Stable river patterns

The river pattern is probably the most spectacular among the many response factors available to natural and slightly modified rivers to adjust to changes in the control factors. River patterns have been studied for centuries and a great deal can be said about them, but today, it is acknowledged that there are two main types, meandering and braiding. There are also patterns that have been qualified as secondary because they are less frequent, though some authors see them rather as sub-patterns of the two main patterns. They include the straight, wandering, anastomosed and anabranching patterns.

NB **The distinctions between the various river patterns, their origin, frequency and evolution over time and space are even today the topic of active research in many countries. A frequent dispute, that we will discuss below, concerns the naturalness of the straight pattern.**

Meandering pattern

Most scientists today acknowledge that **rivers very rarely flow naturally in straight lines**. A number of fairly well understood limiting conditions (geological or tectonic constraints such as fault lines, very steep (torrents) or slight slopes) may result in straight patterns, though generally over very short distances.
It should be noted, however, that the **bankfull channel** of braided rivers is generally almost straight (see the section on the braided pattern).
These particular cases notwithstanding, it may be said that a **straight pattern is almost always indicative of human intervention** (rectification) and synonymous with hydromorphological and ecological alterations.

The different types of meanders

There are two main types of meanders, namely entrenched and free meanders, plus an intermediate type called constrained meanders.

■ Entrenched meanders

Entrenched meanders have developed over millions of years of geological history, either as antecedent streams cutting through topographic areas that are erosion surfaces undergoing uplift (the concept of **antecedence**), or over an erodible surface masking a resistant substratum (the concept of **superimposition**).

There are two types of meanders depending on the origin of the bends. Entrenchment can take place due to:

- continued incision of existing meanders;
- progressive development of bends during incision.

Though their planform may currently be unchanging, entrenched meanders are nonetheless capable of considerable sediment transport.

Figure 61

b- © J.R. Malavoi

Entrenched meanders (San Juan River, Goosenecks State Park, Utah, U.S.).

■ Constrained meanders

In constrained meanders, the lateral movement of all or some of the bends is blocked by the entrenched structure of the valley. Their development is limited in alluvial valleys that river erosion could not calibrate, i.e. widen sufficiently so that the meanders could migrate freely.

These meanders are, however, mobile and have a dissymmetric shape caused by the "wall" effect (valley sides made of hard rock) that slows their lateral expansion and translation downstream (see the theoretical aspects below).

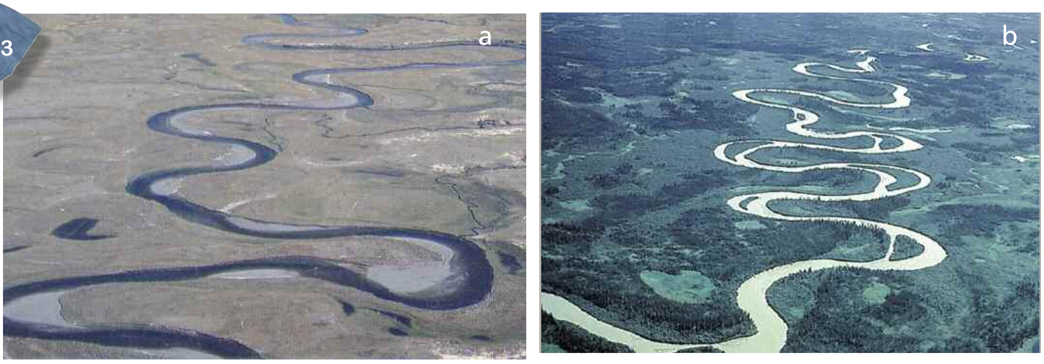
Figure 62

Meanders constrained by slopes difficult to erode (Beaver River in Canada). Note the dissymmetry of the planform. The meanders appear to be increasingly compressed from upstream to downstream (left to right).

■ Free meanders

This is the most frequent type of meanders. They develop over the surface of alluvial plains where they can cut out a planform without any significant geological constraints. On the vertical plane, they cut into old or more recent river alluvium. The pattern is generally sinusoidal.

Figure 63



a- b- © N.D. Smith

Free meanders. (a) Altiplano in Bolivia. Note the abandoned palaeo-channels in the alluvial plain and the point bars that signal significant bedload transport and varied discharges. (b) Meandering river in Alaska at an average discharge level. Chute channels cut off the vegetated point bars.

■ Enclosed meanders

It is possible to find free meanders developing in valley bottoms that are themselves old entrenched meanders.

The latter were dug out millions of years ago by rivers far more powerful than current rivers and their morphometric characteristics (see below) correspond to much higher discharges than current discharges. The current meanders are said to be "underfit" because they are formed by much lower discharges, due generally to climatic reasons or because geological phenomena (e.g. stream capture) deprived them of part of their discharge.

Many examples of such meanders exist in the world, including in France.

Figure 64

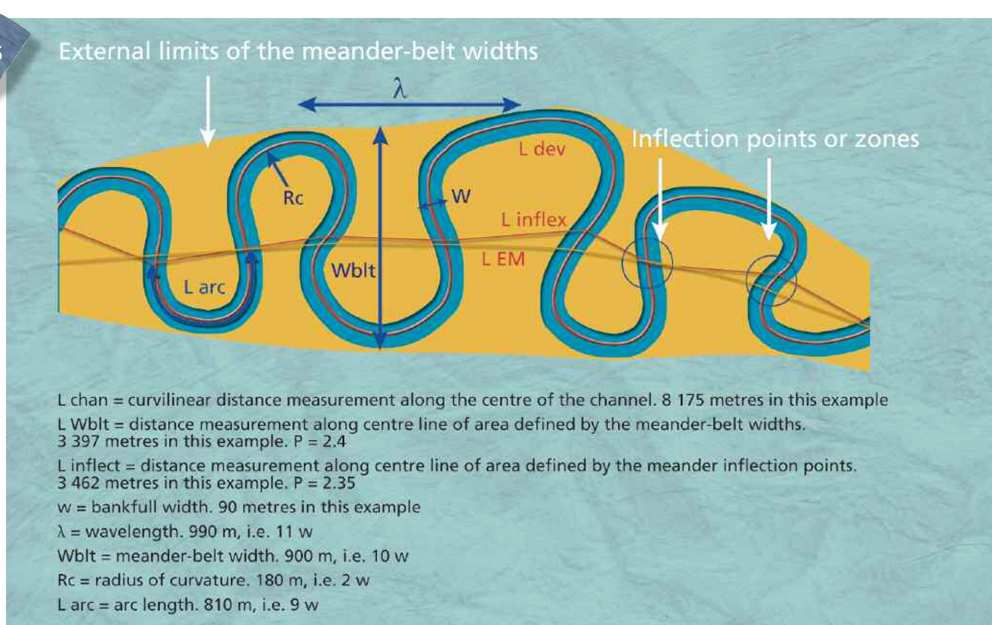
The enclosed meanders of the Rognon River and the current Rognon, with its morphometric characteristics adapted to the contemporary climate. The average width of the valley bottom is 150 metres, that of the current river only 15 metres. The river is almost as sinuous as its "ancestor".

The morphometrics of meandering rivers

The morphometric study of a river or, more precisely, of a uniform geomorphological reach of a river consists of describing a certain number of planform characteristics.

We will see that the morphometric characteristics are good indicators of the hydromorphological operation of a river.

Figure 65



Morphometric characteristics of meandering rivers.

■ Bankfull width

The bankfull width is noted w (width). It is **generally measured at the inflection points between two bends** to avoid the excessive measurements that are often noted in the active parts of bends, where during floods the (concave) cut banks erode and the point bars receive deposits. This is particularly the case for highly dynamic rivers.

The technique employed consists of measuring the width several times over a uniform reach, then averaging the results.

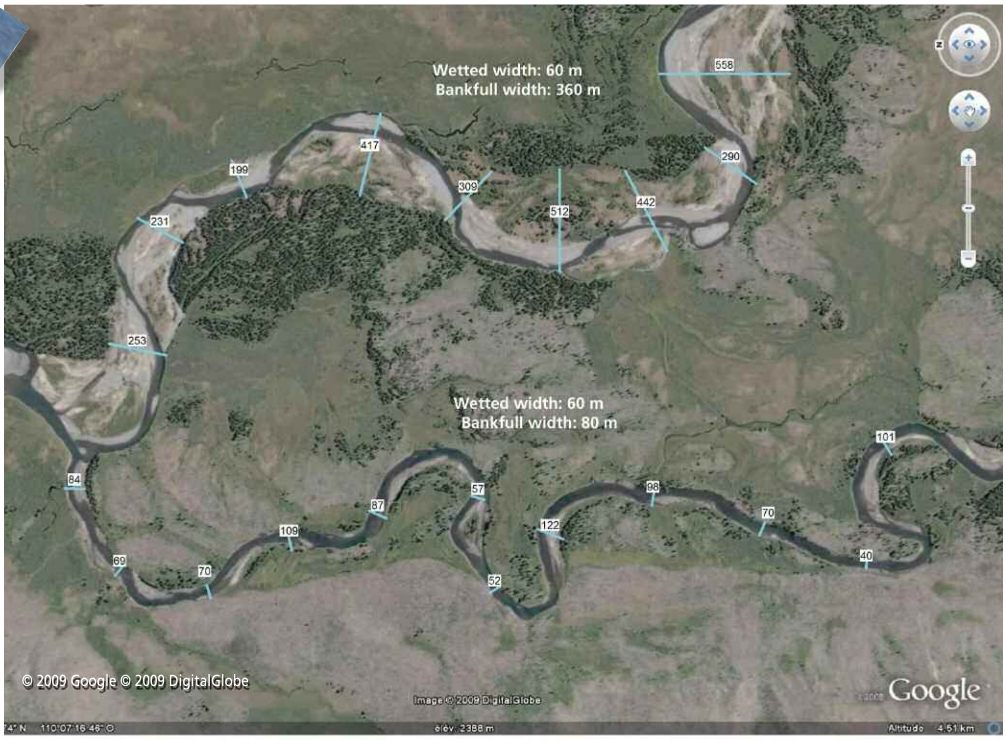
Figure 66

a- b- Géoportail © IGN 2010.

It is advised to measure the bankfull widths in the straight sections or at the inflection points. This is less important for less active rivers (a), on which systematic measurements can be carried out, however it is an important factor in areas where local erosion/deposition processes are significant and where width measurements in the active sections of bends may produce excessive and non-pertinent values if there are few measurements along the reach (b).

The figure below illustrates the significant variability of widths in rivers located very close to one another and having nearly the same size.

Figure 67



Two fairly similar rivers, one probably very active (top) and the other less active. The wetted widths are identical for the observed discharge,identical for the observed discharge, but the top river has a bankfull width 4.5 times larger. The standard deviation in widths represents 36% of the average width compared to 30% for the bottom river in which the bankfull widths are somewhat more uniform.

NB The bankfull width is a crucial morphometric parameter because it serves to calculate "adimensional" values for other river-morphology parameters, which can be used to compare rivers of different sizes and to derive hydromorphological "laws". As noted above, the bankfull width is also an important variable in hydraulic geometry.

■ Sinuosity index

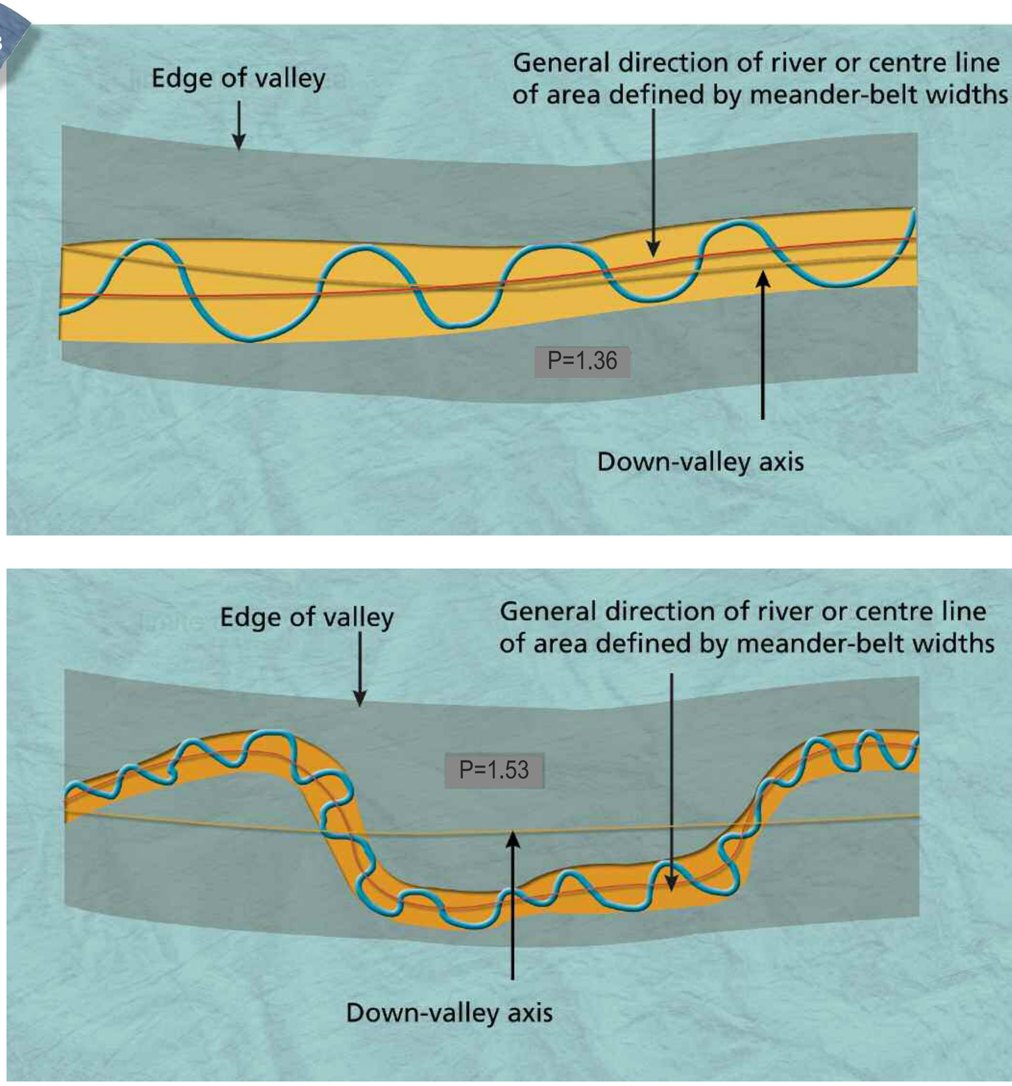
As the name indicates, this parameter quantifies river sinuosity. It is noted **SI** in French documents and **P** in English documents. Two measurement techniques are used, the first being the most common.

Length ratio

This technique consists of measuring the distance along the centre of the riverbed between two points, then measuring the **general direction of the river** between the same two points and dividing the first by the second. For the second measurement, there are two options:

- the "standard" method uses the general direction of the river, which is essentially the distance measurement along the centre line of the area defined by the meander-belt widths;
- the Allen method (1984) uses the distance measurement along the centre line of the area defined by the meander inflection points. This distance is theoretically a bit longer than the previous and the resulting sinuosity index is somewhat smaller.

Figure 68



Calculating the sinuosity index using the centre line of the area defined by the meander-belt widths.

Slope ratio

The other technique consists of dividing the valley slope by the stream slope. The results are fairly comparable to the previous, "standard" technique.

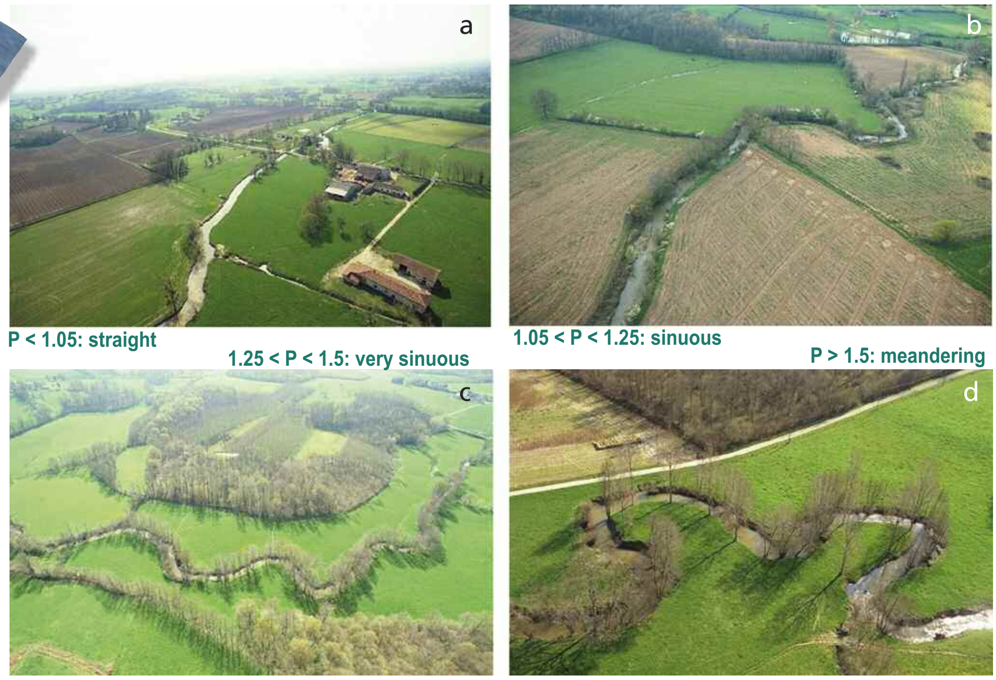
Sinuosity classes

Four sinuosity classes (P) are generally used.

- P < 1.05. The river is virtually **straight.** This is often the case for the bankfull channel of braided rivers (see the section on the braided pattern). This is also the case for many channelised rivers.
- 1.05 < P < 1.25. The river is **sinuous**.
- 1.25 < P < 1.5. The river is **very sinuous**.
- P > 1.5. The river is **meandering**.

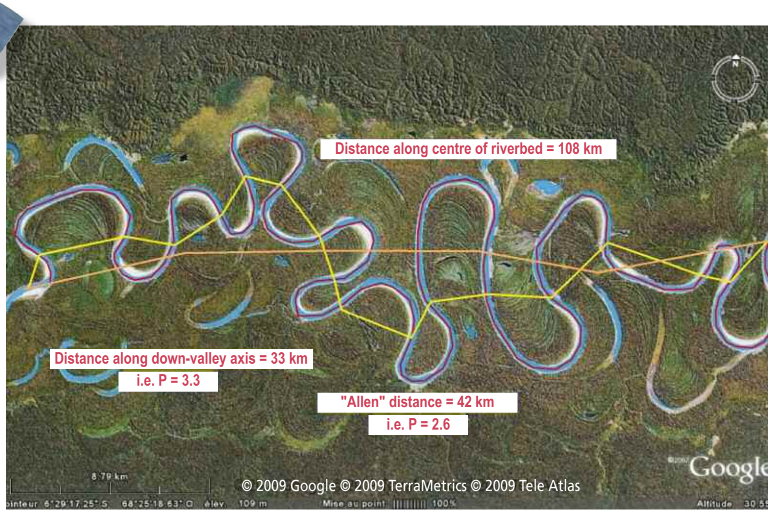
NB The **highest sinuosity indices** can reach values of **3 and even 3.5** if the "standard" method is used.

Figure 69



Visual examples of sinuosity indices.

Figure 70



Example of high sinuosity indices in an Amazonian river.

Figure 71

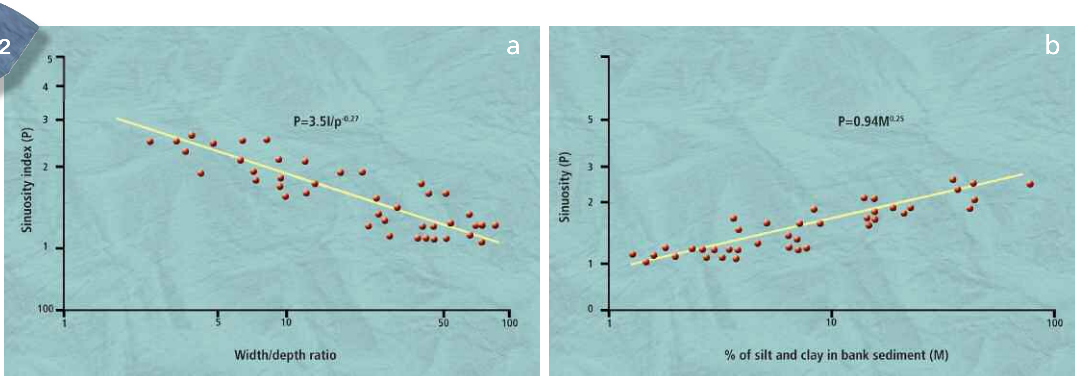
The captain of this boat probably has a very intuitive understanding of just what a high sinuosity index means (Amazon basin).

Figure 72 shows that the sinuosity index is correlated with other hydromorphological parameters such as the width/depth ratio, valley slope and bank texture.

For example, a meandering (high index) river tends to have a narrow and deep riverbed whereas a sinuous river tends to flow in a bed that is wider with respect to its depth. We will see below that the latter is, generally speaking, much more active. Similarly, a river flowing in a valley where the substratum consists of fairly cohesive alluvial deposits has a greater chance of meandering than a river that erodes non-cohesive banks.

Furthermore, straight or virtually straight rivers (at the bottom right in Figure 72a) are those having the highest width/depth ratios. The rivers shown in the figure are **braided rivers.**

Figure 72



Relationship between the sinuosity index and (a) the width/depth ratio, (b) the more or less cohesive texture of the banks (Schumm, 1963).

■ Meander wavelength

The wavelength of a meander is measured between the apexes of two consecutive bends on the same side of the down-valley axis. The result may be a simple distance (metre, km, etc.) or a **relative** (dimensionless) value where the distance is divided by the mean bankfull width (**w**).

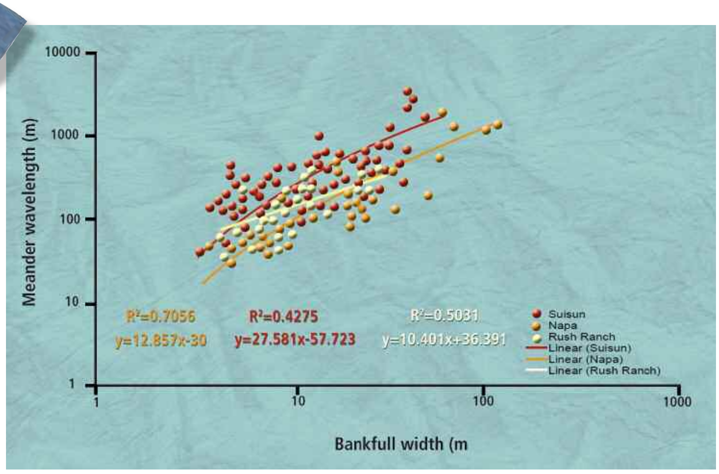
Fairly low relative values generally signal highly meandering rivers (the bends are "squeezed" together) and low geodynamic activity. Higher values signal sinuous rivers (i.e. less sinuous than meandering rivers) that are generally more active in terms of their geodynamic processes.

Caution. Recall (see the section on hydraulic geometry and the figure above) that rivers flowing between cohesive banks (clay, compact silt) are generally more sinuous, narrower and deeper, for river basins of equivalent size, than rivers with non-cohesive and easily erodible banks, i.e. where the mean grain diameter is greater than that of fine sand (0.125 mm). **The division of the wavelength by the mean bankfull width thus provides information not only on the river planform, but also on the consistency of the banks.**

The **average relative values** of meander wavelengths commonly observed in nature are generally between 8 and 15, with a median value of **10 to 12 w.**

NB Even after regionalisation, dispersion of the relative values remains high. As noted above, this would often appear to be due to the fact that the authors have clearly not integrated other discriminant control factors, e.g. bank texture, riparian vegetation, etc. (see Figure 73).

Figure 73

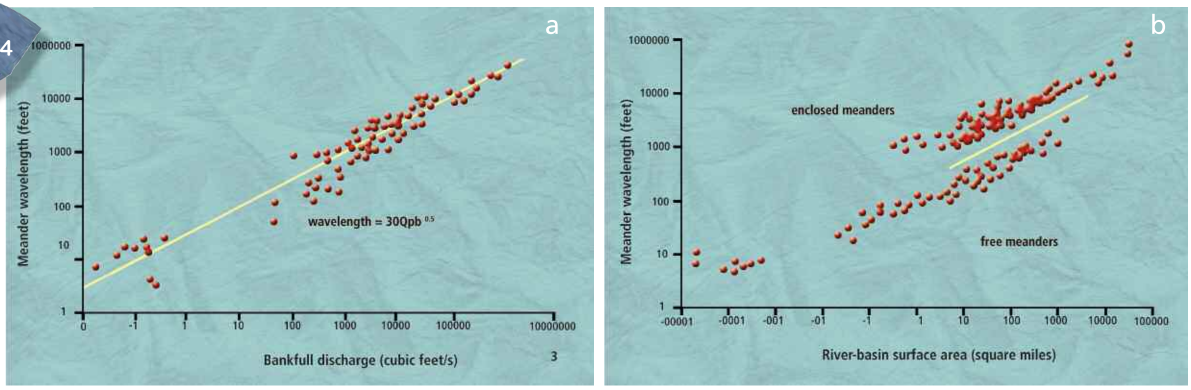


Examples of relationships between meander wavelengths and the bankfull width (Pearce and Collins, 2004).

For meander wavelengths, a number of authors have established relationships similar to those proposed for hydraulic geometry, i.e. relationships with the discharge or directly with the surface area of the river basin (see Figure 74).

It may be noted that in equivalent river basins, **enclosed meanders** are often **ten times larger than current meanders,** which confirms that in the past, discharges were much larger and the climate much more humid than today (see the figure below).

Figure 74



Relationships between meander wavelengths and (a) discharge, (b) the surface area of the river basin (Dury, 1965). Note that enclosed meanders (located in currently temperate zones) are almost ten times larger than current meanders.

■ Meander-belt width

The meander-belt width is generally measured between the apexes of two bends on opposite sides of the down-valley axis. In general, a mean value is calculated for an entire reach. It is also possible to determine the area defined by the meander-belt widths and measure a number of perpendiculars to obtain a statistically valid mean value.

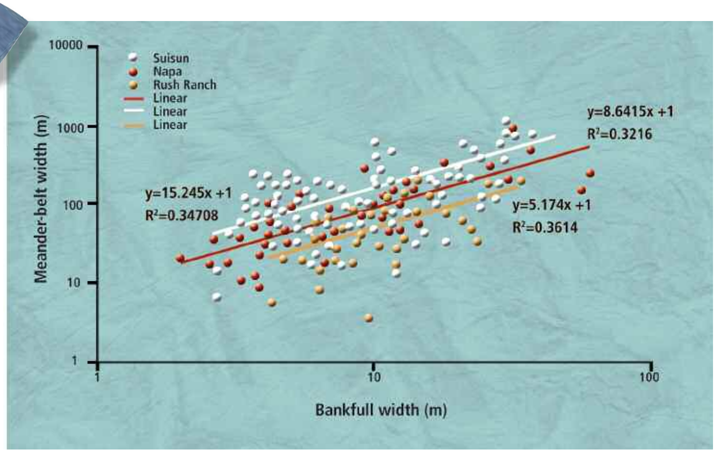
The **relative values of meander-belt widths** in natural rivers range from 5 to 20 w, with a median value of **10 to 12 w.** They are generally lower for less sinuous and high active rivers, and higher for meandering and less active rivers (caution is required because the latter are generally narrower with higher relative values).

Figure 75

Examples of meander-belt width and wavelength calculations (the sinuosity index is 3.5 in the photo on the left and 1.38 on the right).

NB Once again, even after regionalisation, dispersion remains significant.

Figure 76



Regionalised relationships between meander-belt width and the bankfull channel width (Pearce and Collins, 2004).

■ Radius of curvature

This is a useful variable because, as we will see below, when used as a relative value (i.e. divided by the bankfull width), it is **indicative of meander maturity** and of its probable erosion dynamics (the highest erosion rates occur for an Rc/w value between 2 and 3).

The radius of curvature is measured by placing a circle over the two inflection points of a complete bend or, if the meander is too oddly formed, by adjusting the arc of the circle as close as possible to the general shape of the bend. Once again, an average value for a reach is preferable to a single value.

Figure 77

Examples of radius of curvature and width calculations.

■ Arc length

Similar to the other morphometric parameters, the arc length is proportional to the width, but its values are more variable, ranging from **5 to 30 w**. The arc length is generally measured between two inflection points. If the meander is too twisted, the measurement may be taken at the beginning of the "inflection zone".

Figure 78

Examples of arc-length and width calculations.

■ Some exceptions

A significant percentage of meandering rivers have a planform that does not correspond to the hydromorphological laws discussed above. Irregularities in the pattern are generally due to heterogeneities in the soil of the entrenching banks (more or less cohesive alluvium depending on the section of the alluvial plain) and the presence of geological (highly resistant exposed bedrock) or tectonic controls (fault networks).

Figure 79

(a) Highly irregular meanders (Alaska, U.S.). Under these conditions, it is not easy to calculate a wavelength or a mean radius of curvature. (b) Meanders in the Shenandoah River (Appalachia, USA), influenced by the structure of the valley. The image is not deformed! The sinuosity index is 3.9 and the maximum meander-belt width is 48 w.

Caution is also advised concerning measurements that represent only a very specific moment in the development of a stable river pattern. If measurements on morphometric parameters are carried out on a section of the river in which meanders have just been cut off (naturally or artificially), the results and their interpretation may be wildly erroneous (see the figure below). This may also be the case following an unusually high flood.

Figure 80

The current morphometric characteristics do not necessarily correspond to a meandering morphology if the river was modified, more or less recently, by meander cutoffs.

■ In conclusion, a proportionality law

Even if, similar to hydraulic geometry, the morphometric relationships and the corresponding equations produce results showing a high level of dispersion, notably when they are not sufficiently regionalised, they nonetheless establish a **fundamental law of river hydromorphology, i.e. the proportionality law of landforms and processes.**

If the control factors are identical, a small river one-metre wide will function in the same manner as a river 100 or 1 000 metres wide.

The geometric shapes and the gross intensity of the hydromorphological processes are proportional to the size of the river (the bankfull width), which is itself proportional to the water volumes entering the river, which are in turn proportional to the surface area of the river basin.

It is this acknowledged law that makes it possible to study hydromorphological processes using scale models (see the next section).

Figure 81

The proportionality of landforms and processes. (a) Rivers in Yellowstone park, Wyoming, U.S. and (b) rivers in the Amazonian basin.

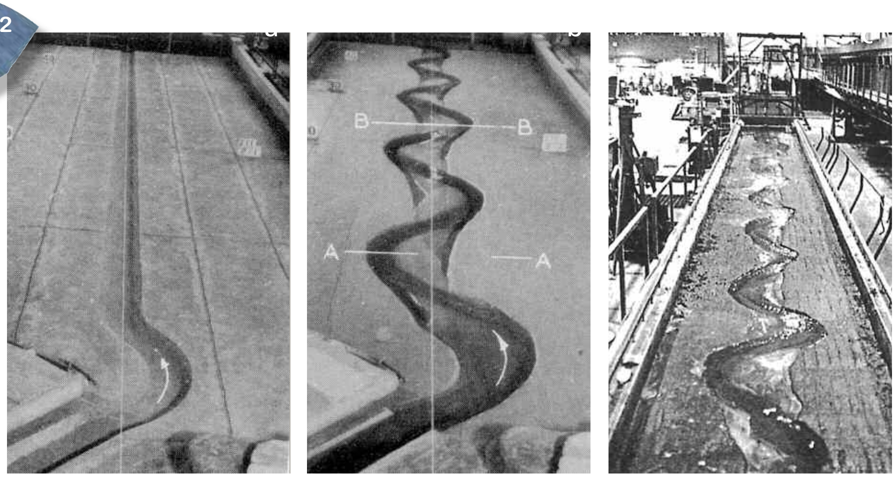
The origin of meanders

Interrogations concerning the origin of meanders date back at least to Antiquity.
They may be divided into two subsets of questions.

- Why do rivers meander?
- Why are meanders so regular?

The figure below shows the development of **perfect meanders in a laboratory** (the pattern is in fact more "very sinuous" than "meandering"). The regularity of the bends is due to the fact that the material used in scale models is generally highly uniform (carefully sifted sand is often used), which is rarely the case in the natural world and explains why natural meanders are less regular.

Figure 82



(a, b) Experiments by Friedkin using scale models (1945). The initial situation is shown on the left, then after three hours at a constant discharge. (c) A very similar experiment by Gardner (1973).

Two main and opposing "schools of thought" attempt to explain the phenomenon of meandering, the school of fluid mechanics, which posits macro-turbulences in river flow, and the school of solid mechanics, which sees meanders as being caused by mechanical compression.

■ Fluid mechanics and turbulence

The main studies on turbulence as the cause of meanders were done by Yalin (1972, 1992, 2001), even if many other researchers have also worked on these processes.

For this school, the principle is simple, i.e. **all moving fluids (water, air, etc.) are subject to turbulence** which is a standard means of energy dissipation. Turbulence occurs in the form of "bursts" along a horizontal (but also vertical) axis which move downstream (or in the direction of the air currents as shown in the figures below) according to a sinusoidal trajectory with a wavelength proportional to the width of the fluid flow.

Figure 83

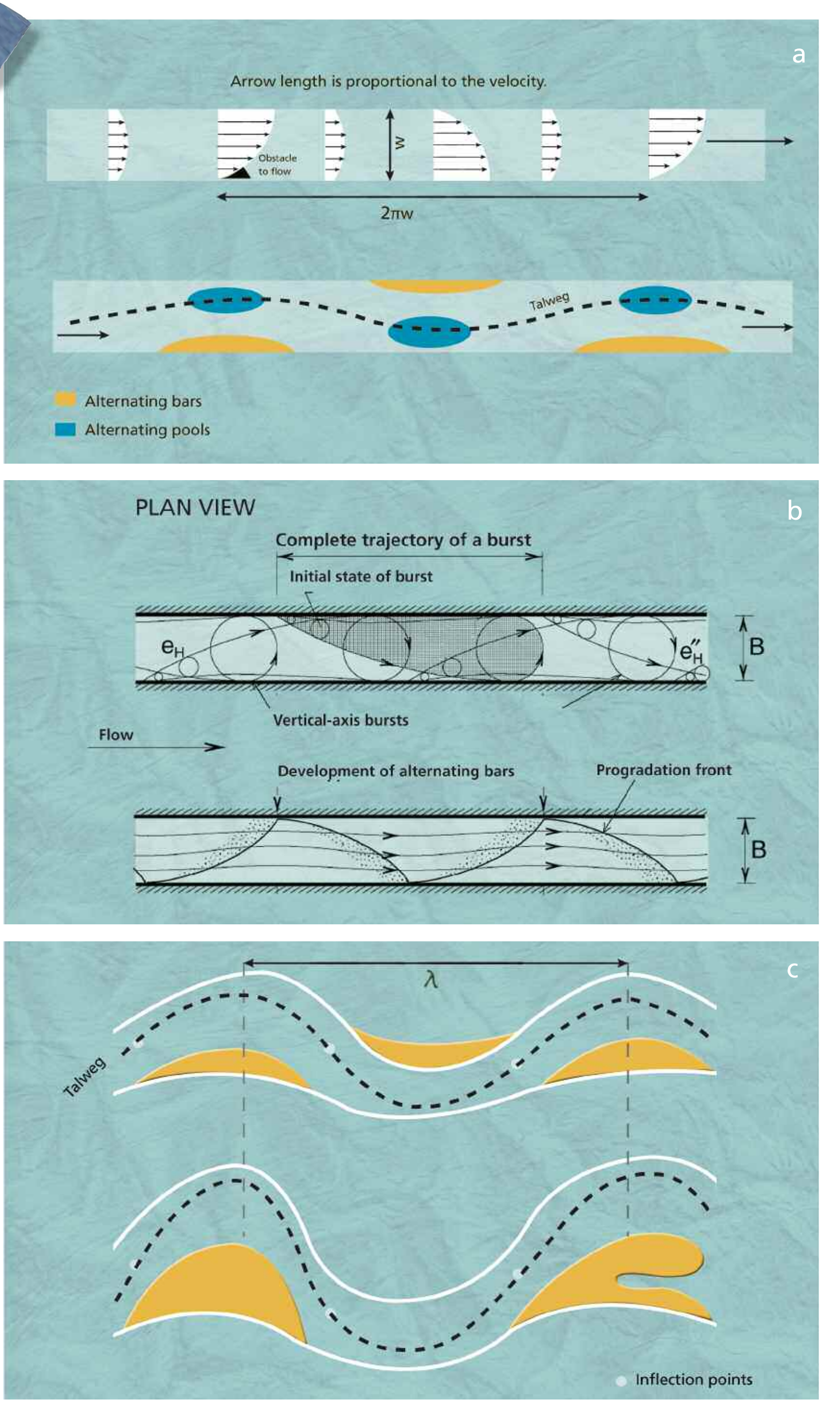
Examples of bursts with a vertical axis generated downstream of an obstacle blocking the fluid flow. The images here show vortexes (Karman vortex street) downwind of islands in the middle of an ocean.

Downstream propagation of bursts in a river results in transport of sediment (if present) and the formation of **alternating bars,** on the condition that the width/depth ratio is not too high, in which case numerous bars form and braiding occurs.

The wavelength of the alternating bars is relatively constant, i.e. between 6 (see the Yalin example, Figure 84) and 10 times the width (Figure 85). The reason for the regularity of the wavelength has still **not been fully explained.**

If the banks are erodible, the alternating bars deflect the current and provoke erosion of the opposite bank, thus creating bends over a short period of time.

Figure 84



Propagation of bursts and the creation of alternating bars. Experiments by Yalin (1972 (a and c) and 2001 (b)). (c) Bends have formed by the end of the experiment.

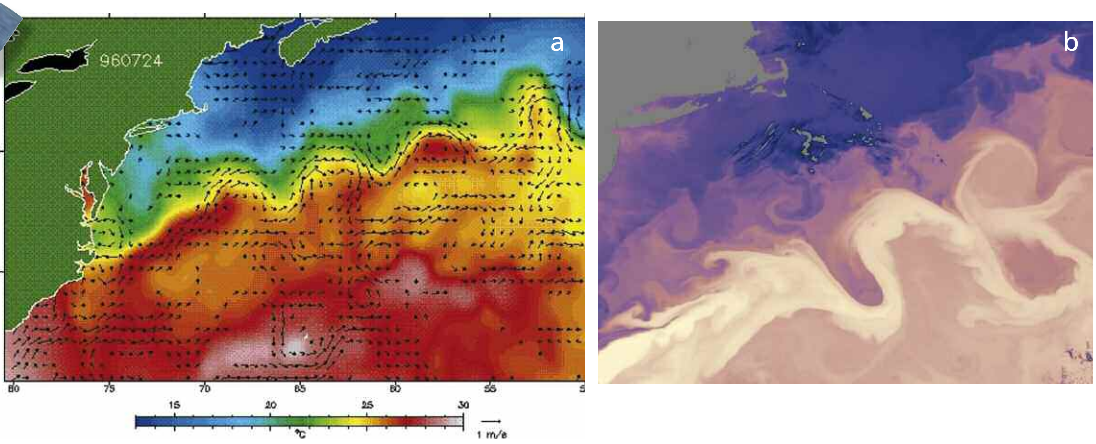
Figure 85

Development of alternating bars along diked sections of the Isar and Rhine Rivers. Note that the wavelength between the apexes of two bars on the same side of the down-valley axis is approximately 8 to 9 times the width. Bends do not form because the banks are not erodible (dikes and stone banking).

NB Alternating bars do not form if there is no or insufficient bedload transport.

The process of "turbulent" meandering may also be found in the Gulf Stream, a warm current flowing between two "banks" of cold water. Note the meander cutoffs and "side channels".

Figure 86



© NASA

Meanders in the Gulf Stream ("bankfull width" = 60 to 80 kilometres). (a) The Gulf Stream revealed by its flow velocities (© NOAA), (b) and by its surface temperatures.

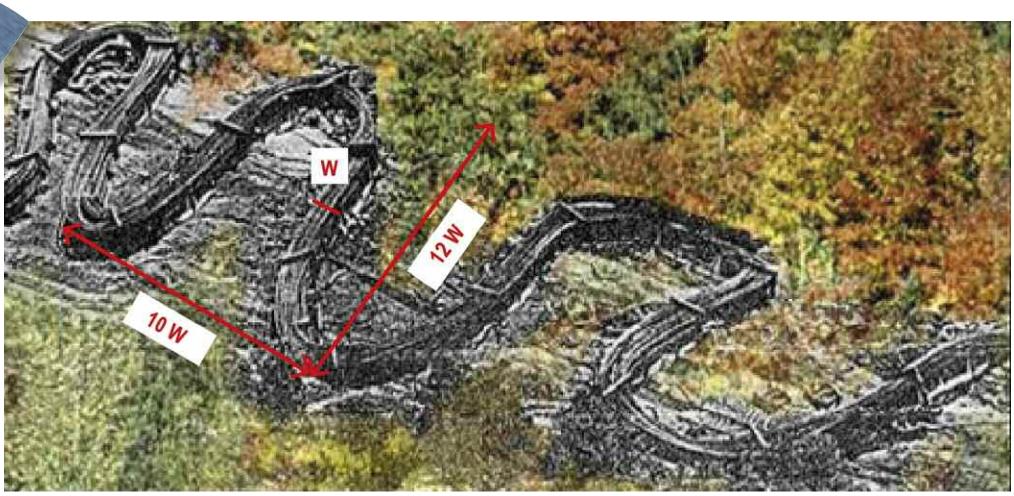
■ Solid mechanics and compression

For this school of thought, which has fewer proponents, the formation of meanders owes nothing to turbulence processes.

These researchers see rivers as deformable, plastic objects, similar to cylinders of modelling clay that one would attempt to push over a more or less plane and more or less rough surface. When pressures are exerted on either side, the result is a deformation which, in plan view, is similar to meanders in a river.

The most widely known example, among those generally presented by the proponents of the mechanistic approach, is that of the freight train that derailed in Greensville in 1965 (Figure 87). The **competing forces** which generated the "meandering" compression were the velocity of the train and the roughness of the substratum which slowed the slide of the train after it derailed.

Figure 87

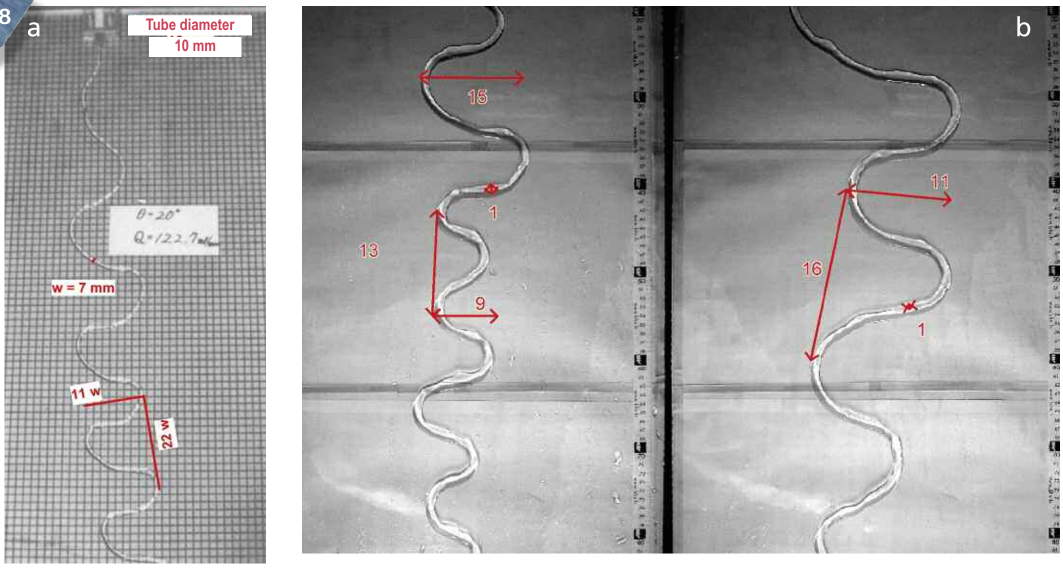


Formation of "meanders" during the Greensville train wreck. Note the wavelength (10 w) and meander-belt width (12 w) (Shetner, 1970, modified).

The other observations in support of this theory are those occurring during experiments on smooth plates. A small (variable) amount of water is allowed to flow down a **smooth, plane surface** (glass or some other material) whose slope can be modified.

Many trials of this type have been carried out since the 1980s, notably by Ikeda *et al.* (1981). Among the more recent experiments that can be presented here are those of Le Grand-Piteira *et al.* (2006, Figure 88).

Figure 88

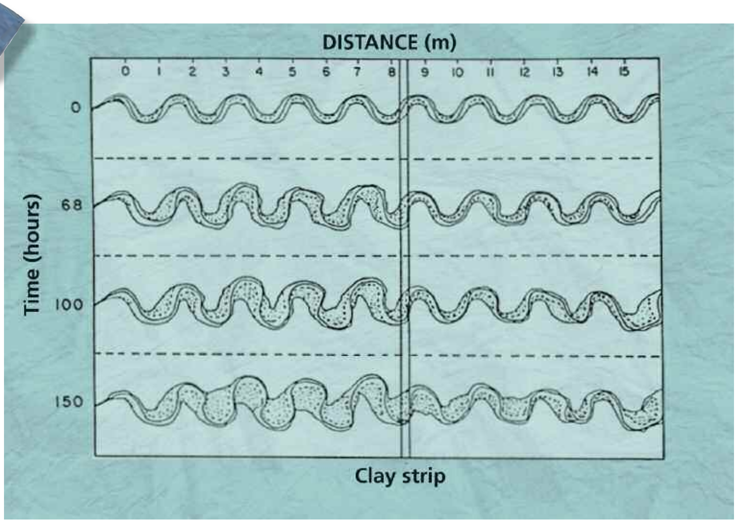


Examples of lab experiments to create micro-meanders on (a) a sheet of glass (Mizumura, 1993), (b) a sheet of mylar (Le Grand-Piteira et al.*, 2006).*

Caution. Meanders develop on a smooth plate only under certain slope and discharge conditions. Flow is virtually laminar, i.e. with little or no turbulence, due to surface-tension phenomena. Bursts are therefore not the cause, but the meanders can be explained as the result of two **competing forces,** i.e. the stream power (slope x discharge) and the roughness of the plate which resists the linear movement of the water.

The solid-mechanics approach may be better observed in scale-model experiments, such as the one presented below (Jin and Schumm, 1986). The experiment takes place in a channel in which a clay strip is installed half-way down the channel and across the entire model. Downstream of the strip, the meanders remain highly uniform and similar to their initial pattern. Upstream of the clay strip, however, the meanders are compressed, their wavelength drops and the meander-belt width increases. The regressive, compressive effect is manifest over a significant distance upstream of the obstacle (at least three bends).

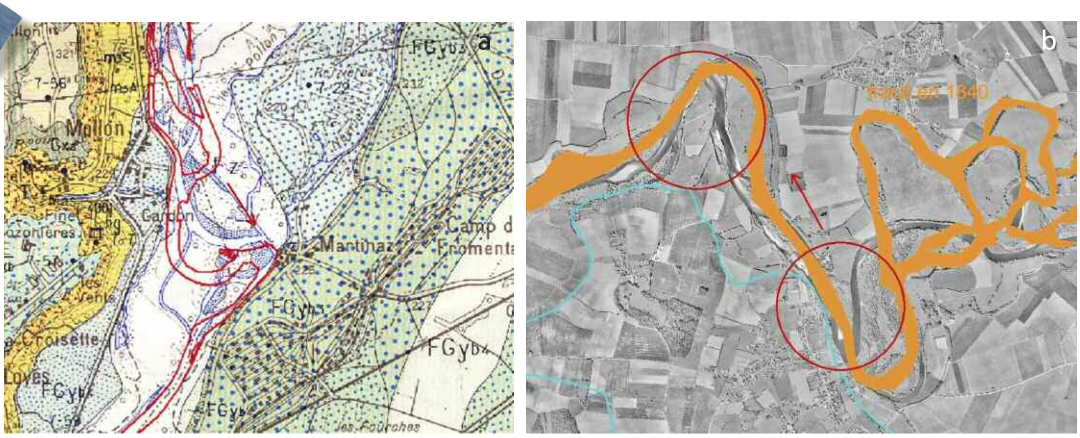
Figure 89



Effect of a clay outcropping on the mechanical deformation of upstream meanders (Jin and Schumm, 1986).

We have observed in many rivers this "compressive" effect caused by an obstacle blocking the smooth translation of meanders downstream, which would be the natural process in the absence of the obstacle.

Figure 90



a- b- BD ORTHO® 2002. © IGN 2010
a- © BRGM

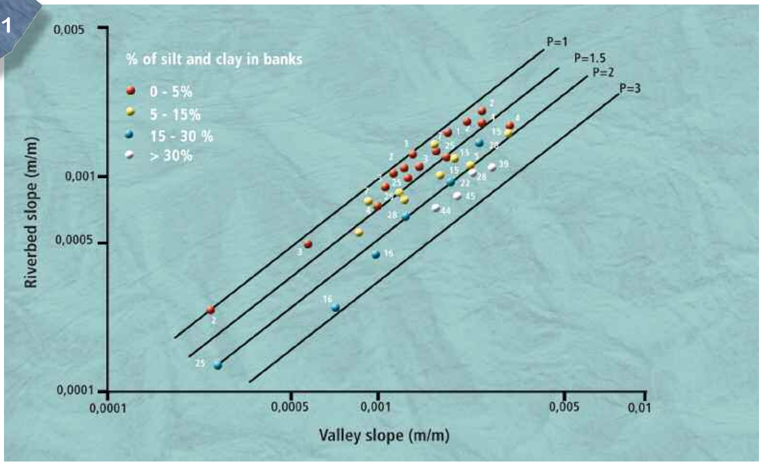
Example of local, mechanical compressions caused by natural or man-made obstacles blocking the downstream translation of meanders. (a) A downstream section of the Ain River (clay outcropping at the foot of a terrace). (b) A downstream section of the Doubs River with, at the top, bank protection systems and, at the bottom, a clay outcropping at the foot of a terrace.

For the proponents of solid mechanics, the **general phenomenon of meandering** in rivers is thought to be caused by the **continuous competition between two opposing forces:**

- stream power (slope x discharge);
- the resistance of the banks which oppose the translation of meanders downstream more or less, depending on the cohesiveness of their sediment.

This hypothesis is supported notably by a number of observations, e.g. Schumm (1963) and later Van den Berg (1995), which indicate (Figure 91) that the greater the cohesiveness of river banks, the more they resist lateral erosion (and the translation of bends downstream) and the more the meanders are compressed (high sinuosity, high meander-belt width and low wavelength).

Figure 91



Relationships between bank cohesiveness (quantified here according to the percentage of silt and clay in the banks) and river sinuosity. The straight lines represent sinuosity indices calculated using the slope-ratio method (Van den Berg, 1995). Note that sinuous and meandering rivers may occur over a wide range of valley slopes and that for a given slope, the river will be increasingly sinuous in step with bank cohesiveness.

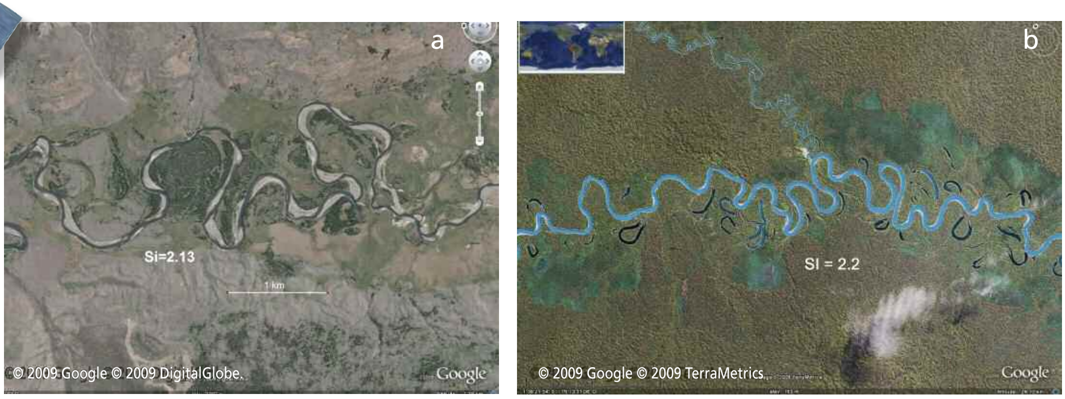
The above would seem to support the compression theory.

- In a river with only slightly cohesive banks (high sand and gravel content), the bends will migrate (translate) easily and rapidly downstream with minimum compression and a moderate sinuosity index (< 1.5). The river is probably fairly active with significant lateral erosion, particularly in the downstream sections of the meanders.
- Conversely, highly cohesive banks will resist meander translation and the latter will be compressed (sinuosity index between 2 and 3). Lateral erosion will take place slowly and progress essentially along an axis perpendicular to that of the valley.

The sinuosity index, for a natural river, may be used as an indicator of bank cohesiveness and of the potential river geodynamic activity.

NB As always, there are exceptions to the rule and some highly sinuous rivers will also be very active. In this case, the presence of a high number of alluvial bars is a secondary indicator (Figure 92).

Figure 92



Two rivers having approximately the same sinuosity index. River (a) is active, river (b) less so.

■ Conclusion on meander theories

The fluid-mechanics (turbulence) approach currently has greater support, however the solid-mechanics (compression) theory is, in our opinion, not without merit and numerous observations in the field would seem, intuitively, to confer it a certain validity. **From the engineering standpoint,** we have often, calling implicitly on the compression theory, advised against blocking the downstream section of an active bend using heavy protection systems to ensure that the phenomenon of regressive compression does not worsen the lateral erosion upstream of the protected area.

In the final analysis, the two theories to describe the processes of energy dissipation, either through turbulence or compression, may be complementary or even identical, but presented differently.

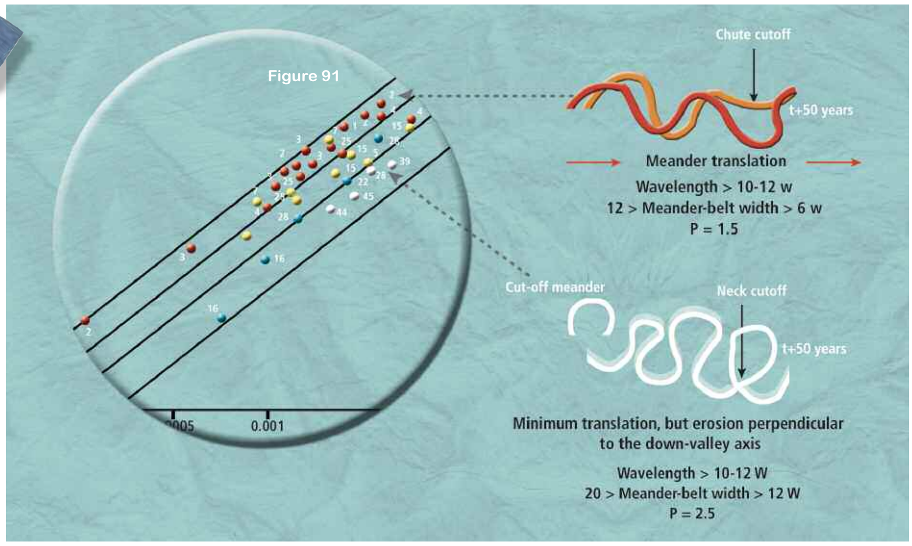
> The main conclusion that may be drawn from the two theories is that **a natural river is never straight,** except for a number of well identified, special cases, i.e. rocky or tectonic controls, a total absence of slope or very high slopes (mountain torrents), or over very short periods, e.g. following artificial meander cutoff.

Meander dynamics

■ Translation, migration, cutoff

Whatever the theory used, it is now acknowledged that bends in rivers are mobile (unless entrenched in a rocky gorge) and move more or less rapidly as a function of various control factors. If we look again at the graph by Van den Berg (1995), it is possible to present the theoretical, natural evolution of the two extreme types of sinuous river (see figure below).

Figure 93



The two extreme types of meander according to the graph by Van den Berg (Figure 91).

At the upper right in the figure, are rivers:

- that are sinuous or very sinuous (sinuosity index < 1.5);
- that are rather active in terms of their lateral dynamics, i.e. maximum erosion in the downstream third of the bends, along the down-valley axis;
- whose typical planform evolution is **meander translation downstream;**
- in which meander cutoff takes place through **chute cutoff** even before the meander has reached its full development (omega shape). The result is a side channel (cut-off meander).

At the lower right in the figure, are rivers:

- that are very meandering (P > 2).
- that are relatively less active in terms of their lateral dynamics, i.e. low level of meander translation downstream and above all extension/expansion perpendicular to the down-valley axis;
- in which **meander cutoff takes place at the neck,** when two concave banks undergoing erosion meet and leave behind a rounded side channel (oxbow lake).

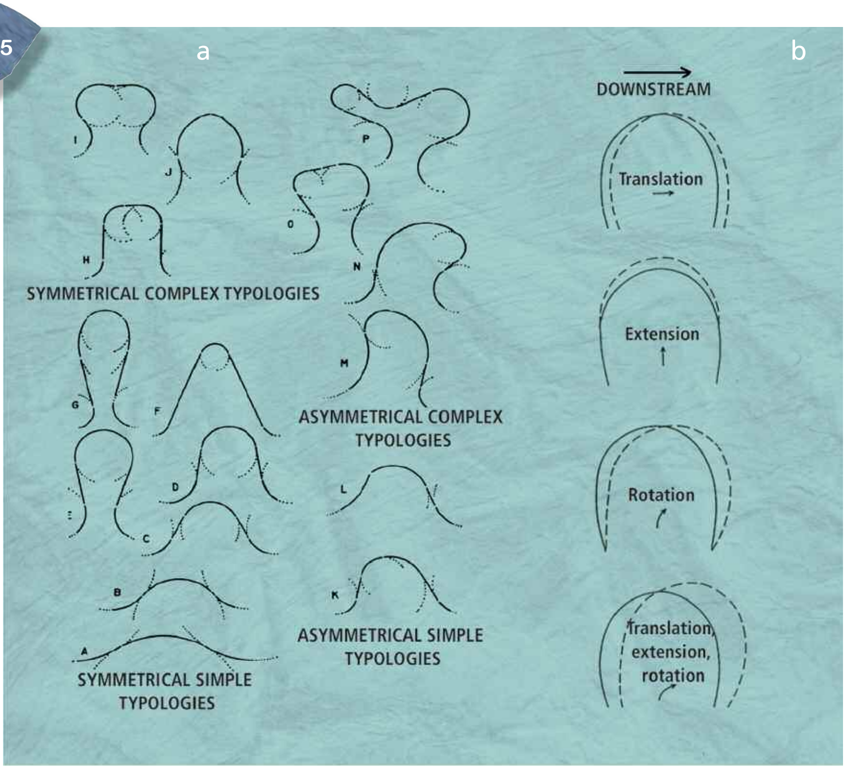
Between these two extremes, there is every possible variation.

Figure 94

The two extreme types of meanders in (a) the Uruguay River basin in Brazil and (b) the upper Amazonian basin in Peru.

The planform evolution of sinuous, single-channel rivers can thus be of several types, to which a number of different cutoff types must be added. A large number of typologies have been established in an attempt to describe more precisely the various types of evolution (see examples below).

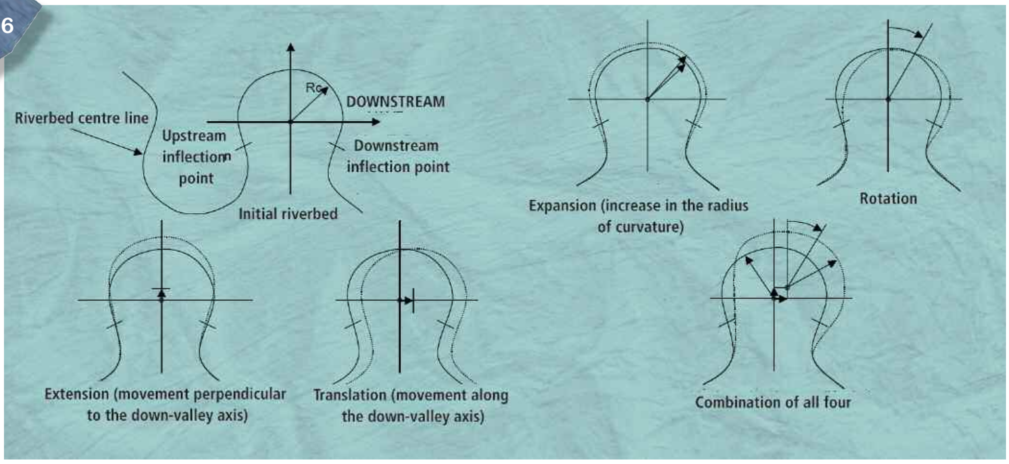
Figure 95



Examples of typologies for the planform evolution of sinuous rivers. (a) Brice (1975), (b) Knighton (1984).

The most recent typology is that of Lagasse *et al.* (2004), who reworked the typology by Knighton (1984) and distinguished four major types of evolution (extension, translation, expansion, rotation) that may all combine (see Figure 96).

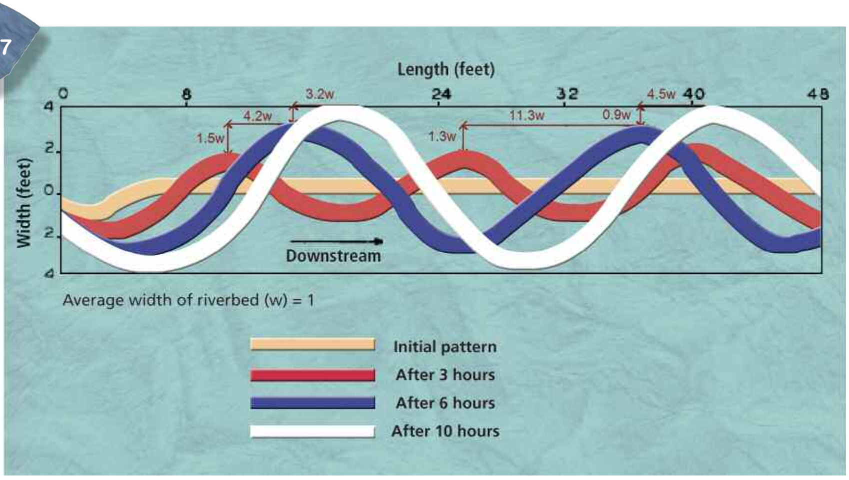
Figure 96



Typology for the planform evolution of sinuous rivers (Lagasse et al.*, 2004).*

The figure below shows the true evolution of a series of meanders in an experimental scale model. Translation clearly dominates among the types of evolution.

Figure 97



Map showing the changes in a scale model of a river during an experiment by Friedkin (1945). There is a triple mechanism involving translation, extension and expansion, but in terms of the mean erosion rate, ***translation dominates*** *with values equal to 3 to 11 times the width compared to 1 to 1.5 times for extension. Note, however, that extension is probably limited by the edges of the experimental system. Note also that the meander-belt width and wavelength increase during the experiment.*

■ Lateral erosion

These general changes in the planform take place through more or less intense processes of lateral erosion, that depend on the stream power and the cohesiveness of the banks.

Lateral erosion on the local level

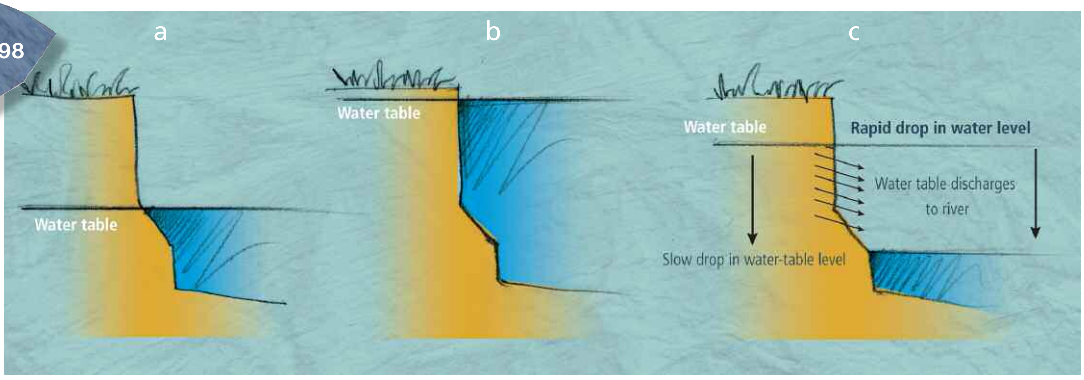
As noted above, in active rivers with non-cohesive banks, the erosion process is dominated by meander translation along the down-valley axis. Conversely, in rivers that are less active and have cohesive banks, the evolution consists above all of extension/expansion perpendicular to the down-valley axis.

On the local level, these erosion processes result in the progressive retreat of the banks at velocities that depend on the type of bank (structure and texture), their height and their degree of vegetation. We will see in the next section that the velocity at which the banks retreat (i.e. the rate of lateral erosion) also depends on additional parameters, including the stream power.

The **important role played by fluctuations in the water table during floods** should also be mentioned. In rivers located in an alluvial plain made up of permeable or highly permeable deposits, the water table rises in step with the increase in discharge.

When the bankfull discharge is reached, the hydrostatic level of the table is in equilibrium with that of the riverbed and, in some rivers, notably in those with banks comprising sand and/or gravel, there is almost no lateral erosion at this stage of the flood. On the other hand, when the waters recede, the level in the riverbed drops much faster than that of the water table, which finds itself perched above the river. The result, as the table empties to the river, is hydrostatic decompression, enhanced entrainment of bank materials and a sudden increase in erosion rates.

Figure 98



Role played by water-table fluctuations in lateral erosion during floods. (a) Before the flood, (b) during the flood (hydrostatic equilibrium), (c) when the water recedes (rapid drop in water level and slower drop in water-table level, which discharges into the river and accentuates bank erosion).

Rate of erosion and dynamic-activity classification of a meandering river

By measuring past erosion rates, it is possible to characterise the geodynamic activity of a river and to predict its future evolution.

Annual rates of lateral erosion in a river may be quantified in two ways:

- by measuring eroded distances, the rate of erosion is expressed in centimetres or metres per year;
- by measuring eroded surface areas, the rate of erosion is expressed in square metres or hectares (ha) per year;

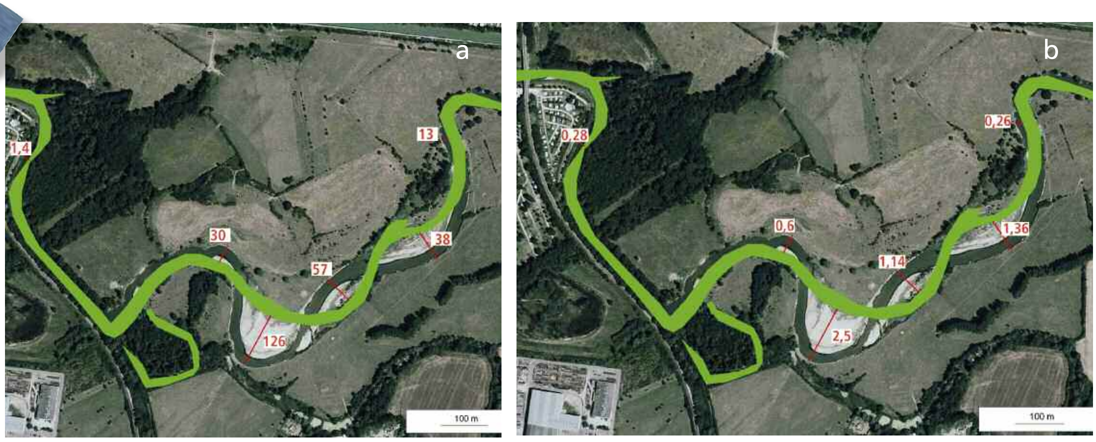
1- Measuring eroded distances using the convexity-sagitta method

One of the methods to determine erosion rates in a river consists of measuring the "convexity sagitta" along active bends using documents (maps or photos) established at least ten years apart in order to reduce the effects of hydrological fluctuations (an interval of 20 years would be ideal for low-mobility rivers).

NB When interpreting the measured erosion values, it is nonetheless important to take into account recent hydrological events in the river because a single low-frequency and/or long flood can provoke significant erosion.

The technique consists of measuring **one sagitta per bend,** at the point of greatest erosion between the two banks shown on the map or photo (see figures below). The length of each sagitta is expressed in metres, then divided by the number of years between the two documents to produce an annual erosion rate (m/year).

Figure 99



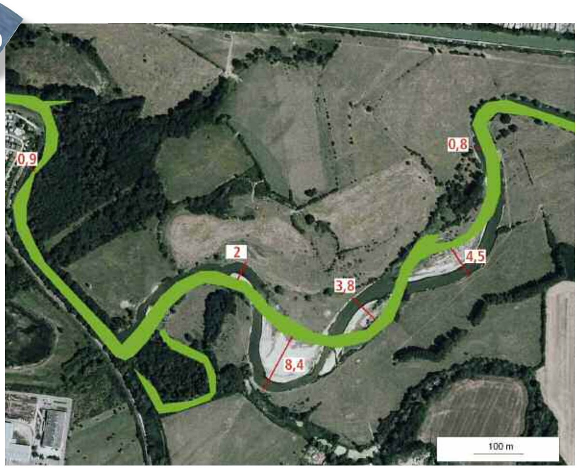
a- b- BD ORTHO® 2002. © IGN 2010.

Measurements using the convexity-sagitta method, (a) measured distances and (b) annual erosion rates from 1950 (green line) to 2002 (aerial photo). The sagitta of the most active bend is 126 metres long, i.e. the annual mean erosion rate of that bend is almost 2.5 metres per year.

Though the rates of erosion expressed in metres are of value, e.g. when informing the local population, in terms of determining the geodynamic operation of the river, it is more useful to know the **relative erosion rates,** i.e. the annual rate divided by the mean width of the river in the studied reach.

The figure below shows that, when calculated using a mean bankfull width of approximately 30 metres, the relative annual erosion rate of the most active bend is 8.4%. This means that each year, the river erodes the equivalent of 8% of its own width.

Figure 100



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Measuring erosion rates relative to the bankfull width.

1a- Dynamic-activity classes

We have devised a classification system for the lateral geodynamic activity of rivers based on relative erosion rates (Malavoi, 2000), notably in view of establishing a national typology.

The system is presented in the table below.

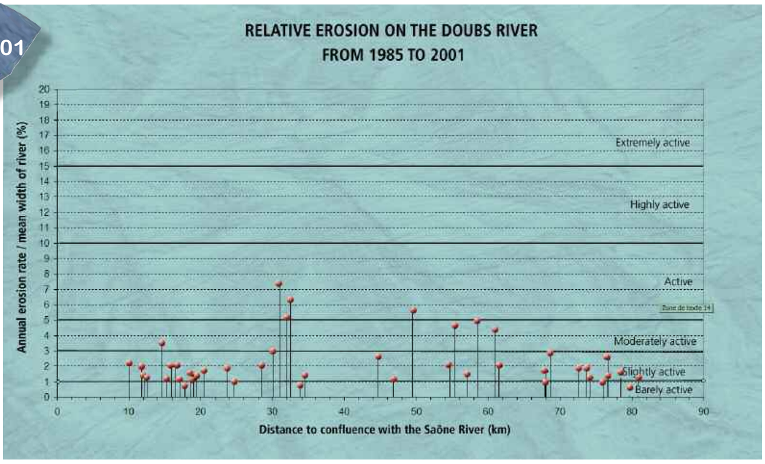
Table 6 *Classes of lateral dynamic activity in a river.*

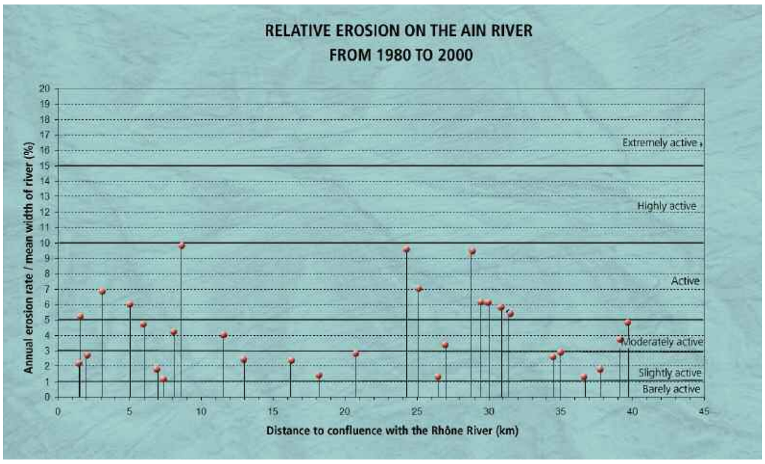
Relative annual erosion rate (% of bankfull width)	Activity class
< 1%	Not or barely active
1 - 3%	Slightly active
3 - 5%	Moderately active
5 - 10%	Active
10 -15%	Highly active
> 15%	Extremely active

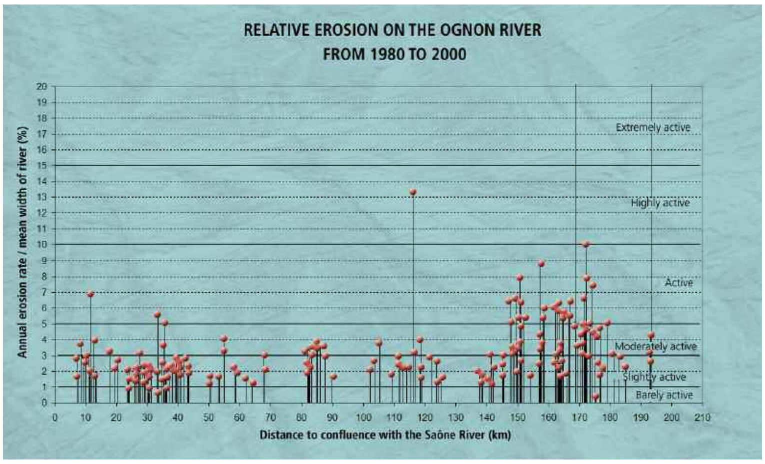
1b- Examples of erosion rates

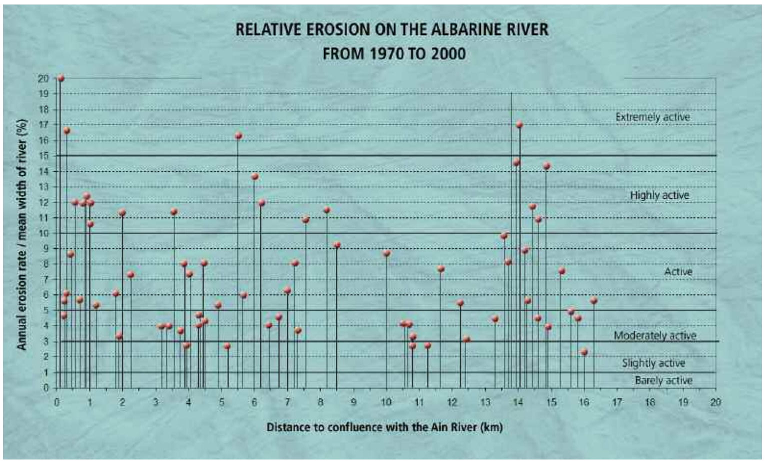
The graphs below present our measurement results for a few rivers. The Ognon is the river with the highest rates and the Doubs with the lowest. This approach and the interpretation of the results can also be broken down into uniform geomorphological reaches.

Figure 101









A few examples of measurements of relative erosion rates on rivers considered fairly active, on the whole. It is clear however, notably on the Ognon River, that the relative intensity of erosion processes can vary greatly, depending on the reach studied.

NB It is important to note that useful data for a geodynamic typology can be gained only in natural meandering rivers that have not been artificially stabilised and that flow freely, i.e. are not affected by waters impounded behind dams and weirs.

If no difference in erosion is visible in the compared documents, that does not necessarily mean that the river has no geodynamic potential. It is necessary to check, notably in the field, that the lack or low level of activity is not due to bank protection systems or the stabilising effect of a reservoir.

Similarly, even if geodynamic activity is observed, for example over a 20-year period, and the reach can be measured and ranked according to a class of lateral-erosion activity, a check should be run to ensure that no bank-protection systems were installed over the period separating the two documents used for the comparison. For example, a bend could erode at a 10% rate per year for ten years, then at 0% for the next ten years if the banks were protected in the meantime. The relative mean rate would then by only 5% per year.

1c- The issue of potential geodynamic activity

This brings us to a more general question concerning how to qualify a river or reach in terms of its potential geodynamic activity. For example, it may be quite useful to know, notably for a hydromorphological-restoration project or when mapping a mobility space, if a given river reach, currently non active following human intervention, would be more active under natural conditions.

This type of analysis requires a typological approach that has been only partially developed to date and is based notably on the geodynamic rank. A given unit stream power combined with a given class of bank erodibility and a given level of sediment input should theoretically produce a quantifiable relative erosion rate. While waiting for a functional typology suited to this type of question, a simpler approach is to use the convexity-sagitta method in each uniform geomorphological reach and to deduce that the reach as a whole should theoretically operate in the same manner. This is because it is rare (but not impossible) that reaches spanning several kilometres have been artificially stabilised over their entire length. Lacking a better solution, currently active zones could therefore be considered representative of the "natural" operation of the river.

1d- Presentation in map form

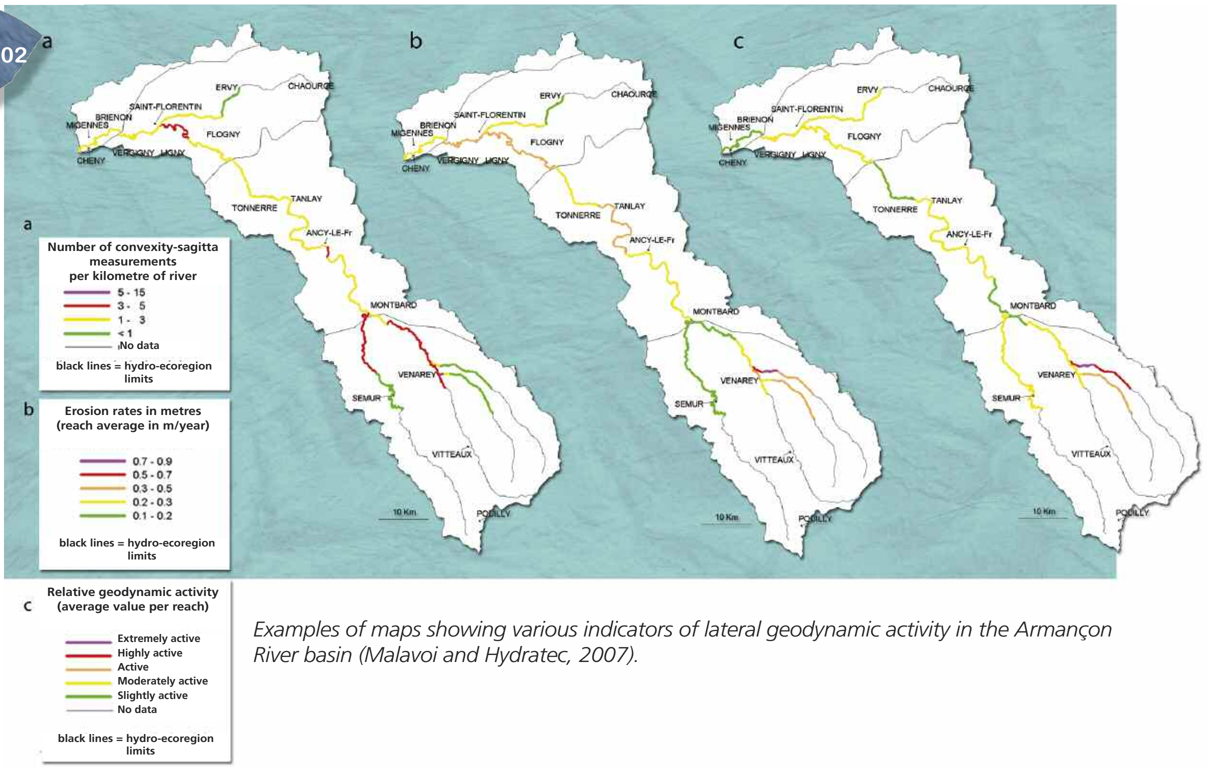
Two parameters are important when attempting to characterise the lateral geodynamic activity of a river or river reach, i.e.:

- the erosion rates, in metres or relative;
- the number of bends being eroded (i.e. the number of convexity-sagitta measurements) per unit of river length (where the unit of length must be proportional to the size of the river).

NB Note that the two parameters may be heavily influenced by human intervention.

In addition to graphs, maps are also a useful way to present and interpret lateral-erosion rates. A few examples of maps indicating the results for each geomorphological reach are shown below.

Figure 102



Examples of maps showing various indicators of lateral geodynamic activity in the Armançon River basin (Malavoi and Hydratec, 2007).

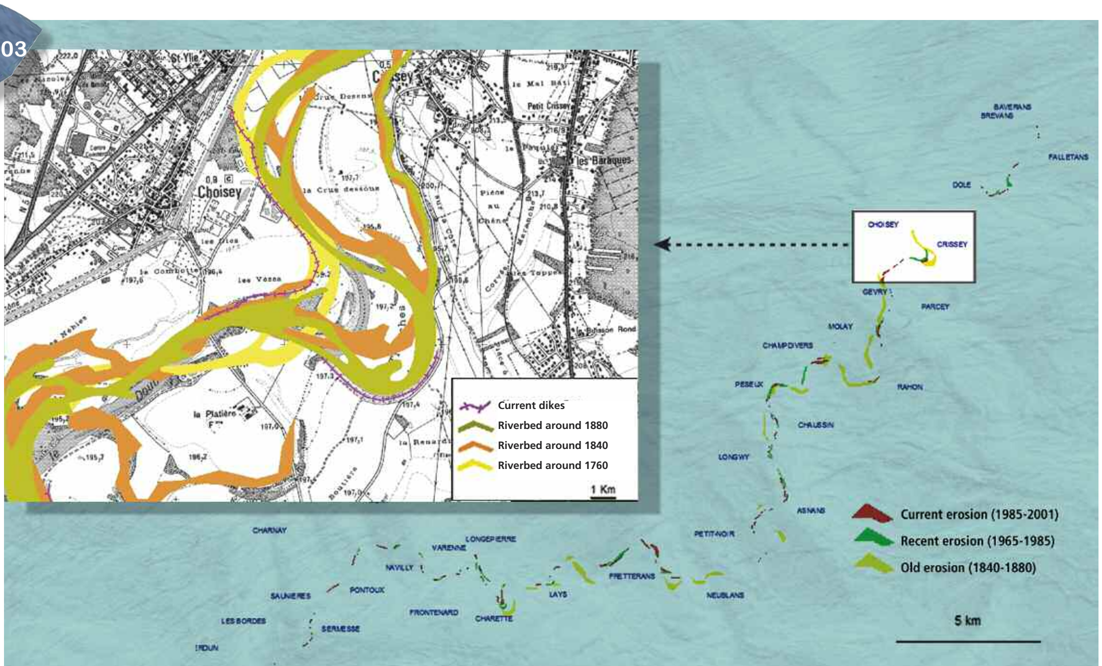
2- The surface-area method

In addition to measuring the eroded distances, where only one value is generally recorded for each bend, it is possible to measure and analyse rates of lateral erosion on the basis of the eroded surface areas. This approach is useful in evaluating:

- land losses (a major socio-economic and socio-political aspect);
- production of alluvial load (this aspect concerns the sediment-transport equilibrium).

By comparatively analysing maps or photos, using a GIS (geographic information system) if available (see the chapter on hydromorphological tools), it is possible not only to measure the convexity-sagitta values, but also to map the eroded surface areas.

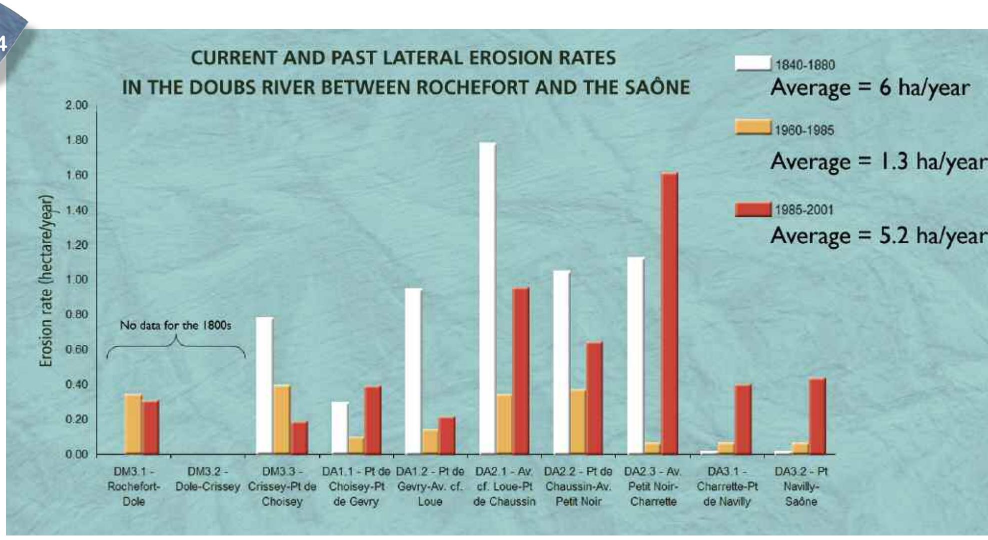
Figure 103



Map of eroded surface areas on the lower Doubs River over three time series (Malavoi, 2004).

This technique provides direct access to precise, spatialised information on past erosion. For example, the map of the Doubs River shows formerly active sectors that are no longer active and formerly inactive sectors that are now active. Presented in graphs (see below) showing average values for each uniform geomorphological reach, the data provide a rapid indication on trends over time and can be used to draw conclusions for the future. There was clearly a reduction in erosive activity in the lower Doubs between 1960 and 1985 (Malavoi, 2004), due to the extraction of large quantities of material which, by reducing the surface areas and volumes of alluvial bars, also reduced the lateral erosion caused by the macroforms.

Figure 104



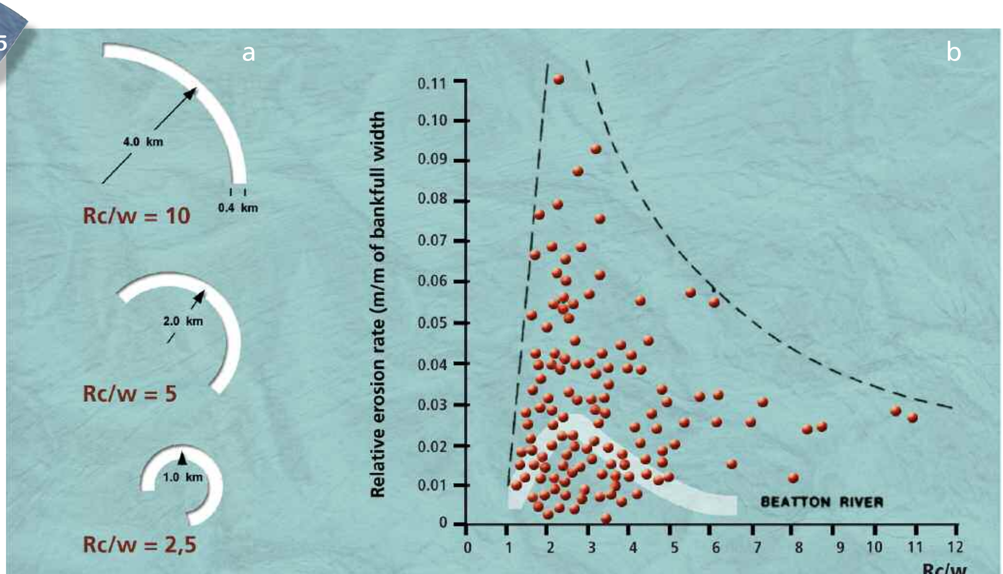
Annual erosion rates for uniform geomorphological reaches on the lower Doubs River (Malavoi, 2004).

3- Meander maturity

From the moment a meander is created (starting from a straight section) until it is cut off (if that occurs), it evolves according to the processes discussed above (expansion, translation, etc.).

Research has shown that erosion rates on the scale of individual bends vary over time as a function of the meander maturity. The most commonly used **maturity index** is the ratio between the radius of curvature and the bankfull width (Rc/w). A number of studies indicate that the highest lateral-erosion rates occur for Rc/w values between 2 and 3, with a **fairly clear peak between 2 and 2.5** (Hickin and Nanson, 1984).

Figure 105



(a) Visual examples of Rc/w values. (b) Relative erosion rates observed in some rivers as a function of the maturity index (according to Hooke, 1991).

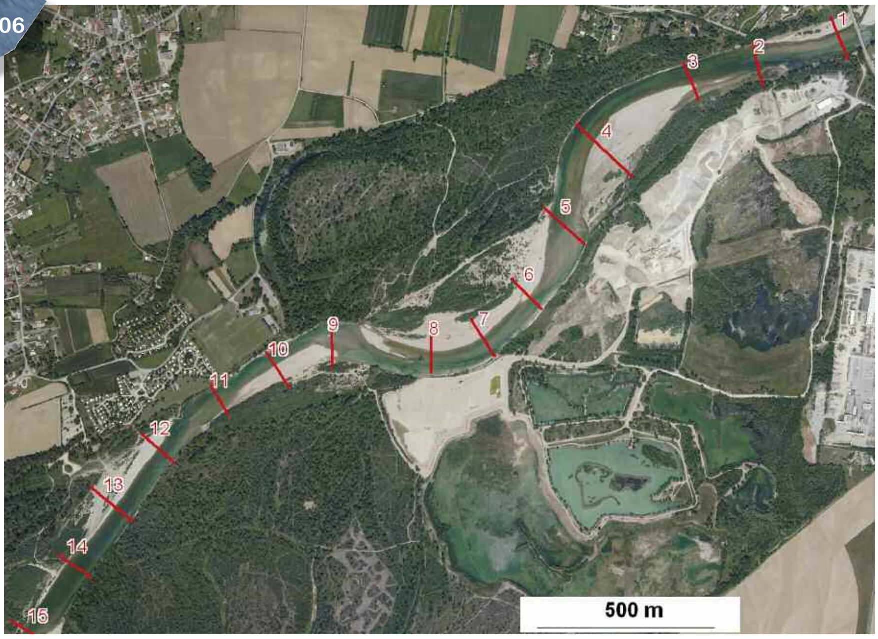
■ Lateral erosion producing sediment load

One of the major consequences of lateral erosion, which affects all types of river except those flowing over bedrock, is that each cubic metre of eroded material injects in the river sediment that immediately contributes to the processes shown in the Lane balance diagram, particularly if the sediment grain size corresponds to that of the bedload.

For example (see Figure 106), the **"fresh sediment"** (in fact, a fossil volume of alluvium accumulated during the Holocene) generated through lateral erosion by a single bend in the Ain River over one year (2004-2005) amounted to approximately **30 000 cubic metres,** corresponding to 600 m (length of the eroded zone) x 10 m (average retreat of the bank) x 5 m (height of the bank with respect to the talweg). Based on an analysis of the cross-section of the bank at the bend, we estimate that over 50% of the volume had a grain size larger than sand and thus contributed to the **bedload.**

This observation lies at the origin of the concept of **mobility space.**

Figure 106



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Lateral erosion of the bend in the Ain River between the marks 5 and 9 produced approximately 30 000 cubic metres of sediment in one year, of which over 50% was coarse sediment (Malavoi, 2008).

Braided pattern

The different types of braids

Braided rivers are characterised by **multiple channels that are highly mobile** over space and time, separated by **alluvial bars generally having little or no vegetation** because annual (or slightly lower frequency) floods regularly wash it away (generally herbaceous or shrub pioneer species).

If the channels are separated by large islands covered with highly vegetated alluvial forms that are spatially and temporally stable, the term "braided pattern" is generally not used. The preferred terms are **anastomosis** and **anabranching** (see the corresponding section below).

However, some authors are of the opinion that it is still a braided pattern if the islands are separated by highly mobile, non-meandering (P < 1.5), wide channels of shallow depth and if the mean elevation of the top part of the "islands" is lower than that of the neighbouring alluvial plain.

Figure 107

© G. O'Beirne

© W. Graf

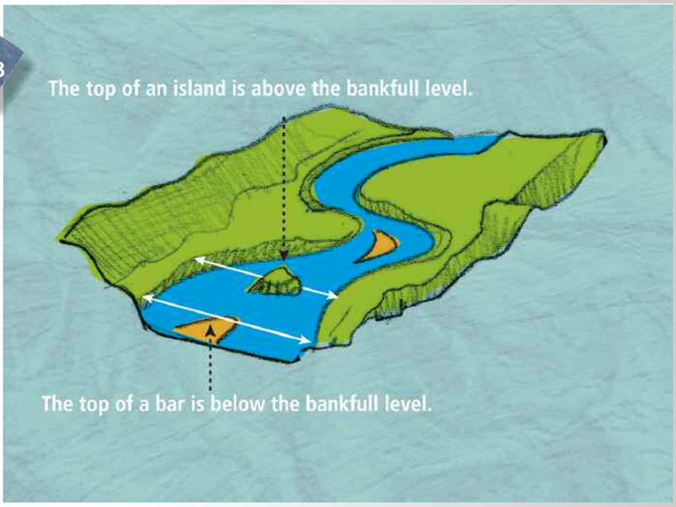
Two examples of braided rivers. (a) Bars without vegetation (New-Zealand). (b) Bars with vegetation, close to the "island" type (Platte River, U.S.).

An easy distinction between islands and bars.

A number of criteria serve to distinguish between the two types of alluvial macroforms.

- Islands are generally covered with different strata of trees whereas bars, if they are vegetated, are covered only with herbaceous or shrub pioneer species because they are frequently carried away by floods.
- Islands are generally stable spatially and temporally whereas bars are frequently entrained and move fairly rapidly downstream.
- Finally, the tops of islands are on the same level as the alluvial plain whereas bars are generally located well below the bankfull level, except in sectors characterised by major sediment accumulation within the bankfull channel.

Figure 108



A secondary, but fundamental criterion in identifying the braided pattern is **significant and observable transport of coarse bedload.**

Frequently, a river may have only one channel during the low-flow period or even no flow in the case of wadis. However, the braided pattern remains visible due to the presence of talwegs and a large quantity of transiting alluvium, whose macroforms often take on the form of long **"tongue-shaped" bars.**

.

Figure 109

Two braided rivers. (a) Low-flow period, (b) a wadi with no water.

For a number of authors, a river is considered braided if, over a certain distance, there are at least two channels separated by alluvial bars. These authors distinguish between braiding intensities using a braiding index (see below).

Figure 110

These two photos show two extreme levels of braiding intensity that depend heavily on the availability of bedload and the erodibility of the banks. (a) The Allier River in France, (b) a river on a sandur in Iceland.

Determining the limits of the old or currently active braided belt

A project to restore a formerly developed river (notably contained rivers) raises the question of the area on which the project should produce an effect. It is preferable to identify beforehand the old braided belt in order to have an idea of the zone involved, even if it is decided that the project should cover only a part of the zone.

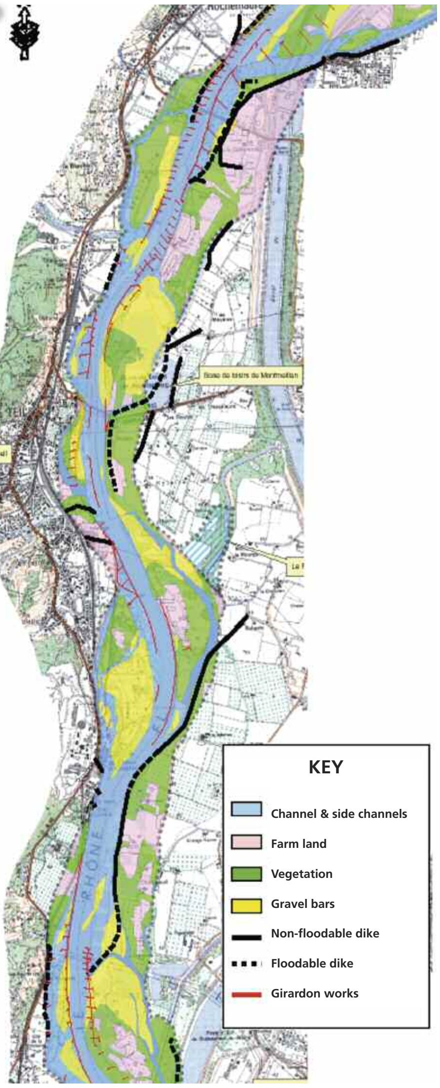
Restoration work may deal with reopening old braided channels to improve flood conveyance and increase biodiversity, and with recreating mobility spaces by removing dikes that are no longer needed. The first type of work has been carried out occasionally on the Rhône River since the 1980s and more systematically since 1997 in the framework of the Rhône ten-year hydraulic and ecological restoration plan which has now been folded into the Rhône Plan (2006). The purpose of restoring mobility spaces, called "reinvigorating the edges" or rewidening in the Rhône Plan, is to reduce flood levels by modifying the bankfull cross section and to bring new areas and pioneer species into play. The stream power during floods will drive erosion and the initial work began in April 2009 on the Old Rhône near Donzère-Mondragon.

Figure 111

© Service Navigation Lyon

The "Miribel islands" along the Rhône upstream of Lyon during the 1957 flood which revealed the complexity of the "fossilised" braided pattern behind the dikes.

Figure 112



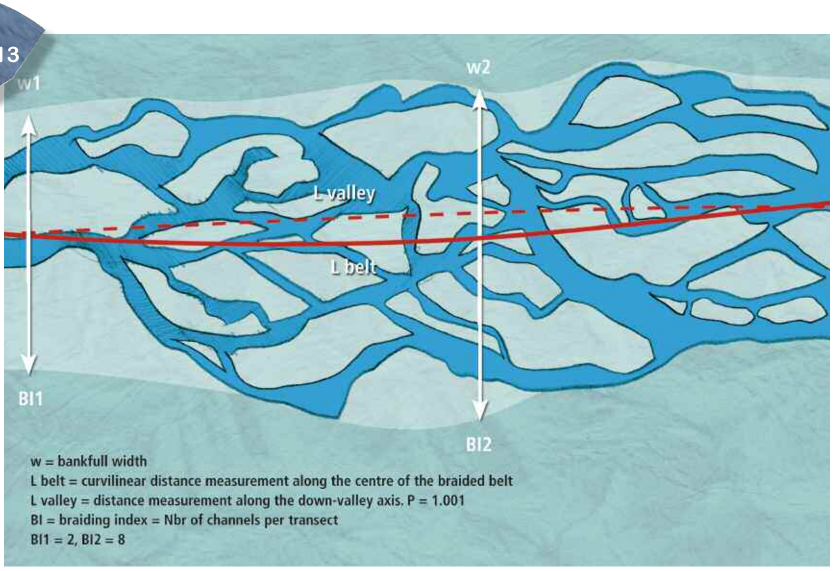
The GIS map (Figure 112) shows the limits of the "historic active tract" of the braided Rhône near Montélimar. It serves as a reference document for restoring old channels and "reinvigorating" the river edges, areas that were partially isolated by dikes since the middle of the 1800s. The map shows the full extension of the braided belt in 1860, but projected with georeferences onto a modern topographical tool. The reference data makes it easier to understand how the sector has changed over the past 150 years.

The braided belt of the Rhône near Montélimar in 1860 (CNR, Université Lyon II).

The morphometrics of braided rivers

In general, fewer morphometric parameters are used to describe braided rivers than single-channel rivers.

Figure 113



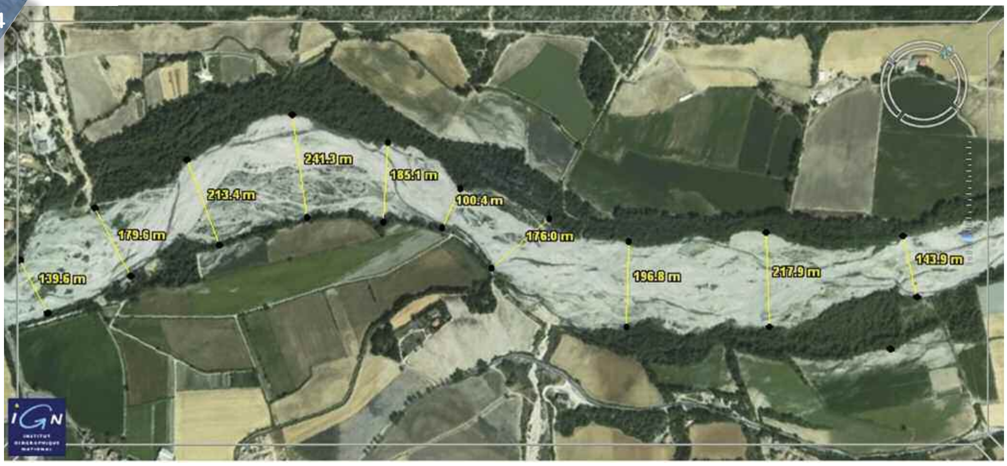
Morphometric characteristics of braided rivers.

■ Bankfull width (braided belt)

Similar to single-channel rivers, the braided belt can be determined **in the field** by measuring the channel to the point where floodwaters enter the flood plain.

However, it is much easier (and almost as precise because more measurements can be taken) to use aerial photos and to measure the braided areas with little or no vegetation. Measurements are made perpendicular to the centre line of the braided belt. Given the wide variations in the width of the braided belt, it is best to carry out a number of measurements in each uniform geomorphological reach and to calculate the average value.

Figure 114



Extrait Géoportail © IGN 2010

Measurement of the bankfull width (i.e. the width of the braided belt).

Some authors also mention, in addition to the width of the braided belt, an "active corridor" which may be the same thing or may include channels not part of the braided belt. This measurement is useful primarily for anabranching rivers that will be discussed later.

■ Sinuosity index of the braided belt

To measure the sinuosity index, it is possible to use the length ratio or the slope ratio (see the previous section) using the centre line of the braided belt.

The braided belt is almost always sub-rectilinear

Generally speaking, the **braided belt is almost always rectilinear** or sub-rectilinear (P < 1.1 or even 1.05), even if the valley slopes can occasionally impose sinuosity. This straightness of the braided belt is due to the fact that the river tends toward the maximum slope (i.e. the valley slope) to ensure optimum evacuation of the alluvial load coming from upstream.

If that is not the case, the river is not a true braided river and river patterns shift progressively to those of the least sinuous (and most active) of the meandering rivers. This transition often includes the "wandering" stage before reaching true meandering patterns.

Figure 115

The sinuosity index of the braided belt is 1.01 (New Zealand).

Sinuous unit channels

The braided belt is always very straight, but the unit channels are often sinuous or even very sinuous, but never meandering because that would correspond to the anastomosed pattern. The morphometric parameters of single-channel rivers may therefore be of use in measuring the unit channels (P, wavelength, meander-belt width, etc.).

Often a dominant channel

In most braided rivers, there is a main or dominant channel (sometimes two), which may also be very sinuous, plus a variable number of secondary channels that contain water if discharge levels are high enough.

Figure 116

During low-flow periods, there is often one or two dominant channels, plus smaller secondary channels that contain water when discharge levels rise (a) Drôme River, (b) Asse River.

It would appear that a clearly dominant and highly sinuous channel is indicative of a spatial or temporal transition to the wandering pattern, probably followed by a sinuous, single-channel pattern. This type of river metamorphosis often occurs when a reduction in transiting bedload volumes takes place (a natural reduction in sediment input or bedload retention in a reservoir).

Figure 117

Examples of the development of a clearly dominant and very sinuous braided channel in two sections of the Durance River which is probably undergoing metamorphosis due to a drastic reduction in the input of coarse sediment (upstream dam and local extraction of alluvial materials over decades).

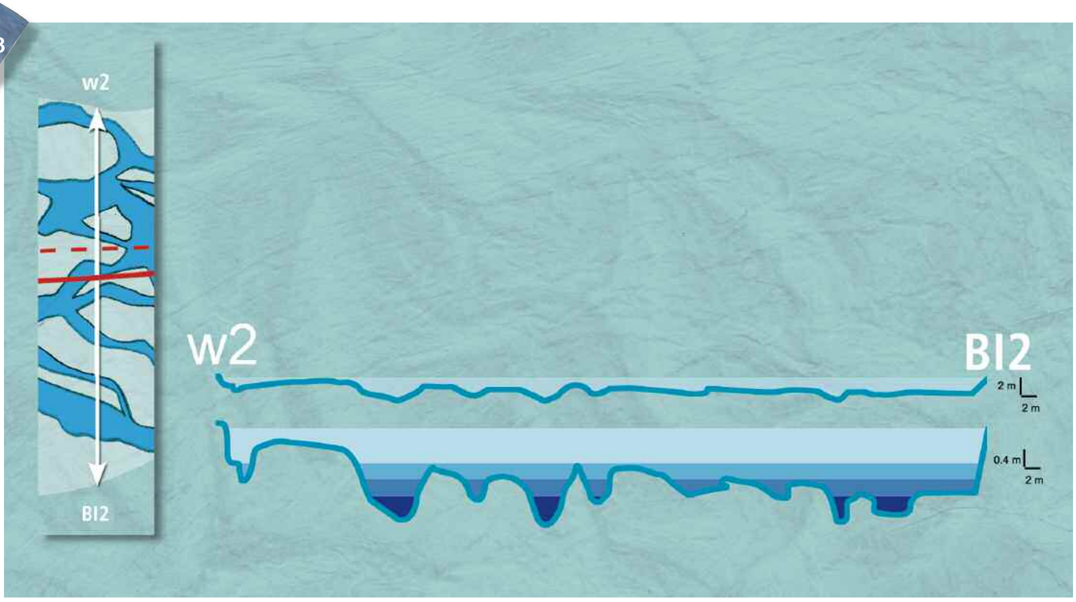
The example in the figure above shows that the river (the Durance) is probably in the process of transiting to a single-channel river with a sinuous pattern due to the currently reduced input of bedload. Note also the encroachment of the alluvial forest along the edges of the braided belt.

Typical cross profile

Recall that braided rivers are wide and shallow, which results in a width/depth ratio generally greater than 50 or even 100. That also means that for equal morphogenetic discharges (or for equivalent river-basin surface areas), braided rivers are **often 5 to 10 times wider** than sinuous, single-channel rivers. That is one of the reasons why **bridges are much less frequent on braided rivers than on single-channel rivers.**

The "typical" cross profile of a braided river presented below, between points w2 and Bl2 in Figure 113, shows that the unit channels are at different elevations and, consequently, fill with water progressively, as a function of the discharge.

Figure 118



"Typical" cross profile of a braided river. In the top profile, the horizontal and vertical axes are scaled identically, in the bottom profile, the vertical axis is magnified five times. The width/depth ratio of the braided belt (light blue section) is approximately 100. Note that the shallower channels fill with water later, depending on the discharge (see the section below on calculating the braiding index).

Braiding indices

Numerous braiding indices have been proposed over the last 40 years and most are presented below. It is advised to calculate indices over uniform reaches.

Two main techniques are possible.

- Count the number of active channels along transects perpendicular to the centre line of the braided belt. The result is the braiding index (Brice, Howard, Ashmore).
- Measure the total length of all channels and divide by the length of the braided belt. The result is the braiding length index (Hong *et al.*, Mosley, Richards).

Table 7 *The different braiding indices.*

Author	Index
Brice (1960, 1964)	2 x (sum of lengths of all bars and islands in reach) / length along centre line of braided belt
Howard *et al.*(1970)	(Average number of active channels per transect) - 1
Ashmore (1991)	Average number of active channels per transect
Hong and Davies (1979), Mosley (1981), Richards (1982)	Cumulative length of unit channels / length of braided belt

The simplest braiding index and the one we recommend is the number of channels per transect (Ashmore, 1991).

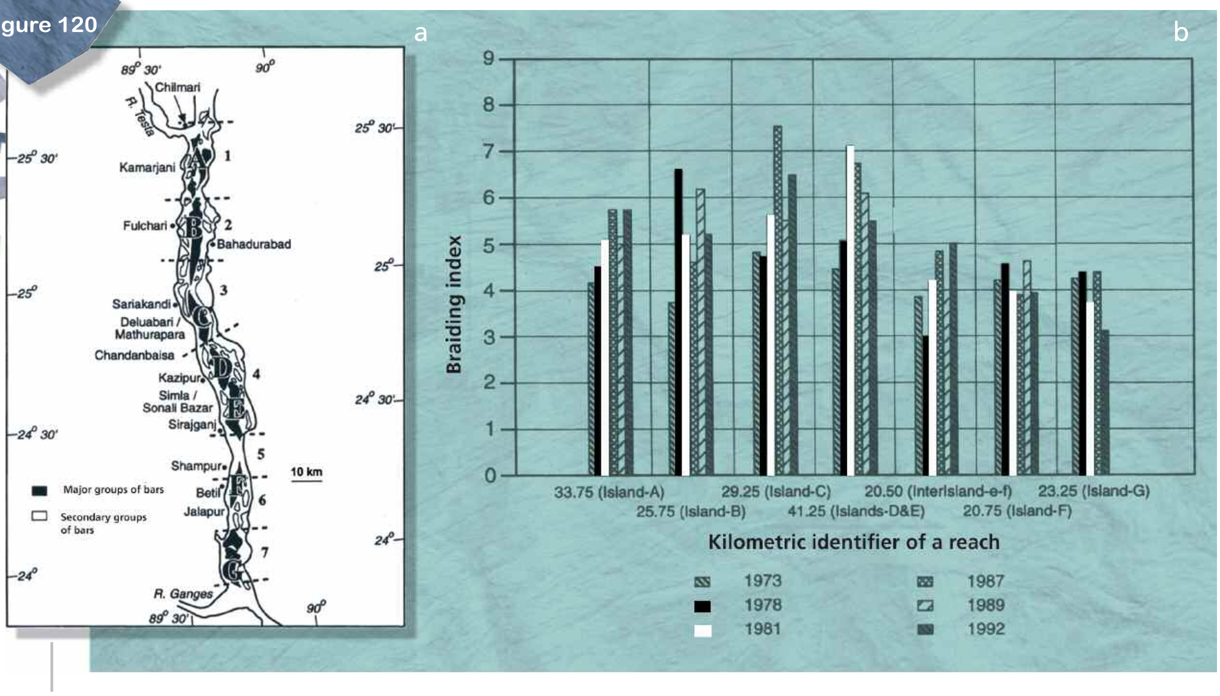
Caution. The main problem with these indices is that the results of the measurement, whether in the number of channels or their length, depend to a great extent on the discharge at the time (see Figures 118 and 119). During a severe low-flow period, there will be only one channel, two more will appear at a higher discharge, on up to the bankfull discharge when there will again be only one channel spanning the entire braided belt.

Figure 119

The image below, showing two photos of the Brahmaputra at different times, makes it very clear that the result of the braiding index will depend heavily on the time of measurement.

In the example below, the authors use the changes in the braiding indices over different reaches of the Brahmaputra to deduce an increase or decrease in sediment input. According to these authors, an increase in the index corresponds to an increase in sediment input and vice versa. The question is therefore whether the indices were measured at equivalent discharges. If not, the changes in the indices simply represent the changes in the discharge.

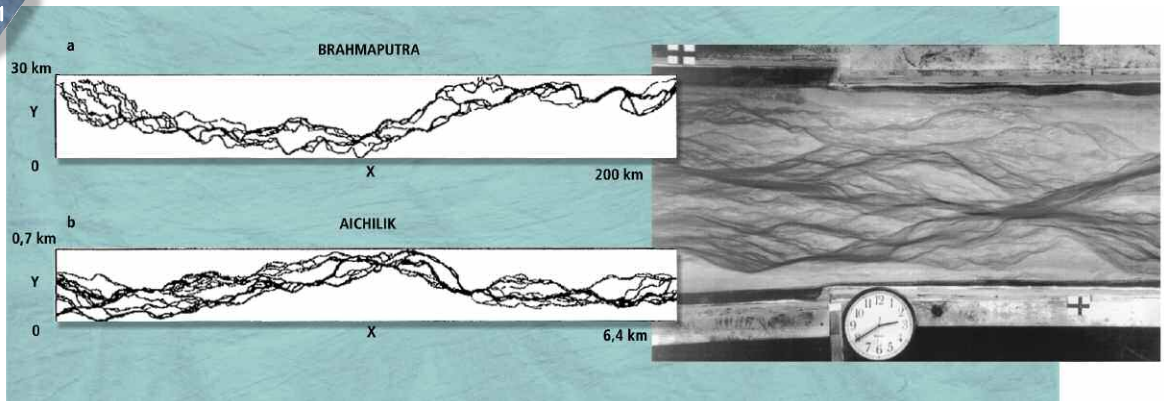
Figure 120



Changes in braiding indices on different reaches of the Brahmaputra. (a) Plan view, (b) graph of braiding indices (Thorne et al., 1993).

Note that, similar to single-channel rivers, there is a general law of proportionality between the processes involved and the patterns of braided rivers, which means that, among other aspects, it is possible to use scale models to better understand how they operate.

Figure 121



Examples of identical patterns of braided rivers (or rather anabranching rivers) having very different sizes. On the right is the result of an experiment using a scale model (Sapozhnikov and Foufoula, 1999).

The origin of braids

The conditions under which braids develop have been identified in part, but discussions continue within the scientific community.

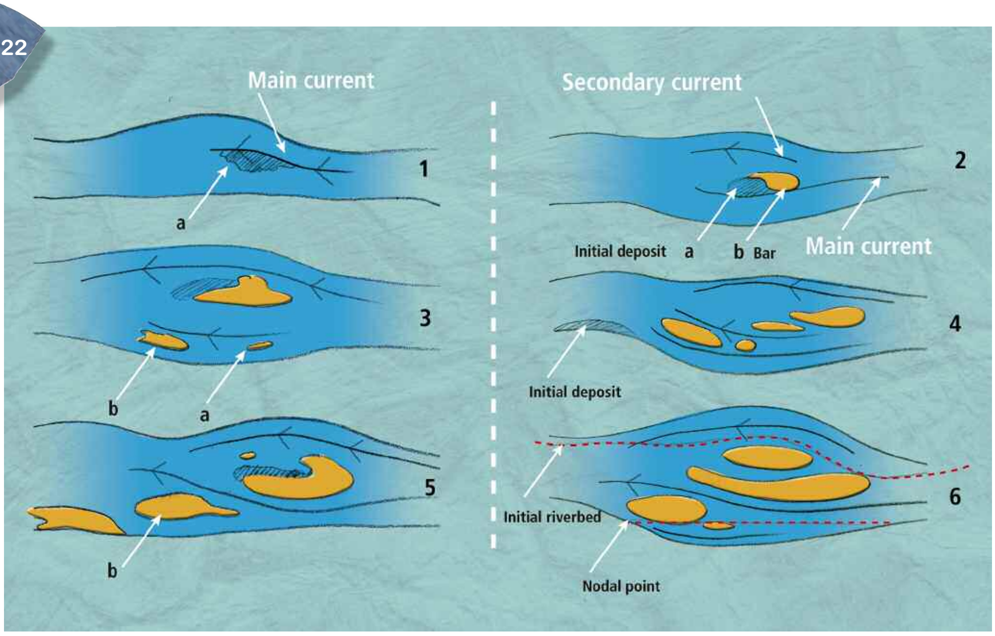
Two main conditions would seem to be unanimously accepted, but there is not complete agreement concerning the secondary conditions.

■ Two main conditions

Over-abundant bedload

Braiding is a symptom of **alluvial "overload" with respect to the mean transport capacity** resulting from the "valley slope x discharge" parameter, i.e. the maximum power of a stream during frequent flooding events (morphogenic-discharge concept). We noted earlier that braided rivers are sub-rectilinear. This is an adjustment in the river planform to generate the greatest possible power to transport the alluvial load. Maximum power is achieved if the river slope is close to that of the valley. The alluvial overload exceeding the transport capacity produces the initial deposits which in turn lead progressively to braiding. The concentration of the deposits in the form of mid-channel bars contributes to diverting the flow to the edges of the riverbed, to bank erosion and to the **progressive widening of the braided belt,** which is one of the main conditions required for braiding (see the figure below).

Figure 122



The origin of braids according to experiments on scale models run by Leopold and Wolman (1957).

If the alluvial overload is purely local, for example at a point where the valley widens suddenly or where the slope is reduced over a short distance, then the braiding phenomenon is also local. If the maximum stream power is systematically lower than that required to regularly transport the alluvial load coming from upstream, then the braiding phenomenon is general.

Conversely, if braiding is general, a sudden narrowing of the valley increases the bankfull transport capacity while depriving the river of the means to widen its bed (see the second braiding condition below). The braided pattern disappears temporarily.

Figure 123

(a) Development of local braiding where the valley widens and conversely, (b) a temporary end of braiding if the valley narrows over a certain distance. The width of the valley bottom is clearly an essential control factor in the geodynamic processes and the resulting morphologies (Eastern Andes, Bolivia).

NB It should be noted that for Leopold and Wolman (1957), braiding is not indicative of excessive alluvial load, but is due to a lack of transport capacity (sediment grain sizes exceeding the river transport capacity).

Easily erodible banks

Braiding requires banks made up of easily erodible materials because, as noted above, a wide and shallow riverbed is required for braiding to develop fully. Yalin and Da Silva (2001) showed that when the width/depth ratio rises to a high level (they did not set a precise level), bursts increase in number in the channels and do not produce alternating bars, but rather multiple bars. In addition, the probability that localised sediment-deposition zones form is higher in a wide braided belt than in a narrow one.

If the banks are highly cohesive (or artificially protected, see below), the deposits present in the form of alternating bars are rapidly carried off by small floods, thus inhibiting their growth and the deposition of additional materials. Braiding does not develop.

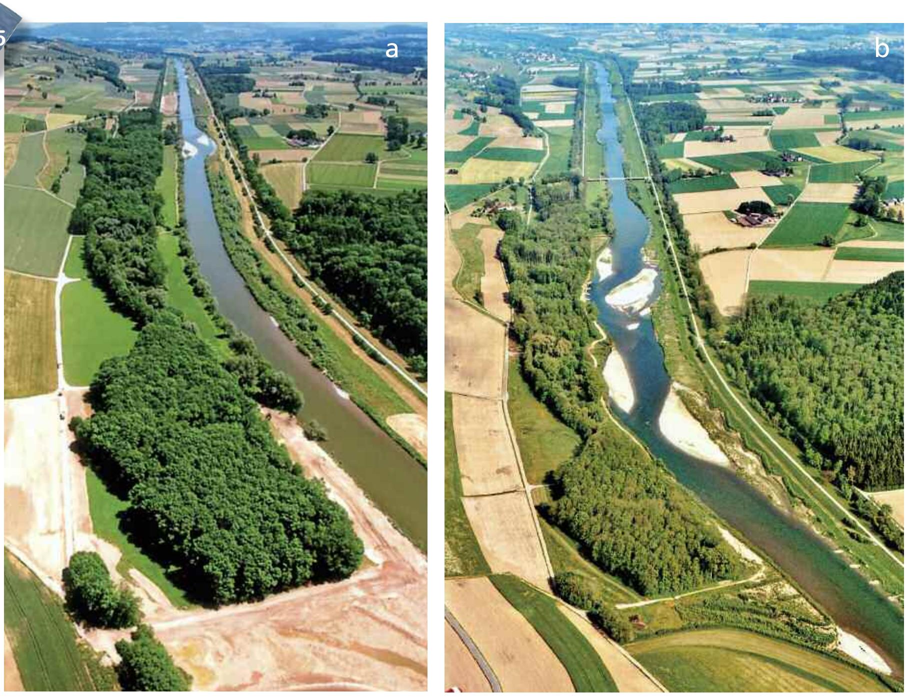
Figure 124

(a) Braiding disappears when it encounters a narrow contained section (lower Drôme River), (b) braiding suddenly starts again at the end of a channelised section (upper Rhône in Switzerland). In the two photos, river flow is from right to left.

Similarly, in the photos below, highly localised braiding starts where a restoration project on the Thur River in Switzerland eliminated the bank-protection systems.

Mackin (1956) attributes a sequence of **meander-braided-meander segments** to variations in bank stability caused by the presence of vegetation and to a **forest-grassland-forest sequence.** Another example is the Turandui River in New Zealand which shifted from a braided to a meandering pattern when willow trees were planted on the banks (Nevins, 1969).

Figure 125



a- b- © C. Hermann, Bhateam

A project to restore active braiding on a section of the Thur River in Switzerland. The sudden widening resulted in a reduction over a short distance of the transport capacity and deposition of some of the transiting bedload.

Note also that bank erosion, which is a factor in riverbed widening and consequently in the development of "optimal" braiding, continuously injects large quantities of additional sediment load into a riverbed that is already "overloaded". The result is a **positive feedback loop** that maintains or amplifies braiding.

■ Secondary conditions

Highly variable discharges

Rapid fluctuations in discharge are often linked to high levels of sediment input. They contribute to rapid bank erosion and to irregular movements (waves) of sediment load that result in the creation of bars (macroforms) that are temporary storage zones for transiting alluvial load. **Variability in discharge is, however, not an essential parameter for braiding in as much as braiding** patterns have been produced in the lab under stable discharge conditions.

Steep slopes or high stream power

A steep slope is often considered an essential parameter for braiding, however the true factor would appear to be the **stream power.** It is the alluvial load coming from upstream that generates the increase in the slope required to transport the load downstream. The slope may therefore be seen as a consequence and not as a cause of braiding.

Though it is true that a braided river must have sufficient stream power to erode its banks and achieve the high degree of bed mobility required for braiding, it is also clear that the power will be tempered by the erodibility of the banks and the grain size of the transported bedload.

Braiding dynamics

■ Lateral erosion or fossilised banks

Similar to sinuous and meandering rivers, braided rivers undergo lateral erosion of both the braided bars and the banks abutting the floodplain. As noted above, intense bank erosion is one of the main conditions required for braiding.

Erosion takes place primarily along the active channels during floods. The photos below show the large eroded curves of **scalloped banks** along channels that are not necessarily active (and may even be dry) at moderate or low-flow levels. This is one of the difficulties in predicting erosion risks along this type of river because lateral erosion can take place anywhere along the braided belt.

Figure 126

Scalloped banks created by lateral erosion along braided rivers. (a) A river in Iceland and (b) the Asse River.

■ Modifications in the bottom of the riverbed

One characteristic of braided rivers is their **thick layer of sediment along the bottom of the braided belt**, due to the abundant quantities of alluvial bedload. During floods, **significant layers of this alluvial bedload can be entrained** (e.g. over 15 metres thick in the Brahmaputra, measured using an echosounder), notably during the migration of macroforms.

When this intense vertical activity takes place along the banks, lateral erosion is worsened and protection systems are no longer effective because they find themselves perched above the active river bottom and undermined.

This empirical observation was probably made long ago by engineers in the Southern Alps where it is possible to see, along many braided rivers (e.g. the lower Var, the Esteron, the Asse), concrete dikes on which concrete parallelepipeds are installed. During floods, these plates slide down the dike as the bottom of the channel drops to protect the foot of the dikes from being undermined. As they drop down, more can simply be installed at the top. Though not particularly aesthetic, this solution would appear to be effective.

This system uses the old technique of coffers installed along braided rivers such as the Arve and the Drac. The flexibility of the wooden structures, similar to modern gabions, led to their deformation, but avoided their destruction.

Figure 127


© Onema

Example of bank protection using concrete plates that slide down to protect the foot of the dike from being undermined when the riverbed drops during floods.

■ Avulsion

Avulsion consists of a change, often sudden, in the course of a river **over a long distance**. It differs therefore from bank erosion and meander cutoff (chute and neck cutoff), which are much more local phenomena.

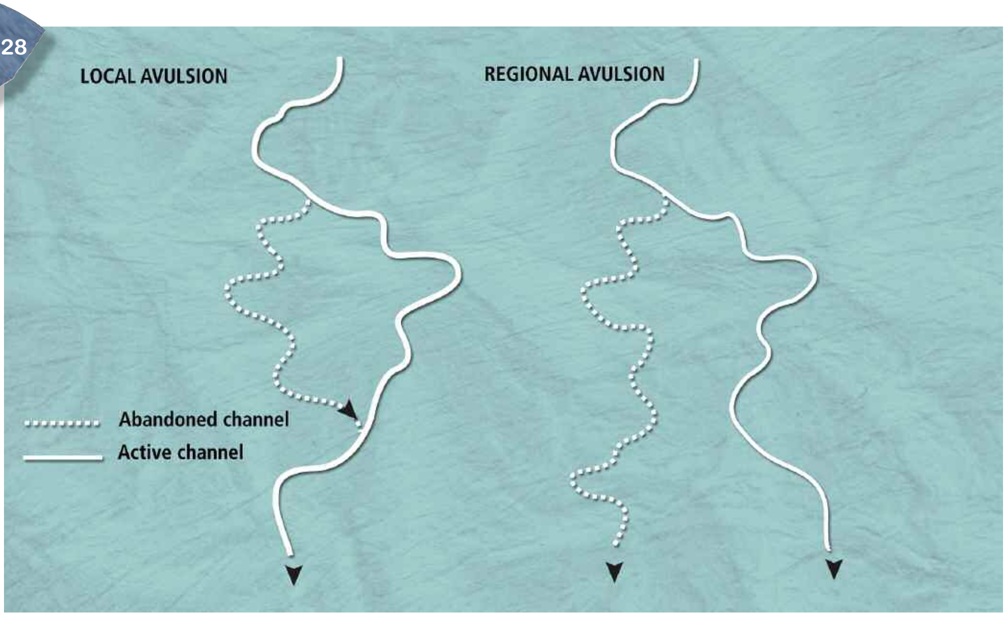
Avulsion is characteristic of braided rivers and of the alluvial fan of torrents. However, it may also occur in meandering rivers, notably at confluences and in their deltas.

Generally speaking, avulsion processes are linked to high sediment volumes that tend to produce a cross profile with the riverbed above the valley bottom or above at least a significant part of the floodplain.

During certain hydrological events involving the transport of large sediment volumes, the main channel can shift from one side of the valley to the other over considerable distances, notably if the main channel is suddenly blocked partially or totally by a large quantity of alluvium.

Avulsions may be local (a few kilometres long) or regional (up to several dozen kilometres).

Figure 128



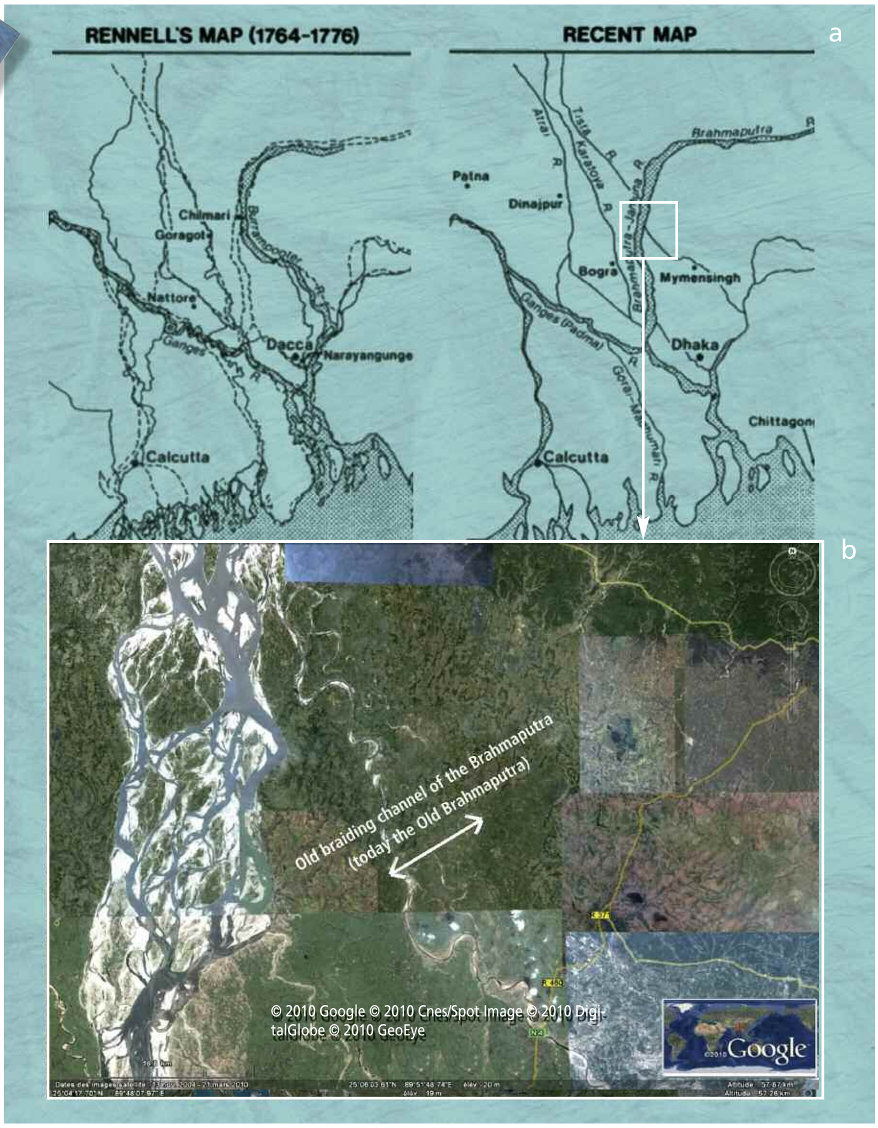
The two main types of avulsions, local and regional (according to Stouthamer, 2001).

Example of regional avulsion

The avulsion of the Brahmaputra in the 1800s is probably the best known and most spectacular example (see the figure below). This major avulsion (over 200 kilometres of abandoned channel) was caused by the massive, but progressive input of sediment and by major tectonic activity in the plain of the Ganges River.

The Old Brahmaputra, which was the main braided channel in the 1700s, is now a river with active meanders that is still supplied with water by the current Brahmaputra.

Figure 129



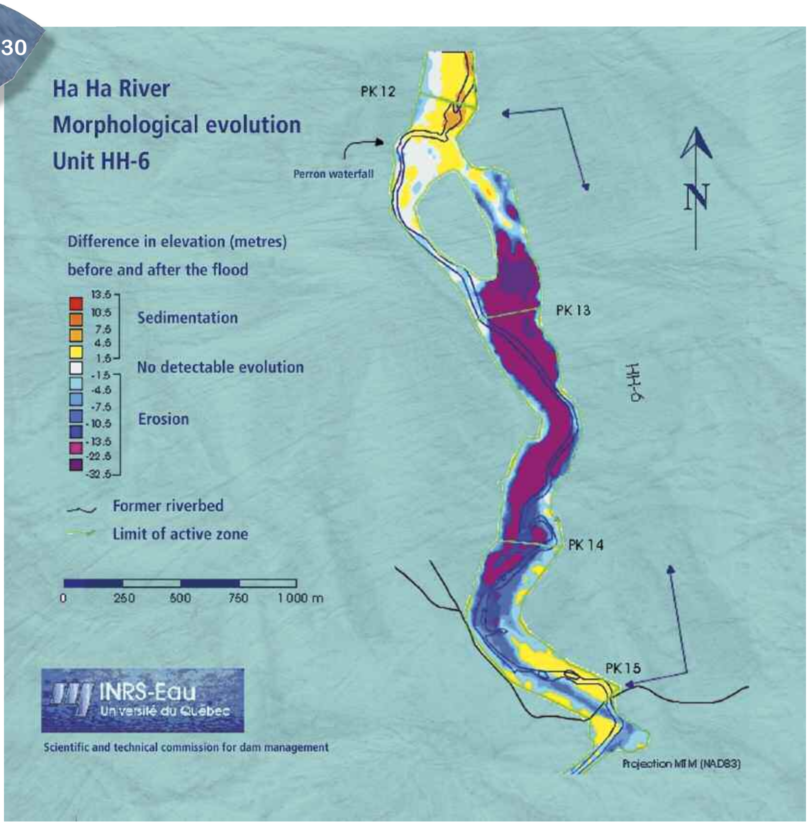
The famous Brahmaputra avulsion. (a) Bristow, 1999, (b) Google Earth. The Old Brahmaputra (the main channel in the 1700s) lies to the east in the photo.

The above example is particularly spectacular, however many local avulsions take place regularly around the world, on both large and small rivers.

Examples of local avulsions

The avulsion of the Ha Ha River (sinuous, single-channel) in Quebec (INRS, 1997) resulted in a new channel that avoided the Perron waterfall, several dozen metres high. The new channel, approximately 75 metres wide (compared to 20 for the old riverbed), struck off to the east of the waterfall before returning to the riverbed some 500 metres downstream. Regressive erosion in the new channel resulted in down-cutting of the riverbed upstream of the waterfall over a distance of approximately 2 kilometres until more resistant materials were encountered. The down-cutting exceeded depths of 30 metres in some places.

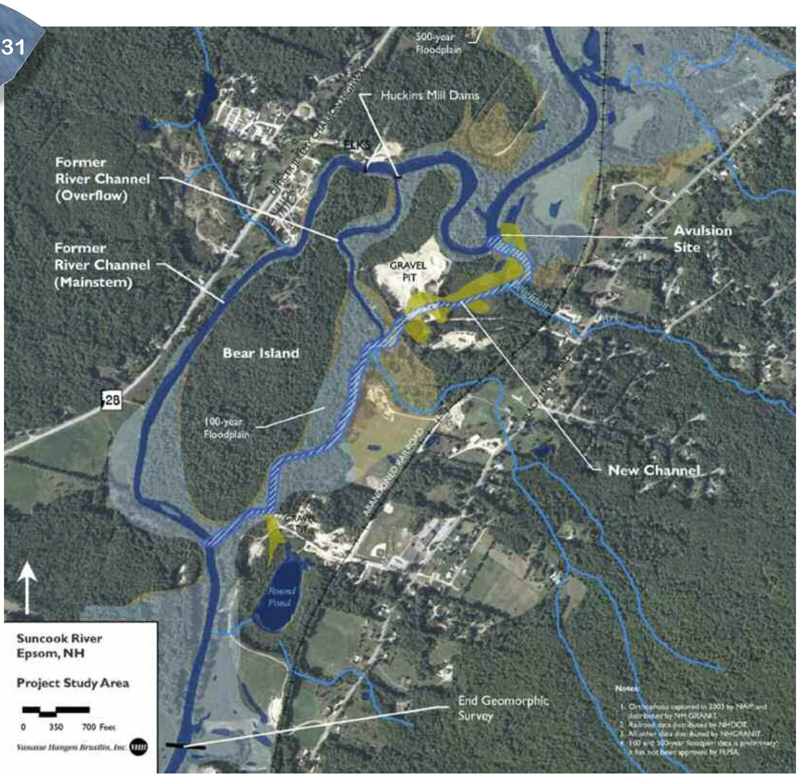
Figure 130



Example of local avulsion on the Ha Ha River in Quebec (INRS, 1997).

Perignon (2007) mentioned the negative impact of mill dams in the local avulsion of the Suncook River (New Hampshire, U.S.). The avulsion was partially enabled by the increased aggradation of alluvial deposits in the riverbed upstream of the dams which blocked the coarse bedload.

Figure 131



Local avulsion of the Suncook River (new channel shown in light blue), probably due in part to aggradation of the riverbed upstream of a mill dam (Perignon, 2007).

The figure below shows that avulsion processes can occasionally repeat. In photo (a), an avulsion has clearly taken place because the north channel has been abandoned and the new channel lies to the south. In photo (b), the main channel has returned to the north and the south channel would appear to be blocked upstream.

Figure 132

Example of repeating avulsions on an active river with major sediment transport (river pattern between braided and anabranching) (Madagascar, Tuléar region). Photo (a) is from Google Earth in 2004, photo (b) is from 2009.

Spatial and temporal evolution during the Holocene

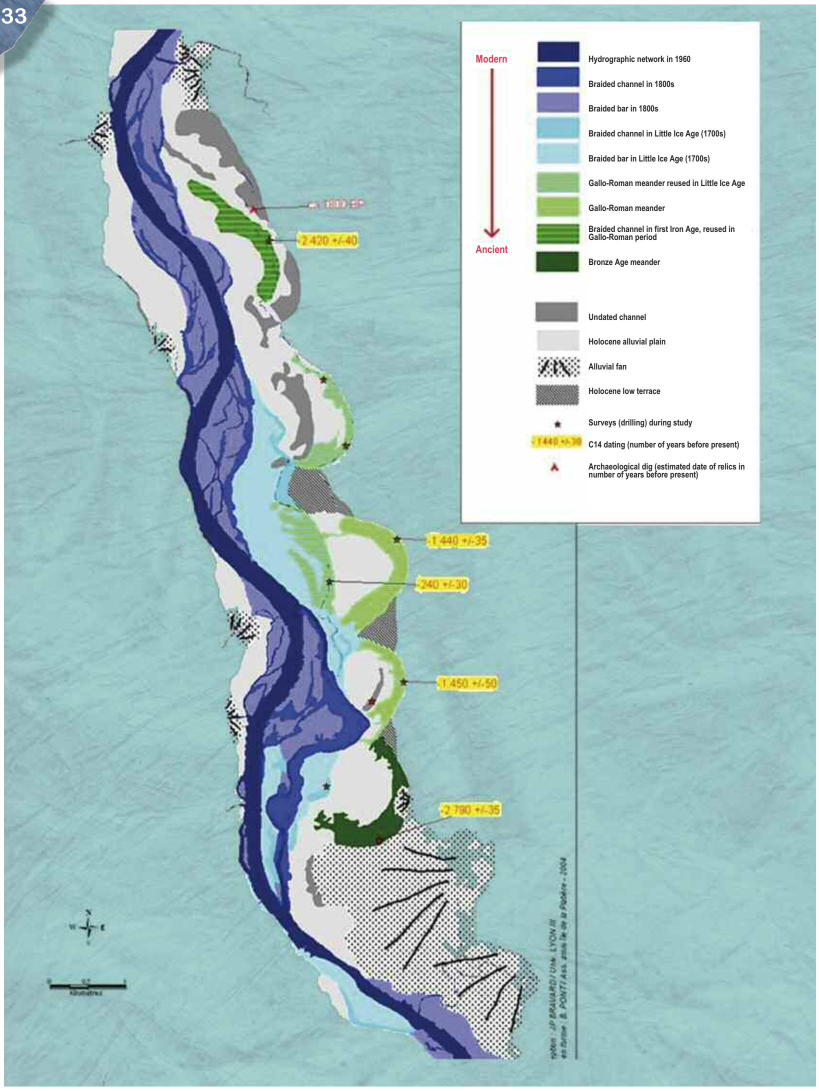
Modifications in braided patterns may be caused by variations in one or more of the control factors discussed above. **However, a modification in sediment input produces the most spectacular results.**

■ From meanders to braids

The hydroclimatic crises during the Holocene, worsened by the increased vulnerability of cleared slopes, contributed to "meanders-to-braids" metamorphoses in rivers when the increase in coarse bedload was significant and when the stream power was strong enough to provoke sediment waves.

Figure 133 (Bravard *et al.*, 2005) shows a section of the Rhône alluvial plain near Péage-de-Roussillon (40 kilometres south of Lyon). The edges of the plain bear clear "scars" of meanders and carbon dating indicates that most of the meanders were cut off during the Gallo-Roman period. Also visible (in blue) is the extension of the braided belt during the Little Ice Age, a period of high sediment transport, sediment storage and metamorphosis. In light blue is an old braided belt that was abandoned following an avulsion, an illustration of the points discussed above.

Figure 133



Collection of river patterns illustrating a metamorphosis of the Rhône during the Little Ice Age (Bravard et al.*,2005).*

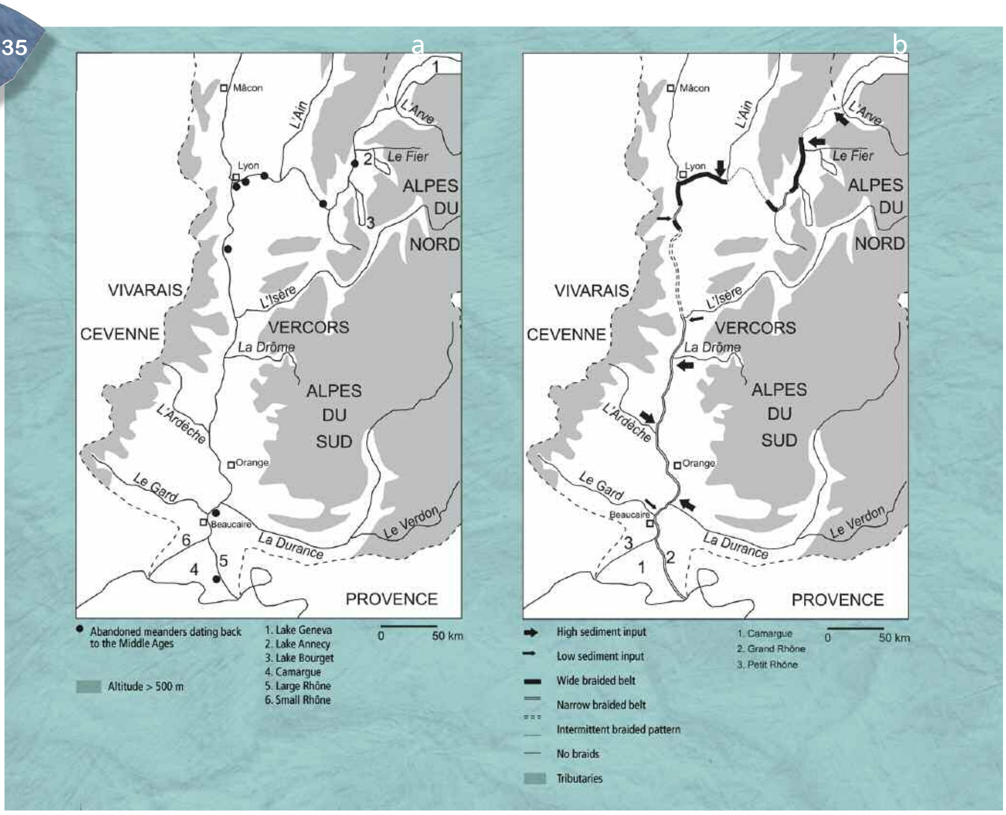
The volumes were so great in the Chautagne region that the sediment "wave" fossilised the former landscape under a layer of pebbles, including the more recent (7th century) sections of the city of Condate and even a forest from the 7th and 8th centuries in a former meander of the Rhône. The figure below shows tree trunks in the silt that filled in the former La Malourdie meander.

Figure 134

© J.P. Bravard

Tree trunks from the fossilised forest in a former meander in the Chautagne region, rising out of the layer of pebbles deposited during the Little Ice Age.

Figure 135



Patterns in the Rhône River (a) during the Middle Ages and (b) around 1860 (Bravard, 2010).

Figure 135a (Bravard, 2010) suggests that the entire French part of the Rhône adopted a meandering pattern during the Middle Ages because the meanders from that period or even earlier (Gallo-Roman) are still visible in the floodplain in the Alps (Chautagne), around Lyon and along the lower Rhône. This pattern corresponded to a long and calm hydroclimatic period (probably with low flood discharges, little erosion of slopes and consequently less coarse sediment).

Figure 135b shows the Rhône in the 1860s, prior to the major flood-control projects involving an extensive system of dikes. The largest braiding patterns were located immediately downstream of the tributaries providing the most sediment (Arve River, but the Rhône gorges did not enable braiding until Seyssel, the Fier, Guiers and Ain Rivers, the tributaries in the Drôme and Ardèche departments and the Durance River). At that time, the Rhône braided over most of its course to the delta. Small gravel was carried to the sea by the Large Rhône. Reaches without braiding or with reduced braiding corresponded to sections further downstream of the tributaries that were less affected by the incoming sediment.

■ From braids to meanders or to sinuous, single-channel riverbeds

If sediment input is reduced for any reason (human efforts to stabilise slopes, climate change, a reduction or interruption in sediment flow caused by a dam), significant changes in the morphological characteristics of the river will occur sooner or later.

An interesting debate deals with the processes that lead to a metamorphosis from a braiding to a meandering pattern.

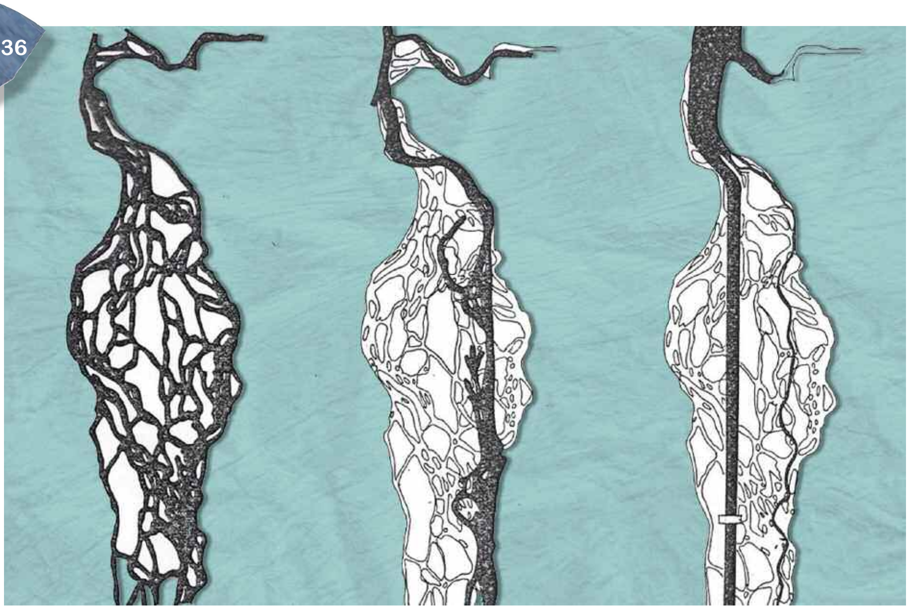
Most of the studies carried out in the Alps highlight reforestation in the mountains, notably in areas covered by RTM (Mountain restoration agency) projects and spontaneous reforestation following the agricultural abandonment of land during the rural exodus that started in the middle of the 1800s and accelerated after the First World War.

However, recent research has questioned this interpretation in that many river basins not touched by the RTM work underwent similar changes, sometimes even earlier. For example, in the eastern part of the Haut-Diois valley, Scots pines colonised the active tract of rivers as early as the 1870s, during a phase of reduced hydrological activity. It is tempting to see in this reduction in braiding in the upper valleys a process similar to that occurring in rivers during the 1800s, i.e. climatic causes would appear to dominate anthropogenic causes. In other words, reforestation policies would simply have accompanied changes that nature had already initiated. The most frequent, initial step in a metamorphosis from a braiding to a meandering pattern is without doubt the down-cutting of the bed into the formerly braided alluvial deposits. Secondary channels tend to dry up and fill with fine sediment. The bankfull channel becomes vegetated, which encourages the water to flow in a main channel. The river pattern becomes progressively sinuous in a single channel. This type of process has been studied in depth on rivers in the Southern Alps, e.g. the Drôme, Roubion and the Durance with its tributaries.

Morphological changes in braided rivers due to a natural or artificial (dams) reduction in bedload are a very common phenomenon (see Figure 10). Changes are rarely sudden. Rivers go through phases of gradual shifts to adopt a sinuous or even a meandering pattern. The wandering pattern is seen as a good indicator of metamorphosis from braiding to meandering, whether it be spatial (e.g. between the upstream and downstream sections of a river) or temporal. Generally, the main channel starts to become sinuous and increases its floodwater conveyance by down-cutting and gradual drying of the secondary channels.

The Rhône in the Chautagne region (Klingeman *et al.*, 1994) provides an instructive example of this process caused, in this case, by development work (Figure 136).

Figure 136



Metamorphosis of the Rhône in the Chautagne region (Savoie and Ain departments) caused by hydraulic civil works. The river in 1860, 1980 and 1984. The 1860 map illustrates the changes in 1980 and 1984 (Klingeman et al.*, 1994).*

In 1980, the metamorphosis to a sinuous riverbed was virtually complete and ended with the CNR bypass (Motz dam and reservoir, bypass canal with the Anglefort power station and the Old Rhône). The controlling factors were:

- the construction of dikes which constrained the active tract starting in the 1780s (not shown);
- the construction of dams with reservoirs starting in 1902 on the lower Fier and in 1925 on the upper Rhône. The Génissiat dam has totally blocked all coarse bedload since 1948;
- extraction of gravel in the riverbed from the beginning of the 1900s until the beginning of the 1980s;
- the construction of the Motz dam with its reservoir, which block downstream transit of alluvial bedload.

Thresholds between the meandering and braided patterns

For many years, geomorphologists have tried to understand why some rivers meander when others braid and, **above all, what control-factor thresholds can, if reached or exceeded, provoke a more or less lasting shift from one pattern to the other.** The preceding section made it clear that significant and lasting metamorphosis can take place, sometimes over just a few decades. This can be a problem because management techniques for braided rivers are very different than those for sinuous/meandering rivers.
For example, among rivers with equivalent morphogenetic discharges, a braided river will require a bridge at least 5 to 10 times longer than a sinuous, single-channel river (in the example below, the bridge is 15 times longer.

Figure 137

Example of the problems for bridges on braided rivers. On this river in New Zealand, starting from its entry in the eastern plain where intense braiding develops, there is only one bridge over a distance of 60 kilometres and it is 15 times longer than the last bridge upstream!

There is also the risk of avulsion in these rivers, i.e. it is necessary to significantly reinforce the abutments of bridges to make sure the river does not bypass them, which is not always possible (see the figure below).

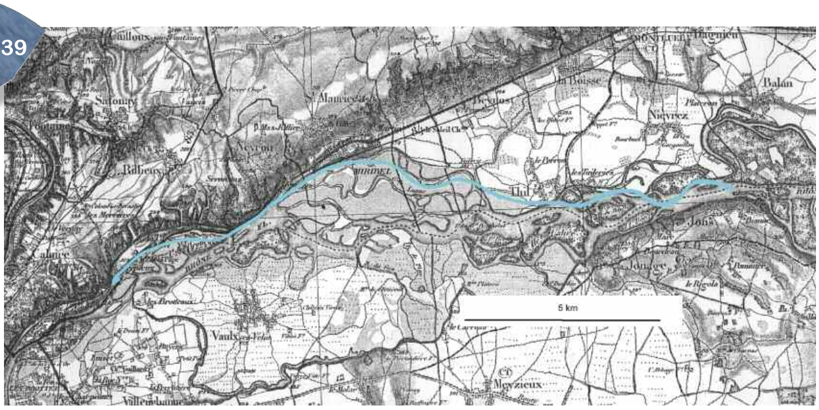
Figure 138

© V. J. Musi

Local avulsion of the Rio Choluteca (Honduras) during the storm flooding in 1998 (hurricane Mitch). The bridge had just been inaugurated.

Navigation on a braided river is more difficult than on a meandering river because of the shallow depths and frequent twists in the main channel. It is necessary to either dredge regularly a channel designated as the navigation channel, signal the best channel after each flood, create a navigable canal in parallel with the river or transform the braided channel into an embanked channel (this was the solution selected for the Rhône upstream of Lyon at the end of the 1800s to ensure navigability for commercial services, see the figure below).

Figure 139



Military map used for background.
© IGN 2010

Creation of the Miribel canal (in blue) at the end of the 1800s to ensure navigability on the braided Rhône upstream of Lyon.

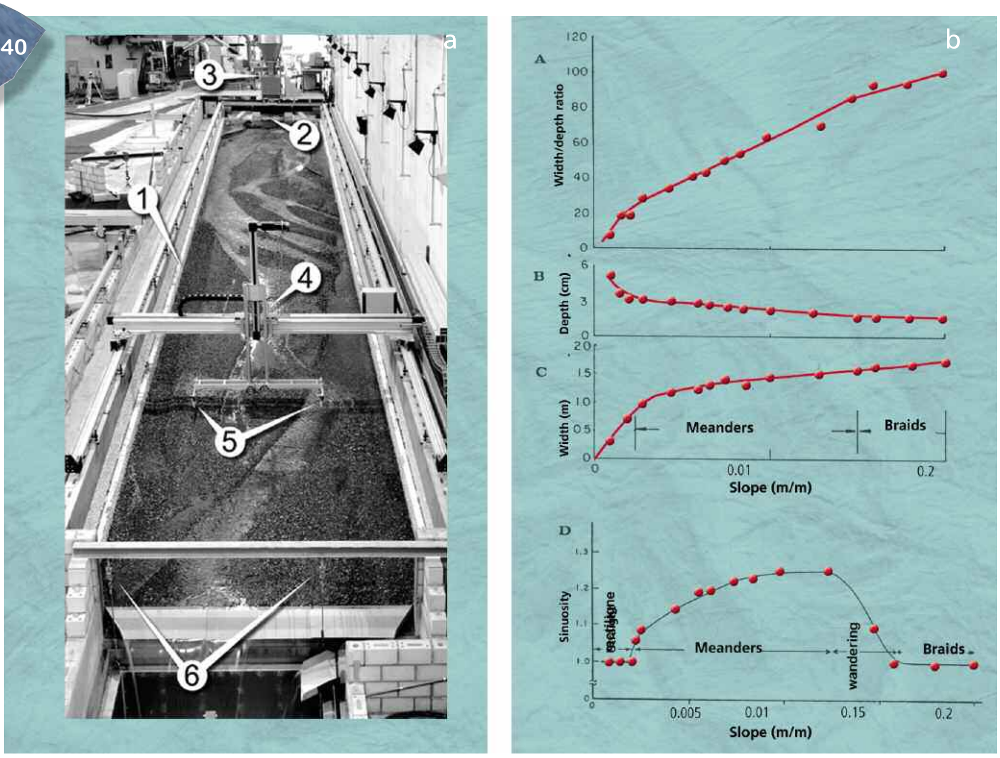
Experiments using scale models

One of the main approaches to better understanding the processes leading to meandering or braiding patterns is experiments using scale models, which avoid the uncertainties inherent in hydrology and the difficulties of carrying out measurements in the field.

Numerous studies have been carried out since the 1940s. Among the most interesting are those of Schumm and Khan (1971 and 1972).

The first series of figures (Figure 140b, A to D) shows the evolution of various cross-profile and planform parameters as a function of changes in the slope (control factor) of the experimental river. Following a clear threshold at the beginning of the experiment, when the very low slope produced a straight pattern, there were then more or less gradual changes in certain parameters, such as the width, depth and the ratio between the two. On the other hand, sinuosity increased progressively (remaining at low levels) before suddenly dropping and shifting to braiding.

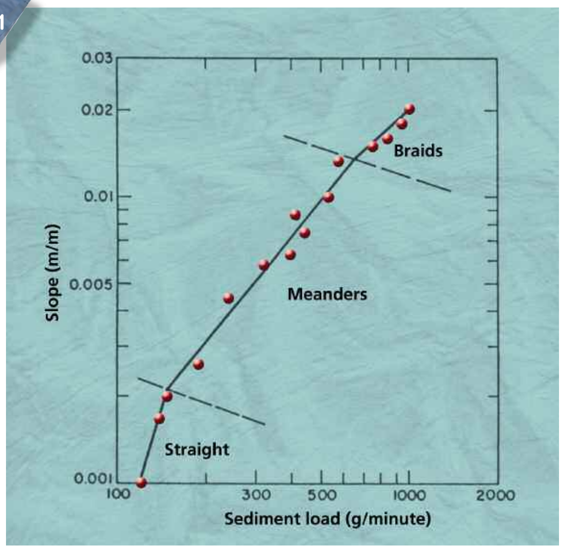
Figure 140



(a) An experimental scale model (photo by ETH Zurich) and (b) the evolution of cross-profile and planform parameters as a function of changes in the slope of the experimental channel (Schumm and Khan, 1971).

The figure below shows the inverse situation, i.e. the change in the riverbed slope and the river pattern as a function of increasing quantities of sediment being injected. The progressive shift to braiding is clear, in step with the increase in slope caused by the increase in alluvial bedload.

Figure 141



Evolution of slope and river pattern in response to an increase in the sediment load (Schumm and Khan, 1971).

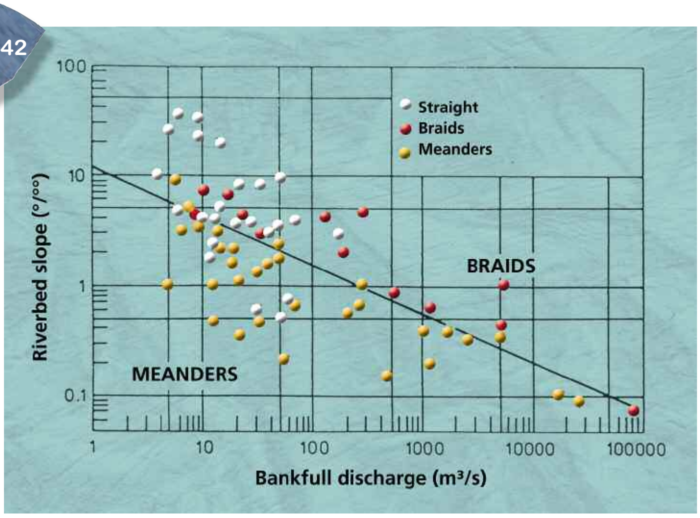
Measurements in the field

In parallel with this experimental research, a number of authors have attempted to detect discriminant thresholds between the two main patterns on the basis of measurements made in the field.

The pioneers, e.g. Lane (1957) and Leopold and Wolman (1957), worked primarily on more easily measurable parameters such as the riverbed slope and the bankfull discharge.

In the figure below, the discriminant line between braided and meandering rivers is defined by $S = 13Qbkf^{-044}$ (with S in °/°° and Qbkf in m³/s). This initial approach, though useful, is impacted by a major bias in that the parameters studied are response factors and incorporate a previous adjustment.

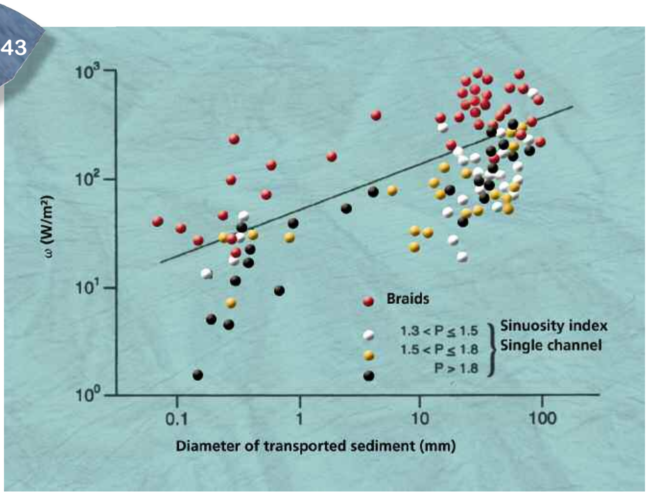
Figure 142



The discriminant line between braided and meandering rivers, based on the riverbed slope to bankfull discharge ratio (Leopold and Wolman, 1957).

More recent studies have attempted to improve the analysis by adding an important parameter, i.e. the type of alluvium transported. The slope and discharge are combined to form the unit stream power (ω) and the median diameter of the sediment is added. The discriminant line is defined by $\omega = 900 D50^{0.42}$ (Van den Berg, 1995).

Figure 143



An example of a braiding/meandering "threshold" (Van den Berg, 1995. P is the sinuosity index).

Figure 143 clearly shows that braided rivers may exist in configurations ranging from low power levels (and small grain sizes) to high power levels (over 100 W/m²) with coarser bedload.

These various approaches, still undergoing scientific development, are particularly useful in identifying "borderline" rivers. In such rivers, the slightest change in power, grain size or any other important control factor can provoke, sometimes suddenly, a shift in the river pattern, with major consequences in terms of river management.

Wandering, anastomosed and anabranching, the secondary patterns in rivers with adjustable morphologies

The river patterns presented in this section are said to be secondary because they represent far fewer kilometres of river than braiding and meandering, the two major, stable patterns. These secondary patterns are characterised by multiple channels.
The first, the wandering pattern, is a transient form, spatially and temporally, between braiding and meandering. The two others, anastomosed and anabranching, are often seen as two sub-types of a large "multiple-channel river" category.

The wandering pattern

The term "wandering" poetically describes a river that hesitates between a number of itineraries. Most authors now see this pattern as a good indicator of a geomorphological transition from a braided pattern to a single-channel pattern (sinuous or meandering) or in the reverse direction.

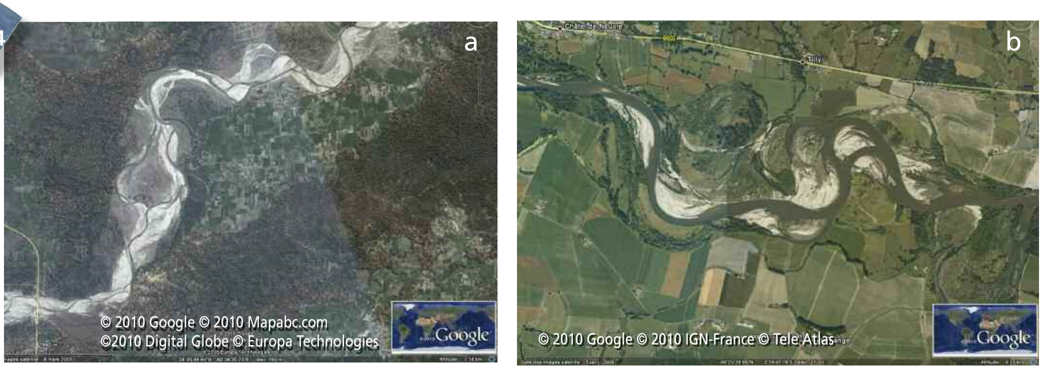
The term **transient pattern** is often used, but this transition may last and signal a form of stability.

The transition may be **spatial,** e.g. when the control factors change over a few kilometres (notably the valley slope), braiding may fade and be replaced by a single channel.

The transition may be **temporal,** e.g. following changes in the control factors (notably the sediment load), the river may initiate metamorphosis and hesitate for a while between braiding and meandering.

In both cases, wandering rivers or river reaches are very close to the threshold between braiding and meandering discussed above. The pattern is characteristic of dynamic rivers with very large bankfull channels (indicative of high sediment transport), alternating sinuous, single-channel sections with braided sections.

Figure 144



(a) A wandering pattern signalling a spatial transition. The braided section descending from the Himalaya is gradually transformed by the reduction in the valley slope and in transported sediment, most of which is stored upstream. (b) A temporal transition. The Allier River has shifted gradually from a braided to a meandering pattern due to the decrease in sediment inputs since the end of the 1800s..

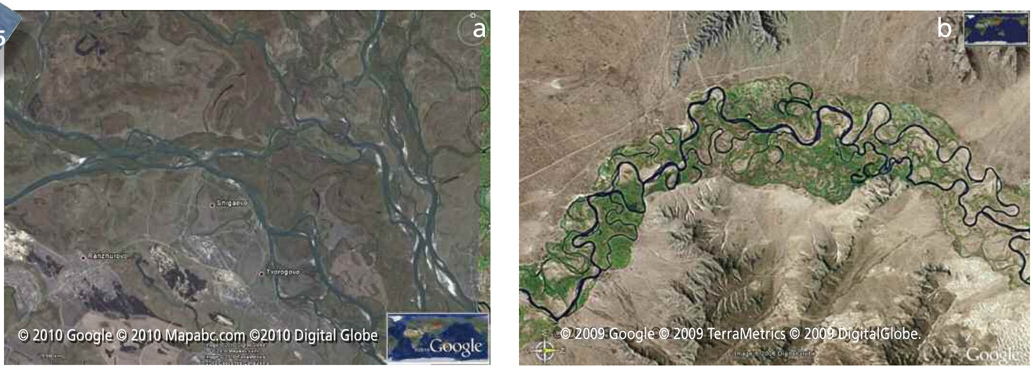
The anastomosed pattern

The term "anastomosed" was created (Schumm, 1968) to describe a set of landforms and processes that differed from braiding. The pattern has multiple channels, but they are stable, sinuous, narrow and deep (low width/depth ratio) and the slope is relatively flat. The current isolates islands that are large in size compared to the channels. The islands are generally cut out of a homogeneous alluvial plain. The total river load is low in volume and in size (reduced bedload), i.e. deposits and the banks are cohesive and stable. Under natural conditions, the riparian vegetation is generally dense.

The channels are often bordered by natural levees. Floodwaters flowing through breaks in the levees create wetlands in the areas beyond. The waters release their suspended load and any low points become lakes. Anastomosed plains are therefore in the process of slowly aggrading. They constitute one type of alluvial plain in the genetic classification by Nanson and Crocke (1992).

NB Anastomosis is a frequent pattern in marine and lake deltas.

Figure 145



Examples of anastomosed rivers. (a) Delta of the Selenga River in Lake Baikal (Russia), (b) the Tuul River in Mongolia.

The conditions conducive to the anastomosed pattern are still not well understood. According to Knighton and Nanson (1993), the existence of the pattern in different types of climate (humid temperate, humid tropical, desert, etc.) would indicate that climate is not the main factor. Below are a few factors providing some information on the conditions.

- The slope and unit stream power are low because the anastomosed reaches are located downstream of the river continuum and as a result, the transport and erosion capacity are limited.
- But the processes involved in creating this river pattern require periods of flow that are sufficiently "aggressive" to carve out new channels in the alluvial plain. These flows are thought to take place during exceptional events, flooding extensive sections of the alluvial plain for long periods. Because the floodwaters cannot erode the banks of the main channel, they create new channels in the plain. The bankfull discharge would thus have no real morphological effect and would serve simply to flood the channels of the pattern.
- The suspended load (the majority) is abundant. It tends to accumulate in the existing channels with stable banks and to block them, thus provoking lateral overflows (avulsions) and the creation of new channels.
- Tectonic subsidence (a slow sinking of the Earth's crust which provokes aggradation of sediment to compensate) is thought to be a local condition, similar to a rise in the base level (an eustatic rise in the sea level which affects the river locally, alluvial fans acting as downstream control factors, etc.).
- One aspect of the hydrological regime (a ratio between exceptional discharges and Q2 discharges of 20 to 40) is, however, thought to be a universal condition. It is possible that this ratio is not indicative of a particular mode of operation, but of a succession of contrasting climate-hydrological phases.

Anastomosed patterns may last a long time, several thousands of years (the Magdalena River in Colombia) or even tens of thousands of years (Cooper Creek in Australia). Generally speaking, they are a planform pattern that is part of a sediment system that is aggrading more or less rapidly (in the vertical dimension) and can thus be considered a **stable pattern.**

Smith *et al.* (1989) proposed a non-temporal dynamic model broken down into five steps:

- the avulsion stage with the creation of new channels in one part of the alluvial plain (an active phase with strong floods);
- the anastomosed stage with slow aggradation, a virtually stable stage;
- the "reversion" stage in which new channels are not created and the water concentrates in a limited number of increasingly large channels (the start of a low-activity stage);
- the end of anastomosis and a shift to a meandering pattern (a low-activity stage of variable length);
- clogging of the channel by silt bars followed by strong floods that restart the cycle again with avulsion and anastomosis.

The anabranching pattern

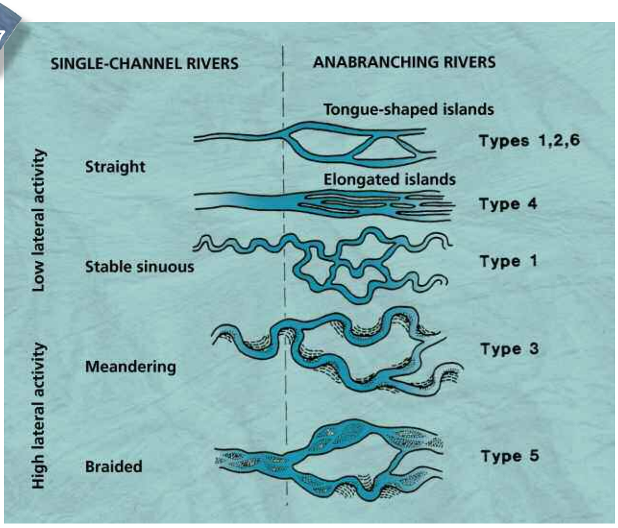
The term anabranching is reserved for river channels that diverge from the main channel and then fold back in downstream, sometimes after several kilometres of separation. The distinction is not always clear between anabranching and anastomosed rivers, and in some cases even braided rivers.

Figure 146

Examples of anabranching patterns. (a) Type 3 anabranching according to Nanson and Knighton. (b) Type 5 anabranching.

Nanson and Knighton (1996) made a proposal to establish anabranching as a vast generic category including the anastomosed pattern and other similar river patterns.

Figure 147



Anabranching river patterns (Nanson et Knighton, 1996).

Influenced by the many and varied examples from Australia, they recycled older definitions, stipulating that anabranching rivers form "systems of multiple channels characterised by vegetated or otherwise stable alluvial islands that divide flows at discharges up to nearly bankfull". The islands are stable over a time scale of several decades or centuries.

An explicit assumption in the typology proposed by these authors (Figure 147) is that the landforms are in equilibrium with the current climatic conditions. They also exclude anastomosed rivers that have cut, totally or partially, into bedrock.

The selected types are based on an increasing energy and grain-size gradient, as well as on a number of morphological characteristics presented below.

- Type 1. These rivers represent the classic anastomosed pattern (or anabranching cohesive-sediment river). They have a very low unit stream power (< 8 - 10 W/m^2) and sinuous, narrow and deep channels. Sub-types represent situations where deposits are more or less clastic or organic.
- Type 2. These rivers transport primarily sand and have a low unit stream power (< 10 - 15 W/m^2), but high lateral channel mobility due to the lack of cohesiveness of the banks.
- Type 3. These rivers transport a mixed load (sand or gravel bedload and silt suspended load) and have sinuous channels with fairly high lateral mobility due to the unit stream power that can reach 50 W/m^2 in the main channels.
- Type 4. These rivers have straight channels and form elongated sand islands. They may be found in the arid regions of central Australia. The unit stream power is generally between 15 and 35 W/m^2.
- Type 5. These rivers transport primarily gravel and pebbles, and have high lateral mobility due to a unit stream power of 30 to 100 W/m^2 (they are known as wandering gravel-bed rivers).
- Type 6. These rivers, located in mountain regions, have a bed composed of pebbles and boulders. The coarse nature of the substratum means that the megaforms are stable.

Figure 148

Extreme case of type 1 anabranching in the upper Amazonian basin. The two divergent channels join again 125 kilometres downstream.

In short, the anabranching pattern, relatively rare, requires a number of special conditions in terms of the discharge and slope (i.e. energy), the flow regime (major differences between the mean and exceptional discharges), transiting sediment (generally fine and cohesive) and vegetation (which stabilises the islands created).

Two types of mechanism lie at the origin of the multiple channels and islands (Nanson and Knighton, 1996):

- avulsion, which creates breaks in the levees, carves out new channels in the alluvial plain or occupies previously abandoned channels. Current research would seem to indicate that avulsion processes, independently of the other control factors, are the main cause leading to the development of the anabranching pattern (Jerolmack and Mohrig, 2007);
- accretion, whether in the form of a river basin filling (prograding delta, estuary, subsiding interior basin) or aggradation of channel bars leading to the formation of islands and ridges separating the channels.

Figure 149

Type 5 anabranching in the Brahmaputra (Bangladesh). Note the secondary channels, occasionally hundreds of metres wide, that operate in an autonomous manner, similar to meandering rivers.