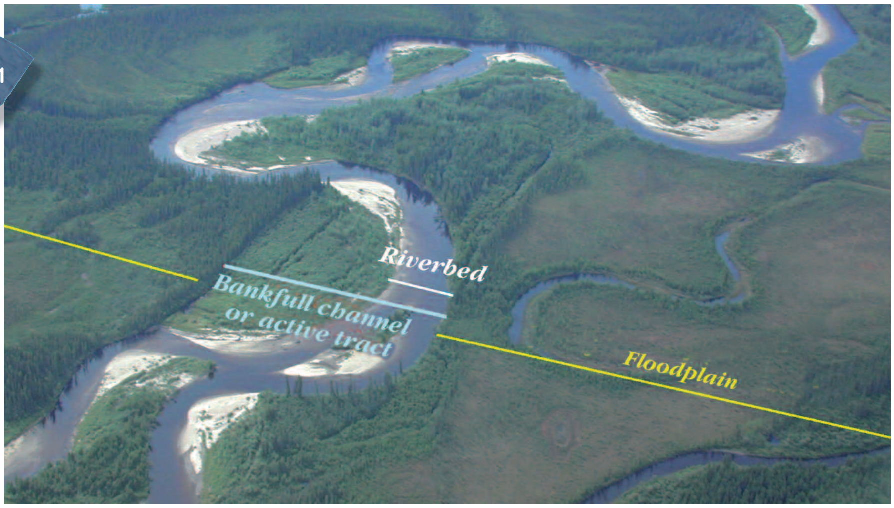
- the **riverbed,** i.e. that part under water for all discharges between the low flow and the interannual mean discharge;
- the **bankfull channel,** i.e. that part under water for all discharges between low flow and the bankfull discharge. This "active tract" is made up of alluvial banks with little or no vegetation, that are restructured and renewed by fairly frequent hydrological events (generally annual to two-year floods). It is often considered the main temporary storage zone for the alluvial bedload transiting over a time scale of decades;

NB For hydraulic engineers, the riverbed includes what geomorphologists call the bankfull channel. It includes the entire zone covered by the bankfull discharge and, in general, a single roughness coefficient is applied.

- the **floodplain** (a hydrological concept if the submerged area is considered, otherwise a geological and geomorphological concept if the alluvial sediment and the related landforms are considered). The floodplain is submerged during events that occur infrequently to rarely (Holocene alluvial floodplains, marked "Fz" on geological maps, correspond more or less to the areas submerged by 100-year floods). Within the floodplain of higher-order rivers, it is often possible to distinguish spatial units comprising the remains of older morphologies, indicative of past river dynamics, e.g. side channels more or less connected to the active channel, marshes (siltated side channels), etc.

All of these spatial units are generally interconnected via the surface hydraulic network or via underground flows. Their origin, structure and evolution are directly related to the past and present river dynamics and may be seen as the elements of a more complex system, the river hydrosystem (Roux, 1982; Amoros *et al.*, 1987, see Figure 3).

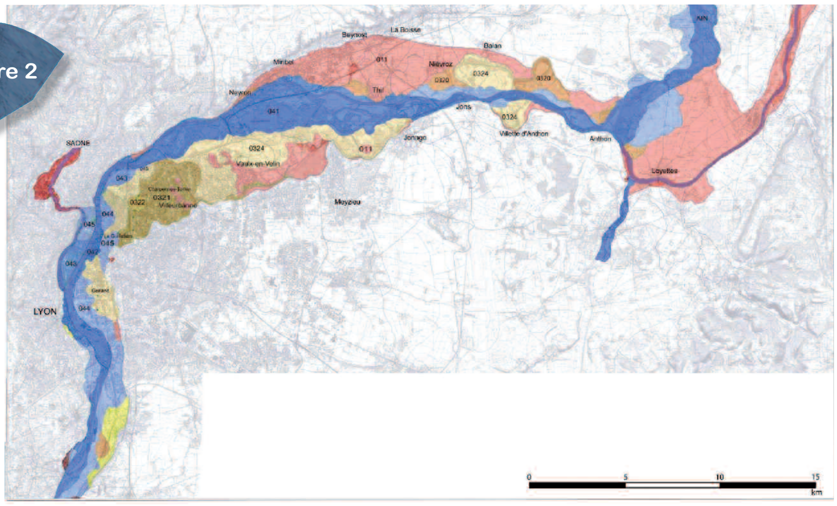
Figure 1



The riverbed, bankfull channel and floodplain of a river hydrosystem (Yukon, Alaska, source: USGS. All rights reserved). Note the side channels in the floodplain which can carry some of the flood discharge.

The inventors of this concept, that was formulated and tested on the Rhône river, signal that it is particularly well suited to large rivers or at least to those having a floodplain sufficiently vast to include a patchwork of the geomorphological and ecosystem units listed above, notably the sub-systems in the floodplain.
For example, Figure 2 below is a map of the alluvial plain of the Rhône between the southern Jura mountains and the town of Givors, showing the Holocene Fz alluvium of the geological map (Bravard *et al.*, 2008).

Figure 2



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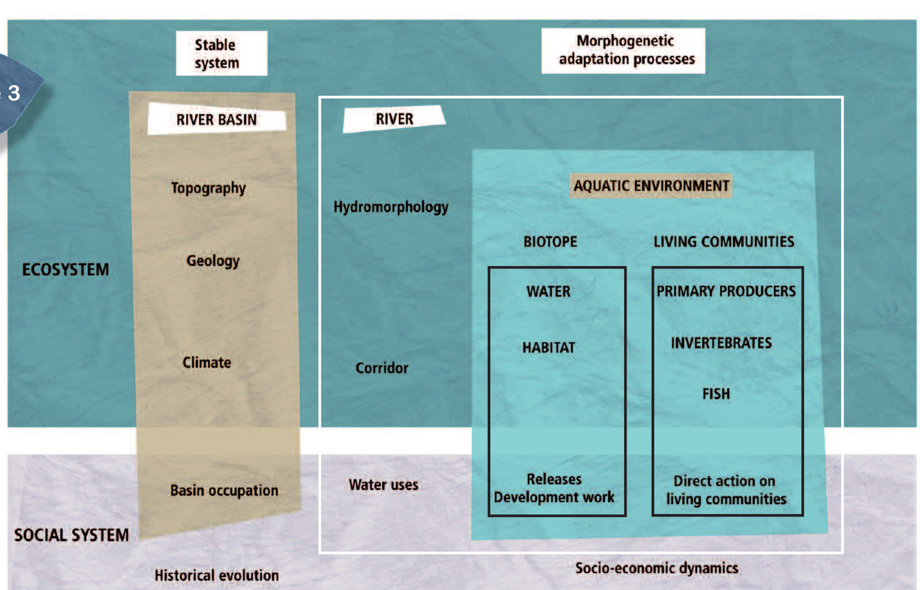
The spatial units of the Rhône alluvial plain in the region of Lyon, marked according to their genetic origin during the Holocene (Bravard, et al. *2008).*

In the figure above, there are three main colours.

- The pink sections indicate areas where the alluvium was deposited during the first half of the Holocene. They are not subject to flooding due to relative aggradation caused by bed degradation that may itself have been caused by endogenous factors (sediment balance impacted by a low sediment load and bed erosion, see below) and/or tectonic uplift in the vicinity of the Alpine-Jura mountain range. These areas are thus part of the alluvial plain, but not subject to flooding.
- The tan and yellow sections correspond to areas where the risk of flooding ranges from low to high. They were formed from the middle of the Holocene to the end of the Middle Ages by the Rhône, which comprised meanders or braids, depending on the period.
- The blue sections correspond to the bankfull channel that was formed from the 1300s to the 1800s by the Rhône depositing its coarse bedload and forming braided channels. These sections, formerly flooded even at relatively low discharges, are now often located behind dikes and fairly well protected.

Figure 3



Hydrosystem compartments (according to P. Paris).

The theory behind the dynamic equilibrium of rivers

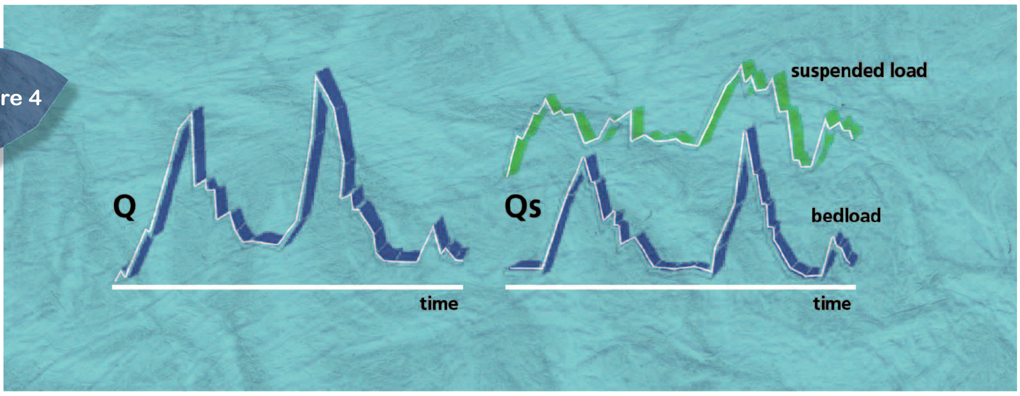
Under relatively constant natural conditions, rivers tend toward a steady state based on two types of factors (Schumm, 1977).

- **Control factors** (or extrinsic factors), such as water discharge and sediment load, which produce effects on the river-basin scale. These factors are themselves influenced by the climate and land cover (which conditions surface flows and protects against erosion). They fluctuate over different time scales and different spatial compartments in the river basin. **Control factors directly impact the river and determine its physical evolution.**
- **Response factors** (or intrinsic factors), which produce effects on the scale of river sections. They include, among others, the width of the river, its sinuosity and the slope of the section. Response factors are the means by which **the river adjusts to changes in the control factors** (climate change, significant and lasting changes in land cover, etc.).

Among the control factors, two are of fundamental importance and determine to a large extent the river dynamics:

- **water discharge (Q)** which, combined with the slope, determines the power of the river[1];
- **sediment discharge (Qs),** particularly the alluvial bedload comprising the coarse sediment.

Figure 4

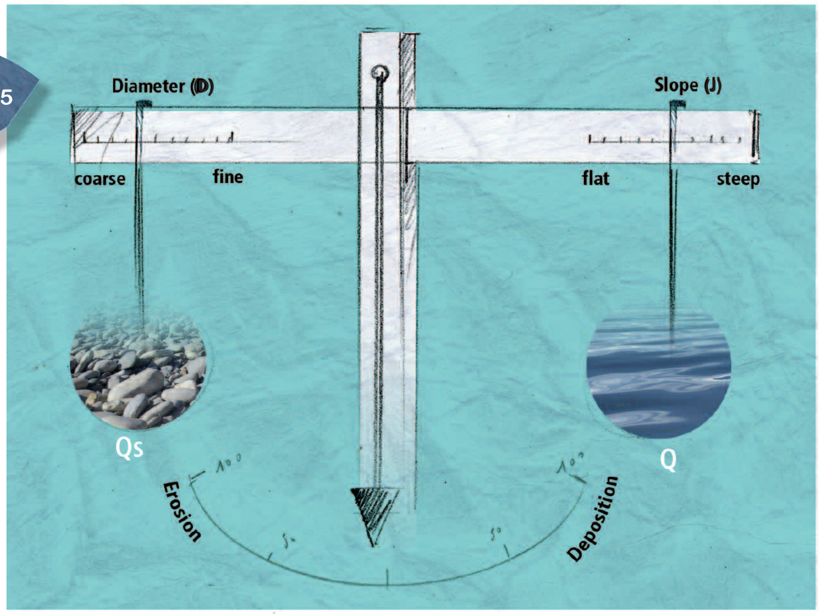


The two main control factors in river dynamics (according to Thorne, 1997).

Fluctuations over space and time of the water-discharge factor and the bedload factor are generally in phase on a scale of one or more centuries. Over shorter time scales, the situation is more complex. A hydroclimatic crisis may provoke major flows causing morphological adjustments on the scale of river reaches. Downstream progradation of the sediment wave, caused by slopes upstream releasing coarse sediment or erosion of upstream valley-bottom deposits, is theoretically shifted in time and its rate of transit is slower (approximately a few hundred metres per year).

[1]Stream power is the product of the slope x discharge x density of water. It depends on the hydrological conditions, the general morphology (valley slope and shape) and the local morphology (pattern) of the river. Variability is therefore spatial (different morphologies of river reaches) and temporal (notably over the short term due to floods).
- Gross stream power (Ω) is calculated as $\Omega = \gamma QJ$ (in Watt/m).
- Unit stream power (ω) is calculated as $\omega = \Omega / l$ (in Watt/m²),
where γ is the density of water (9810 N/m³), Q the discharge (m³/s), J the hydraulic gradient in m/m, l the width of the riverbed for the given discharge (m).

Figure 5



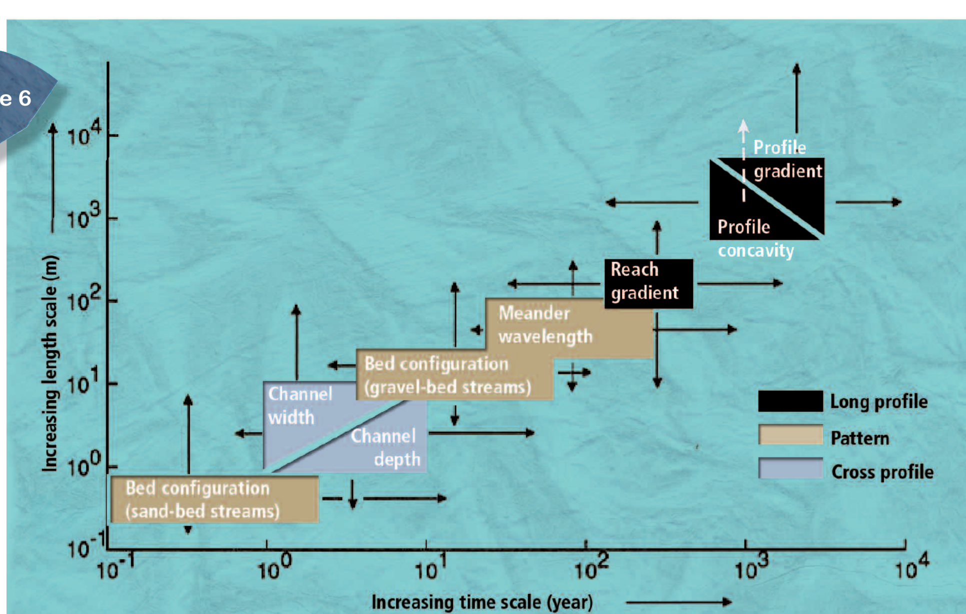
Lane's balance diagram and the concept of river dynamic equilibrium (according to Lane, 1955).

The Lane diagram (1955) shows that all rivers tend toward an equilibrium between the alluvial load arriving from upstream (characterised by its volume Qs and its grain size D) and the water discharge Q which, in conjunction with the slope J, provides the energy required to evacuate the load.

Very simply put, the basic operation of river dynamics may be presented as the continuous oscillation of the needle of a scale on which one pan is filled with coarse sediment (Qs) and the other with water (Q). In that the respective quantities and the ratios between these elements fluctuate widely over intervals of days, years or millennia, there is **continuous adjustment in the river morphology, oscillating around average conditions, through the processes of erosion and deposition.**

Short, minor oscillations correspond to minor adjustments in river landforms, e.g. bed macroforms, channel width and depth, size of meanders. Long, major oscillations correspond to adjustments profoundly affecting river morphology and processes over occasionally very long reaches (planform or river pattern, slope) (see Figure 6).

Figure 6



Temporal scales of adjustments by various geomorphological components of the channel. The linear distances shown on the Y-axis are purely indicative and apply best to rivers in temperate zones (according to Knighton, 1984).

Other control factors have varying impacts on geodynamic processes and the resulting landforms. Below, we list three sets of factors.

■ Valley slope and dimension, created over thousands of years and sometimes even longer. The morphology of valley bottoms depends on their initial conditions:

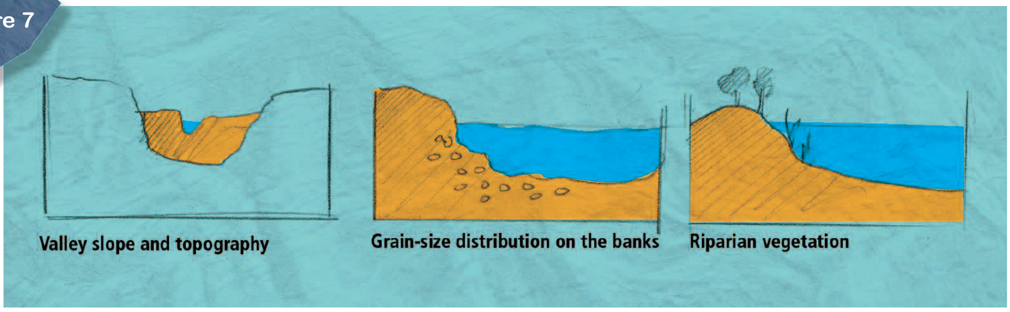
- narrow valleys progressively deepened by talweg incision into the bedrock (limestone canyons), for example the Causses region and Provence;
- V-shaped valleys carved into the crystalline and metamorphic rock of very old ranges such as the Vosges and the Massif Central;
- wide tectonic basins with flat bottoms, occasionally characterised by continuing subsidence, e.g. the Alsatian graben, the Limagnes region in the Loire and Allier departments, the Saône plain south of Dijon;
- glacial valleys narrowed by rock bars and with overdeepened basins that subsequently fill with fine sediment once the ice tongue has melted, e.g. in the Alps and the Pyrenees;
- valley bottoms surrounded by periglacial terraces (plains and plateaux in France) and fluvioglacial terraces downstream of the mountain ranges covered with glaciers a number of times during the Quaternary period. Tectonic uplift and adaptation over long periods to load and discharge conditions characteristic of interglacial periods resulted in nested landforms with terraces persisting toward the bottom of slopes. These types of valleys are found notably in the Paris and Aquitaine basins;
- valley bottoms overdeepened by the retreat of the sea during cold periods and then filled during the eustatic rise in sea levels around 6000 BP once global warming had produced its effect on sea levels worldwide. The most striking examples are the estuaries of the Seine, Loire and Gironde rivers.

■ Sediment characteristics along the bottom of the river bed and the banks, which determine erodability and are themselves the product of the geological history of the valley. If the valley bottom is subsequently filled, the materials may be composed of:

- coarse materials deposed by glaciers, rocks falling down slopes, coarse river materials transported during periods of high stream transport capacity (e.g. during phases of hydro-climatic crises during the Holocene period). These types of valley bottom are found in mountain ranges and foothills. Characteristics include sediment grain sizes exceeding the current transport capacity of the river and steep slopes that were suitable for the transport of abundant, coarse loads;
- fine materials, clay and silt, transported by rivers having a lower transport capacity. These rather cohesive materials may result in some resistance to lateral erosion if the river passes through them;
- a mixture of materials that are generally highly erodable.

■ Vegetation on the banks, a "living" factor and thus subject to greater fluctuations than the two previous factors. Vegetation depends notably on climate change and anthropogenic factors. Trees, shrubs and certain herbaceous species can, thanks to their root system, provide banks with some protection against erosion. This depends to a large extent on the structure of the deposits on the bank (thickness of the topstratum of fine sediment overlying the gravel).

Figure 7



Secondary control factors in river dynamics (according to Thorne, 1997).

It is generally acknowledged that all rivers can bring a fairly wide range of response factors into play to structure their morphology according to the variations in water and sediment discharge and any modifications in the other control factors.

The response factors include:

- bankfull width;
- mean bankfull depth;
- mean bed slope;
- sinuosity.

Natural rivers are said to be in "dynamic equilibrium" or "quasi-equilibrium" (depending on the time scale used to analyse the phenomenon). They continually adjust their width, slope, sinuosity, etc., in step with the short-term fluctuations of the control factors. The concept of "dynamic equilibrium" does not mean that the physical characteristics of the river are not modified over the given time period, but on the contrary that they continually adjust back and forth, across a set of average conditions.

The basic approach to a good hydromorphological assessment must therefore consist of identifying the threshold beyond which the oscillations and the resulting physical modifications are no longer part of the equilibrium process and begin to signal malfunctions.

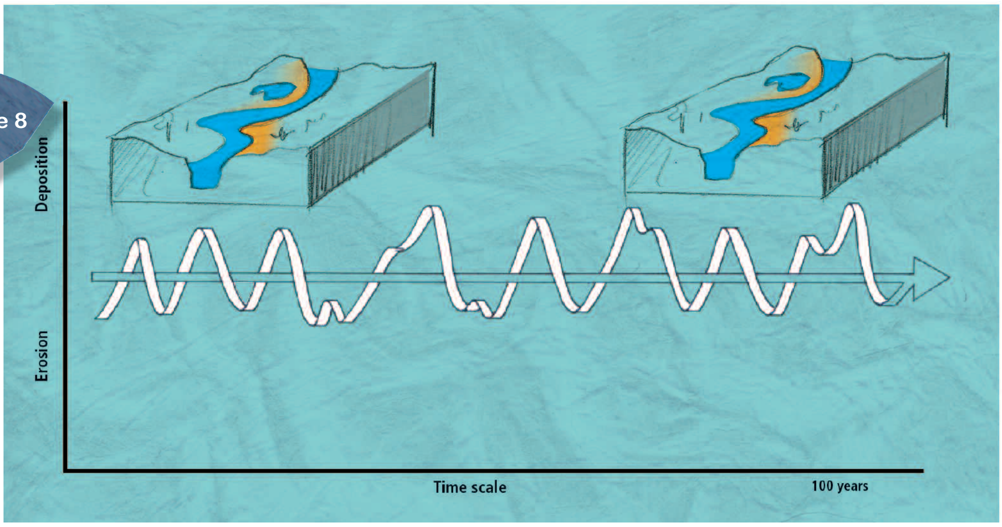
Water and sediment discharge are not, in fact, the only parameters involved in initiating adjustment processes. Any modification, even natural changes, in one of the response factors can theoretically lead to modifications in the river system, in part or in whole, through a complex process of interactions and reactions.

For example, a cut-off meander, whether due to natural or anthropogenic causes, results in a local increase in the river slope that will augment bank erosion both upstream and downstream until the increase in sinuosity has, in turn, restored the original slope. The system continues to operate under conditions of dynamic equilibrium.

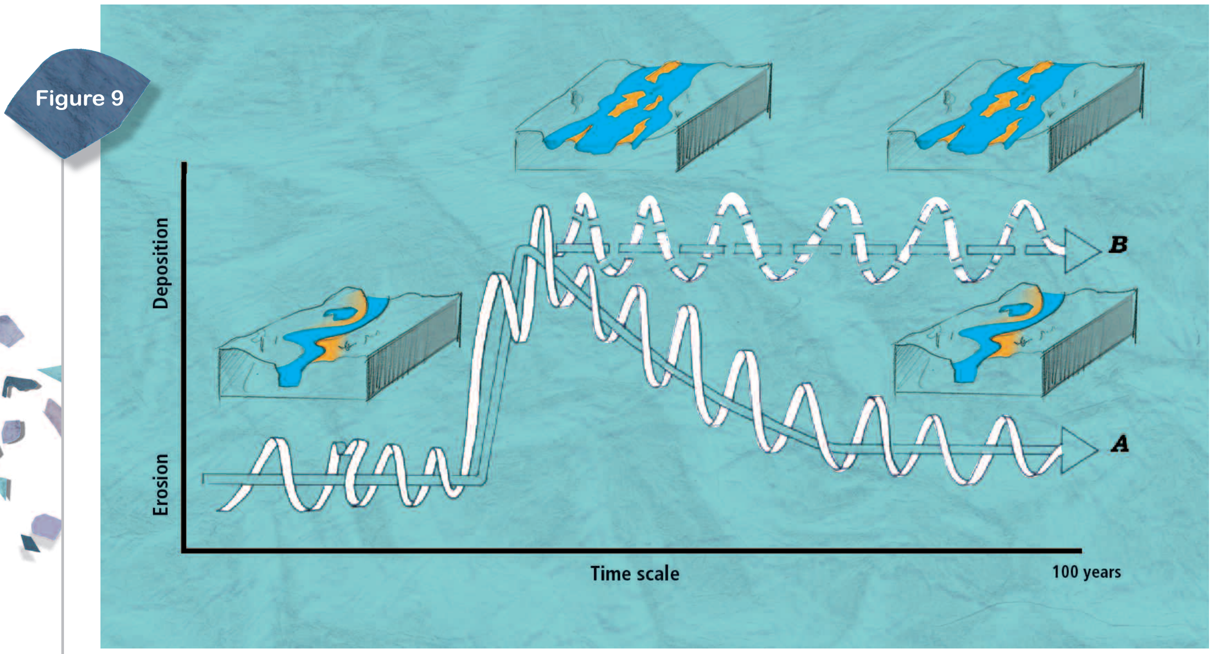
On the other hand, the extraction of gravel from the riverbed can result in durable modifications of the erosion and deposition processes. A gravel pit draws in bedload from upstream (due to the local increase in the slope), thus resulting in erosion downstream because the trapped bedload frees up stream power that is then available to transport more sediment downstream. However, the drop in the level of the bed over a more or less long reach is reversible if gravel extractions are halted and if the sediment from upstream is sufficient to restore the original conditions.

River morphology or, in simpler terms, the river pattern can thus vary spatially, but also temporally depending on changes in Q and Qs. If the modifications are fairly limited (minor oscillations around average values), the river pattern remains more or less stable, at least over the short term (50 years, a century, see Figure 8).

Figure 8

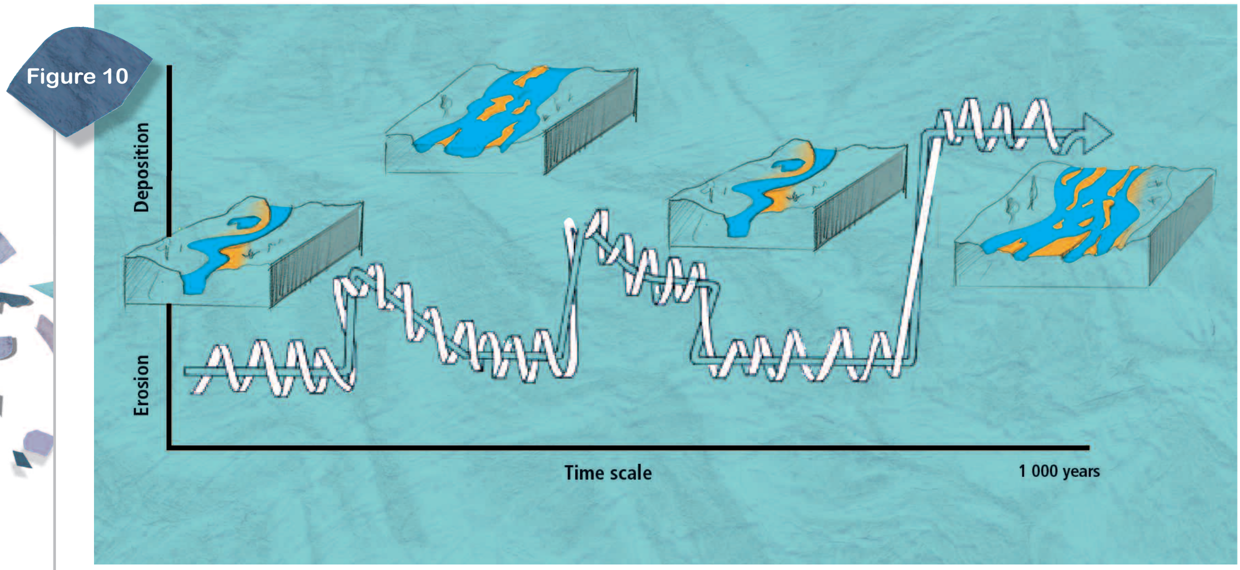


The dynamic equilibrium with minor changes in morphology. The vertical oscillations correspond to the movements of the needle in Lane's balance diagram. The drawings show the corresponding changes in morphology (according to Sear, 1996).



Temporary change (A) and more durable change (B) (according to Sear, 1996).

If major change occurs but does not last long (e.g. a local weather event resulting in major input of alluvium), the river shifts for a while to a new morphology characterised by factors different than those of the equilibrium, then gradually returns to the prior pattern (Figure 9A).
If, however, the modifications persist over time, e.g. a major reduction in sediment load due to climate change or significant anthropogenic modifications (dams, etc.), the river pattern may be durably changed and then remain in that state, with slight oscillations around **a new equilibrium**. This is called **"river metamorphosis"** (Figures 9B and 11).



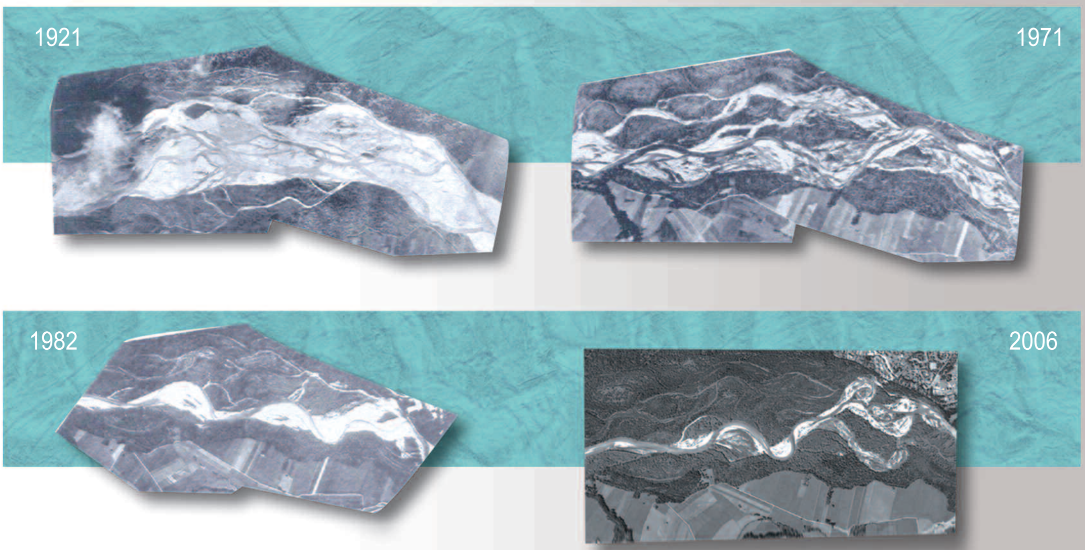
Changes in river pattern over the mid to long term (according to Sear, 1996).

Over the long term, modifications and changes in the river pattern (river metamorphosis) can be fairly frequent, as a function of Q and Qs or major external disturbances (oscillation in the sea level, tectonic movements, major civil work, etc.).

A particularly instructive example of river metamorphosis due to anthropogenic causes is the Isar River in the Geretsried plain in Bavaria, Germany, over the 1900s.

Following the construction of hydroelectric dams along the upstream reaches during the 1950s, the river, which formerly had a braided pattern spanning a width of almost 600 metres, compensated by down-cutting into its bed to form a single channel less than 100 metres wide. The river pattern may today be called "wandering". The bed shifts sideways over the coarse alluvium dating back to the period before the dams. Note that the formerly braided zone is now a handsome alluvial forest.

Figure 11

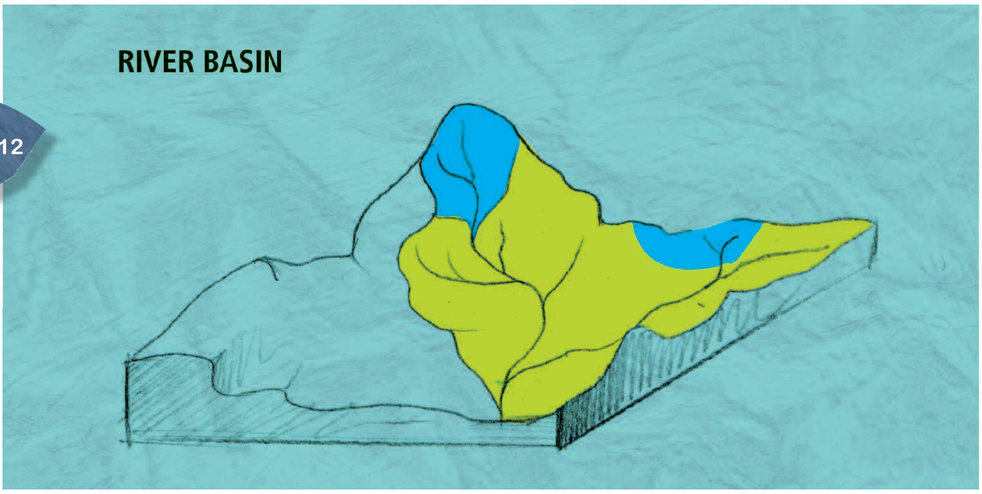


Metamorphosis of the Isar River in the Geretsried plain following the construction of hydroelectric dams upstream of the reach shown (Wagner and Wagner, 2002) and Google Earth (for the 2006 image).

The two main control factors (Q and Qs) and their role in river response on the river-basin scale

It is on the river-basin scale that the two main control factors in river dynamics, i.e. water discharge and sediment discharge (primarily the bedload), produce concrete results. They depend on weather events and the state of the river basin, which in turn condition the origin and transmission of water and sediment flows.

Figure 12



A river basin and its sub-basins consist essentially of a topographical situation and a hydrographic network conveying water and sediment.

Water discharge

Precipitation falls on a given area called the river basin according to a frequency, intensity and duration that depend on the climate and the weather conditions. Run-off occurs more or less quickly and intensely depending on the type of soil and rock, and on the type of land cover (forest, grass land, cultivated fields, etc.). At the outlet of each sub-basin (catchment), i.e. at a precise point determined by the topography and the hydrographic network, and at the outlet of the basin itself, a water discharge Q flows, which is the volume of water exiting the basin per unit of time (cubic meters per second, per day, per year).

Run-off will exceed infiltration if the precipitation falls on an impermeable soil or substratum (metamorphic rock, clay and marl, built-up areas), i.e. a given volume of rainfall will result in a larger discharge at the outlet of the river basin than if it falls on permeable soil (limestone or sand sub-soils, humus-rich soils). Similarly, soil with a given permeability will shed more run-off water if it is cultivated than if left as a forest or grass land.

Many manuals on hydrology exist if the reader wishes to obtain more detailed information on the water discharge of a river basin and its origin (e.g. Jones, 1997; Cosandey and Robinson, 2000; Musy and Higy, 2004).

Sediment discharge

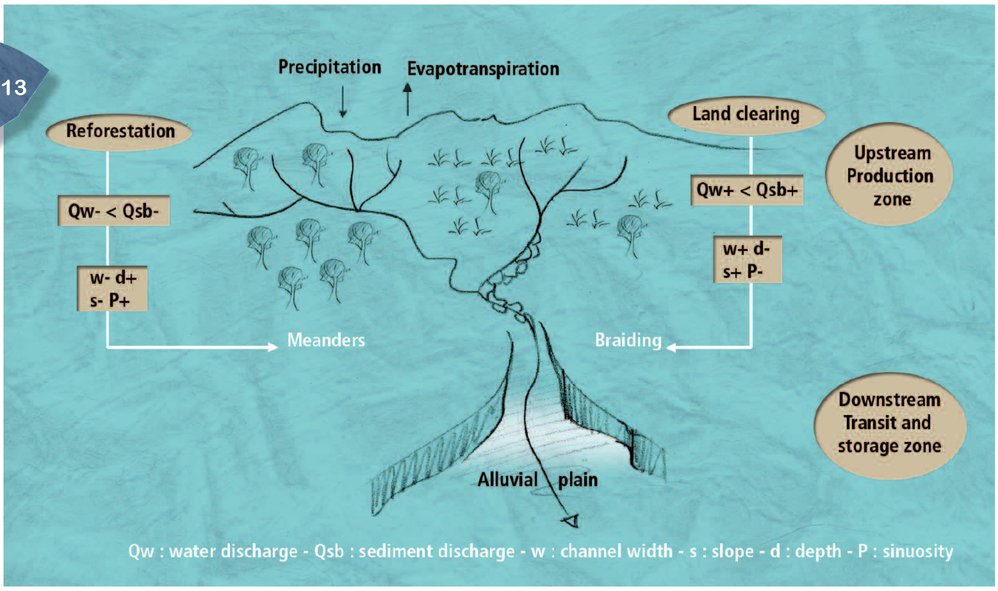
Sediment discharge in a river also comes from the river basin, notably via external sources (erosion from the surrounding slopes). We will see that lateral erosion of the alluvial banks (internal sources of the river system) supplies a non-negligible percentage of the sediment discharge.

In the next chapter, we will present the origin and propagation of sediment discharge, particularly the coarse sediment called the bedload that is indispensable for the geodynamic equilibrium of the river. It should be noted that the coarse alluvial bedload is also the site of numerous habitats required by aquatic and riparian living communities.

Flows and dynamic operation of river systems on the river-basin scale

Figure 13 presents two, very different river basins in a context of high stream power.

Figure 13



Different responses of sub-basins and the rivers draining them to different levels of water and sediment discharge (Bravard and Salvador, 2009).

On the left, the sub-basin was replanted (or trees grew back spontaneously) following a period during which the land was cleared for farming. In this case, run-off and water discharge (Q-) are reduced, but not as much as the sediment discharge (Qs-) from the surrounding slopes. The protection provided by the land cover is effective primarily against erosion. The result is a shift in the response factors, with a reduction in the width and the slope (bed erosion), and an increase in the depth and the sinuosity of the channel. The river pattern produced by these factors is that of meanders (sinuosity).

The sub-basin on the right has been cleared. The result is an increase in the flow of water due to run-off (Q+), but the increase in sediment flows (Qs+), caused by major surface erosion, is even higher. The adjustment factors shift, but inversely compared to the sub-basin on the left. The result is a channel clogged with material and that gradually adopts a braided pattern. Downstream, the reduction in the grain size, due to the deposition of the largest sediment and its wear, means that the water discharge is capable of clearing the sediment load and the river gradually shifts to a new pattern comprising a single, sinuous (meandering) channel.