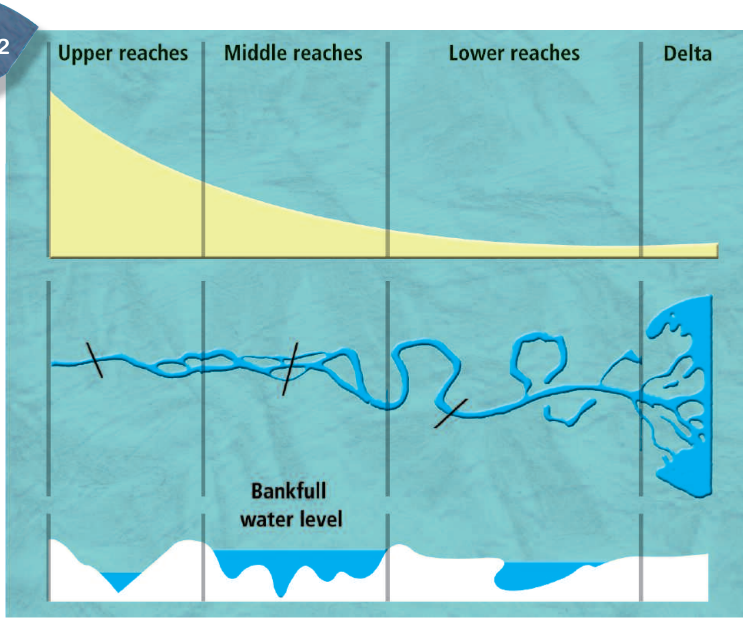
Response /adjustment factors

We saw in the preceding chapters that the characteristics and fluctuations of certain control factors determine river geodynamic processes and the resulting landforms. Rivers adjust to these factors through a certain number of response (or adjustment) factors, notably:

- their slope (long profile);
- bankfull width and depth (cross profile);
- their pattern (meanders, braids, anastomoses, etc.), an aspect to which an entire chapter will be devoted.

Figure 42



Theoretical diagram of changes in rivers from upstream to downstream and in the characteristics of the three main response factors (slope, pattern, cross profile).

The order in which these factors respond (and their relative importance) has not been clearly determined to date. Does the long profile adjust first, followed by the cross profile and then the river pattern? Do all these factors respond simultaneously? Do other factors play a role as well? Etc. More than anything else, studies on physical models reveal the high degree of variability in Nature and in the intensity of adjustments.

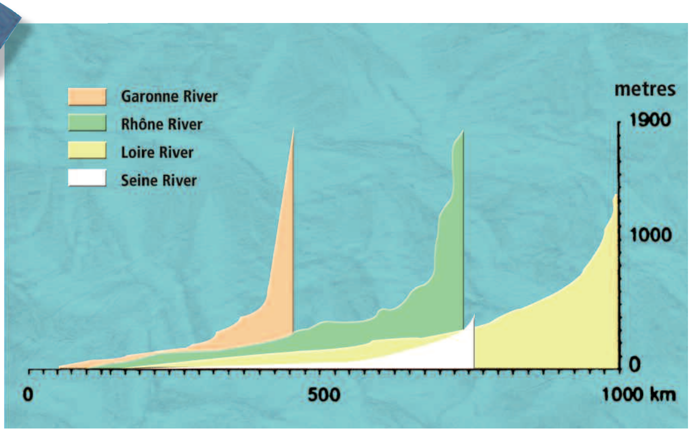
Long profile

Only a very general analysis of the long profile is presented here. More detailed analysis is available in the chapter on river patterns.

Concept of a steady gradient

Over thousands, even millions of years, adjustments in the long profile of a river result in a characteristic concave curve, often called the steady gradient. It is the product of the **dynamic equilibrium between erosion and deposition processes** oscillating around the average values of the control factors impacting the river to date. It should be noted that tectonic activity, among other factors, can significantly disrupt this concept.

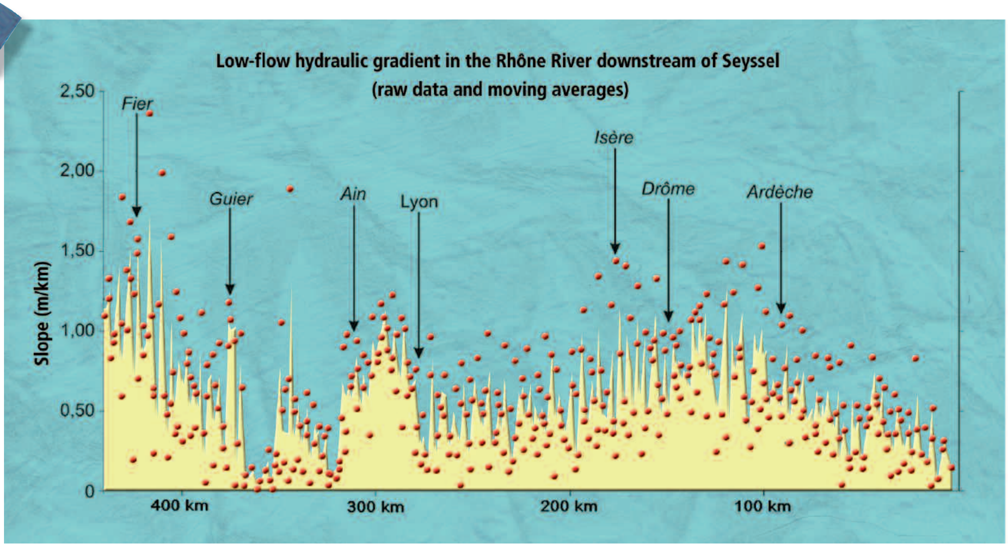
Figure 43



Examples of long profiles for several major rivers in France.

It may often be observed that long profiles, even when "steady", are not totally "smooth" (like the Loire and Seine Rivers), but include occasionally sudden shifts that may be due to geological or physiographical changes, for example.

Figure 44



Variation in the mean slope per kilometre of the Rhône River between Seyssel and the Mediterranean. Kilometre 0 on the right is at the mouth of the Rhône. Data from 1860, prior to the major development work (Bravard, 2010).

Figure 44 (Bravard, 2010) shows a long profile of the Rhône River that is quite different than the theoretical smooth profile (the figure shows the last 400 km of the Rhône before the Mediterranean, whereas Figure 43 shows the entire profile). The high slope-per-kilometre values at kilometres 280 to 300 and 370 to 420 are the direct result of bedload input from mountain tributaries (Arve, Fier, Guiers and Ain Rivers). These are therefore purely transient slopes. The high value at kilometre 340 is due to old inputs of coarse sediment (alluvial fans of torrential tributaries) that the Rhône cannot clear out with current discharge levels and to exposed bedrock. The high values from the Isère River to the confluence of the Ardèche River are due to major sediment inputs, but also to tectonic influences that raised the middle section of the Rhône valley over the Quaternary period, revealing limestone slabs (highly prevalent in the Donzère-Mondragon area).

Concept of the "base level" or the "downstream control level"

The **overall adjustment** of the long profile of a river occurs with respect to a "base level" or "downstream control level" that is the sea level for rivers flowing to the sea and the altitude of the confluence for tributaries (see Figures 45a and 45b).

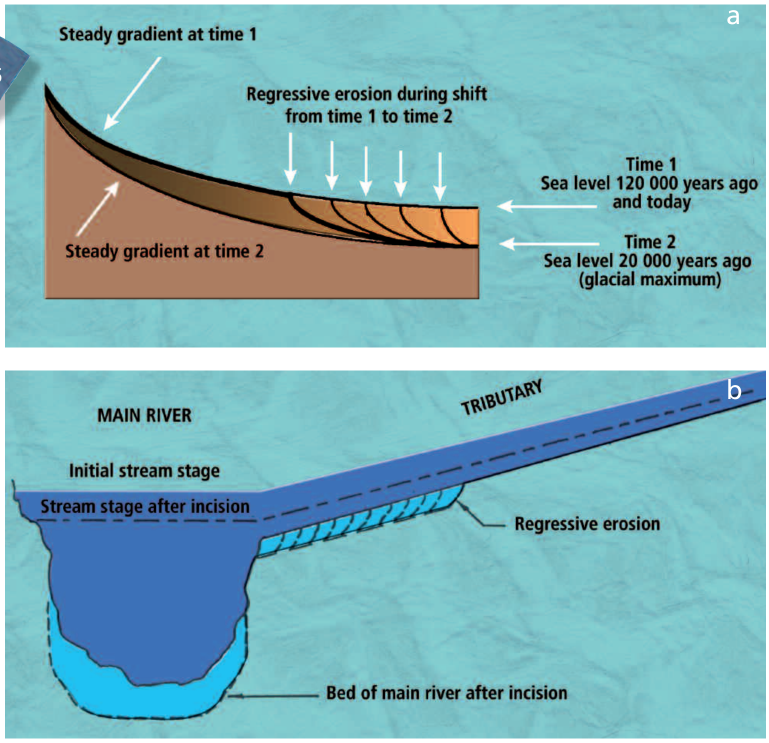
Local adjustments, for example on the scale of geomorphological reaches, may depend on more local control factors, e.g. natural or artificial weirs, sudden narrowing or widening of the valley, etc.

If the base level drops for any reason, natural or anthropogenic, the long profile adjusts more or less rapidly through **bed incision** (**regressive erosion**). A new, lower long profile develops, imposed by the lower base level, and connects to the former profile at a knickpoint that retreats upstream. If the base level rises, the long profile adjusts through **aggradation,** i.e. the river fills in its channel until it compensates for the new base, thus acquiring a lower slope, at least in its lower reaches.

■ Examples of overall adjustments to the profile

In the example below, regressive erosion takes place over millennia (120 000 to 20 000 years ago) following a drop in the sea level, then aggradation occurs (20 000 to 6 000 years ago) following a rise in the sea level.

Figure 45



a) Example of a theoretical adjustment in the long profile of a river in response to variations in the sea level (eustatic variations) caused by glaciations. Erosion is regressive during the period from 120 000 to 20 000 years ago, then the deposition process (filling in) is progressive over the period from 20 000 years ago to the Holocene (current) period.
(b) Adjustment through regressive erosion of the entire hydrographic network in response to changes in the base level (due here to incision of the bed of the main river).

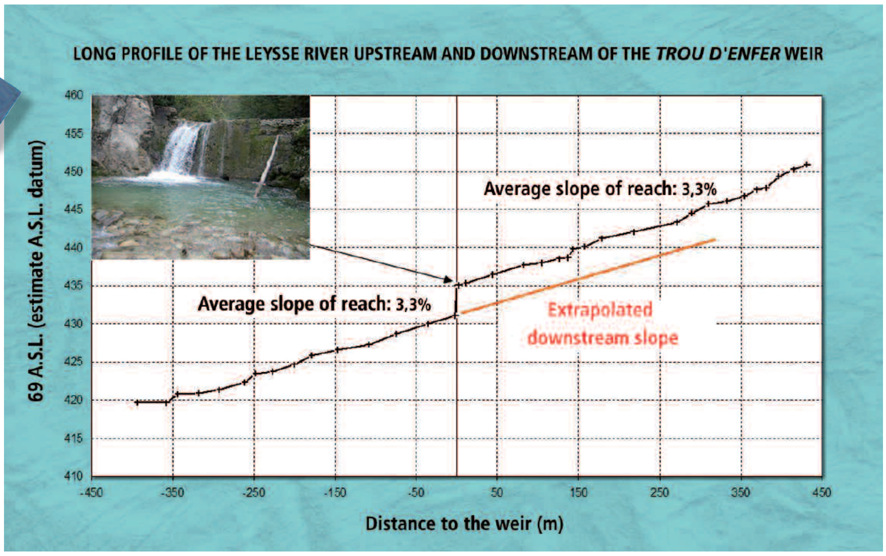
■ Examples of local adjustments to the profile

Installations in rivers may cause local adjustments to long profiles.

Regressive aggradation upstream of a weir

Construction of a weir on a river receiving high volumes of bedload results in two adjusted reaches with identical slopes one century later (the Leysse River in Savoy, France, in the example below).

Figure 46



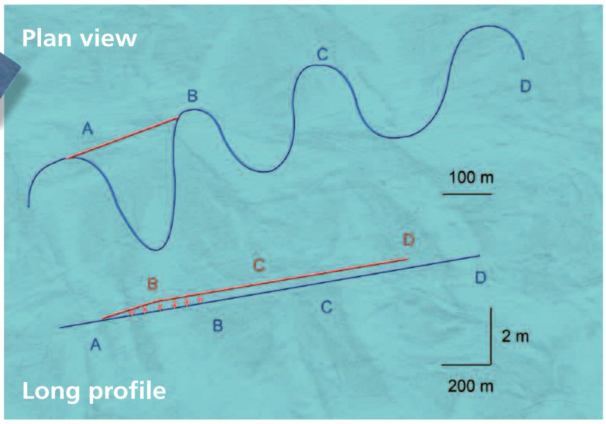
Local adjustment of the long profile to an artificial downstream control factor (weir). The resulting steady slope is identical both upstream and downstream, but with a 4-metre shift at the weir (Malavoi, 2007).

Regressive erosion following artificial meander cutoff

The theoretical example below presents a "classic" case of river engineering. Following an artificial meander cutoff (A-B), the local slope is multiplied by the sinuosity coefficient (2.5 in this case). Points B, C and D are now "closer" to point A (the reduction in distance is equal to the difference between the distance between A and B before and after the cutoff). The river will reduce the slope by down-cutting and attempting to create a new meander, until it recovers its steady slope.

If planform adjustment is possible (no protection of the banks following the artificial cutoff), regressive erosion will be limited both spatially and temporally. If the new bed is protected against lateral erosion, regressive erosion may continue far upstream. To avoid this problem, engineers often install a bed stabilisation weir at point B.

Figure 47



Theoretical example of an artificial meander cutoff that may lead to regressive erosion (the blue line is the riverbed before the cutoff, the red line after). Note that the scale of the long profile is not the same as that of the plan view because the total distance was reduced by approximately 15%. The slope is 0.001.

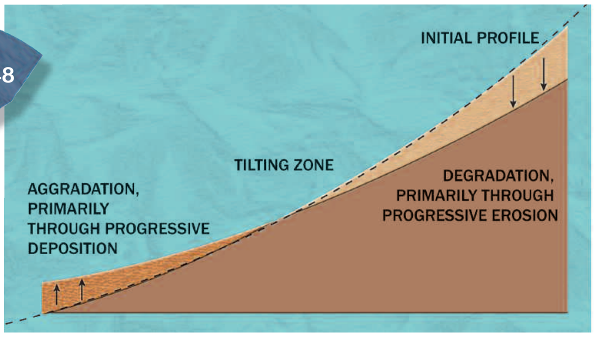
Adjustments caused by modifications in water and sediment discharges

In addition to the external control imposed by the base level, the long profile as a whole can be lastingly adjusted in response to significant modifications in the water and sediment inputs. The Lane balance provides us with the means to understand the role of the Q and Qs control factors in modifications of the long profile of a river.

The example in Figure 48 shows the change in the long profile due to a drastic reduction in sediment input. The adjustment in the profile takes place through widespread bed degradation, primarily in the form of progressive erosion. Contrary to regressive erosion (see the example above), bed incision by progressive erosion is caused by a deficit in sediment. Because the river dissipates less energy in sediment transport, greater **transport capacity** is available to erode the bed. Erosion therefore takes place from upstream to downstream until the river reaches its maximum transport capacity and/or a slope is produced that is no longer capable of transporting sediment (**a slope with no transport capacity**). The Rhône upstream of the Ain tributary provides a good example of progressive erosion occurring over a long time span (since the end of the last glacial period).

The figure below illustrates the two-fold adjustment of the long profile. The upstream section of the river is confronted with a deficit of coarse sediment and degrades. The downstream section, on receiving the sediment eroded from the riverbed (or from the banks if they are erodible), aggrades. There is a **tilt in the long profile** on either side of a tilting point or zone.

Figure 48

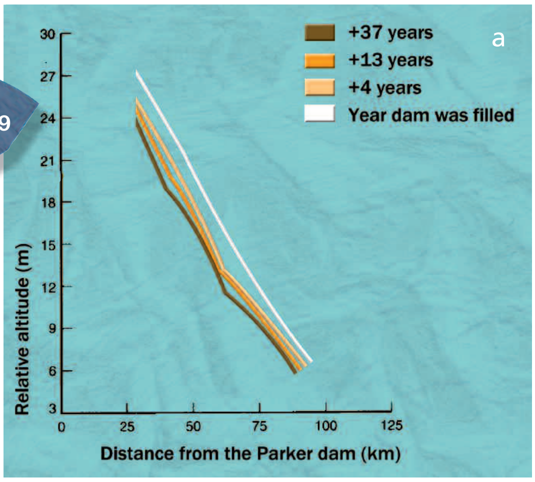


An example of long-profile adjustment due to a drastic reduction in sediment input. The long profile is said to "tilt".

Adjustments due to anthropogenic causes

This type of progressive erosion has often been observed downstream of dams. Dams almost completely block the alluvial bedload arriving from upstream and provoke an adjustment downstream. This phenomenon is clearly illustrated by the example below in the Colorado River (Williams and Wolman, 1984). Bed degradation spread downstream very rapidly and over two metres of down-cutting were observed 90 km downstream! At the same time, aggradation took place 150 km downstream (see Figure 49b).

Figure 49



(a) Incision of the bed of the Colorado River downstream of the Parker dam (Williams and Wolman, 1984).
(b) Progressive aggradation 150 km downstream, due to deposition (alternate banks) of the material eroded upstream (Google Earth).

Cross profile

In addition to or independently of adjustments in the long profile, all rivers having a minimum amount of mobility space (a concept that we will discuss later) and enough power can adjust more or less rapidly their cross profile to natural or artificial fluctuations in control factors and to any direct human impacts.

Similar to the long profile and the river pattern (discussed in the next chapter), it is now acknowledged that rivers can achieve a **steady cross profile** suited to the average water and sediment values existing to date and to the other control factors (valley slope and width, type of alluvium, riparian vegetation).

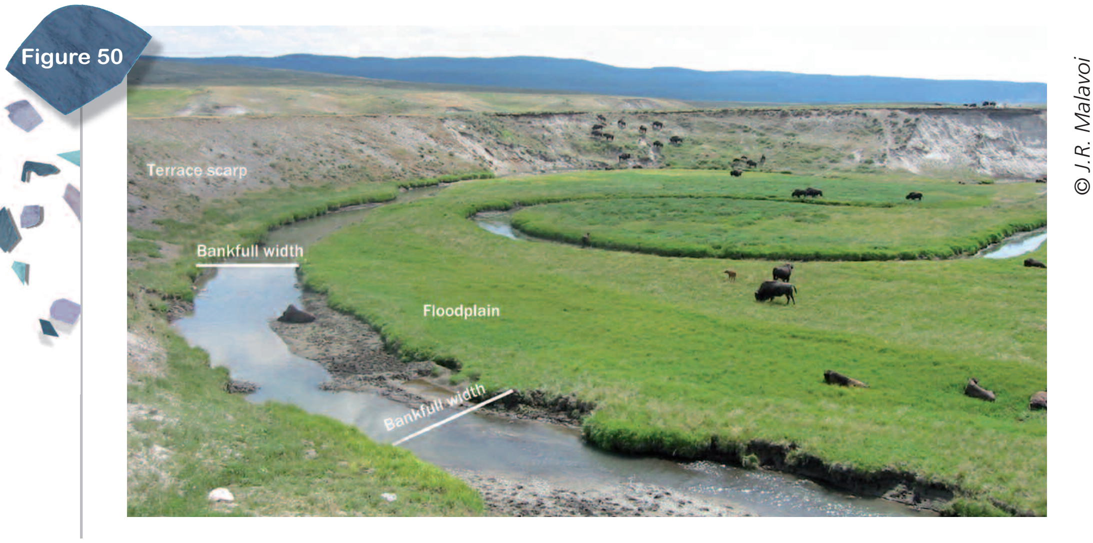
Hydraulic-geometry concepts

During the 1800s in India, English and Indian engineers attempted to create irrigation canals whose planform, long profile and cross profile were designed to remain stable over time, to ensure regular discharges and reduce maintenance costs (notably those caused by sedimentation downstream of connection points to rivers with high suspended loads). Based on numerous experiments, they developed the **"regime" theory**, linking discharge, width, depth and slope.

This theory was subsequently used during the 1900s to explain, then predict the geometric characteristics of natural rivers. Great numbers of measurements have been made on natural rivers since the 1950s, both in the U.K. and in the United States. They resulted in an expanded "regime" theory, called the **theory of hydraulic geometry**. The pioneering work was done by Leopold and Maddock (1953) as well as Hey and Thorne (1986). Their observations revealed the strong correlations between the water volumes arriving in a river (or the substitute value, i.e. the surface area of the river basin) and the geometric characteristics of the river at a given point.

■ Bankfull cross profile

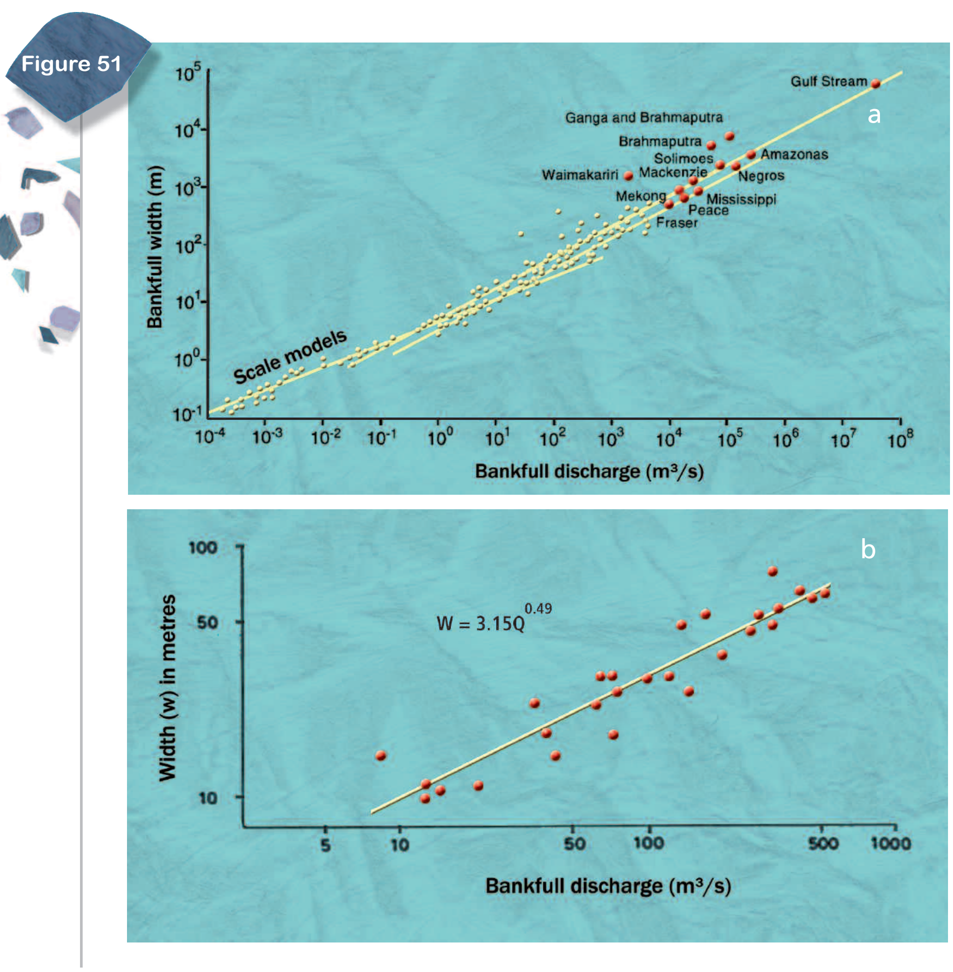
The most important cross-profile measurements in terms of their geomorphological significance are those which correspond to the **bankfull channel,** i.e. the last stage before the river overflows into the **floodplain**. The bankfull concept is also used by legal experts to determine the public domain in public rivers. The term used is *plenissimum flumen*. The width and depth are measured under the bankfull conditions, shown in the photo below.



Example showing the "bankfull" characteristics of a small river in Yellowstone park, in the U.S.

■ Some data

The examples below present measurement results that were used to develop hydraulic-geometry equations. Note that the initial measurements and the derived equations were carried out without taking regional (climate, geology) or local (riparian vegetation, texture of bank sediment) specificities into account and were therefore confronted with significant statistical dispersion. More recent studies are increasingly regionalised or topically oriented (riparian vegetation, rivers in urban or rural basins, etc.) and as a result the precision of models has increased.

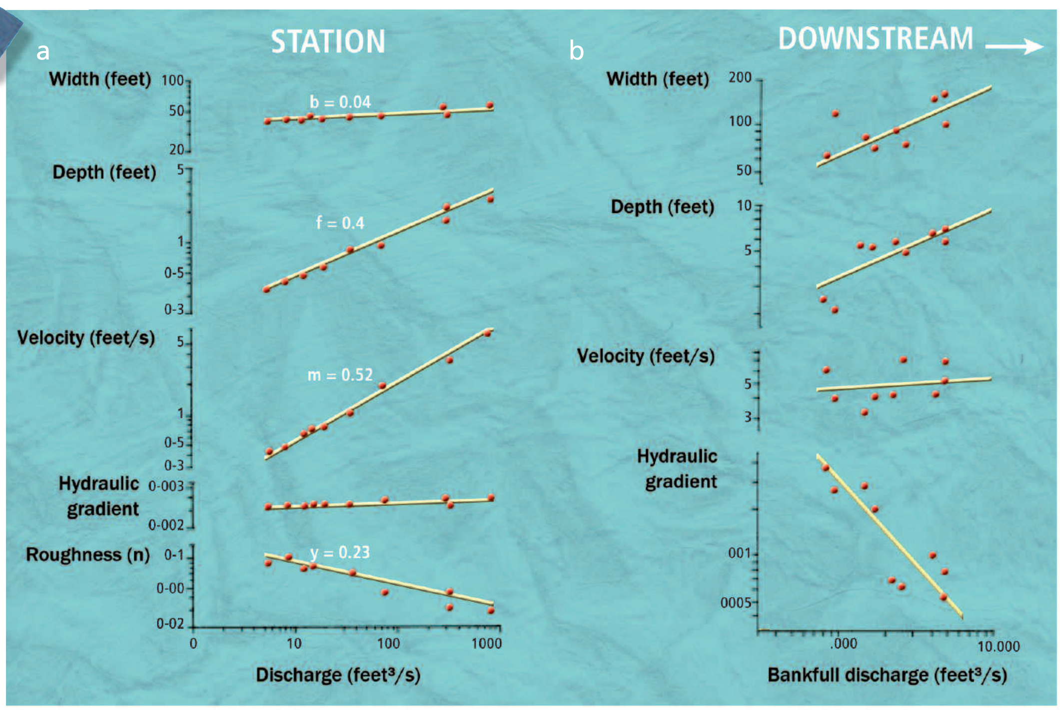


Examples of relationships between the bankfull discharge and the channel width (Schumm, 1960).

A majority of researchers have worked on two approaches to the relationships involved in hydraulic geometry.

- **At-a-station hydraulic geometry,** which can be used to see the changes in geometric parameters at a given station (e.g. on the scale of a cross profile), when the discharge increases.
- **Downstream hydraulic geometry,** which can be used to see the changes in the same parameters in a river, but while progressing from upstream to downstream, in which case the change represents the effects produced by an increase in the bankfull discharge.

Figure 52



Examples of hydraulic-geometry relationships a) at-a-station and b) downstream (Wolman, 1955).

Hydraulic-geometry equations are based on the correlations observed between the discharge and the geometric characteristics of the riverbed, generally in the form:

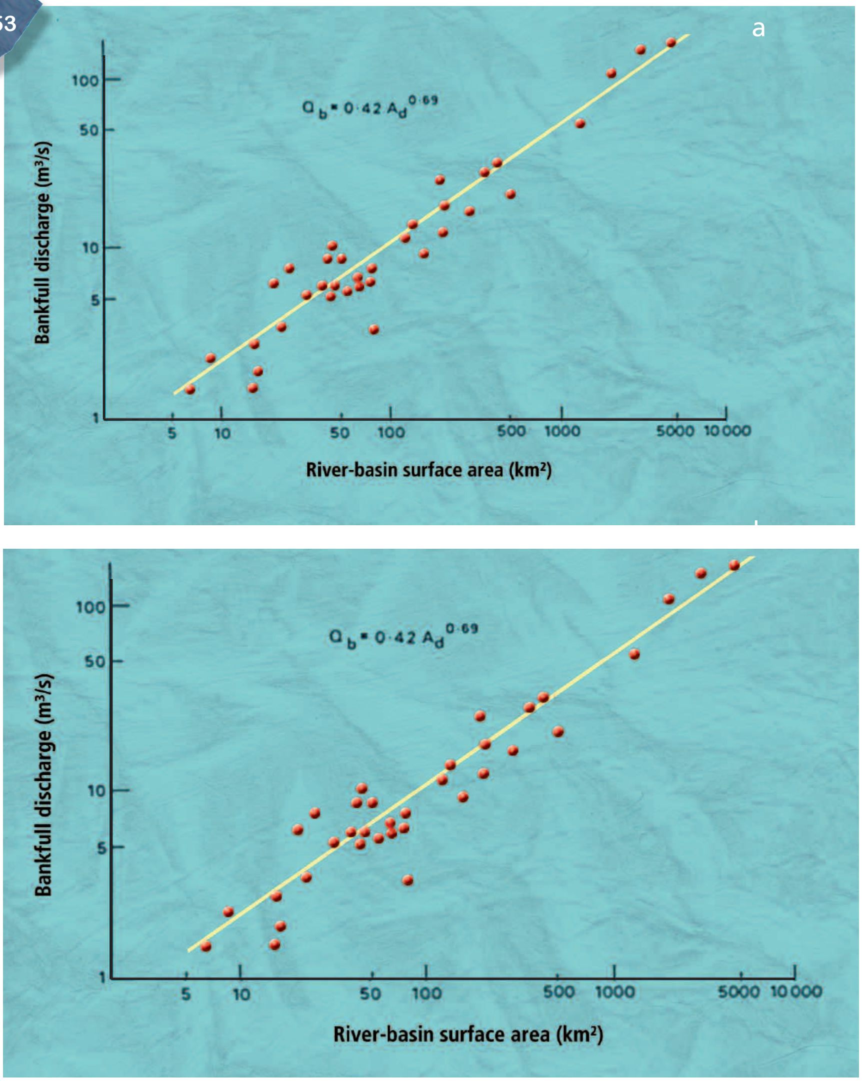
$$y = aQ^b$$

where y is a bed dimension (width, depth), Q is a reference discharge (the bankfull discharge for the downstream geometry, a value ranging from low flow to the bankfull discharge for at-a-station geometry) and a and b are constants (often the same across a region) used to adjust the equation to the field data.

In that it is fairly easy to identify and regionalise the relationships between a reference discharge and the surface area of a river basin (Figure 53), a number of hydraulic-geometry equations are presented directly as follows:

$$y = aRBSA^b$$

where RBSA (river-basin surface area) replaces Q.



Examples of relationships between the river-basin surface area and the bankfull discharge.
(a) Not regionalised (Dunne and Leopold, 1978).
(a) Regionalised (McCandless and Everett, 2002).

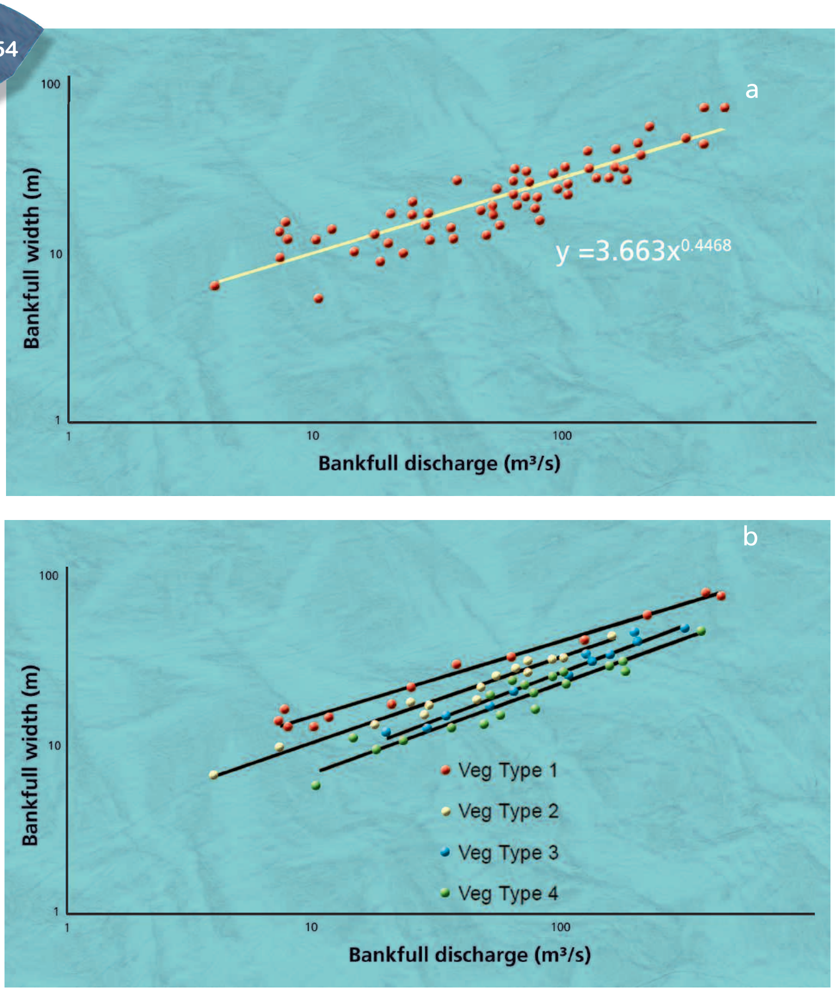
An example of the most commonly used hydraulic-geometry equations is provided by Hey and Thorne, 1986 (see the table below). The equations are derived from measurements carried out on 62 gravel-bed rivers in the U.K. Note that the authors are of the opinion that bank vegetation is a major control factor.

The data shows that the bankfull width of rivers with non-vegetated banks (vegetation type 1) is almost double that of rivers with highly vegetated banks (vegetation type 4).

Table 4 *The equations of Hey and Thorne and their field of application (1986).*

Equation	Field of application (based on the studied sample)
Bankfull width (w) w = 4.33 $Q^{0.5}$ (m) vegetation type 1 w = 3.33 $Q^{0.5}$ (m) vegetation type 2 w = 2.73 $Q^{0.5}$ (m) vegetation type 3 w = 2.34 $Q^{0.5}$ (m) vegetation type 4	Bankfull discharge (Q): 3.9 - 424 m³/s Bankfull sediment discharge (Q): 0.001 - 14.14 kg/s Mean grain diameter (D50): 0.014 - 0.176 m Texture of bank sediment: composite: gravel, fine sand, silt, clay Type of riparian vegetation: 1: 0% trees and shrubs, 2: < 5%, 3: 5 - 50%, 4: > 50%
Bankfull depth (d) d = 0.22 $Q^{0.37}$ $D50^{-0.11}$ (m)	Valley slope (Sv): 0.00166 - 0.0219 Planform: straight to meandering Main facies: riffles / pools
Bankfull hydraulic gradient S = 0.087$Q^{-0.43}$ $D50^{-0.09}$ $D84^{0.84}$ $Qs^{0.1}$	

Figure 54



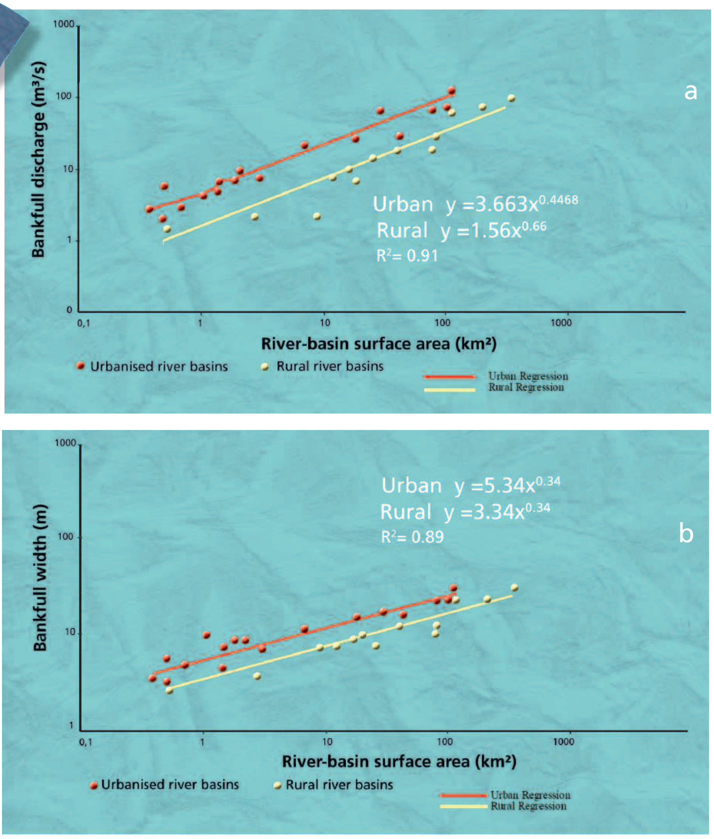
Hydraulic-geometry equations developed by Hey and Thorne (1986).
(a) Data presented without separating the types of vegetation and (b) separating them. The fit is much better.

These equations are most useful for hydrological-engineering purposes and notably for:

- evaluating the impact of hydraulic work (recalibration, rectification, etc.);
- determining the targeted size of reconstructed riverbeds during hydromorphological-restoration projects.

Note that research is still underway to improve our knowledge in this field. In addition to regional aspects, scientists now integrate the level of urbanisation in the river basin (see below).

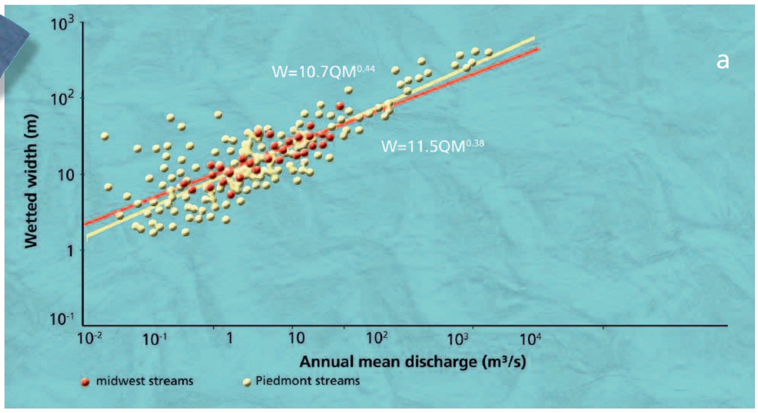
Figure 55



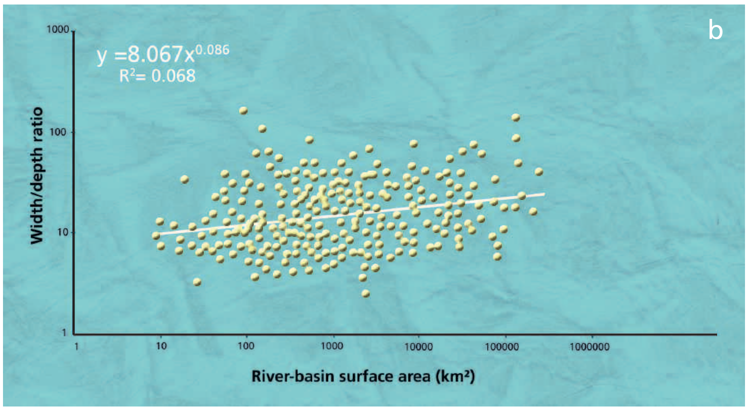
Examples of hydraulic-geometry relationships including the level of urbanisation in the river basin. The data reveal that in river basins of identical size, rivers in urbanised basins have higher discharges and correspondingly greater widths than rivers in rural basins (Harman et al.*, 1999).*

Caution. In some cases, the **dispersion of the original data** remains high, even for regionalised data (see the examples below). That is probably because other control factors (riparian vegetation, texture of bank sediment, etc.) must be more precisely taken into account. Another possibility is that there may simply be no correlations (see Figure 56b).

Figure 56



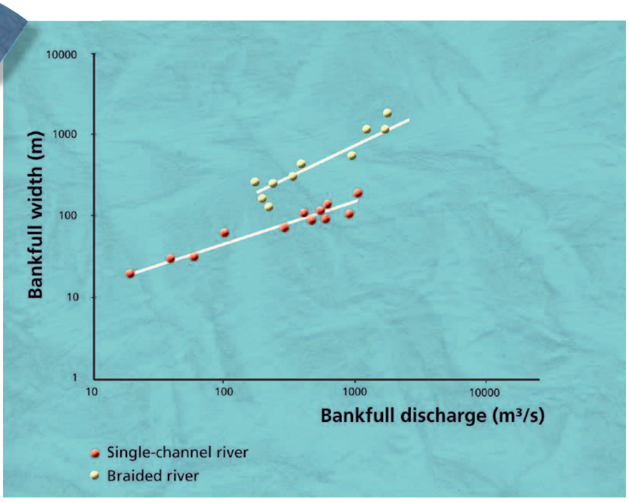
(a) Example of regionalised correlations between the wetted width and the mean discharge (Kolberg and Howard, 1995).



(b) Example of correlation between the river-basin surface area and the width/depth ratio (Tennakoon and Marsh, 2008, regionalised measurements on rivers in Queensland, Australia). There is commonly a ten-fold factor between the lowest and highest values!

Note also that at equal discharges, braided rivers are generally much wider (and much less deep) than single-channel rivers (we will discuss this aspect later). The figure below indicates that the coefficient between the two types of river is approximately 3 to 5.

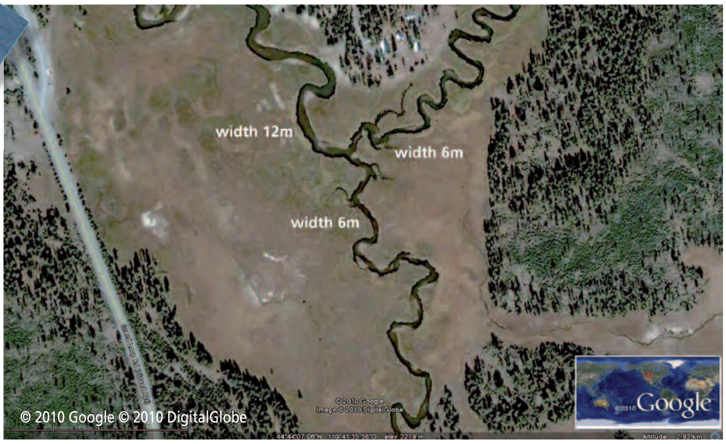
Figure 57



Differences in width between single-channel and braided rivers with equivalent discharges (Ashmore, 1999).

Finally, below is a figure showing the confluence of two rivers having the same width. The result is a river twice as wide (who would have guessed?).

Figure 58



An application of hydraulic-geometry laws. 6 + 6 = 12 (Yellowstone park, U.S.).

Width/depth ratio

The ratio of the average bankfull width to the average bankfull depth (noted w/d) is a useful geometric characteristic for a number of reasons.

In hydromorphological terms, it is a typological parameter **indicating the geodynamic activity of the river.** For example, fairly dynamic rivers with significant lateral erosion and high sediment inputs have relatively high w/d ratios of 20 or more. **Braided rivers** often have w/d ratios near or even greater than 100.

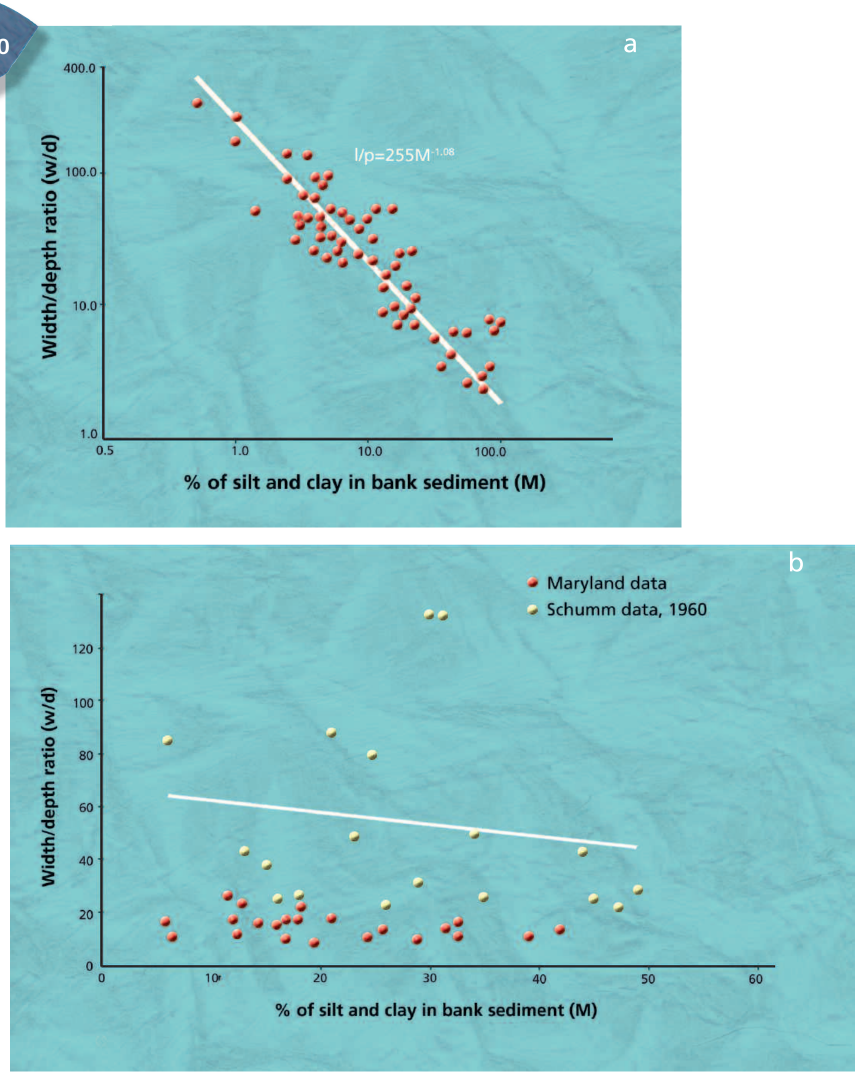
Figure 59

a- b- c- d- © J.R. Malavoi

Four examples of width/depth ratios. The correlation with the intensity of geodynamic processes (lateral erosion and sediment transport) is clear.

The w/d ratio also informs on **bank cohesiveness**. The greater the cohesiveness, the narrower and the deeper the river. Conversely, if the banks are not very cohesive, rivers tend to be wider and shallower (see Figure 60). The trends are identical to those for riparian vegetation in that the two parameters (vegetation and cohesiveness) both encourage vertical erosion and limit lateral erosion. Note, however, that data dispersion is again high (a factor of 3 to 5 between high and low values), but recent efforts to regionalise the data would tend to reduce dispersion.

Figure 60



(a) Width/depth ratio as a function of silt and clay percentages in banks (according to Schumm, 1960).
(b) A part of the Schumm data confronted with the much lower Maryland data, (McCandless and Everett, 2002).

Caution. In spite of the subsisting uncertainties, these examples clearly show that a **low width/depth ratio, i.e. a ratio characteristic of a narrow and deep river, does not necessarily signal a hydromorphological malfunction,** as is sometimes thought. Such characteristics may be completely natural and the result, notably, of the texture of the bank sediment, which is one of the secondary control factors. A hydromorphological study is required to determine if the characteristics are natural or caused by anthropogenic alterations.

Bankfull discharge

One of the most useful results of the past 50 years of research on the relationships involved in hydraulic geometry is the recurrence interval of bankfull discharges (for information on field measurements, see the chapter on "Tools for hydromorphological studies").

As early as the 1950s, the pioneers in river geomorphology (Wolman, Leopold, etc.) demonstrated that **the discharge filling the bankfull channel just prior to overflowing into the floodplain had a relatively high frequency** (generally annual to two-year floods). Several decades of research confirmed these initial results and it is today widely acknowledged that the bankfull discharge of a river is **close to the daily flood level with a two-year frequency,** even if slight regional differences exist (see Table 5), notably concerning the texture of bank sediment and the characteristics of the river basin (some rivers overflow at Q 1-year and some at Q 3-years, but very few overflow at Q 0.5-year or Q 10-years, unless there are anthropogenic causes).

NB This **geomorphological law** is valid only for fairly natural rivers (little human impact) and does not hold particularly well for braided rivers.

The relationship between this geometry and the frequent discharge levels is still not well understood. A large number of authors mention the concept of dominant discharge, i.e. a frequent discharge capable of creating the most effective cross profile to regularly transport downstream the volume of sediment supplied by the river basin. The dominant discharge would correspond to the bankfull discharge.

Table 5 *Examples of bankfull-discharge frequencies according to several authors (summary prepared by Wilkerson, 2008).*

Studied area	Recurrence interval of the bankfull discharge (Qbkf)	Authors
Western U.S.	1.4 (average)	Castro and Jackson (2001)
Belgium	0.7 - 5.3	Petit and Pauquet (1997)
Eastern half of the U.S.	1.5	Leopold *et al.* (1995)
Wyoming (Green River basin)	1.7 (median)	Lowham (1982)
North America	1.58	Dury (1981)
NW section of the Colorado basin	1.18 - 1.4 (mode)	Andrews (1980)
Queensland (Australia)	1.1 - 1.85	Dury *et al.* (1963)
England and Wales	0.46	Nixon (1959)

This law is highly useful for hydromorphological engineering.

- It can be used to inform local inhabitants that a natural river often overflows into its floodplain and that such phenomena are not a malfunction, but rather an indicator of good river operation.
- It is a means to identify and even quantify the impact of certain types of hydraulic work (notably recalibrations). If the bankfull discharge strays notably from Q 2-year (e.g. if the overflow occurs only at Q 5-year), it is certain that the river has been recalibrated with the usual hydromorphological and ecological consequences (Wasson *et al.*,1998).
- It can be of use in sizing a new riverbed for hydromorphological-restoration projects.