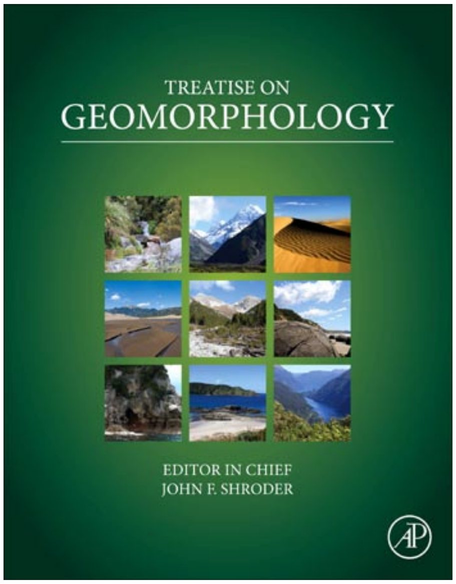

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12.4 River Processes and Implications for Fluvial Ecogeomorphology: A European Perspective

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Abstract

In this chapter, the state of the art of the research of fluvial processes and their linkages with ecology are presented, with a focus on European physical context. European river systems have experienced a long history of catchment-wide (land-use changes) and in-channel human disturbances (channelization, dams, sediment mining, etc.). In many rivers, the impacts on river morphology culminated in the twentieth century, particularly during recent decades, and major alterations to river functioning are also forecast for the nearby future due to climate changes. Considerable progress in understanding, quantifying, and modeling channel processes has emerged from recent European research and findings on sediment transport, bank erosion, and the formation of various channel patterns in rivers are discussed. Major concepts linking the structure and functioning of river ecosystem with fluvial processes are presented, followed by a discussion of the impacts of geomorphic processes on the connectivity, habitat heterogeneity, and a scale of flood disturbance in riverine ecosystems. With the increasing emphasis on reestablishing good ecological quality of European rivers, an improved understanding of the impacts of hydromorphology on river biodiversity and defining the scientific bases for river management and restoration by the use of process-oriented approach are necessary.

12.4.1 Introduction

Physical river processes are increasingly seen as vital for creating and maintaining physical habitats and aquatic and riparian ecosystems. As a result, their understanding as well as linkages and feedbacks with ecology and hydrology are assuming crucial importance for river management and restoration.

European river systems have experienced a long history of human impacts and modifications including changes in catchment and floodplain land use; channelization; flow regulation, particularly the installation of dams; and sediment mining (Petts et al., 1989). These disturbances have induced complex and multiple phases of channel adjustments, with a number of detrimental environmental, ecological, and societal effects (Bravard et al., 1999). A first step for understanding present process–form interactions and predicting future trends of channel adjustments is to reconstruct the past history of human impacts and the long-term trajectory of channel changes.

Physical processes and their linkages with ecosystem quality have become a priority within the context of the Water Framework Directive (WFD; European Commission, 2000), with 'hydromorphology' forming one of the aspects that need to be considered in the monitoring and ecological assessment of rivers. This increasing focus on the physical habitats created by geomorphological processes has highlighted the importance of these processes in sustaining biodiversity.

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Against this background, the aim of this chapter is to synthesize the current state of the art in relation to fluvial processes and their linkages with ecology. In particular, the importance of process-oriented approaches and strategies for river management and restoration are emphasized with a focus on the European physical context.

12.4.2 The Long-term Perspective: Past, Present, and Future Trends in Channel Adjustments

Fluvial landscapes follow complex trajectories in time depending on their geographical context, because they result from the combination and the overlay of three main interacting factors: hydrological and morphological processes; biological interactions; and human setting (Dufour and Piégay, 2009). Rivers continuously adjust to environmental conditions following a trajectory of adjustments as environmental conditions change. The conjunction of key drivers is continuously variable in time and space (climate, vegetation cover, and human activities) and the local conditions are always new. Reconstructing the fluvial trajectory and the impacting factors are key issues for understanding past evolution and possible future trends of a fluvial system.

12.4.2.1 Past Trends in Channel Adjustment

Changes to catchment and riparian vegetation cover were the earliest human activities inducing significant adjustments to river channel and valley floor morphology. In Europe, deforestation was linked with pastoral and then agricultural activities that started in the Neolithic period, *ca* 4500 BC (Williams, 2000). Since then deforestation across Europe has progressed with some phases of notably increased intensity, such as the Roman period, culminating in peak levels of deforestation in the nineteenth century. At this time, most montane and foothill slopes across Europe were under cultivation or grazing. Because the intensity of slope wash on cultivated slopes exceeds that on forested slopes by a few orders of magnitude, deforestation was commonly accompanied by aggradation on valley floors (Starkel, 1995). From the seventeenth to the nineteenth centuries, the intensity of runoff and erosion on hillslopes became so high that widespread channel aggradation occurred with a downstream-progressing transformation of single-thread to braided channels in many mountain and piedmont valley reaches (e.g., Wyżga, 1993a; Gurnell et al., 2009). In contrast with continuing deforestation in other parts of the world, during the twentieth century the trend was reversed in many European catchments, especially montane ones (**Figure 1**). This increasing forest cover contributed to a reduction in catchment sediment supply (Liébault et al., 2005) followed by channel narrowing and incision (e.g., Kondolf et al., 2002; Lach and Wyżga, 2002; Keesstra et al., 2005) and a decline of multi-thread channel patterns in many rivers (Gurnell et al., 2009).

In addition to catchment land-use disturbances, European rivers have experienced a long history of in-channel human modifications stretching back to Roman times (Petts et al., 1989; Billi et al., 1997). Up to the nineteenth century, the most common modifications were embankments, channelization, and flow diversions, which were undertaken to provide flood protection, support the expansion of agriculture, and, lately, to improve navigation along large rivers. From the end of the nineteenth century, apart from reafforestation and interventions for stabilizing hillslopes (**Figure 2(a)**), a large number of check dams were built along headwater channels in many mountain areas (**Figure 2(b)**) coupled with larger dams along downstream river reaches. These structures drastically reduced the sediment supply to downstream reaches and also created discontinuities in the fluxes of water and sediment, impacting morphological processes and their interrelationships with ecological dynamics. However, large impacts on river morphology became most marked in many rivers during the twentieth century, and, particularly, during recent decades, in response to increasing urban and industrial development after World War II.

Numerous studies on European rivers have demonstrated similar trends of channel adjustments. These have included an early, historical period characterized by aggradational processes affecting different components of the fluvial system (alluvial plain, channel bed, and delta), followed by a reversal of the general aggradational trend in the late nineteenth century and twentieth century (**Figure 3**) as a result of various types of human disturbances (Petts et al., 1989; Łajczak, 1995; Bravard et al., 1997) and widespread hillslope reafforestation and upland sediment retention, against a background of climate changes following the end of the Little Ice Age. These trends have been observed in many parts of Europe, including the piedmont areas of mountain (Liébault and Piégay, 2002) and Mediterranean (Hooke, 2006) regions.

A significant expansion in the literature on channel adjustments has occurred during the last two decades, with studies focusing on river channel changes caused by human disturbances emanating from many areas of Europe, including France (Liébault and Piégay, 2001, 2002), Poland (Wyżga, 1993b, 2001a, 2001b, 2008), Italy (Rinaldi and Simon, 1998; Rinaldi, 2003; Surian and Rinaldi, 2003; Surian et al., 2009a) (**Figure 4**), Spain (Garcia-Ruiz et al., 1997; Rovira et al., 2005), and the United Kingdom (e.g. Winterbottom, 2000). In particular, in-channel sediment mining has been widely recognized among the human impacts inducing large effects on river morphology during the twentieth century (Rinaldi et al., 2005; Rovira et al., 2005). Despite the different types of disturbances, common channel responses have been observed, with two dominant types of morphological adjustments being channel incision and narrowing. In most cases, these responses have been attributed to alterations in sediment fluxes (Liébault and Piégay, 2002; Surian and Rinaldi, 2003), but where upstream progression of channel changes have occurred, channelization and a resultant increase in the river's transport capacity have been implicated (Wyżga, 2008; Zawiejska and Wyżga, 2010).

These channel adjustments have had dramatic environmental and societal effects (Bravard et al., 1999), including many ecological effects such as: (1) destruction or reduction of in-channel alluvial features that are important for habitat diversity; (2) bed coarsening and loss of gravel of a size suitable for fish spawning; (3) water-table lowering and consequent effects on riparian vegetation; and (4) disruption of

Figure 1 Examples from French Alpine regions of increasing forest cover on hillslopes and fluvial corridors, and associated channel narrowing. (a) Ubaye River and its tributary, Riou Bourdoux (downstream Barcelonnette, Southern Alps). Reproduced from Piégay, H., Grant, G., Nakamura, F., Trustrum, N., 2006. Braided river management: from assessment of river behaviour to improved sustainable development. In: Sambrook-Smith, G.H., Best, J.L., Bristow, C.S., Petts, G.E. (Eds.), Braided Rivers: Process, Deposits, Ecology and Management. Special Publication 36 of the International Association of Sedimentologists. Blackwell, Oxford, pp. 257–275, with permission from Wiley. (b) Drome River in the Vercheny Plain, 30 km upstream of Saillans. Reproduced from Kondolf, G.M., Piégay, H., Landon, N., 2002. Channel response to increased and decreased bedload supply from land use change: contrasts between two catchments. Geomorphology 45, 35–51.

lateral hydraulic connectivity with the floodplain, with the latter effectively becoming a terrace, and a resulting loss of wet areas and related habitats.

Given all these negative impacts, a capability to predict or generate possible scenarios of future trends of channel adjustments is essential to prevent their consequences. An example of such a capability is the analysis of how different sediment management strategies might affect future channel dynamics (Surian et al., 2009b).

12.4.2.2 Riparian Vegetation and Channel Change

One particular consequence of changes in morphological channel pattern over time is their effect on riparian vegetation. Phases of dynamic channel change, such as those that occurred during the Little Ice Age, were characterized by an open landscape dominated by pioneer vegetation communities, whereas phases of more stable channel morphology favored the establishment of woodland dominated by hardwood species (**Figure 5**). At a reach scale, the physiognomy of the fluvial landscape was also shaped by direct human impacts on riparian vegetation, including woodland clearance, grazing, burning, and agricultural land use, all of which favored pioneer stages and nonwoody communities.

Initially underestimated by fluvial geomorphologists, the influence of riparian vegetation (both standing and dead trees) on the morphological river pattern is now well established (Corenblit et al., 2007; Francis et al., 2009; Gurnell et al., 2009). Modification to channel morphology can be driven not only by changes in sediment supply and/or flood discharges but also by changes in local human activities (e.g., grazing abandonment). This point is critical in the European context because most river corridors have experienced strong human influence over several centuries (Petts et al., 1989) and even millennia (e.g., Higler, 1993). Thus, the general trend over the Holocene has been a decrease in natural habitats and a progressive humanization of riparian areas. However, this human impact has varied due to changes in population densities and technology with some periods apparently suffering more intense impacts, such as the Roman period or the climatic optimum during the Middle Ages. Historical data document heavily impacted riparian areas during the nineteenth century, when they were extensively grazed or cultivated and dominated by a predominantly open landscape and pioneer vegetation communities (e.g., Kondolf et al., 2002).

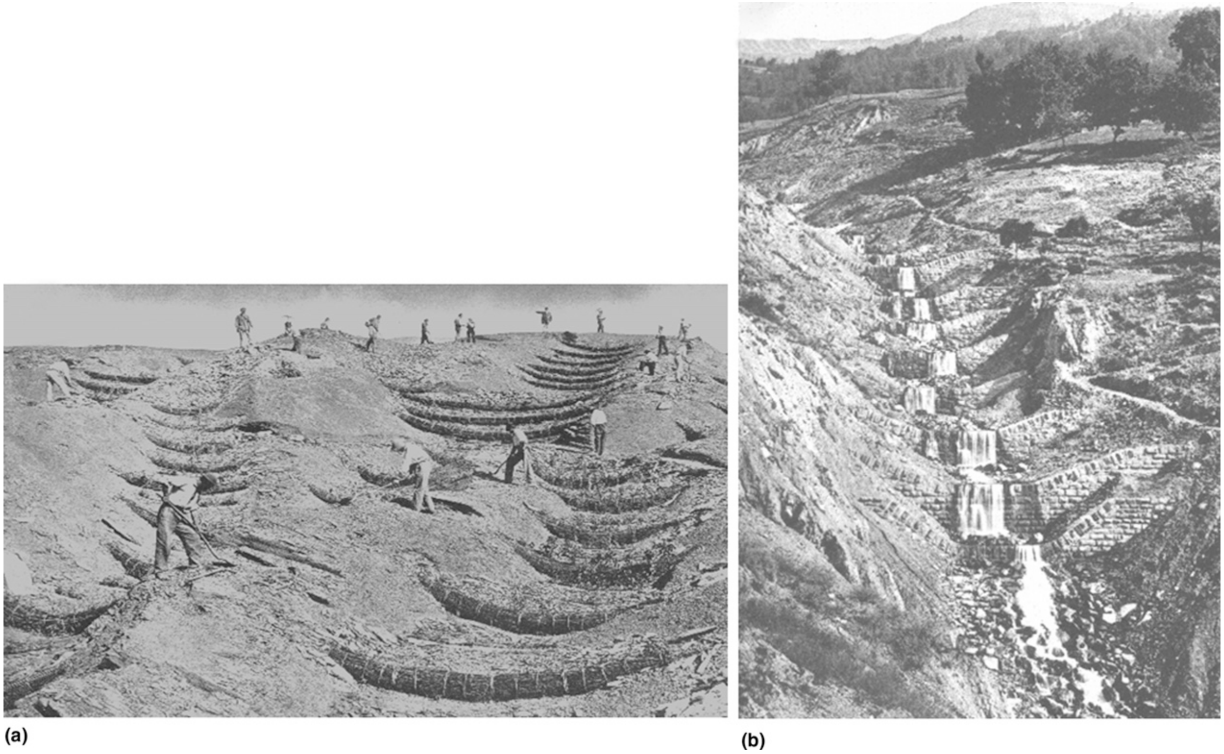

Figure 2 Examples of works done at the end of the nineteenth century in France for stabilization of hillslopes (a), and longitudinal profile of mountain streams (b). Reproduced from Piégay, H., Rinaldi, M., 2006. Gestione sostenibile dei sedimenti in fiumi ghiaiosi incisi in Francia. Atti Giornate di Studio ''Nuovi approcci per la comprensione dei processi fluviali e la gestione dei sedimenti. Applicazioni nel bacino del Magra.'' Sarzana, 24–25 October 2006. Autorità di Bacino del Fiume Magra, pp. 59–80, with permission from Autorita.

Figure 3 Sedimentary record of the aggradational/degradational tendencies of the middle Raba River, Polish Carpathians, from the last two centuries. The shallow braid was eroded in the upper part of the sequence of overbank deposits and filled with massive gravel at about the turn of the twentieth century, with the culmination of the aggradational river tendency. A high position of the braid above the low-water level in the contemporary channel testifies to the rapid incision of the Raba over the last century. Marks on the rope stretched along the cut bank are spaced at 1-m intervals. Reproduced from Wyżga, B., 2008. A review on channel incision in the Polish Carpathian rivers during the 20th century. In: Habersack, H., Piégay, H., Rinaldi, M. (Eds.), Gravel-Bed Rivers VI: From Process Understanding to River Restoration. Developments in Earth Surface Processes 11. Elsevier, Amsterdam, pp. 525–555.

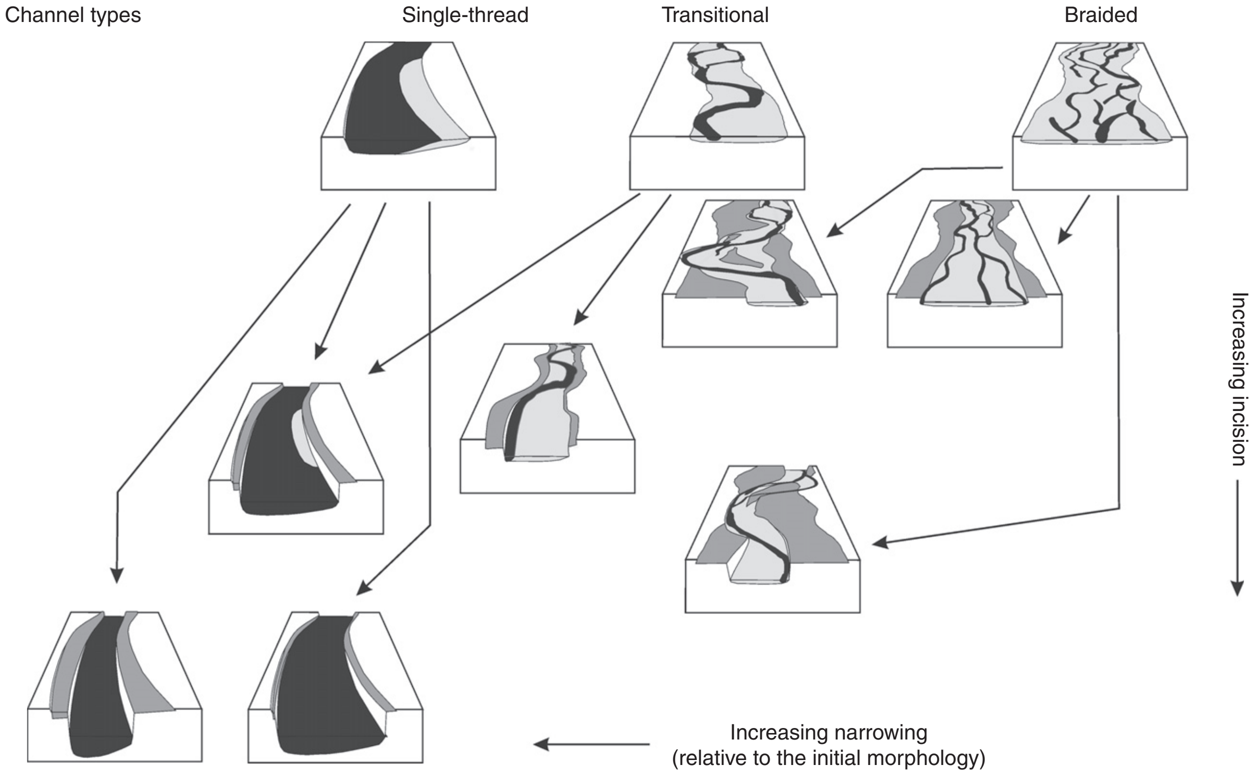

Figure 4 Summary of main types of channel adjustments in Italian rivers during the past 100 years. Starting from three initial morphologies, different channel adjustments were observed according to variable amount of incision and narrowing. Modified from Surian, N., Rinaldi, M., 2003. Morphological response to river engineering and management in alluvial channels in Italy. Geomorphology 50, 307–326.

The relatively high fluvial activity at that time contributed to the maintenance of an open landscape, notably in high-gradient river reaches. Since about the end of the nineteenth century, European river margins have exhibited two different trends. Along upland and piedmont river reaches, a decrease in population density and changes in management practices have allowed an increase in the area of riparian forest. At the same time, many valley reaches, especially in lowland areas, have remained under cultivation and grazing or, where protected from flooding, have experienced industrial or urban development.

The progressive clearance of riparian vegetation, coupled with removal of wood from channels, has led to a heavy decrease in wood loading in European rivers. Although this has eliminated a considerable source of hydraulic roughness from channels, the desnagging of European rivers has not resulted in vertical instability of their beds (Brierley et al., 2005), probably because the reduction in flow resistance has been compensated by an increasing sediment supply as a result of deforestation across the catchment. Only in the twentieth century, when catchment sediment supply decreased following an increase in forest cover, could the lack of hydraulic roughness associated with woody debris contribute to the rapid channel incision that has been recorded recently in many European rivers. This trend contrasts with the situation in North America and Australia where rivers and valleys were the first landscape features modified after European settlement and where clearance of riparian vegetation and removal of woody debris immediately induced rapid, deep channel incision (Brierley et al., 2005).

12.4.2.3 Impacts of Climate Change on Channel Dynamics

Besides human activities, climate change is another important factor inducing long-term channel adjustments due to its impacts on the amount and timing of runoff, the vegetation cover, and activation or suppression of sediment sources. For instance, increased frequency/magnitude of floods and enhanced fluvial activity during the second half of the Little Ice Age (1750–1900) were documented across vast areas of Europe (Rumsby and Macklin, 1996). In mountain and piedmont areas of Western, Central, and Southern Europe, they coincided with the phase of intense agricultural and pastoral activities on hillslopes and led to increased sediment delivery to channels, bed aggradation, channel widening, and river braiding (e.g., Bravard, 1989; Wyżga, 1993a).

Although climate change during the Little Ice Age and the rate of subsequent twentieth-century warming are considered exceptional in the Holocene, they are relatively small in comparison with projected global temperature increases of 1.4–5.8 °C under various scenarios over the twenty-first century (European Commission, 2005). A moderate temperature increase in Southern, Central, and Eastern Europe is forecast to be accompanied by a reduction in precipitation totals, whereas a much larger increase in temperature associated with increased winter and spring precipitation is forecast for Northern Europe (European Commission, 2005). Moreover, the incidence of extreme summer precipitation events is predicted to increase over large areas of Europe (e.g., Christensen and Christensen, 2004).

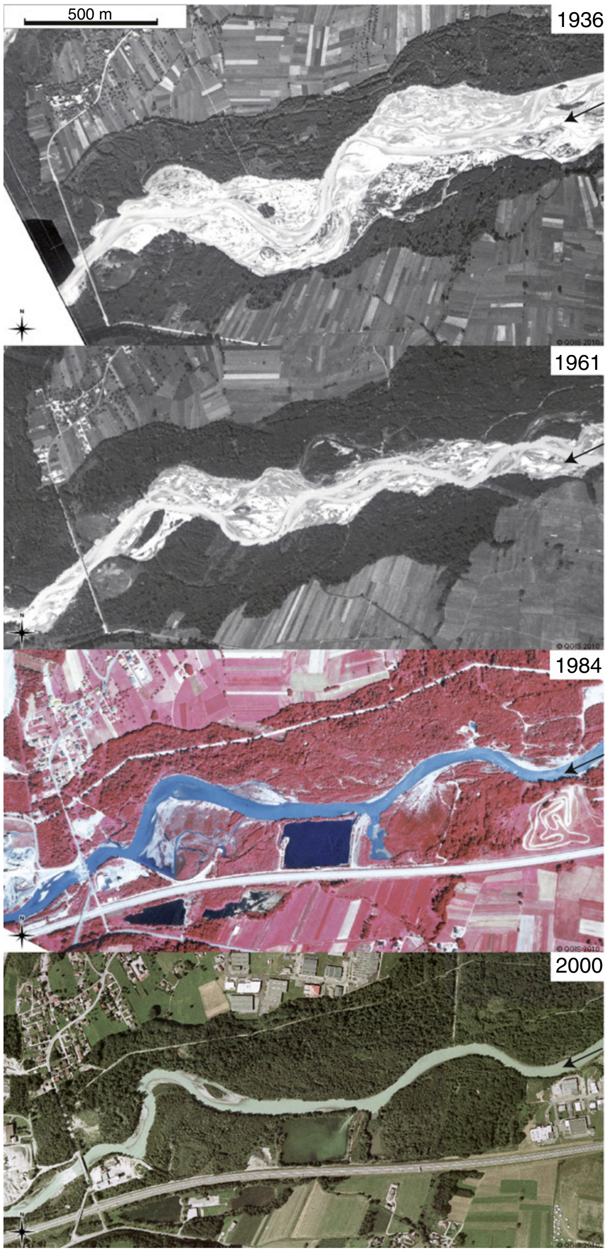

Figure 5 Corridor evolution from 1937 to 2000 of the Arve River (tributary of the Rhône River, France). Watershed land-cover changes, dams, embankments, and gravel-mining-generated channel metamorphosis from a braided to a single-thread channel morphology. Source: IGN.

These climate changes will have significant impacts on physical and ecogeomorphological processes in rivers. With increased temperature and reduced precipitation in catchments, many smaller rivers in Southern Europe may change from perennial to seasonal ones. A reduction in the density of vegetation cover in the region will tend to increase soil erosion (Nearing et al., 2005) and catchment sediment supply, resulting in increased bedload flux in rivers and the development of nonarmored channel beds (cf. Reid et al., 1999). Across most of the continental area of Europe, the increased occurrence of extreme rainfall events will intensify flash flooding, increase soil erosion (cf. Nearing et al., 2005), and, because of the nonlinear relationship between catchment water and sediment discharges (Coulthard et al., 2008), sediment delivery to channels is likely to increase substantially. By contrast, in Northern Europe the magnitudes of the snowmelt floods that are typical of this region are likely to decrease despite increased winter precipitation. This is because a larger proportion of winter precipitation is likely to fall as rain and there may also be an increased occurrence of midwinter thaws that will tend to reduce the amount of water accumulated in the winter snow pack. The opposite tendencies of precipitation totals in Central and Northern Europe may cause differing trends in the evolution of glaciers and proglacial rivers in the Alps and Scandinavian Mountains. In the Alps, rapid retreat of glaciers, coupled with reduced sediment delivery to proglacial rivers, may result in their progressive stabilization by developing riparian vegetation (cf. Gurnell et al., 1999), whereas in Scandinavia, glacier advance linked with increased sediment production may induce enhanced river braiding.

While predicting changes to ecogeomorphological river processes under rapid climate change is subject to great uncertainty, it is clear that both riverine habitats and biocoenoses will substantially alter with future channel adjustments, latitudinal and altitudinal shifts in the density and composition of riparian vegetation, changes to water temperature, river regime and the persistence of runoff, etc. This suggests that the historical state of rivers and riverine biocoenoses may be unsuitable for defining reference conditions for evaluating the hydromorphological and biotic quality of rivers.

12.4.3 Progress in Understanding and Modeling Channel Processes Related to Fluvial Ecogeomorphology

12.4.3.1 Sediment Transport

Physical processes, including those of sediment production, transport, and storage, are increasingly seen as vital for the ecological functioning of fluvial systems. Among these, sediment transport is certainly one of the most important in natural river channels, and its measurement and prediction continue to receive considerable attention. Progress in understanding and modeling sediment transport has been facilitated by the collection of extensive field data over recent decades under a relatively wide range of flow, bed load transport, and channel slope conditions, which has supported the development of new bed load formulae and/or the testing of older, well-known equations (Diplas and Shaheen, 2008). In some cases, these data have also provided the opportunity to investigate the behavior of gravel streams and the structure of channel beds in the context of watershed processes and characteristics (i.e., Hassan et al., 2008). Collection of new field data has certainly received a boost from recent technological progress, with traditional methods and sampling being combined with innovative techniques such as the use of piezoelectric sensors (Rickenmann and McArdell, 2008) or the magnetic bedload movement detector (Hassan et al., 2009).

12.4.3.2 Bank Erosion

Bank erosion is second key process in fluvial dynamics, which has a large influence on a series of physical, ecological, and socioeconomic issues. It has become progressively recognized that some lateral dynamics associated with bank erosion have positive effects in terms of the promotion of riparian vegetation succession, the establishment and evolution of river and floodplain morphology, and the creation of dynamic habitats crucial for aquatic and riparian species (Florsheim et al., 2008).

The identification and prediction of the spatial distribution of bank processes, the tendency to lateral channel mobility, and its controlling factors collectively form an important issue. As a first approximation, the lateral mobility distribution at a river network scale can be related to interaction between stream energy (or power) and boundary resistance. It is also well recognized that bank retreat is the integrated product of three interacting groups of processes (subaerial processes, erosion processes, and mass wasting). In combination, these suggest the existence of changing bank process dominance across a hypothetical drainage basin in response to downstream variations in energy conditions, bank material, and climatic conditions (see, e.g., Lawler, 1992). More recently, Fonstad and Marcus (2003) have hypothesized the existence of self-organized in riverbank systems, such that they can change internally (i.e., organize themselves) without any change in the magnitude and frequency of external inputs to the system.

Although a comprehensive theory or model capable of predicting the location and amount of lateral mobility at a catchment scale is not yet available, significant progress in modeling various processes has been made at the scale of a single bank profile. A recent comprehensive review on modeling bank-erosion processes by Rinaldi and Darby (2008) emphasized how dynamic interactions and feedbacks between different processes are the key to understanding riverbank dynamics (**Figure 6**). Developments of a simulation approach based on the interaction of the main physical processes (hydrodynamics, groundwater, and mass failure) are reported in Rinaldi et al. (2008b). Numerical modeling approaches, however, need to account for the large parameter

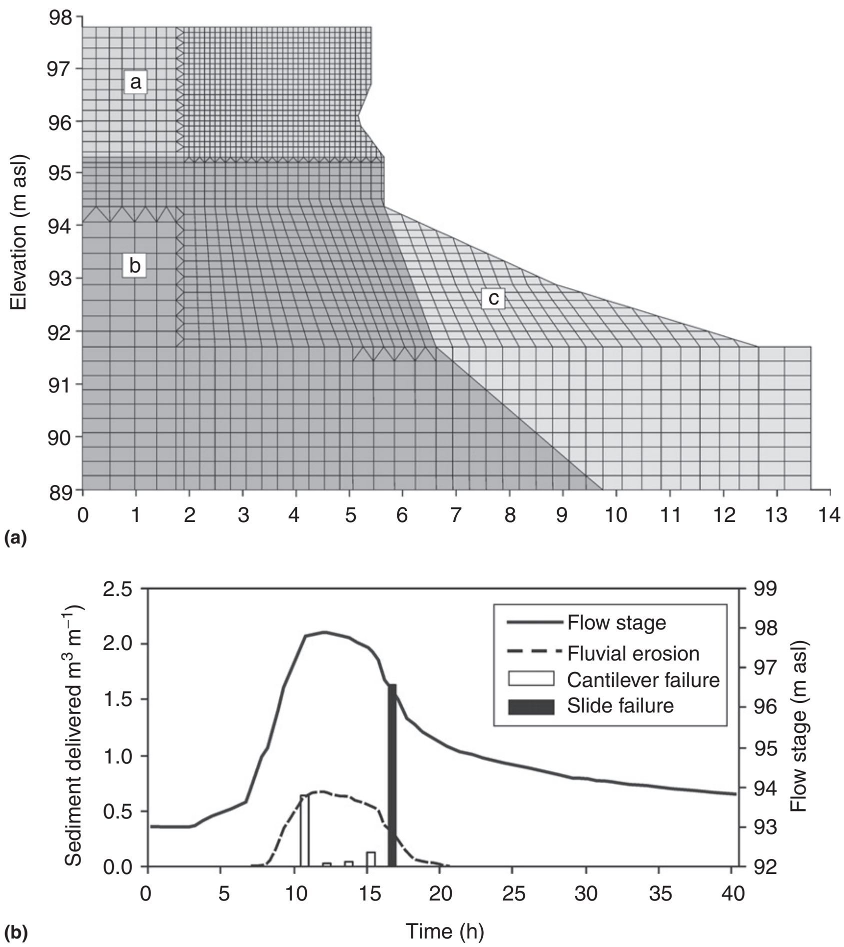

Figure 6 Riverbank stability analysis by the application of integrated groundwater flow–fluvial erosion–mass failure models to a bank of the Sieve River, Italy. (a) Discretization of the riverbank for the groundwater flow model; (b) results of the simulation in terms of sediment delivered by the different processes. Modified from Rinaldi, M., Darby, S.E., 2008. Modelling river-bank-erosion processes and mass failure mechanisms: progress towards fully coupled simulations. In: Habersack, H., Piégay, H., Rinaldi, M. (Eds.), Gravel-Bed Rivers 6: From Process Understanding to River Restoration. Series Developments in Earth Surface Processes 11. Elsevier, Amsterdam, pp. 213–239.

uncertainties, as is illustrated in some first attempts to quantify these effects on bank stability modeling (see, e.g., Samadi et al., 2009). Because a mechanistic, process-based approach may be impractical to implement when the relevant processes are difficult to parameterize, an empirical approach of bank profile evolution may be preferred in some cases (see, e.g., Pizzuto, 2009).

An obvious linkage between bank and ecological processes is represented by the role that riparian vegetation may have on bank stability. Recently, much progress has been made in this field, in particular emphasizing understanding and modeling of hydrological effects and mechanical root reinforcement (Simon and Collison, 2002; Pollen, 2006; Van De Wiel and Darby, 2007). Prediction of bank failure including vegetative elements is very relevant for quantifying wood recruitment in the fluvial system (Downs and Simon, 2001) as well as for managing and/or mitigating excessive sediment input (Simon et al., 2006).

12.4.3.3 Channel Pattern

Understanding the linkages between ecology and geomorphology in fluvial systems requires a deep knowledge about their spatial and temporal scales of evolution (for instance Hupp and Rinaldi, 2007). In particular, each major channel pattern (braiding, meandering, and anastomosing) is characterized by specific channel processes that control the system dynamics. Recent developments in geomorphological research have focused in this direction, taking advantage of both empirical observations and mathematical modeling to attain a quantitative description of river forms and processes, and of their evolution.

Braided rivers are characterized by a multitude of interconnected, highly movable channels, separated by bars or relatively short-lived islands developing through vegetation encroachment on mid-channel bars. Generally, they are characterized by high values of the stream power and by a large amount of transported sediment that is widely deposited in the braidplain (Ashmore, 1991). A distinct feature of braided rivers resulting from their complex sedimentary structure and flow patterns is their thermal behavior. Widely varying water temperatures reflect the occurrence of multiple branches with different physical dimensions affected by surface – subsurface water exchange through the hyporheic zone. This temperature patchiness, in addition to their flow velocity, sedimentary, morphological, and vegetation complexity, has strong ecological importance (Gurnell et al., 2005; Acuna and Tockner, 2009). Braided rivers were once very common in European regions, although they have undergone dramatic changes in the last century, mainly due to human activities (see Surian and Rinaldi, 2003; Gurnell et al., 2009).

The occurrence of many branches and nodes of different sizes, continuously interacting to support a highly dynamic planform evolution, makes braided rivers extremely complex and the identification of their inherent spatial and temporal scales challenging, although statistical studies suggest that their multichannel geometry is self-affine over a range of spatial scales (Foufoula-Georgiou and Sapozhnikov, 2001). However, in the last decade, the development of remote-sensing survey techniques has greatly improved the potential to monitor braided channel networks at the high spatial and temporal resolutions needed to advance scientific understanding (Lane et al., 2003; Westaway et al., 2003). The use of aerophotogrammetry, terrestrial and airborne light detection and ranging (LiDAR), and satellite multispectral imagery allows the investigation of channel processes in relation to flood events and the influence of vegetation patterns on river morphology.

At a large spatial scale, patterns of sediment transport activity in braided channel networks suggest that just a few branches are simultaneously active (Ashmore, 2001). As a result, it is possible to distinguish between a total braiding index and an active braiding index, where the latter is generally 40–60% of the former. Bertoldi et al. (2009b) proposed dimensionless relationships between external parameters (discharge, longitudinal bed slope, and grain size) and average planform parameters, distinguishing between a local scale related to sediment transport and a single branch or node, and a global scale that represents the historical legacies of temporal evolution.

At the local scale, a peculiarity of multithread rivers is the presence of confluences and bifurcations that act as links between the various branches. Confluences have been widely studied (e.g., Best, 1988; Rice et al., 2008) focusing on both their morphological evolution and their fully three-dimensional (3D) flow fields (Rhoads and Sukhodolov, 2004). Recently, Parsons et al. (2007) investigated the 3D flow field and mixing processes in a large confluence–diffluence unit using acoustic Doppler current profiling coupled with bed topography survey. Recently, bifurcation dynamics have been investigated by a combination of quantitative experimental, numerical, analytical, and field-based research (Bolla Pittaluga et al., 2003; Zolezzi et al., 2006; Bertoldi and Tubino, 2007; Kleinhans et al., 2008). This research has identified the occurrence of stable bifurcations with strongly asymmetric water partition in the distributaries. Water and sediment fluxes in particular branches (or braids) depend on local flow conditions constrained by gradient, channel curvature, the aspect ratio of the branches, and they can also be strongly affected by the presence of vegetation and by the migration of sediment bars.

Numerical modeling of braided systems is a challenging task because of the continuous and rapid rearrangement of the branches and nodes. The standard approach that solves the governing equations for the fluid and solid phases (Enggrob and Tjerry, 1999) can be used only for small areas and short time intervals, and so alternative models for braiding have been developed. Murray and Paola (1994) have shown that a simple cellular model is able to reproduce many features of braided networks. Thomas and Nicholas (2002) and Coulthard et al. (2007) improved this methodology, showing that it can be used also to model actual river evolution. Jagers (2003) has also studied the problem of modeling planform changes in braided rivers, by implementing two different models: a neural network and a branches model, testing their accuracy with observed data. The latter approach seems to be the most promising in ensuring good temporal predictability from physically based evolution rules. Recently, Perona et al. (2009) proposed a stochastic model for sediment and vegetation dynamics in Alpine braided rivers, where the key processes were floodplain erosion driven by floods and colonization of vegetation patches (**Figure 7**). The model reproduces changes in riparian vegetation cover well.

Meandering is the most common planform configuration of single-thread channels. Meanders are more likely to develop in rivers wandering through cohesive alluvial plains, but they can form also in nonsedimentary and tidal environments (Seminara, 2006). Channel axis evolution has been widely studied through geomorphological field observation (e.g., Hooke, 2008), and theoretical fluid dynamic-based model (see Camporeale et al. (2007) for a review). In particular, a planform evolution equation has been obtained (Zolezzi and Seminara, 2001) relating the outer bank erosion (and inner point bar accretion) to the 3D flow field induced by axis curvature. This allows a good description of bed configuration and flow field, both in time and in space.

Recent contributions add further ingredients to this general picture that support better understanding of the spatial scales at which eco-geomorphological linkages can take place. Increasingly detailed field measurements are revealing much about the functioning of meanders, for example, the potential influence of the flow field in sharp bends (Blanckaert and de Vriend, 2005), whereas larger-scale observations of chute cutoffs have investigated their impact on long-term channel sinuosity (Stolum, 1996; Hooke, 2004; Camporeale et al., 2005) and their association with the chaotic nature of planform meander evolution and the occurrence of self-organized behavior.

Advances in modeling have included the use of computational fluid dynamics to predict the formation, development, and migration of free-forming meander bends, through a fully 3D model (Ruther and Olsen, 2007). The development of a cellular scheme has included a novel technique for determining bend radius of curvature, used to drive meandering and lateral erosion (Coulthard and Van De Wiel, 2006). The impact of spatial variations in channel width on wavelength selection, mid-channel bar formation, and bank erosion (Luchi et al., 2009), and the long-term evolution of meanders as a function of their morphological regime (Frascati and Lanzoni, 2009) and their migration speed (Crosato, 2008) have also been investigated through numerical modeling. A key advance based on modeling has been investigation of the role of vegetation growth in controlling the long-term evolution of meander planforms (see Perucca et al., 2006, 2007).

Recently, anastomosing rivers have been recognized as a distinct channel pattern type that was probably quite common in the past across the lowlands of Europe. Such rivers consist of multiple, low-energy, interconnected channels separated by long-lived, vegetated islands, which are large relative to the channels and originate through floodplain fragmentation (Knighton and Nanson, 1993). The channels are narrow, deep, and laterally stable due to the low erodibility of vegetation-reinforced banks (Gradziński et al., 2003). An anastomosing channel pattern develops through manifold avulsions coupled with slow abandonment of old channels under an aggradational sedimentary regime linked with a rise of base

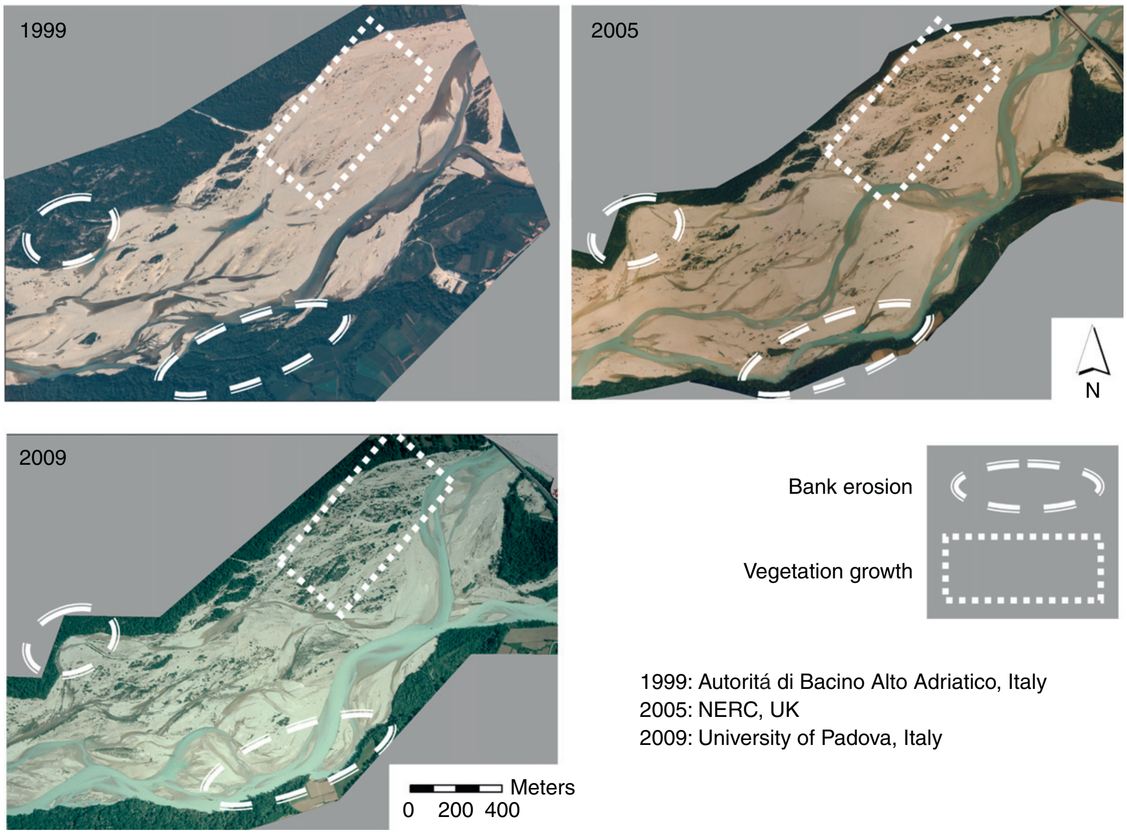

Figure 7 Example of morphological evolution of a gravel-bed braided river over a time span of 10 years. Location of floodplain bank erosion and extensive vegetation growth are highlighted.

level (Makaske, 2001), substrate subsidence, and blocking of the channels by growing aquatic vegetation (Gradziński et al., 2003) or debris dams (Harwood and Brown, 1993). Anastomosing rivers are now rare in Europe, because they characteristically occur toward the lower reaches of river networks, where channel gradients are relatively low and channel banks are composed of fine cohesive alluvial sediments, and where such multithread channels have historically been simplified to support navigation. However, they were much more common before the era of riparian deforestation and river channelization (Brown and Keough, 1991) and a few such multithread systems with narrow, deep, and laterally stable channels still remain active in valley reaches unaffected by channelization works (e.g., Brown, 1997; Gradziński et al., 2003).

12.4.4 River Processes and Ecogeomorphology

12.4.4.1 Ecological and Geomorphic Processes

During the last three decades, several scientific concepts have been developed to link the structure and functioning of river ecosystems with fluvial processes. Notably, the concepts were complementary rather than competitive, addressing different aspects of the functioning of fluvial systems. The River Continuum Concept (RCC; Vannote et al., 1980) predicted changes in the balance between allochthonous inputs and autochthonous production of organic matter as well as in the resultant composition of the macroinvertebrate communities that occur in response to changing physical conditions along the river continuum. In contrast to the previous concepts of river zonation, the RCC indicated that a watercourse is an open ecosystem in which gradual changes in physical conditions (such as the width, depth, flow characteristics, complexity of the flow network, and interaction with the bank) are associated with continuous changes in the structure of riverine biocoenoses from the headwaters to the lower reaches. The Flood Pulse Concept (FPC; Junk et al., 1989) focused on the lateral exchange of water, nutrients, and organisms between river channel and the connected floodplain. It emphasized strong interactions between hydrological and ecological processes, indicating that the pulsing of river discharge is the driving force in the river–floodplain system. Floods were considered as disturbances leading to a regular setback of floodplain community development, maintaining the system in an immature but highly productive stage. Tockner et al. (2000) extended the FPC, indicating that expansion–contraction cycles occurring below bankfull (flow pulses) also exert a significant influence on the size and heterogeneity of habitat, connectivity, and functional processes in river ecosystems. Moreover, recognition of the hyporheic zone as a habitat for some groups of river biota (Stanford and Ward, 1988) as well as water and nutrient exchange across the channel bed indicated the significance of vertical connectivity of river ecosystem.

Geomorphic processes operating in particular river reaches determine morphological characteristics of the river channel, floodplain, and valley sides and thus the arrangement of river biocoenoses along the river continuum. Vertical tendencies of the channel bed, which reflect persistence or disruption of dynamic equilibrium, influence the degree of connectivity between the river channel and its floodplain, the frequency of floodplain inundation, and the scale of modification to the floodplain portion of the riverine ecosystem caused by flood disturbances. Bed degradation, especially if operating in watercourses underlain by a thin cover of alluvium, weakens water/nutrient circulation across the channel bed, reduces the size of the hyporheic zone, and may lead to complete loss of the hyporheos with bedrock exposure on the riverbed.

Although the above-mentioned ecological models mostly focus on the productivity of the river ecosystem, evaluation of the ecological integrity of European watercourses is mainly based on the diversity of river biocoenoses. Connectivity, habitat heterogeneity and a moderate scale of flood disturbance are key factors controlled by the dynamics of fluvial processes, which contribute to the maintenance of high biodiversity of the riverine ecosystem (Ward et al., 1999). Disequilibrium fluvial processes disadvantageously modify lateral and vertical river connectivity, whereas longitudinal connectivity is disrupted or reduced due to dam and weir construction. Successional phenomena and flood-related channel migration, erosion, and deposition of sediment and organic matter (including large wood) create a complex mosaic of terrestrial and aquatic habitats within the river corridor with suitable conditions for diverse organisms and their different life stages. The location of patches with given habitat conditions changes through time (shifting habitat mosaic; Pringle et al., 1988, Stanford et al., 2005) but, under dynamic equilibrium conditions, their amounts and proportions remain more or less the same (see, e.g., Van der Nat et al., 2003). Absolute magnitudes of floods are determined by hydrological phenomena but the disturbances they cause in the floodplain portion of riverine ecosystem depend also on the vertical tendency of the river channel (Dufour and Piégay, 2008). In aggrading river systems, increased frequency/intensity of flood scouring and deposition prevents recovery of plant communities before the next disturbance, whereas in incising river systems the terrestialization of aquatic water bodies within the floodplain and the maturation of plant communities occur with reduced frequency/intensity of flood inundation, scouring, or deposition of the floodplain surface. In both cases, the tendencies result in reduced biodiversity of floodplain communities (Hupp and Bornette, 2003). In accordance with the intermediate disturbance hypothesis (e.g., Ward and Stanford, 1983), a highly diverse, shifting mosaic of plant species on a floodplain can be maintained only with the intermediate frequency and intensity of flooding (Hupp and Bornette, 2003) that typifies the floodplains bordering vertically stable rivers.

12.4.4.2 Fluvial Geomorphology and River Restoration in Europe

River restoration in Europe, as well as in other parts of the world, is increasingly including consideration of physical processes, such as bank erosion, sediment transport, channel incision, and water flow patterns, as a necessary condition for enhancing river conditions and promoting channel recovery. The first applications of morphological restoration in Europe were located in northern countries (United Kingdom, Denmark, etc.), and were mainly implemented on short reaches of low-energy, generally small streams. Restoration measures included increasing the variability in channel width and depth, recreation of meanders, reintroduction of gravel to recreate fish spawning habitats, and reconnecting former channels to the main channel (see for example Brookes, 1990).

Since the 1990s increasing scientific debates have occurred regarding the appropriate spatial scale of interventions (local scale vs. reach and basin scale), and the consequent need to consider process-oriented approaches and self-restoration strategies (Clarke et al., 2003; Palmer et al., 2005; Wohl et al., 2005). A progressive evolution toward process-based restoration has occurred, where the aim is to restore natural geomorphic processes to promote conditions of self-sustaining physical diversity, rather than tackling problems through local interventions. In addition, applications of morphological restoration have shifted toward higher-energy, bedload-transport-dominated channels (e.g., in the piedmont Alpine areas). In such environments, successful restoration must include the full spectrum of scales and consideration of the related natural processes and human boundary conditions (Habersack and Piégay, 2008). Notwithstanding these increasing experiences and evolving approaches, European 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 (see Gumiero et al., 2008). However, there are exceptions to this general trend, with a number of restoration projects implemented during the last two decades, that have included considerations of morphological forms and processes, including: (1) channel widening and dike relocation further away from the channel (Jäggi and Zarn, 1999; Habersack and Piégay, 2008); (2) former channel reconstruction and reconnection (Schropp, 1995; Schropp and Bakker, 1998; Simons et al., 2001; Gurnell et al., 2006; Habersack and Piégay, 2008; Hornich and Baumann, 2008; Muhar et al., 2008); (3) sediment reintroduction or promotion of bedload supply input from floodplains, tributaries, and hillslopes (Habersack and Piégay, 2008; Rollet et al., 2008); and (4) enabling natural recruitment (Gregory and Davis, 1992) and artificial placement of large wood (Gerhard and Reich, 2001).

Besides specific restoration measures and actions, preservation or recreation of natural physical features also requires a sustainable management of associated processes by modifications in management policy and related legal recommendations. A relevant example is provided by the application of the Erodible Corridor Concept (Piégay et al., 2005), which is now a recommended procedure within the French legislation that incorporates well-defined constraints for bank protection and mining authorization policies. Application of the ECC concept is increasing in other European countries (e.g., Poland and Italy, see Nieznański et al. (2008) and Rinaldi et al. (2009), respectively).

At the conclusion of the IVth ECRR International Conference on River Restoration 2008, the following points were identified for future developments (Rinaldi et al., 2008a): (1) the importance of a clear spatial and temporal context for restoration strategies; (2) the need for a range of approaches and to involve interdisciplinary groups; (3) a critical need to integrate geomorphology and ecology; and (4) the use of process-based approaches and the integration of process understanding with morphological interventions.

12.4.4.3 Hydromorphology and WFD

The European Commission (EC) WFD (European Commission, 2000) introduced the term 'hydromorphology', which considers physical habitat conditions for aquatic biota as they are determined by hydrological regime and morphological pattern. After several decades of concern about pollutants as major impacts on the ecological integrity of watercourses, identification of major stressors for river ecosystems now concentrates on modifications to the flow regime, impacts of artificial barriers on biota migration, water flow and sediment transport, and modifications of river channel and floodplain forms and processes (Vaughan et al., 2009). Following its introduction, hydromorphology has increasingly become a cross-disciplinary topic at the interface between hydrology, geomorphology, and ecology, and it is rapidly becoming central to practical applications for sustainable river management (Newson and Large, 2006).

The inclusion of hydromorphological quality within the WFD creates new perspectives and opportunities to embed consideration of physical processes in future restoration actions and strategies. At the same time, the WFD poses a series of issues, such as the problematic definition of a reference state, the assessment of deviation from that state, and the ecologically driven strategies for restoration, which must be delivered by regulators.

Nowadays, there is wide agreement that it is inappropriate to define a static reference state for the morphological forms and processes in a river subject to restoration. The static reference state concept should be replaced by a guiding image of a dynamic river ecosystem (e.g., Palmer et al., 2005), which actively reacts to the fluctuations of water discharge and sediment flux and progressively adjusts to catchment environmental changes. To satisfy this requirement, reference processes and reference process–form interactions need to be collectively considered and defined within dynamic river systems or reaches in a variety of European environments (Bertoldi et al., 2009a; Dufour and Piégay, 2009).

European Standard EN-14614 (CEN, 2004) requires an assessment of channel, river banks, riparian zone, and floodplain features, and is an open guidance on which a detailed methodology for hydromorphological assessment, incorporating consideration of ongoing geomorphic processes, can be developed. However, the methodologies used up to now in most European countries tend to reflect river habitat survey procedures. Most of them were not originally developed to fit with the WFD requirements and provide poor consideration of processes and channel adjustment trends, because the main focus of a river habitat survey is on the presence and quantity of channel physical features. However, an increasing consideration of processes rather than forms has been observed in recent years, with some examples of new developing methods in France (Wiederkehr et al., 2010 or SYRAH procedure by Chandesris et al., 2008), Spain (Ollero et al., 2007), and Italy (Rinaldi et al., 2010).

Interdisciplinary research is still needed in the areas of ecology and geomorphology (i.e., ecogeomorphology) to appropriately implement hydromorphological assessment and monitoring procedures within the scope of the WFD. The most important contribution needed is interpretation of the contribution of physical processes and forms to biodiversity, and the hydromorphological component of the ecological quality in rivers.

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