# Geomorphological approaches for river management and restoration in Italian and French rivers



(Article begins on next page)

# Geomorphological Approaches for River Management and Restoration in Italian and French Rivers

Massimo Rinaldi

*Department of Civil and Environmental Engineering, University of Florence, Florence, Italy*

Hervé Piégay

*University of Lyon, CNRS-UMR 5600, Site of ENS, Lyon, France*

Nicola Surian

*Department of Geography, University of Padua, Padua, Italy*

River management and restoration in Italy and France are increasingly considering physical processes and trends of channel adjustment as a basic knowledge for enhancing river conditions and promoting channel recovery. Italian and French rivers are characterized by a long history of human disturbances and land use changes. As a consequence, trends of channel adjustments and related management problems are similar, with a historical phase of aggradation followed by a period (last century) of intense channel incision and narrowing. A general overview on recent progress in using geomorphic approaches to river management in Italy and France is presented here by illustrating a series of examples of studies and management applications. A synthetic state of the art on the recent morphological changes of Italian and French rivers is first reported. Some examples of quantification of bed load are also illustrated, providing a necessary quantitative knowledge for possible interventions or strategies for promoting bed load recovery. Finally, examples are provided to illustrate how an understanding of geomorphic processes is used to define regional visions and associated tools for planning and targeting actions and to promote sustainable actions from local to catchment scale.

## 1. INTRODUCTION

Nowadays, it is widely recognized that physical processes, including those of sediment production, transfer, and storage, are fundamental to the ecological functioning of fluvial systems [see, for example, *Boon et al.*, 1992; *Goodson et al.*, 2002; *Kondolf et al.*, 2003; *Wohl et al.*, 2005; *Brierley and Fryirs*, 2005; *Florsheim et al.*, 2008; *Habersack and Piégay*, 2008]. The geomorphic dynamics of rivers is increasingly seen as vital for creating and maintaining the physical habitats that underpins the survival of aquatic and riparian flora and fauna. Sediment transport, bank erosion, and associated channel mobility represent key physical processes, and their understanding is of crucial importance for defining management strategies and river restoration measures.

Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools
Geophysical Monograph Series 194

10.1029/2010GM000984

As a consequence, river management and restoration in Italy and France, as in other parts of the world, are increasingly taking fluvial processes into account as a necessary condition for enhancing river conditions to improve ecosystem value or provide other benefits for society. Geomorphic problems of fluvial systems and their management are, to some extent, similar in these two countries, with both having a long history of human impacts and similar trends of land use changes and channel adjustments during the last few centuries. In both cases, a progressive reduction of sediment delivery at a regional scale, due to dam constructions, steep upland stream regulation, and land use change, has affected many regions, with the effects particularly evident in the piedmont areas of mountain regions [*Liébault and Piégay*, 2001, 2002; *Surian and Rinaldi*, 2003]. Recent (last century) intensive sediment mining has had one of the most important impacts, inducing further channel changes, with severe bed incision (maximum of 12 to 14 m) especially significant [*Peiry*, 1987; *Bravard*, 1991; *Landon et al.*, 1998; *Rinaldi and Simon*, 1998; *Surian and Rinaldi*, 2003; *Rinaldi et al.*, 2005]. Such morphological changes have had abiotic and biotic consequences followed by ecological and economical impacts [*Bravard et al.*, 1999]. This critical situation in terms of management (channel instability problems, limitations of flood regulation works, and biodiversity decrease) has led to an increasing need for sustainable management of the bed load and other physical processes, but also to undertake measures for mitigating the impacts of channel incision [*Bravard et al.*, 1999; *Habersack and Piégay*, 2008; *Liébault bault et al.*, 2008].

The aim of this chapter is to provide a general overview of recent progress in the application of geomorphic approaches and concepts to river management and restoration, in the specific context of Italian and French rivers. This will be achieved by illustrating a series of case studies and examples, with a particular focus on some rivers of central and northern Italy and of southeastern France. The case studies mainly include alluvial, mobile gravel bed rivers, most of them with a present or previous braided pattern associated with relatively high bed load. In these environments, the energy available due to steep slopes is important, and channel features are sensitive to changes in control parameters (peak flow regime and bed load input). The geomorphic diagnosis established to design actions combined much knowledge from the different disciplines of this research field, involving engineers, geologists, and geographers. A wide space-time framework is considered to understand variability and provide a long term and sustainable vision of river functioning. This approach is combined with traditional local-scale engineering to provide quantitative assessments and physical process understanding. The structure of the chapter reflects how this geomorphic knowledge can be achieved and applied for sustainable river management, by illustrating the following points: (1) the need for historical analysis to highlight the temporal trajectory and sensitivity to changes, (2) the need to evaluate the sediment budget so as to understand the balance between sediment transport and delivery, and (3) use of all this knowledge for designing regional visions, strategies, and targeting actions.

## 2. MORPHOLOGICAL CHANGES OF RIVER CHANNELS

A detailed retrospective study, including an analysis of morphological channel changes and trends of adjustment and relations with potential causes, represents the first fundamental step in the definition of appropriate strategies for river management and restoration. It is important to identify channel changes and the types of adjustments that have generated the present channel morphology at a time scale of the order of the last 100–200 years and to identify the trajectory of channel evolution [*Brierley and Fryirs*, 2005; *Dufour and Piégay*, 2009], so as to understand present process-form interactions and the response of the river system to human impact or other natural factors. Understanding this trajectory is important for predicting whether proposed restoration actions have a chance to be successful or not, depending on the capacity of the river to react to them and to understand the present river behavior. Independent of any restoration actions, the river is changing, as it is not static but dynamic, and any intervention must anticipate this change so that these corrective measures can be sustained.

During the last decade, many studies have been addressed to understand and clarify the past and recent evolution of fluvial systems in Italy and France. In France, several studies have been focused on the piedmont Alpine area, and they have been able to identify the main types of channel adjustments and associated causes [e.g., *Liébault and Piégay*, 2001, 2002]. Sediment delivery has decreased at a regional scale due to dam construction, steep upland stream regulation, locally reducing or interrupting sediment transport, and in-channel mining, which removes and stores sediment locally sometimes over decades. Moreover, this mountain area has undergone another significant change, a major afforestation due to human depopulation and agricultural decline, which reduced land sensitivity to erosion and decreased sediment delivery. This factor is then exacerbating the sediment deficit downstream resulting from damming, torrent controls, and in-channel mining, since the rivers are not yet adjusted to this factor and whose effects are still propagating downstream.

This significant land use change has not only been observed in the catchment areas but also along the major river corridors. Afforestation within the river corridors, in areas which were actively used for grazing, also explains the generation of new natural processes such as the introduction of wood and its transfer within the hydrographic network (Figure 1). All these phenomena have been responsible for channel metamorphosis at a network scale with narrowing and incision as the common response, the former usually occurring slightly before the incision as it was mainly associated with floodplain/catchment abandonment (circa 1930s to the late 1960s), whereas incision reached a peak in the 1970s in relation to intense mining activity.

In Italy, systematic studies on channel adjustments were carried out from the end of the 1990s [*Rinaldi and Simon*, 1998; *Surian*, 1999; *Rinaldi*, 2003; *Surian and Rinaldi*, 2003]. More recent studies [i.e., *Surian et al.*, 2009a] have involved a systematic analysis of channel changes over the last 200 years, on a larger number of study cases, with the aims of reconstructing the channel changes and understanding the relationship between channel adjustments and various human interventions. Twelve rivers in northern and central Italy have experienced almost the same processes in terms of temporal trends; however, the magnitude of adjustment varies on a case-by-case basis, according to several factors such as the original channel morphology [*Surian et al.*, 2009a]. After a historical phase of dominant floodplains and in-channel aggradation (in some cases since Etruscan-Roman times until the nineteenth century [*Billi et al.*, 1997; *Caporali et al.*, 2005]), river channels underwent two phases of narrowing (up to 80 %) and incision (up to 8 to 10 m), which started at the end of the nineteenth century (phase I), and was very intense from the 1950s to the 1980s (phase II). A series of human impacts have been recognized as responsible for these channel changes. Referring to a series of representative case studies in northern and central Italy reported by *Surian et al.* [2009a], the main human impacts and relative periods and duration include (1) various types of

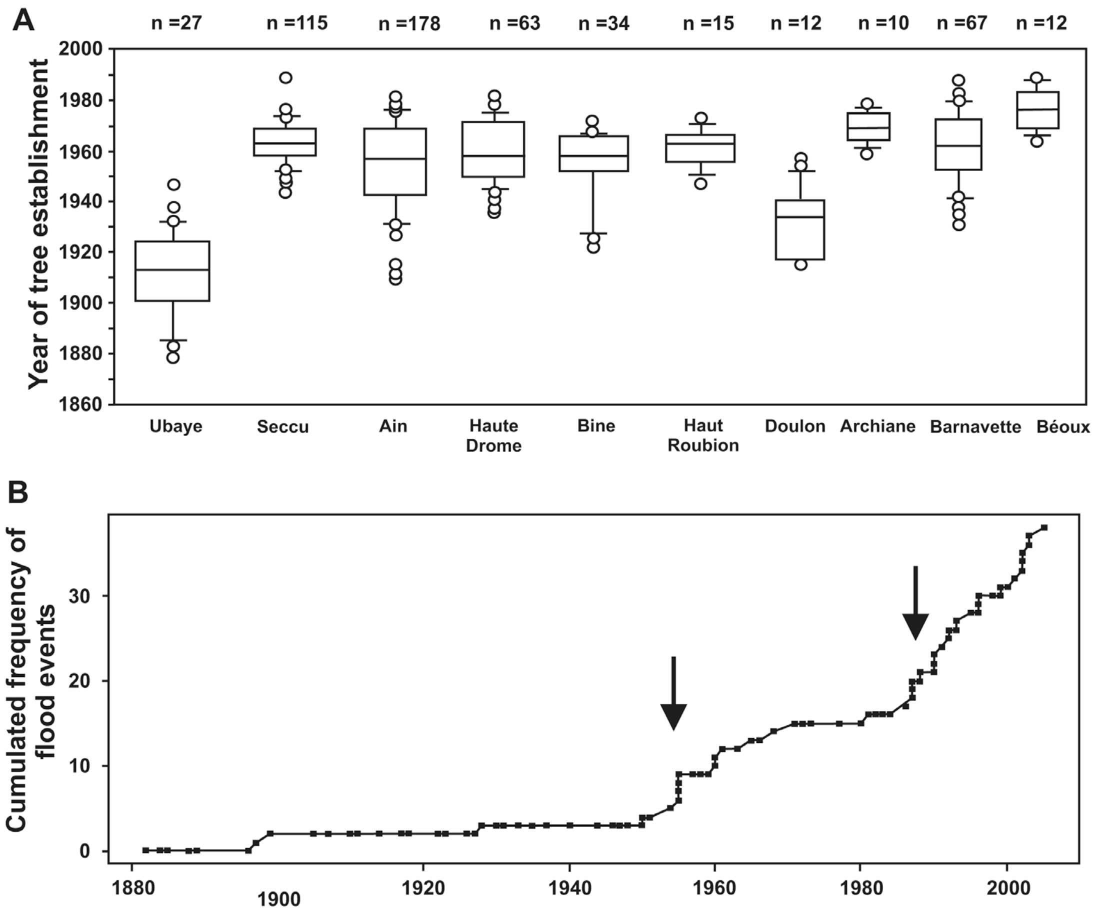


**Figure 1.** (a) Date of tree establishment in mature units of the riparian forests of a few French southeast rivers. (b) Cumulative frequency of wood jams during floods that occurred in rivers of the northern French Alps between 1880 and 2005 based on press articles. Modified from *Le Lay* [2007].

river training works, such as groins, levees, and bank protections (nineteenth to twentieth century); (2) afforestation, slope stabilization, and construction of weirs along tributaries in the upper portions of the catchments (from 1920s to 1930s); (3) dams (mainly 1930s–1960s); and (4) sediment mining (mainly from 1960s to 1980s). Such interventions have caused a dramatic alteration of the sediment regime, whereas effects on channel-forming discharges have seldom been observed. Then, over the last 15–20 years, channel widening and sedimentation have been observed along parts of the reaches (phase III), while a continuation of the previous phase of incision and narrowing was also observed in other cases. Among 24 subreaches analyzed in the study of *Surian et al.* [2009a], six cases have shown a continuation of channel narrowing, while in 18 cases, an inversion of the trend of channel width adjustments was observed. Among these 18 cases, 14 subreaches have revealed an increase up to 20% and in only four cases, an increase higher than 20% of the original width in the nineteenth century. Therefore, the magnitude of widening and aggradation has generally been much lower compared to those of the previous phases of narrowing and incision.

Various factors can be considered to explain this inversion of trend for part of the study rivers. First, the cessation of the intense period of gravel mining (since the end of the 1980s) can be considered the most important factor, implying higher in-channel sediment supply [*Rinaldi et al.*, 2009; *Surian et al.*, 2009a]. Second, the occurrence of some large flood may have been the driving factor during the most recent phase of adjustment, as evidenced by the evolution of the Orco River, where a very large flood (the largest recorded in the twentieth century) occurred in October 2000 [*Surian et al.*, 2009a], and by the Magra River and Vara (its main tributary), where two flood events with estimated return period of about 20–30 years occurred on 2000 and 1999, respectively [*Rinaldi et al.*, 2009].

A schematic summary of the main types and phases of channel adjustments is illustrated in Figure 2, relative to a series of case studies of the central and northern Apennines (Cecina, Magra, Vara, and Panaro rivers [*Rinaldi et al.*, 2008]). Similar trends have been observed along rivers of the piedmont Alpine area [*Pellegrini et al.*, 2008; *Surian et al.*, 2008, 2009a].

Based on the studies previously mentioned, Italian and French rivers exhibit many common characteristics and trends of evolution, both in terms of channel adjustments and human disturbances. They also possess some differences in terms of controlling factors and evolution scenarios. In both countries, channel incision and narrowing have been identified as the two main types of adjustments, although channel narrowing in Italian rivers appears less associated with land use changes in the river corridor and more related to sediment mining. Besides, bed incision generally also reaches higher amounts in the Italian rivers also as a consequence of intense sediment mining.

Cases of recent widening are also observed along some of the French rivers, notably on the lower Ain River [*Rollet*, 2007] or along the Drôme [*Liébault*, 2003], and appear to be associated with more intense floods that occurred in the 1990s. This recent trend does not counteract the long-term narrowing evolution observed, and it can be interpreted as a short-term fluctuation of channel width associated with the

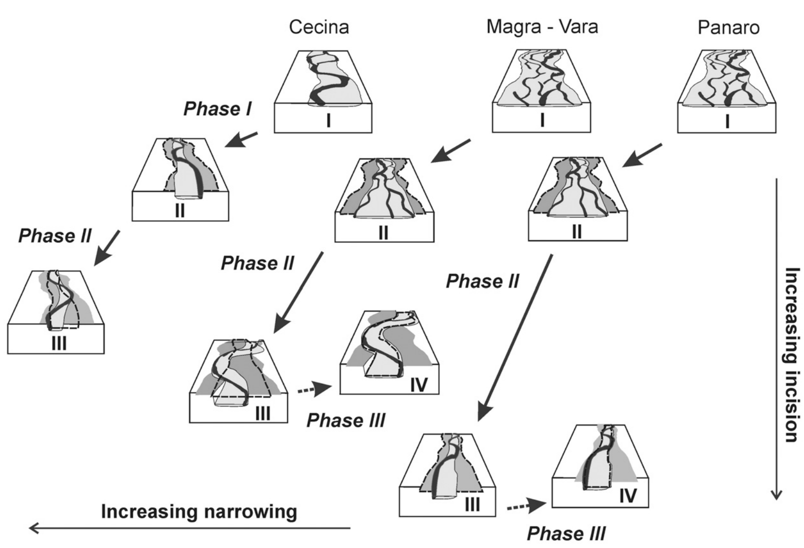


**Figure 2.** Summary of the types of channel adjustment for three study cases (Cecina, Magra-Vara, Panaro rivers) in the Apennines of central northern Italy. Modified from the work of *Rinaldi et al.* [2008].

intense floods. This period, characterized by floods with a similar intensity, mirrors those observed at the end of the nineteenth century, notably on the Rhine and the Rhône, for which we have long hydrological series, showing that these events are not unusual within this period of time. As shown by *Piégay et al.* [2009], however, the magnitude of this widening is low if compared to the magnitude of narrowing observed at the contemporary time scale and concurs with the intensity of channel width fluctuations related to flood series, as we have observed on different rivers and notably on the Drôme. Moreover, a new narrowing trend is observed following these 1990s/early 2000s events, notably on the Drôme and other braided rivers located in the French Alps [*Hervouet*, 2010], and interpreted as a recovery process acting in a fairly stationary trend.

These geomorphic changes observed at a regional scale in both France and Italy are also observed in the Pyrenees [i.e., *Garcia-Ruiz et al.*, 1997; *Rovira et al.*, 2005] and can be considered a general response to the pressures of human society across Europe, with remarkable differences to what is observed in other parts of the world where deforestation and its impact is more commonly described.

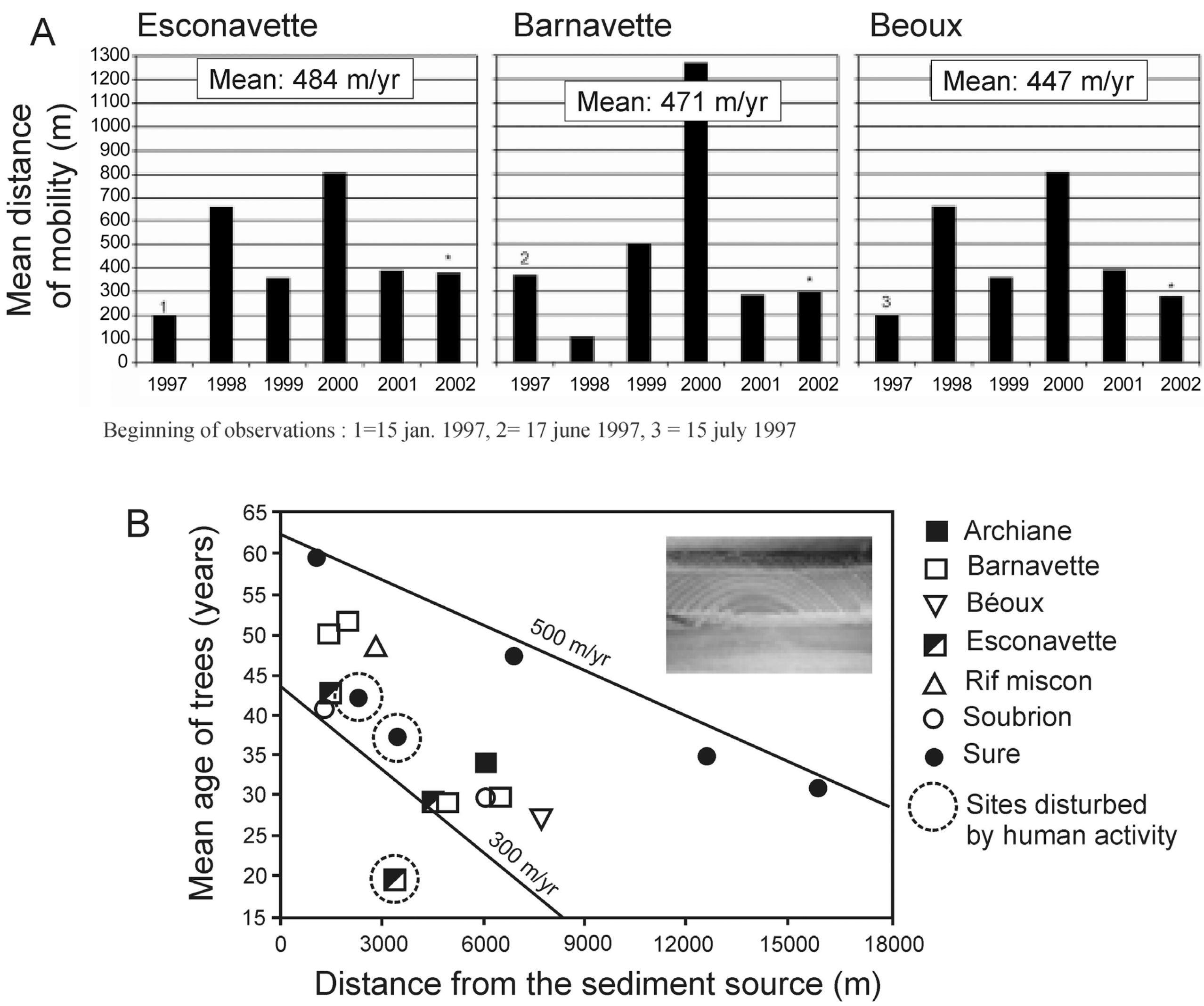


**Figure 3.** Evidence of sediment deficit propagating downstream along the Drôme River. (a) Mean annual distance of bed load propagation along three tributaries of the Drôme surveyed between 1997 and 2002. Modified from the work of *Liébault and Clement* [2007], reprinted with permission from Copibec. (b) Mean age of mature trees established along tributaries of the Drôme according to the distance from the sediment sources. Modified from the work of *Liébault et al.* [2005], reprinted with permission from John Wiley and Sons.

The research undertaken in the Drôme catchment has demonstrated that the afforestation has generated a deficit of sediment that is propagating downstream [*Liébault*, 2005; *Liébault et al.*, 2008]. This deficit is observed 15 km downstream from the sources using dendrochronological evidence, and the mean annual distance has been estimated to 500 m $yr^{-1}$ using both longitudinal trend fitted on the dendrochronological data but also observations of bed load migration using tracers (Figure 3). Similar observations have been made downstream of dams along the Ain River. Aerial photo analysis combined with longitudinal survey of the coarsest grain size of bar heads showed that a sediment deficit is observed with a mean annual propagation of ~500 m as well [*Rollet*, 2007; *Rollet et al.*, 2008]. These two examples of propagation of sediment deficit resulting from human pressures that occurred between the 1940s and the

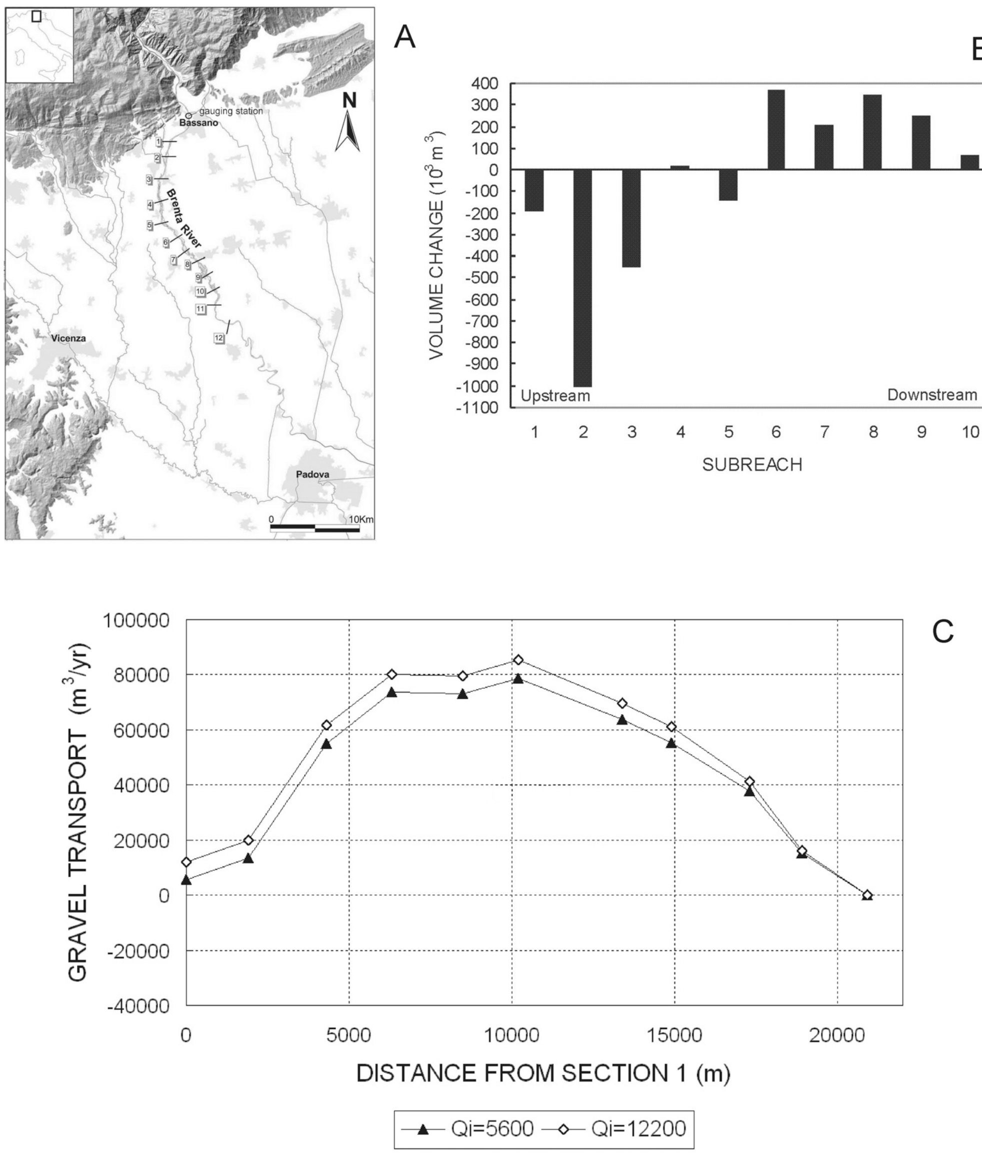


**Figure 4.** Bed load estimate using a morphological approach along the Brenta River. (a) Location of the 11 monumented cross sections used for the sediment budget. (b) Erosion and deposition volumes computed by subreaches for the period 1984 to 1997. (c) Gravel budget represented as sediment transport at subreach boundaries. The budget was computed using two possible conditions, i.e., sediment transport equal to 5600 and 12,200 $m^3$ $yr^{-1}$ at the upper section of the study reach. Modified from the work of *Surian and Cisotto* [2007], reprinted with permission from John Wiley and Sons.

1960s clearly demonstrate that the adjustment process at the regional scale is just beginning. The adjustment occurred only 15 km downstream from the sediment sources on the Drôme and 12 km downstream from the Allemand Dam along the Ain, suggesting that the adjustment will probably continue downstream for years.

## 3. QUANTIFICATION OF BED LOAD AND SEDIMENT BUDGETS

In recent years, much progress has been made in the measurement and prediction of bed load transport on gravel bed rivers. In the last decades, sediment budgeting based on morphological approaches has been studied in different geographical contexts based on various sets of data [i.e., *McLean and Church*, 1999; *Ham and Church*, 2000; *Brewer and Passmore*, 2002]. The technique involves the evaluation of bed load by assessing the morphological changes that reflect erosion, transport, and deposition of sediment over a given period. The morphological method is based on the continuity principle applied to bed material in the channel zone and involves the quantification of sediment inputs, outputs, and storage changes in a defined reach:

$$S_o = S_i - \Delta S, \tag{1}$$

where $S_o$ is the bed material output, $S_i$ is the bed material input, and $\Delta S$ is the change in storage. If these variables are measured over a period of time, then the equation becomes

$$Q_o = Q_i - (1-p)\, \partial S/\partial t, \tag{2}$$

where $Q_o$ is the volumetric transport out of the reach per unit time $\partial t$, $Q_i$ is the volumetric transport into the reach per unit time, and $p$ is the porosity of the sediments.

Sediment budgeting using the morphological approach in gravel bed rivers has been applied over a variety of spatial and temporal scales, from discrete bars and single flow events, to extended channel reaches of several kilometers and decadal intervals or longer. Depending on the scale, methods and data sources used to estimate channel changes can also vary, from detailed direct field surveys to combinations of archived channel long profiles, cross sections, and remote sensing sources for characterizing topographical and planimetric changes.

Examples of application of the morphological approach for sediment budgeting for some Italian and French rivers include the works of *Rollet* [2007], *Surian and Cisotto* [2007], and *Simoncini* [2008].

The first case reported here is the Brenta River [*Surian and Cisotto*, 2007], which is one of the largest rivers draining the Dolomites (Southern Alps, Italy), having a length of 174 km and a drainage basin of 1567 $km^2$. The morphological sediment budget was constructed to analyze the present condition of river in terms of bed load transport and sediment sources. The morphological method was applied to a 21 km reach, using 11 monumented cross sections surveyed in 1984 and 1997 (Figure 4a). The construction of the gravel budget involved the following steps: (1) estimating the net change in area for each cross section, (2) estimating the net change in volume for each subreach, (3) analyzing grain size to estimate the proportion of material transported on the bed and its porosity, and (4) identifying a cross section where sediment transport is known. Once a net change in area was estimated for each cross-section, values of adjacent sections were averaged and multiplied by the distance between them to obtain the net change in volume for each subreach [*Griffiths*, 1979]. The estimate of change in volume shows clearly that, in the upper part of the study reach, erosion has been the dominant process, whereas deposition has occurred predominantly in the lower part (Figure 4b). The overall gravel budget, represented as gravel transport at subreach boundaries, is shown in Figure 4c for two possible conditions of bed load at the upper section of the study reach. These two conditions were based on (1) available measurements of suspended load and (2) possible contributions of bed load to the total load based on bed load-to-suspended load ratios of 0.33 and 0.15. The sediment budget obtained, although affected by some approximations, is useful to investigate the spatial variations of bed load along the reach. The budget shows that gravel transport increases significantly in the upper part of the study reach, remaining relatively constant in the middle part and then decreasing to zero in the last 11 km of the study reach. Such spatial variations in gravel transport highlight that there are major contributions of local erosion to bed load transport and, therefore, to the total sediment deposited in the study reach.

Having determined that most of the material available for transport is sourced from local erosion with only a small proportion derived from upstream (i.e., from the drainage basin), investigations can be concentrated on local erosion to determine the proportion between the channel bottom and banks. The analysis of cross-sections revealed that bank erosion was the dominant process in the period 1984 to 1997, contributing 83% of the total erosion in the study reach. The next step was to make an estimate of the material eroded from the banks. Areal changes along the banks were estimated using aerial photographs, whereas bank heights were estimated using lidar data and field observations. After correcting for porosity and fine sediment, the total amount of gravel coming from the banks was 110,000 $m^3\ yr^{-1}$. This implies that the amount of gravel coming from the banks was 10 to 20 times larger than the amount coming from the drainage basin (5600 to 12200 $m^3\ yr^{-1}$, see Figure 4c).

The budget was calculated for the period 1984–1997, and over that period, the channel mainly experienced widening. Over this period, gravel deposition occurred mainly within the channel, and very small portions of the channel were stabilized by vegetation.

Another approach in sediment budgeting involves the use of sediment transport equations for each of a series of discrete, relatively homogeneous, subreaches within the study river. Based on the sediment continuity equation, a mean annual sediment budget can be obtained for each subreach by estimating the difference between the input of bed load from the upstream subreach (assuming the flow is at its transport capacity), plus the input from any major tributaries and the output from the given subreach:

$$\Delta Q_{s\,(i)} = Q_{s\,\mathrm{IN}\,(i-1)} + Q_{s\,\mathrm{IN}\,(t)} - Q_{s\,\mathrm{OUT}\,(i)}, \qquad (3)$$

where $\Delta Q_{s\,(i)}$ is the mean annual sediment budget (m$^3$ yr$^{-1}$) for the subreach ($i$), $Q_{s\,\mathrm{IN}\,(i-1)}$ is the mean annual sediment input (m$^3$ yr$^{-1}$) from the upstream subreach ($i - 1$), $Q_{s\,\mathrm{IN}\,(t)}$ is the mean annual sediment input (m$^3$ yr$^{-1}$) from tributaries in the subreach ($i$), and $Q_{s\,\mathrm{OUT}\,(i)}$ is the mean annual sediment output (m$^3$ yr$^{-1}$) from the subreach ($i$). In contrast to geomorphological sediment budget, this approach does not account for observed changes of the river channel in a given time interval, but rather expresses the tendency of each subreach to aggrade (positive values) or degrade (negative values) given its hydraulic and sedimentary characteristics.

This approach has been applied to the Magra and Vara rivers (central and northern Italy) in a study aimed at defining a program for future sediment management [*Rinaldi et al.*, 2009]. In this specific case, four bed load equations were used (Shields, Schoklitsch, Parker, and Meyer-Peter and Müller, in the form corrected by *Wong and Parker* [2006]), as they were considered the most suitable for the characteristics of the study rivers. The estimated mean annual bed load sediment budgets are summarized in Figure 5. Sediment budgets derived from the four bed load equations differed by 1 or 2 orders of magnitude but gave consistent results in relation to overall incision/aggradation tendencies for 22 out of 23 subreaches. These tendencies were then used, in combination with other parameters, to define a classification of the river aimed at aiding sediment management (see following sections).

An attempt to calculate the gravel budget by including the contribution of the river banks has also been undertaken. Mean annual rates of bank retreat were obtained by comparison of recent aerial photographs, while bank height and composition were obtained by field measurements. The results have shown that, on a total of nine subreaches that were interpreted to have a tendency to incision without consideration of the banks, six of them changed their tendency to

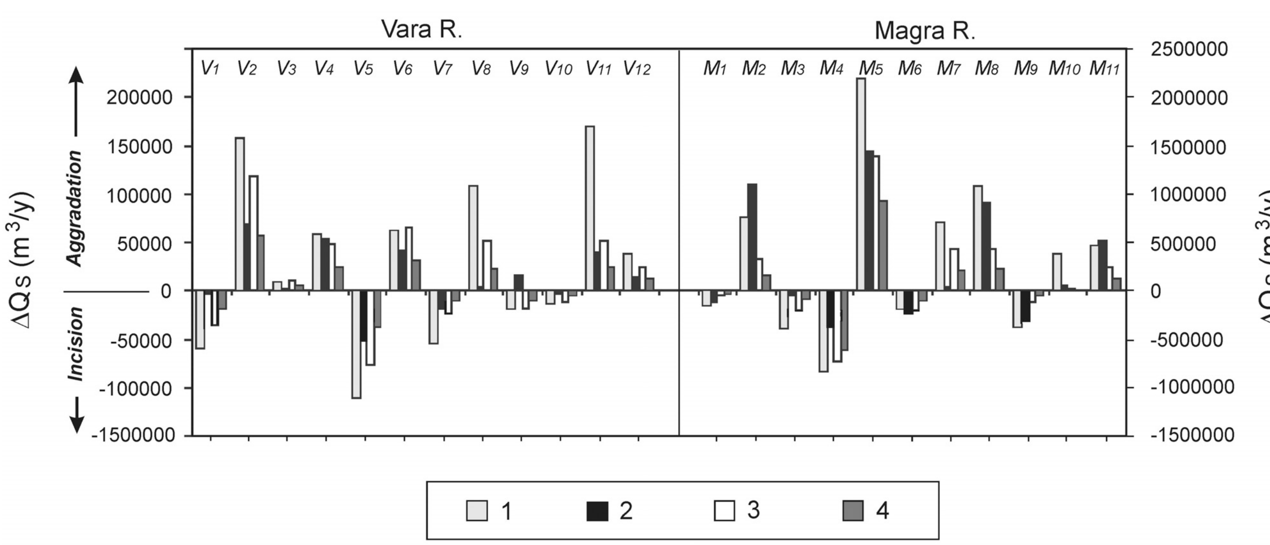


**Figure 5.** Sediment budget using bed load equations for the Magra and Vara rivers. $\Delta Q_s$ represents the mean annual sediment budget for a given reach. (left) Values calculated by the Schoklitsch formula are shown. (right) Values calculated by the other formulas are shown. Positive values indicate a tendency of the reach to aggrade; negative values indicate tendency to incision. Shading is defined as follows: 1, Shields equation; 2, Schoklitsch equation; 3, Parker equation; 4, Meyer-Peter and Muller equation. *V*1 to *V*12 and *M*1 to *M*11 indicate reaches of the Vara and Magra rivers, respectively. Modified from the work of *Rinaldi et al.* [2009], reprinted with permission from John Wiley and Sons.

aggradation once the banks were included in the calculations. Both the sediment budgets on the Brenta and on the Magra and Vara rivers, although with different approaches, have demonstrated in a quantitative way the role of the banks as a significant source of bed load sediment in the pluri-decadal adjustment context that we observed in this study.

These reach-scale approaches can also be combined with an estimate of bed load delivery from subcatchments, to facilitate comparison with independent calculation methods and to assess the relative contributions of valley reaches and upstream basins. Such approaches can be based on detailed field measurements and extrapolations for establishing potential scenarios for sediment management. Field data on annual bed load transport can therefore provide a gross assessment of bed load transport conditions in neighboring catchments for which no data are available. A key-contribution of this type of study comes from the works of *Liébault* [2005] and *Liébault et al.* [2008] in France reporting bed load yields for a series of rivers and streams of the Southern French Prealps, which were used to establish a regional law linking catchment size and the mean annual bed load transport (Figure 6).

Following these examples, some critical points can be discussed as follows.

1. The major incision and narrowing that occurred along Italian and French rivers has created a new floodplain that has not yet adjusted to the new sediment supply and transport conditions. As a consequence, when large magnitude floods occur as in the 1990s, then channel widening can introduce significant amount of gravel to the river, which, in turn, smoothes the impact of mining activity. The question is now to define the period of time required for the floodplain to adjust to the new conditions and to see if the bank erosion can be a long-term process of sediment delivery or only a transitional one. The example of the Ain River provides additional elements to this discussion. Along the Ain River downstream from the Allemand Dam, the historical analysis of aerial photos was combined with field survey of bank height and estimates of overbank sedimentation to develop a sediment budget over the 1980 to 2000 period [*Rollet*, 2007]. It appears that bank erosion re-introduced 205,000 $m^3$ of sediment per year, but 210,500 $m^3$ $yr^{-1}$ were stored following bar encroachment by vegetation. As a consequence, this river is not significantly incised, notably in the reaches where the channel is actively mobile is not recharged by bank erosion, and sediment is therefore thought to be sourced mainly from upstream. When damming occurs, the channel begins to transport sediment stored in the bed providing a winnowing process and associated channel incision. Once incision occurs in the channel, it seems that it is much less mobile, so that sediment loading from bank erosion is not significant.

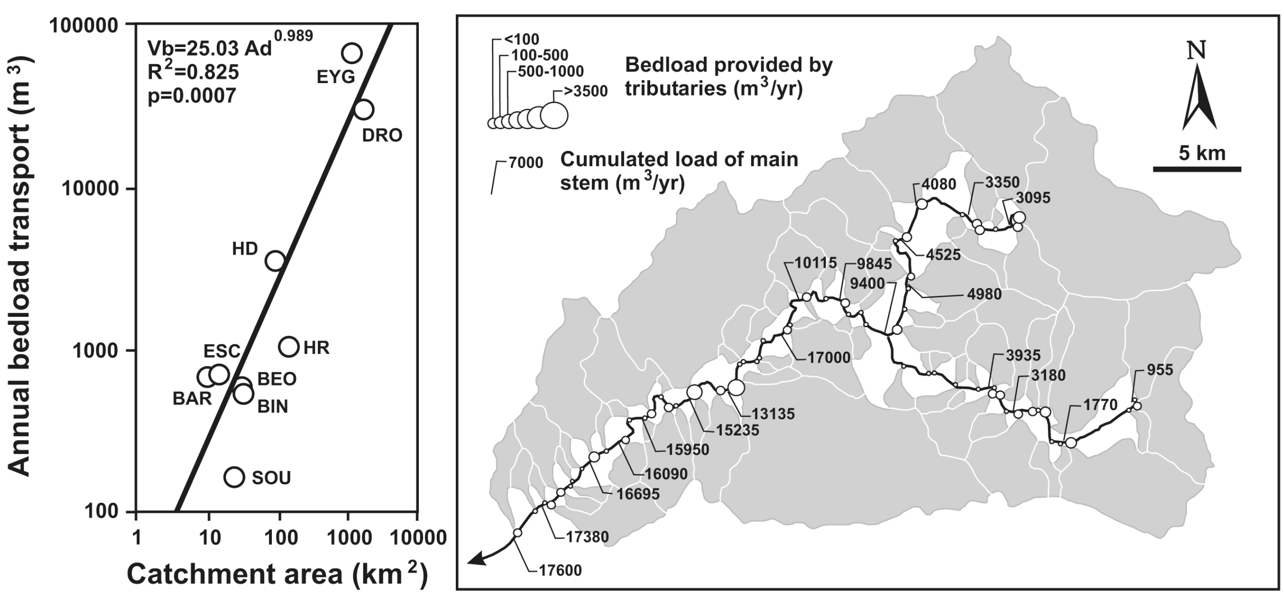


**Figure 6.** Bed load contributions at catchment scale: (left) calibration of the statistical law from field surveys and archived data performed on three catchments of the Drôme, the Eygues, and the Roubion and (right) its application to the Eygues River network. Modified from the work of *Liébault et al.* [2008], reprinted with permission from Wiley-Blackwell.

2. The bed load contribution from the uplands must be better known where it seems that sediment delivery is decreasing and the rivers are using the valley sources during the widening process. Preliminary work was done to extrapolate local known sediment transport rates to better understand basin contribution, but the inner catchment complexity must be better characterized for targeting potential actions on sediment transport restoration and preservation. It is important to determine where the most active tributaries are located and their contributions to the bed load transported by the main stream, as this can help in sustainable sediment management.

3. Over the last decade, geomorphologists often consider processes rather than forms when promoting restoration actions or mitigations, since these are more sustainable, long-term efficient measures for channel adjustments. Nevertheless, the question of "sustainable solutions" is still underexplored. It is important to consider the appropriate time scale when promoting sustainable solutions. Even if we have a good understanding of past adjustments, it is still difficult to provide a clear scenario of the future adjustments because the process is not completely ended, and there still are floodplain properties that can slow down the adjustment time. The use of local known physically based processes in the extrapolations that we can do at catchment scale is therefore a new scientific frontier to provide data for sustainable scenarios. Prospective geomorphology is a new application, where important uncertainties must be identified and time scales of channel adjustments need careful consideration if we really want to move from a local-scale traditional expertise to the promotion of long-term sustainable options [*Pont et al.*, 2009]. Thinking process rather than form is easy to say, but it is difficult to apply.

## 4. APPLICATION OF GEOMORPHIC APPROACHES TO RIVER MANAGEMENT AND RESTORATION

Even if important uncertainties must be considered, the low level of understanding that we have of rivers has been used for improving river management and restoration in Italy and France. As it is promoted in other parts of the world, applied initiatives are increasingly including considerations on physical processes, such as bank erosion, sediment transport, channel incision, and water flows, among others, as a necessary condition for enhancing river conditions and promoting channel recovery.

Channel incision and other related adjustments have had dramatic environmental and societal effects [*Bravard et al.*, 1999], and there is an increasing effort to mitigate its consequences and promote channel recovery. The following possible scientific approaches and management strategies can be identified, depending on the decision makers involved, the spatial scale that are considered (local, drainage basin, and national scale), and the geomorphic conditions of the river on which management actions are promoted. This could include (1) promoting a regional vision, based on a geomorphic diagnosis, and identifying associated tools for planning, targeting, and regulating actions and (2) promoting sustainable actions at the local/catchment scale, aimed at preservation, mitigation, or restoration of physical processes and associated channel features. Some examples of application of these possible approaches are provided in the following sections.

### *4.1. Promoting a Regional Vision and Associated Tools for Planning and Targeting Actions*

Braided rivers are generally characterized by high energy, low bank resistance, and a large amount of transported sediment, creating highly dynamic channels, bars, and islands that provide valuable in-channel and riparian habitats. They can alternate expansion and contraction phases, depending on various factors such as sediment supply and the occurrence of large floods. Figure 7 provides a conceptual framework on how various management measures can be associated with different evolutionary phases [*Piégay et al.*, 2006]. Braiding intensity (dotted gray line) decreases with decreasing sediment supply: $t_1$ and $t_2$ represent time-points along a trajectory of evolution from high sediment loads, high braiding intensity (expansion phase) to low sediment supply, low braiding intensity (contraction phase). Social and economic benefits of braided rivers (solid black line) describe a bell-shaped curve, with intermediate levels of braiding providing the most benefits. Ecological benefits (dashed black lines) of braided rivers differ from one system to another according to other parameters (low flow conditions, turbidity, versus diversity). Following trend A, ecological diversity has a peak at an intermediate level of braiding, mostly in riparian environments. Some rivers can also follow trend B (e.g., Fraser River and Platte River) providing ecological value not only at the intermediate levels of braiding but all along the braiding stage; their ecological interest diminishes once the gravel surface area decreases, and the associated optimal habitat conditions are no longer present.

In practical terms, historical geomorphology of rivers must be known at a regional level to understand where they are located on the socioeconomic curve and what the most appropriate management strategies integrating channel evolution at a decadal scale are. Process understanding is important to consider the sensitivity of systems to change and the associated time scale of changes. According to the energy, the distance of the concerned reach to the sediment sources,

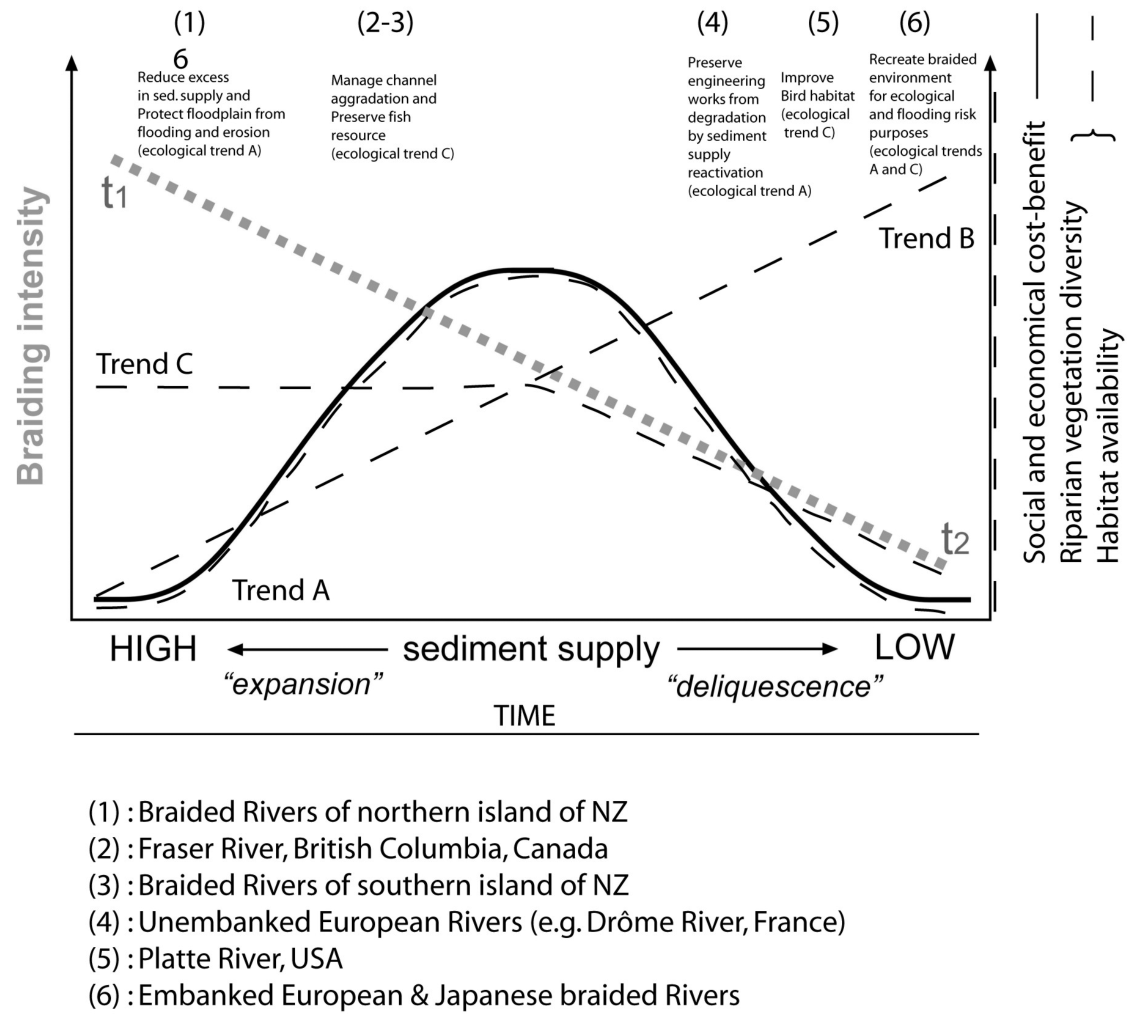


**Figure 7.** Conceptual framework for understanding the relationship between braiding intensity as a function of sediment supply and the ecological and human benefits derived from braided rivers. From the work of *Piégay et al.* [2006], reprinted with permission from John Wiley and Sons.

the capacity of the riparian vegetation to establish, and the time scale of changes all can vary.

Braided rivers were common in Alpine regions during the last century, even if they have undergone dramatic changes due to human activities. Few braided rivers still exist in northeastern Italy (for example the Tagliamento River) and in southeastern France [*Piégay et al.*, 2009], and there is a need to promote their preservation. In a recent study, *Surian et al.* [2009b] have made an attempt to discuss systematically the possible future scenarios of channel changes, starting from past and present trends and considering potential sediment yield and connectivity. The five selected gravel bed rivers in northeastern Italy have undergone notable channel adjustments in the last 100 years, specifically narrowing by up to 76%, incision by up to 8.5 m, and changing from braided to wandering or single-threaded rivers. Alteration of sediment fluxes has been the main factor driving such channel adjustments and has been due to in-channel mining, dams, or other upstream factors (e.g., torrent control works in the drainage basin). Evolutionary channel trends show that channel recovery is ongoing in several of the selected reaches, since widening and aggradation have occurred over the last 15 to 20 years. Channel recovery has been possible because sediment mining has significantly decreased or ceased along the study reaches, but several constraints on sediment fluxes remain. Notably, dams and other transverse structures reduce connectivity with upstream sediment sources to various degrees.

To set restoration goals, it is worth avoiding the identification of a reference state [*Kondolf et al.*, 2007], which hardly can be defined in fluvial systems with a long history of human impact. Instead, it would be useful to restore geomorphic processes that do not imply restoring the channel morphology of the beginning of the twentieth century, i.e., before the major adjustments took place. Pragmatically, the two main goals could be (1) stopping channel incision where it is still occurring and (2) promoting channel widening and shifting, to enhance the natural corridor mosaics and the associated flora and fauna species.

To assess the potentials and limitations of channel recovery, the analysis proceeded in two steps [*Surian et al.*, 2009b]: (1) the identification of the recent trajectory of channel change and (2) the definition of restoration goals for three different scenarios, basin- and reach-scale interventions, reach scale only, and no interventions. Four categories of channel were defined taking into account recent channel

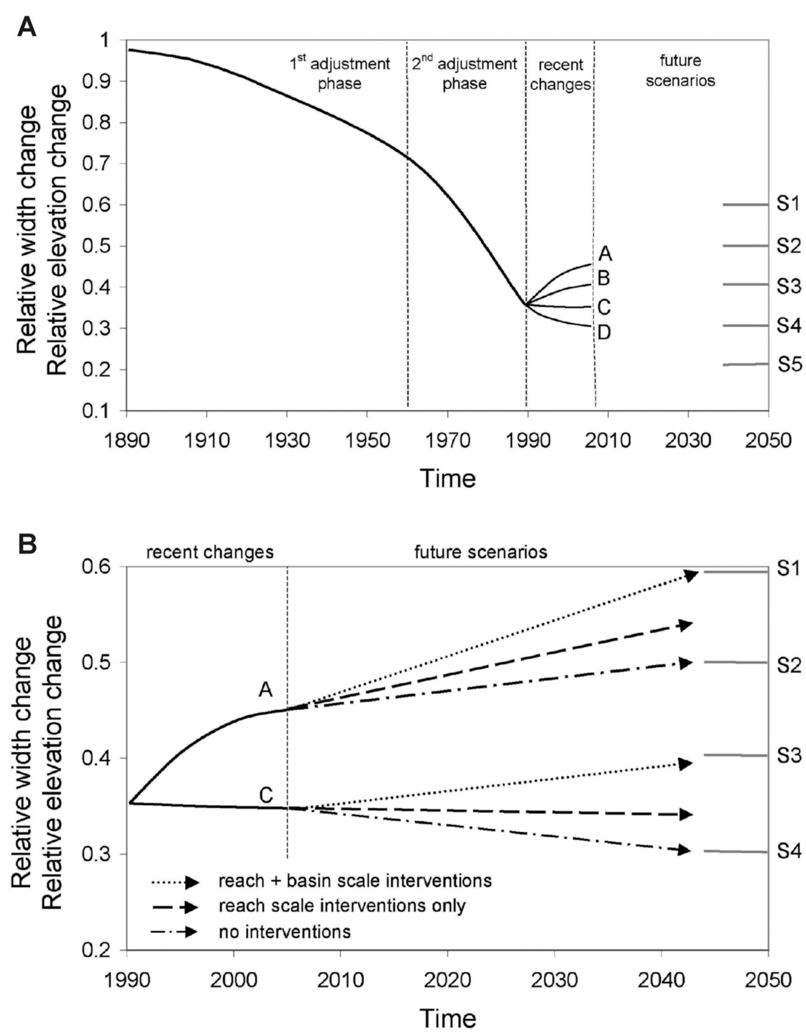


**Figure 8.** (a) Channel adjustments and possible future scenarios of channel recovery in selected rivers of northeastern Italy. The relative magnitude of width and bed-level changes over the twentieth century and four different trajectories of the last 15 to 20 years (A, high recovery; B, moderate recovery; C, slight recovery or no significant changes in channel morphology; D, no channel recovery) are shown. (b) Future scenarios of channel changes according to different strategies of sediment management. The trajectories of possible future evolution are shown for two categories (A and C) out of the four categories shown in Figure 8a. Modified from the work of *Surian et al.* [2009b], reprinted with permission from John Wiley and Sons.

evolution (Figure 8a): A, high recovery; B, moderate recovery; C, slight recovery or no significant changes in channel morphology; and D, no channel recovery. Restoration goals are then defined in the context of an intermediate time scale (40 to 50 years), assuming simplified boundary conditions. It is assumed that there will be no dramatic changes in land use and human activities within the fluvial system in the next 40 to 50 years (e.g., dams will not be removed). Also the morphological effects of very large flood events (e.g., >100 years return period) are not taken into account because of the great uncertainty in assessing such effects using a simple conceptual model. Five future states are shown in Figure 8a, but the entire range is possible as a set of future endpoints. The ways in which different sediment management strategies (reach- and basin-scale interventions) could affect future channel dynamics were analyzed (Figure 8b). Without any intervention, channel recovery would be possible in those reaches that have a relatively high degree of connectivity with upstream sediment sources or tributaries (e.g., category A in Figure 8b). However, further incision and narrowing could be expected in those reaches where connectivity is low or very low. Reach-scale interventions, such as the definition of an erodible corridor and removal of some bank protections, are the most feasible interventions to allow an increase in the supply of coarse sediment. This should help those reaches suffering from reduced upstream connectivity reach an equilibrium condition (e.g., category C in Figure 8b), while it could lead to significant channel recovery in those reaches where bed load transport has been altered to a minor extent (e.g., category A in Figure 8b). A more substantial channel recovery could be obtained through interventions at the basin scale (e.g., adoption of open check dams and sediment transfer downstream of dams). Even though both reach- and basin-scale interventions may be carried out, it is likely that channels will not recover to the morphology they exhibited in the first half of the twentieth century, since sediment yield and connectivity will remain less than during the nineteenth centuries and the first half of the twentieth century. A further step of this analysis could be the use of numerical models. An example of this approach is the application of a model such as Cellular Automaton Evolutionary Slope And River (CAESAR) [*Coulthard et al.*, 2007], which has the capability to reproduce the main features of the braiding morphology and its evolution to long river reaches and over some decades [*Ziliani and Surian*, 2009]. Numerical modeling also allows the exploration of different scenarios from those analyzed using the conceptual model, which relies on simplified assumptions. For instance, the effects of climate change, very large floods, or remarkable changes in land use at catchment scale all can be assessed through a multiscenario approach that includes a wide range of flow and sediment regimes. This would eventually allow the prediction of more complex evolutionary trajectories than those identified by the conceptual model (Figure 8b).

### *4.2. Promoting Sustainable Actions by Implementing Management Strategy Designs*

A first option for promoting sustainable actions is to develop and implement legislative recommendations and management strategy designs. The identification of a “free space,” “functional mobility corridor,” “streamway” [*Malavoi et al.*, 1998] or of an erodible corridor [*Piégay et al.*, 2005] is now a procedure that is recommended in French legislation, with clear constraints for implementing bank protections or authorizing mining in floodplains of shifting rivers. The Management Master plan for the Rhône district states that gravel transport and bank erosion are positive processes to be preserved. In such a legislative context, there is a clear expectation in terms of planning tools in order to define actions on reaches where problems are identified. The use of GIS and orthophotographs to characterize the physical character of rivers to locate specific geomorphic features and reaches sensitive to changes or human pressures is one way to target actions at a network-based scale [*Alber and Piégay*, 2011; *Wiederkehr et al.*, 2010]. In Italy, the definition of such a “streamway” has been required for the Basin Authority Plans, but this was generally identified only in terms of flooding hazard, with few examples that used a geomorphological approach. However, the importance of the erodible corridor concept is increasingly recognized, and some examples of its mapping exist (Tagliamento and Magra rivers).

The case of the Magra River (central northern Italy) is an important example developing an overall strategy for promoting sustainable sediment management [*Rinaldi et al.*, 2009], where the identification of a functional mobility corridor was included in a wider management context. The procedure is composed of four main aspects that are described below.

*4.2.1. Synthesis step.* This is the simplification of diagnostic data to establish a single indicator of geomorphic health. Four indicators were used to summarize diagnostic information: (1) secular bed-level changes (at the scale of about 100 years, i.e., from 1900 to 2006), (2) decennial trend of bed-level adjustments (from 1989 to 2006), (3) bed-level recovery since 1950, and (4) hydraulic sediment budget. From the combination of these four basic indicators, six classes of a geomorphic health index were defined, and three macroclasses were used ((1) prevailing stability-aggradation conditions, (2) intermediate conditions, and (3) past incision, present tendency to incision, and low recovery) to which specific management actions were assigned (see next step).

*4.2.2. Strategic step.* In the strategic step, proposed actions are based on the previous synthesis. A series of management actions to promote sediment recovery at the scale of the main alluvial channels (Magra and Vara) were defined and associated with each of the macroclasses of channel conditions defined above. These include the following: M1, move sediments trapped upstream of weirs; M2, move in-stream sediments; M3, move sediments accumulated on the floodplain into the channel; M4, carry out a bed load release downstream of dams; M5, move sediments in situations of hydraulic risk (for aggradation); M6, introduce sediments deriving from other reaches; and M7, introduce sediments in situations of risk (for local scour).

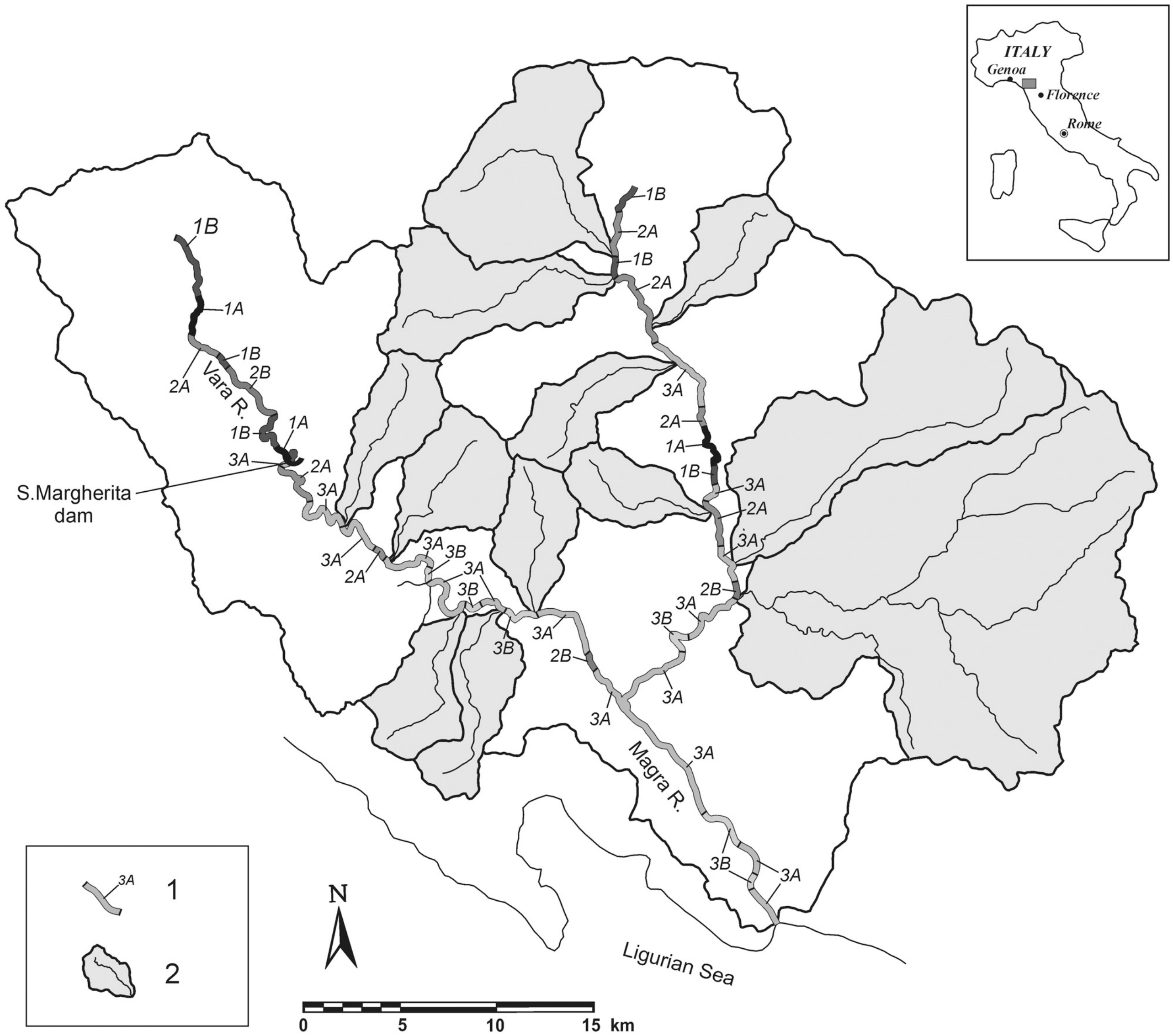


**Figure 9.** Schematic representation of the main elements included in the “map of strategies for sediment management.” Numeral 1 indicates classification of the river segments based on the geomorphic health index. Codes from 1A to 3B, follow a gray scale from black, corresponding to class 1A (highest geomorphic health), to light gray, corresponding to class 3B (lowest geomorphic health). Numeral 2 shows subcatchments selected for potential sediment recharge. The center point of the catchment has approximately the following coordinates: latitude 45°15′N and longitude 9°53′E. Modified from the work of *Rinaldi et al.* [2009], reprinted with permission from John Wiley and Sons.

A series of reaches where the functional mobility corridor encouraged additional sediment supply from eroding banks were identified. Finally, a series of conservation measures (for example, do not stabilize landslides or hillslopes in direct connection with the river channel network) were associated to the catchment areas and features identified as zones of natural sediment recharge. These include the following: C1, do not stabilize landslides; C2, do not stabilize hillslopes in direct connection with the river channel network; C3, do not stabilize eroding stream banks; C4, do not build new transverse hydraulic structures; C5, do not build new longitudinal hydraulic structures; and C6, avoid maintenance of existing hydraulic structures. Obviously, these actions are not applicable in erosion or flood-risk sensitive reaches, such as urbanized areas or areas with particular high-risk elements (single buildings or infrastructure elements).

*4.2.3. Practical methodology to promote sediment delivery.* This step included two different aspects: (1) management of channel mobility and (2) identification of suitable areas for potential sediment recharge. Regarding the first aspect, this was based on the definition of the functional mobility corridor (or erodible corridor) and identification of the reaches where lateral channel mobility can be allowed and/or promoted. Second, to define an overall plan for sediment management at a catchment scale, some basic evaluation of potential recharge at the subcatchment scale was carried out. A semiquantitative approach was used, similar to that recently applied to the catchment of the Drôme River, France [*Liébault et al.*, 2008], to obtain a classification of the basin areas with relative potential for sediment recharge.

*4.2.4. Mapping strategies for a sustainable management of bed sediment at the catchment scale.* A "map of strategies for sediment management" was carried out for the Basin Authority of Magra River as a technical tool to be used for future river management. This map synthesized aspects of morphological evolution, sediment budget assessment, and areas of potential sediment recharge as described above, it reports river segments and associated sediment management recommendations, and it identifies suitable areas for potential bed load recharge and associated management actions and/or measures at both network and catchment scales (Figure 9).

### *4.3. Promoting Restoration Actions*

Beyond legislative recommendations and/or management strategy designs, another possible option is to implement restoration actions to repair or improve existing conditions so that the ecological benefits can be increased. In fact, the current critical management situation (i.e., problems related to channel incision, sediment deficit, and associated biodiversity decrease) has progressively made river restoration a challenging issue in France and Italy, and this trend is reinforced by the European Water Framework Directive, which aims to ensure that rivers attain a good ecological status by 2015.

As in other parts of the world, a progressive shift from small-scale interventions toward "process-based restoration" is observed, where there is an aim to restore natural geomorphic processes to promote conditions of self-sustaining physical diversity. Restoration actions have also shifted toward higher energy, bed load-transport-dominated channels (e.g., in the piedmont Alpine areas). In such environments, successful restoration must include the full spectrum of scales and consider the related natural processes and human boundary conditions [*Habersack and Piégay*, 2008].

In France, a significant number of restoration actions have been carried out during the last few decades, mainly focusing on local scales to enhance fish habitats with artificial structures complicating flow velocity, water depth, and grain size conditions, but also at reach scales to restore processes (reflooding, remeandering, recovering of sediment transport, etc.) (Figure 10). Some of these interventions involve specific consideration of morphological forms and processes, including the following [*Habersack and Piégay*, 2008]:

1. Sediment reintroduction or promotion of bed load supply from floodplains, tributaries, and hillslopes is considered, including the removal of bank protection to recreate natural banks and promote sediment recharge. Relevant applications of this type of approach are relative to the Ain River [*Rollet et al.*, 2008], on the Drôme catchment [*Liébault et al.*, 2008], and a feasibility study is actually being conducted on the Rhine downstream from the Kembs Dam on a 45 km long bypassed section.

2. Former channel reconstruction and reconnection are considered. Old channels were typical features along many peri-alpine rivers, but most of them have been disconnected because of channel narrowing and incision. Their restoration is a well-accepted strategy by local authorities, and significant cases of promoting lateral reconnection by dredging former channels have been implemented in the Rhône restoration plan [*Habersack and Piégay*, 2008].

3. Enlarging river space is also a common practice in central Europe. In rivers of Switzerland and Austria with similar characteristics to the Alpine rivers of northern Italy and southeastern France, much channel widening of previously embanked reaches have already been performed for safety purposes as well as for ecological improvement.

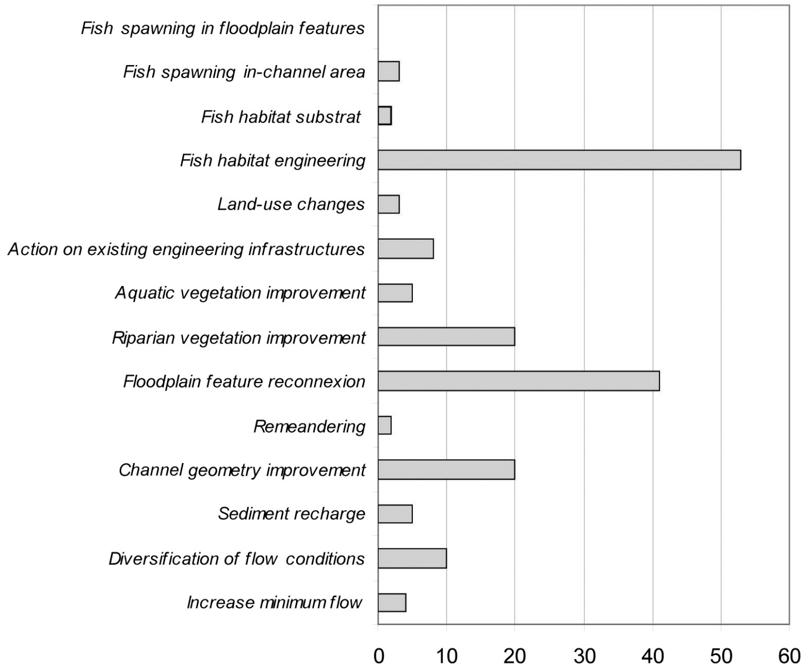


**Figure 10.** Summary of restoration actions censed on the web for the southeastern France: Rhône-Alpes and PACA regions. Data from *Morandi* [2009]. $N = 176$ actions.

Floodplain lowering is also becoming an issue promoted in a win-win perspective, aiming to improve riparian ecosystems along incised river channels with a dry and disconnected floodplain and to cut peak flows downstream by increasing the flood retention capacity of such corridors.

In Italy, notwithstanding increasing experience and evolving approaches, river restoration using geomorphic principles is still in its infancy, emphasizing analysis (i.e., assessment of problems, proposition of strategies, and interventions based on comprehension of processes, etc.) rather than implementing specific interventions. Recently, *Rinaldi and Gumiero* [2008] carried out a brief overview of a series of research projects (Ombrone and Pesa in the Arno River catchment; Vara, Magra, and Panaro rivers) that propose strategies to reconcile flood risk and restoration objectives. All the case studies are similar in that they involve a common morphological channel evolution (channel incision, narrowing, and sediment deficit). The proposed strategies of management and restoration take into account the past channel evolution and are compatible with present trends of channel adjustments. In particular, the option of promoting channel recovery, by allowing natural channel adjustments, rather than morphological reconstruction, is identified as the best strategy, being that the sediment load and stream power of these rivers is sufficiently high.

Several challenging issues and open points still remain for a wider application of process-based morphological restoration, including (1) feasibility of such interventions, in relation to possible negative consequences in terms of other uses and risk conditions; (2) sustainability and self-maintenance of reactivated processes or recreated forms in the long term; and (3) ecological benefits of such measures are still under investigation, and there is an urgent need to link ecological to geomorphological processes.

## 5. CONCLUSIONS

This chapter presented an overview on recent progress in using geomorphic approaches to river management and restoration by providing a series of case studies and applications to some Italian and French rivers.

Knowledge of channel evolution, temporal trajectory of adjustments, and causes and sensitivity to changes provides the basis for defining channel and sediment management strategies. Most Italian and French alluvial rivers considered here are characterized by a similar history of human disturbance and trends of channel adjustment, with a historical phase of aggradation followed by a period of intense channel incision and narrowing, yet these river systems differed in terms of their controlling factors and evolution scenarios.

Cases of recent widening are also observed along some of the Italian and French rivers, and this widening appears to be associated with the cessation of intense gravel mining (Italian rivers) and/or with more intense floods that occurred in the 1990s. The sediment deficit resulting from human pressures that occurred between the 1940s and the 1960s within the Drôme and Ain catchments (France) demonstrates that the adjustment process at the regional scale is just beginning, and will probably continue downstream for many years to come. These types of channel adjustments have led to an increasing need for sustainable management of bed load transport and other physical processes.

The quantification of bed load transport and bed sediment budget, therefore, is fundamental to understanding the balance between sediment transport and delivery. Various examples of a morphological approach for sediment budgeting have been provided. For the Brenta River (northeastern Italy), where the spatial variations of bed load along the reach were analyzed, most of the material available for transport was sourced from local erosion. and only a small proportion was derived from the drainage basin. The analysis also showed that bank erosion was the dominant process from 1984 to 1997, contributing 83% of the total erosion in the study reach. For the Magra and Vara rivers (central and northern Italy), sediment budgets were constructed using sediment transport equations for each of a series of discrete subreaches to classify their tendency to incision or aggradation. Examples of bed load yields for select rivers of the Southern French Prealps were used to establish a regional law linking catchment size and the mean annual bed load transport.

Finally, previous knowledge for designing regional visions, strategies, and targeting actions were used to assess these rivers. Examples were presented to illustrate how scientific approaches and management strategies can be used to promote a regional vision, based on a geomorphic diagnosis, and identifying associated tools for planning, targeting, and regulating actions, and to promote sustainable actions at the local/catchment scale, aimed at preservation, mitigation, or restoration of physical processes and associated channel features.

## REFERENCES


Alber, A., and H. Piégay (2011), Spatial disaggregation and aggregation procedures for characterizing fluvial features at the network-scale: Application to the Rhône basin (France), *Geomorphology*, *125*, 343–360, doi:10.1016/j.geomorph.2010.09.009.

Billi, P., M. Rinaldi, and A. Simon (1997), Disturbance and adjustment of the Arno River, Central Italy. I: Historical perspective, the last 2000 years, in *Management of Landscapes Disturbed by Channel Incision, Stabilization, Rehabilitation, Restoration*, edited by S. S. Y. Wang et al., pp. 595–600, Cent. for the Comput. Hydrosci. and Eng., Univ. of Miss., Oxford.

Boon, P. J., P. Calow, and G. E. Petts (1992), *River Conservation and Management*, 470 pp., John Wiley, Chichester, U. K.

Bravard, J. P. (1991), La dynamique fluviale à l'épreuve des changements environnementaux: Quels enseignements applicables à l'aménagement des rivières?, *La Houille Blanche*, *7–8*, 515–521.

Bravard, J. P., G. M. Kondolf, and H. Piégay (1999), Environmental and societal effects of river incision and remedial strategies, in *Incised River Channels*, edited by A. Simon and S. E. Darby, pp. 303–341, John Wiley, Chichester, U. K.

Brewer, P. A., and D. G. Passmore (2002), Sediment budgeting techniques in gravel-bed rivers, *Geol. Soc. Spec. Publ.*, *191*, 97–113.

Brierley, G. J., and K. A. Fryirs (2005), *Geomorphology and River Management: Applications of the River Style Framework*, Blackwell, Oxford, U. K.

Caporali, E., M. Rinaldi, and N. Casagli (2005), The Arno River floods, *G. Geol. Appl.*, *1*, 177–192.

Coulthard, T. J., D. M. Hicks, and M. J. Van de Wiel (2007), Cellular modelling of river catchments and reaches: Advantages, limitations and prospects, *Geomorphology*, *90*, 192–207, doi:10.1016/j.geomorph.2006.10.030.

Dufour, S., and H. Piégay (2009), From the myth of a lost paradise to targeted river restoration: Forget natural references and focus on human benefits, *River Res. Appl.*, *25*, 568–581, doi:10.1002/rra.1239.

Florsheim, J. L., J. F. Mount, and A. Chin (2008), Bank erosion as a desirable attribute of rivers, *Bioscience*, *58*(6), 519–529.

Garcia-Ruiz, J. M., S. M. White, T. Lasanta, C. Marti, C. Gonzalez, M. P. Errea, B. Valero, and L. Ortigosa (1997), Assessing the effects of land-use changes on sediment yield and channel dynamics in the central Spanish Pyrenees, in *Human Impact on Erosion and Sedimentation, Proceedings of Rabat Symposium S6*, edited by D. E. Walling and J. L. Prost, *IAHS Publ.*, *245*, 151–158.

Goodson, J. M., A. M. Gurnell, P. G. Angold, and I. P. Morrissey (2002), Riparian seed banks along the lower River Dove UK: Their structure and ecological implications, *Geomorphology*, *47*, 45–60, doi:10.1016/S0169-555X(02)00140-X.

Griffiths, G. A. (1979), Recent sedimentation history of the Waimakariri River, New Zealand, *J. Hydrol. N. Z.*, *18*, 6–28.

Habersack, H., and H. Piégay (2008), River restoration in the Alps and their surroundings: past experience and future challenges, in *Gravel-bed Rivers VI: From Process Understanding to River Restoration*, edited by H. Habersack et al., *Dev. Earth Surf. Processes*, *11*, 703–735.

Ham, D. G., and M. Church (2000), Bed-material transport estimated from channel morphodynamics: Chilliwack River, British Columbia, *Earth Surf. Processes Landforms*, *25*, 1123–1142.

Hervouet, A. (2010), Analyse temporelle de la structure et de la dynamique de végétalisation des rivières en tresses des Alpes du

Sud, Mémoire de fin d'étude d'ingénieur, report, 71 pp., ENGEES and Université de Lyon (UMR 5600), Lyon, France.

Kondolf, G. M., H. Piégay, and D. Sear (2003), Integrating geomorphological tools in ecological and management studies, in *Tools in Fluvial Geomorphology*, edited by M. G. Kondolf and H. Piégay, pp. 633–660, John Wiley, Chichester, U. K.

Kondolf, G. M., H. Piégay, and N. Landon (2007), Changes in the riparian zone of the lower Eygues River, France, since 1830, *Landscape Ecol.*, *22*, 367–384, doi:10.1007/s10980-006-9033-y.

Landon, N., H. Piégay, and J. P. Bravard (1998), The Drôme river incision (France): From assessment to management, *Landscape Urban Plann.*, *43*, 119–131.

Le Lay, Y. (2007), Les hommes et le bois en rivière. Représentations, pratiques et stratégies de gestion dans le cadre de l'entretien des cours d'eau, Ph.D. thesis, Univ. of Lyon, Lyon, France.

Liébault, F. (2003), Les rivières torrentielles des montagnes drômoises: Évolution contemporaine et fonctionnement géomorphologique actuel (massifs du Diois et des Baronnies), Ph.D. thesis, 358 pp., Univ. Lumiére Lyon 2, Lyon, France.

Liébault, F. (2005), Morphological response of an alpine torrent to watershed reforestation (The Sure Torrent, Southern French Prealps), *Stud. Geomorphol. Carpatho-Balcanica*, *XXXIX*, 50–69.

Liébault, F., and P. Clement (2007), La mobilité de la charge de fond des riviéres torrentielles méditerranéenes, *Geogr. Phys. Quat.*, *61*(1), 7–20.

Liébault, F., and H. Piégay (2001), Assessment of channel changes due to long-term bedload supply decrease, Roubion River, France, *Geomorphology*, *36*, 167–186.

Liébault, F., and H. Piégay (2002), Causes of 20th century channel narrowing in mountain and piedmont rivers of southeastern France, *Earth Surf. Processes Landforms*, *27*, 425–444, doi:10.1002/esp.328.

Liébault, F., B. Gomez, M. Page, M. Marden, D. Peacock, D. Richard, and C. M. Trotter (2005), Land use change, sediment production and channel response in upland regions, *River Res. Appl.*, *21*, 739–756, doi:10.1002/rra.880.

Liébault, F., H. Piégay, P. Frey, and N. Landon (2008), Tributaries and the management of main-stem geomorphology, in *River Confluences and the Fluvial Network*, edited by S. Rice et al., pp. 243–270, John Wiley, Chichester, U. K.

McLean, D. G., and M. Church (1999), Sediment transport along lower Fraser River 2. Estimates based on the long-term gravel budget, *Water Resour. Res.*, *35*, 2549–2559.

Malavoi, J. R., J. P. Bravard, H. Piégay, E. Hérouin, and P. Ramez (1998), Détermination de l'espace de liberté des cours d'eau, *Guide Tech. 2*, 39 pp., Schéma Dir. d'Aménagement et de Gestion de l'eau Rhône-Méditerr.-Corse, Lyon, France.

Morandi, B. (2009), Retour d'expérience sur les suivis réalisés en matière de restauration des cours d'eau sur le territoire métrotropolitain, Mém. de master 1, Univ. Paris, UMR 5600 CNRS, Lyon, France.

Peiry, J. L. (1987), Channel degradation in the middle Arve river, France, *Reg. Rivers Res. Manage.*, *1*, 183–188.

Pellegrini, L., F. Maraga, O. Turitto, C. Audisio, and G. Duci (2008), Evoluzione morfologica di alvei fluviali mobili nel settore occidentale del bacino padano, *Ital. J. Quat. Sci.*, *21*(1B), 251–266.

Piégay, H., S. E. Darby, E. Mosselman, and N. Surian (2005), A review of techniques available for delimiting the erodible river corridor: A sustainable approach to managing bank erosion, *River Res. Appl.*, *21*, 773–789, doi:10.1002/rra.881.

Piégay, H., G. Grant, F. Nakamura, and N. Trustrum (2006), Braided river management: From assessment of river behaviour to improved sustainable development, in *Braided Rivers: Process, Deposits, Ecology and Management*, edited by G. H. Sambrook-Smith et al., *Spec. Publ. Int. Assoc. Sedimentol.*, *36*, 257–275.

Piégay, H., A. Alber, L. Slater, and L. Bourdin (2009), Census and typology of the braided rivers in the French Alps, *Aquat. Sci.*, *71*(3), 371–388.

Pont, D., H. Piégay, A. Farinetti, S. Allain, N. Landon, F. Liébault, B. Dumont, and A. Mazet (2009), Conceptual framework and interdisciplinary approach for the sustainable management of gravel-bed rivers: The case of the Drôme River basin (SE France), *Aquat. Sci.*, *71*(3), 356–370.

Rinaldi, M. (2003), Recent channel adjustments in alluvial rivers of Tuscany, Central Italy, *Earth Surf. Processes Landforms*, *28*(6), 587–608, doi:10.1002/esp.464.

Rinaldi, M., and B. Gumiero (2008), Restoring geomorphic and ecological processes in incised rivers: Problems, criteria and approaches in the Northern Apennine (Italy), *4th ECRR International Conference on River Restoration*, edited by B. Gumiero et al., pp. 457–466, Ind. Graf. Ital., Costabissara, Italy.

Rinaldi, M., and A. Simon (1998), Bed-level adjustments in the Arno River, central Italy, *Geomorphology*, *22*, 57–71.

Rinaldi, M., B. Wyżga, and N. Surian (2005), Sediment mining in alluvial channels: Physical effects and management perspectives, *River Res. Appl.*, *21*, 805–828, doi:10.1002/rra.884.

Rinaldi, M., L. B. Teruggi, C. Simoncini, and L. Nardi (2008), Dinamica recente ed attuale di alvei fluviali: alcuni casi di studio appenninici (Italia Centro-Settentrionale), *Ital. J. Quat. Sci.*, *21*(1B), 291–302.

Rinaldi, M., C. Simoncini, and H. Piégay (2009), Scientific design strategy for promoting sustainable sediment management: The case of the Magra River (Central-Northern Italy), *River Res. Appl.*, *25*, 607–625, doi:10.1002/rra.1243.

Rollet, A. J. (2007), Etude et gestion de la dynamique sédimentaire d'un tronçon fluvial à l'aval d'un barrage: Le cas de la basse vallée de l'Ain, Ph.D. thesis, 305 pp., Univ. of Lyon 3, Lyon, France.

Rollet, A. J., H. Piégay, G. Bornette, and H. Persat (2008), Sediment dynamics, channel morphology and ecological restoration downstream a dam: The case of the Ain River, *4th ECRR International Conference on River Restoration*, edited by B. Gumiero et al., pp. 497–504, Ind. Graf. Ital., Costabissara, Italy.

Rovira, A., R. J. Batalla, and M. Sala (2005), Response of a river sediment budget after historical gravel mining (the lower Tordera, NE Spain), *River Res. Appl.*, *21*, 829–847, doi:10.1002/rra.885.

Simoncini, C. (2008), Studio delle problematiche legate ai sedimenti fluviali ed applicazione di una metodologia finalizzata alla gestione a scala di bacino idrografico, Ph.D. thesis, 189 pp., Univ. di Firenze—Univ. of Lyon, Lyon, France.

Surian, N. (1999), Channel changes due to river regulation: The case of the Piave River, Italy, *Earth Surf. Processes Landforms*, *24*, 1135–1151.

Surian, N., and A. Cisotto (2007), Channel adjustments, bedload transport and sediment sources in a gravel-bed river, Brenta River, Italy, *Earth Surf. Processes Landforms*, *32*, 1641–1656, doi:10.1002/esp.1591.

Surian, N., and M. Rinaldi (2003), Morphological response to river engineering and management in alluvial channels in Italy, *Geomorphology*, *50*, 307–326, doi:10.1016/S0169-555X(02)00219-2.

Surian, N., L. Ziliani, L. Cibien, A. Cisotto, and F. Baruffi (2008), Variazioni morfologiche degli alvei dei principali corsi d'acqua veneto-friulani negli ultimi 200 anni, *Ital. J. Quat. Sci.*, *21*(1B), 279–290.

Surian, N., M. Rinaldi, L. Pellegrini, C. Audisio, F. Maraga, L. B. Teruggi, O. Turitto, and L. Ziliani (2009a), Channel adjustments in Italian rivers: Evolutionary trends, causes and management implications, in *Management and Restoration of Fluvial Systems with Broad Historical Changes and Human Impacts*, edited by L. A. James et al., *Spec. Pap. Geol. Soc. Am.*, *451*, 83–95.

Surian, N., L. Ziliani, F. Comiti, M. A. Lenzi, and L. Mao (2009b), Channel adjustments and alteration of sediment fluxes in gravel-bed rivers of North-Eastern Italy: Potentials and limitations for channel recovery, *River Res. Appl.*, *25*, 551–567, doi:10.1002/rra.1231.

Wiederkehr, E., S. Dufour, and H. Piégay (2010), Localisation et caractérisation semi-automatique des géomorphosites fluviaux potentiels. Exemples d'applications à partir d'outils géomatiques omatiques dans le bassin de la Drôme, *Geomorphol. Relief Processus Environ.*, *2*, 175–188.

Wohl, E., P. L. Angermeier, B. Bledsoe, G. M. Kondolf, L. McDonnell, D. M. Merritt, M. A. Palmer, L. Poff, and D. Tarboton (2005), River restoration, *Water Resour. Res.*, *41*, W10301, doi:10.1029/2005WR003985.

Wong, M., and G. Parker (2006), The bedload transport relation of Meyer-Peter and Müller overpredicts by a factor of two, *J. Hydraul. Eng.*, *132*(11), 1159–1168.

Ziliani, L., and N. Surian (2009), Modelling past and future channel changes in a large gravel-bed river, paper presented at Geoitalia 2009, Rimini, Italy, 9–11 Sept.

---

H. Piégay, University of Lyon, CNRS-UMR 5600, Site of ENS, 15 Parvis René Descartes, F-69007 Lyon, France.

M. Rinaldi, Department of Civil and Environmental Engineering, University of Florence, Via S. Marta 3, I-50139 Firenze, Italy. (mrinaldi@dicea.unifi.it)

N. Surian, Department of Geography, University of Padova, Via del Santo 26, I-35123 Padova, Italy.