River Conservation
Challenges and Opportunities

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Chapter 3 Offprint

River's Architecture Supporting Life

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Chapter 3

River's Architecture Supporting Life

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Physical and biological processes are inseparable in rivers. Fluvial ecosystems are adapted to change and need physical instability (floods) to keep ecological integrity. Impacts such as damming, channelization, and changes in land use, alter river dynamics. Rivers are distinct from each other, and so are solutions to their problems. Available scientific and technological knowledge must be the bases for a sound river management.

3.1. River form: The starting point for conservation

Rivers are among the most complex and dynamic systems in nature. They constitute natural units characterized by more or less frequent transfers of water and sediments that, in turn, support life. While moving through stream courses, water and sediments connect all river compartments, from the basin headwaters to the lowland deposition zones (e.g. Leopold et al. 1964; Richards 1983). The failure to appreciate this fundamental connection underlies many of the current environmental problems in river conservation and management.

River form and sediments create and maintain a variety of instream habitats that support the life of many organisms. A river habitat refers to the substrate, flowing water, organic debris, amongst others, which provide support for organisms i.e. animals and plants that live in the stream. Many river features can be distinguished, including *Riffles*, shallow zones where the water flows swiftly over rocks; *Pools*, deeper zones with more slow water; *Bars*, accumulations of sediments forming islands and forcing the water through secondary channels; and *Oxbows*, lakes formed when a meander is cut off. Each one of these habitats offers opportunities to different assemblages of organisms. Even within a single river habitat, there are many places where different animals can live. For instance, in a single riffle some organisms can select the areas with fastest current; some others seek shelter behind rocks. Riparian vegetation, the plants that grow in the floodable banks, is also an important element in the architecture of many rivers, and they exert a strong influence on river conditions (Chapter 9). Therefore, healthy riparian zones are key to a healthy in-stream habitat.

Physical and biological processes are inseparable in river systems; and they need geomorphic disturbance to keep ecological integrity

Humans modify and alter rivers. They can affect the physical functioning of fluvial systems both by land-use changes at the basin scale and by within-channel activities, singularly dams, channelization and gravel mining. All these perturbations alter water and sediment delivery to the drainage network, and the mass and energy transfer within it. Changes in land use (i.e. afforestation, deforestation, urbanization) affect runoff and sediment supply at the large scale and in the long term (Chapter 2). In turn, dams affect the water flow regime and sediment delivery over the long term and over long distances. Channelization, leveeing and rip-rapping transform channel geometry, change hydraulic properties of the flow and disconnect the streamcourse from its alluvial plain. Instream mining (i.e. extraction of sediments from streams and adjacent floodplains) acts locally by depleting the channel of sediments, and its effects can propagate down and upstream over decades.

Within this context, this chapter aims at providing a general view of the importance of the interaction between flow forces and sediments to shape rivers, and their relation with ecosystem functioning. We therefore introduce concepts of fluvial geomorphology and show selected examples to illustrate the discourse. Examples do not seek to be exhaustive and right away subject to extrapolation, but simply constitute a basis to interpret the geomorphic (i.e. physical) contribution to river ecological integrity. Analysis of physical processes provides a comprehensive framework for river sciences, enabling us to view water, sediments, and resultant physical features as fundamental elements to understand and inform conservation and restoration measures in the system. Conservation and restoration starts from the understanding of river physical processes and dynamics. River management that neglects focussing on mass and energy balances as the factors driving river functioning is bound to failure.

3.2. What is in there? Water, pebbles… and sometimes mud

The structure of alluvial river channels (namely, its basic *architecture*) is formed of sediments that experience cycles of entrainment, transport and deposition (e.g. Church 2006). Most rivers on Earth are alluvial, i.e., water runs through loose mixtures of sediments that have been previously deposited. These sediments form the basic structure of rivers; within them water moves upwards and downwards, and laterally in direct connection with groundwater in the floodplains; sediments host a variety of fauna and flora, and support riparian vegetation.

Sediments of different sizes and shapes form the complex architecture of streamcourses. Heterogeneity of substrate guarantees the maximum ecological diversity in a fluvial system

The architecture of river channels is controlled by the interactions between water discharge, the size and sorting of bed sediments, the supply of new sediments from the catchment, and their transport downstream. These interactions control the moments in which river channels change and their temporal sequence and magnitude. Floods are physical disturbances for river-dwelling organisms.

From the point of river morphology, fluvial sediments can be divided into bed material and wash material. Bed material corresponds to the coarse sediments supporting the channel and banks and, ultimately, determines the form of streamcourses (Figure 3.1A and 3.1B), which is an important part of river habitats.

On the other hand, wash material correspond to fine sediments transported for longer distances in suspension. Wash material does not determine the form of alluvial channels but influences the upper bank morphology (Church 2006). These fine sediments are often deposited into the coarser bed material, clogging the near-surface pores and thus affecting the structure of the framework (Figure 3.1C). This effect may influence the cohesiveness of bed sediments and their stability and alter habitat conditions for biota, for instance, by reducing refuge in the interstitial space. Hence, physical characteristics are key factors controlling habitat conditions that are essential to maintaining the ecological diversity of a particular fluvial system.

Ecological diversity of river ecosystems is directly linked to the heterogeneity of physical habitat conditions, including flow hydraulics and substrate. However, there are important scale considerations related to organism size. For invertebrates the relevant scale of physical heterogeneity is that of the patch (i.e. centimetres to metres), whereas fish, which are larger and more mobile, depend on heterogeneity at the reach-scale, hundreds of metres to kilometres (Poff 1997). This functional relation between spatial scale and optimal ecological diversity is

Figure 3.1: *A) A mountain reach with a complex architecture including riffles, pools, central bars and secondary channels (Feshie River, Scotland, UK; arrow shows flow direction). The inset zoom shows how morphological complexity changes in relation to the scale in which it is investigated. B) Sediments are mixed horizontally and vertically: Gravel and cobble sediments in a complex arrangement (Ribera Salada, Southern Pyrenees). C) Fine sediments deposited during low flows clog the spaces between gravel particles (Isábena River, Southern Pyrenees)*

conceptually represented in Figure 3.2. Sediments of different sizes and shapes form the complex architecture of streamcourses (i.e. their form). Substrate heterogeneity and topographic complexity are requisites for ecological diversity, which in turn is linked to river health.

3.3. Shaking beds move organisms: Life requires complexity and change

Relatively immobile bed sediments (i.e. cobble-boulders) are important habitats for invertebrates. These large particles offer a more diverse habitat for colonization and better food resources (i.e. because of organic material that they can retain or the more developed biofilm that can grow on them) than less stable environments. This contrasts with the more mobile sand and gravel, where even small increases in flow move particles and scour benthic animals. Thus, the reach-scale habitat diversity depends on the relative availability of stable and unstable areas of stream bed, as well as refugia and still waters. In rivers with high contents of fine sediments, siltation blocks the transport of oxygenated water to the sediments and thus results in death salmon eggs and other fish. Besides, clogging of beds by fine sediments also reduces invertebrate diversity

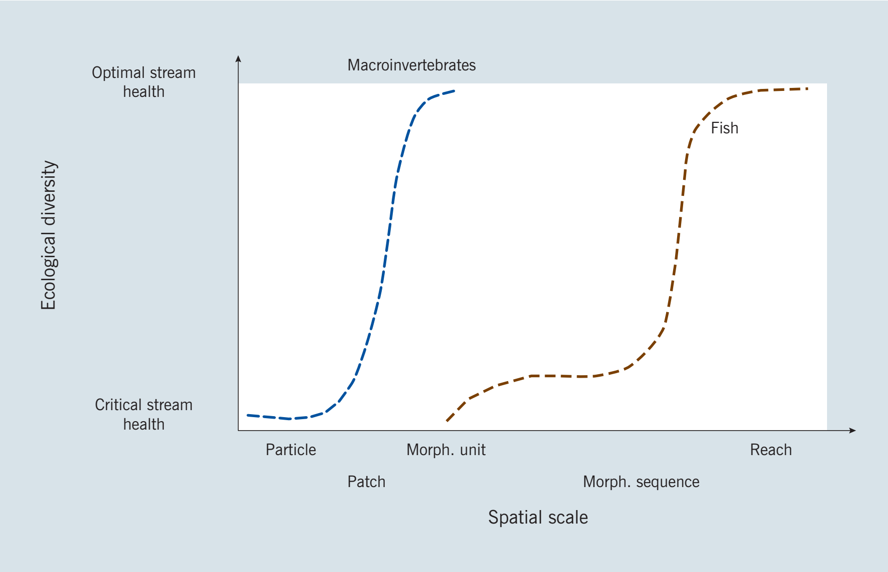


Figure 3.2: *Functional relations between spatial scale and optimal ecological diversity. Ecological diversity is directly linked to the heterogeneity of physical habitat conditions, including flow hydraulics and substrate, but invertebrates respond at smaller spatial scales than fishes (Note that the term* Morphological unit *refers to single elements present in a river channel i.e. bar, riffle, pool; whereas* Morphological sequence *refers to groups of units that alternate in the river channel i.e. riffle-pool sequence)*

(Gibbins et al. 2007). In any case, river beds experience disturbance (floods) from time to time. Flood frequency and magnitude depend on climate and basin characteristics (Chapter 2), but their disturbance effects are relatively larger in reaches where sediments move more easily. Thus, hydrology and sedimentology interact to control habitat diversity and functionality.

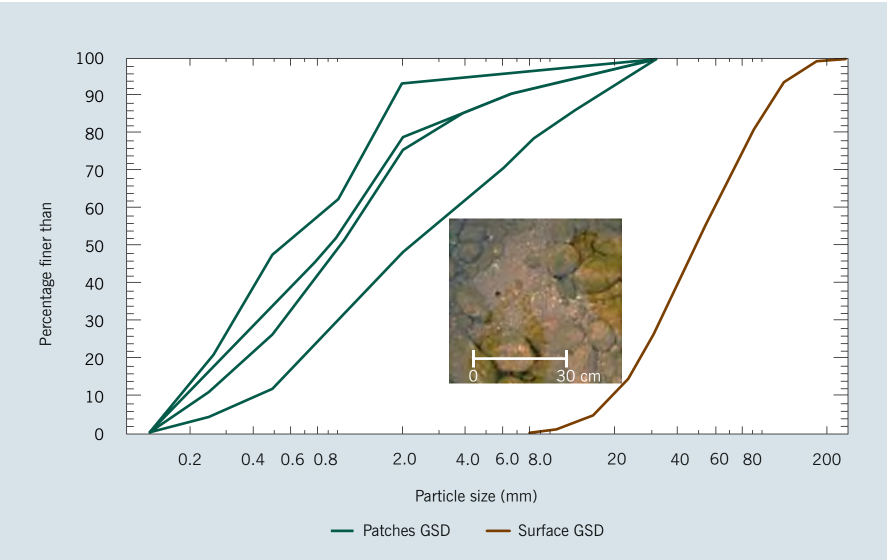
Channel shape and sediment size are related to flow energy, expressed by the combination of discharge and gradient of the river. This relationship commonly referred to as Lane's Balance shows that a change in any of the variables will cause a change in the others such that equilibrium is restored. When a channel is in equilibrium the sediment being transported into the reach is transported out of it, without significant deposition of sediment in the bed (aggradation, or building up of sediments), or excessive bed scour (degradation, or downcutting of the channel). It should be noted that by this definition of stability, a channel is free to migrate laterally by eroding one of its banks and building sediments on the one opposite at a similar rate. When the supply of water or sediments are changed channel geometry and bed composition adjust towards new configurations. These changes can result from many different causes, from changes in erosion rates in the basin to changes in climate. Changes in channel geometry also occur as the discharge rises and falls during the year, but these changes are frequently minor.

Floods determine the disturbance regime (i.e. frequency and magnitude) experienced by a given reach and, consequently, the associated ecological responses.

Hydrological variability is considered the main factor affecting the organization of riverine communities, contributes to key ecological processes (Yount and Niemi 1990), and is essential for river conservation and renaturalization. The temporal persistence of invertebrates or fish communities is determined not only by the resistance of the communities, but also by their rate of recovery from a given perturbation (Poff et al. 1997). When a flood occurs, flow energy dissipates along the streamcourses, eventually eroding channel bottom and banks, thus temporarily altering the *normal* (i.e. usual) habitat conditions. But even with small increments in river discharge (i.e. well below flood episodes), parts of the bed may get disturbed and community alterations occur. This is the case, for instance, of invertebrate communities living in patches of fine sediment usually located behind obstacles or in depressions in the river-bed (Laronne et al. 2001, Figure 3.3). Patches constitute an excellent example of the bio-physical complexity of rivers. Patches of fine sediment are the first to be moved when the flow rises, and their scouring can trigger massive invertebrate drift, and therefore facilitate passive downstream movement of those individuals.

River science has often faced difficulties in matching the study of physical and biological elements; this fact may be due to diverging objectives of the scientists analysing one or the other element, but also to technical limitations on sampling and modelling. Field experiments are not easy to carry out but they may

Figure 3.3: *Typical grain-size distribution (GSD) of patches (the fine particles in the inset photo and the coarse surface material (the larger particles in the inset photo). Example from the gravel-bedded Ribera Salada (Southern Pyrenees)*



Source: Redrawn from Gibbins et al. (2007b).

shed some light onto this type of interactive processes. As an example, Vericat et al. (2007) developed a portable flume (Figures 3.4A and 3.4B) that can be placed *in situ* within riverchannels and be used to modify local water velocity.[1] This field experimentation has shown that a small amount of bedload transport suffices to trigger massive invertebrate drift, demonstrating that magnitudes of physical and biological disturbance are often out of phase.

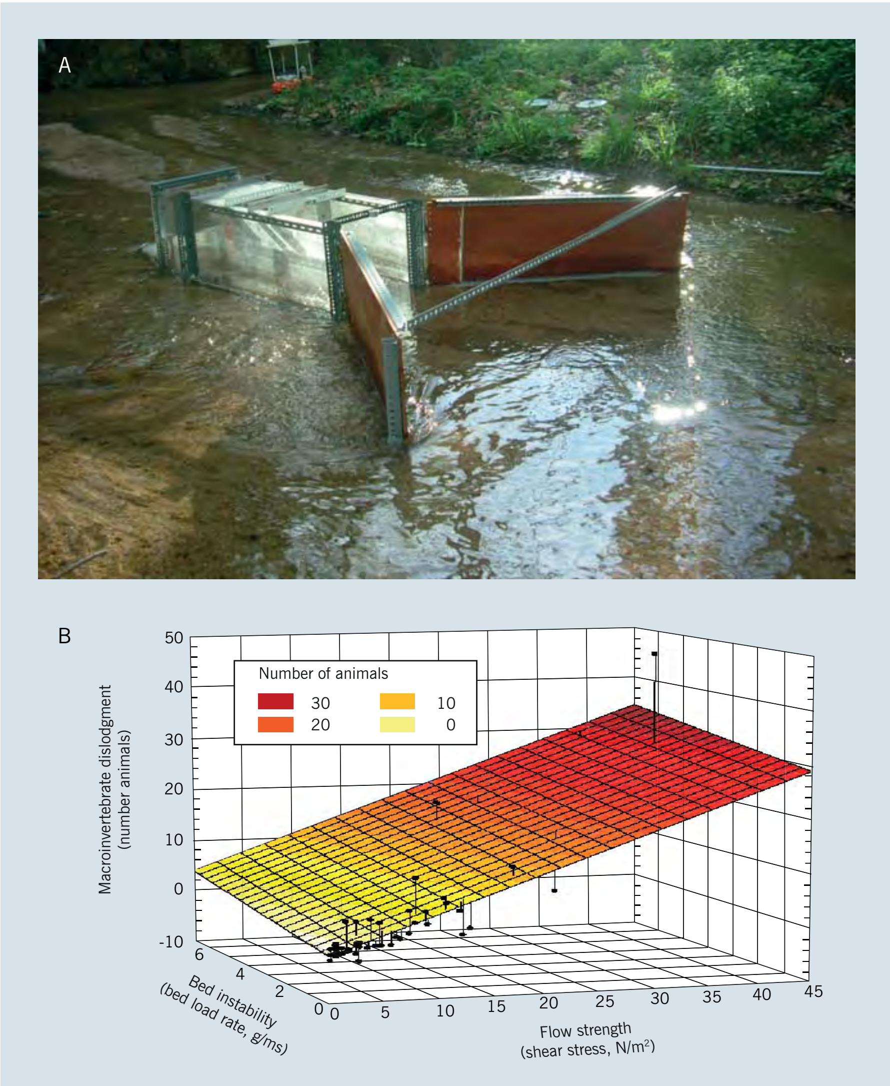


Figure 3.4:
A) Portable flume (Vericat et al. 2007) used to manipulate hydraulic conditions over patches of stream bed. It helps study the interactions between hydraulics, sediment transport and invertebrate drift. The wooden doors used to manipulate hydraulic conditions inside the flume are shown here in their open position, i.e. forcing the water velocity to increase. B) Diagram showing a 3-D model of the relations between flow strength (shear stress), bed mobility (bed load transport rate) and the loss of animals from patches of the gravel bedded Ribera Salada. Black points represent the raw data values, while coloured areas the modelled values. For more details on those biophysical relations see Gibbins et al. (2007)

[1] See http://www.agu.org/pubs/eos-news/supplements/2007/41-410.shtml for details.

3.4. Rivers react to human actions

We have so far examined the effect of natural perturbations; but today it is particularly important to understand how humans interfere with natural processes, and how natural processes may be preserved and/or restored. From the many types of impacts on river channels and their basins, some act locally and have short duration, while others propagate over longer terms and distances (see Table 3.1). We will focus on two common disturbances affecting physical processes: dams (long-term) and gravel mining (local, short-term).

Rivers have been the main water resource for humans over history. Economic development following industrial revolution in many countries, singularly in Europe, was linked to increased demand for water and energy. Rivers supplied both. Many streamcourses have been progressively dammed through human history. Particularly, large rivers started to be regulated mostly since the 19th century. Regulation has grown exponentially through the 20th century and has permitted increasing water supply and hydropower production, well beyond the intrinsic climatic variability of many regions. Worldwide there are more than 45,000 large dams (larger than 3×10^6 m^3).[2] Arid regions account for the highest number of reservoirs/dams. A paradigm is the Iberian Peninsula, a semi-arid and water thirsty country, which assembles approximately 3% of the world's dams, mostly dedicated to agricultural, industrial and urban demand. The effects of reservoirs on flow regime depend on their size relative to river runoff, their purpose (e.g. irrigation, hydropower, flood control), and their operating rules. This complexity precludes simple generalisations about the effect of dams on discharge distribution (Williams and Wolman 1984).

Table 3.1: *Main human impacts affecting water and sediment-related processes in rivers, and their extension over different space and time scales (see Figure 3.5 for illustrations)*

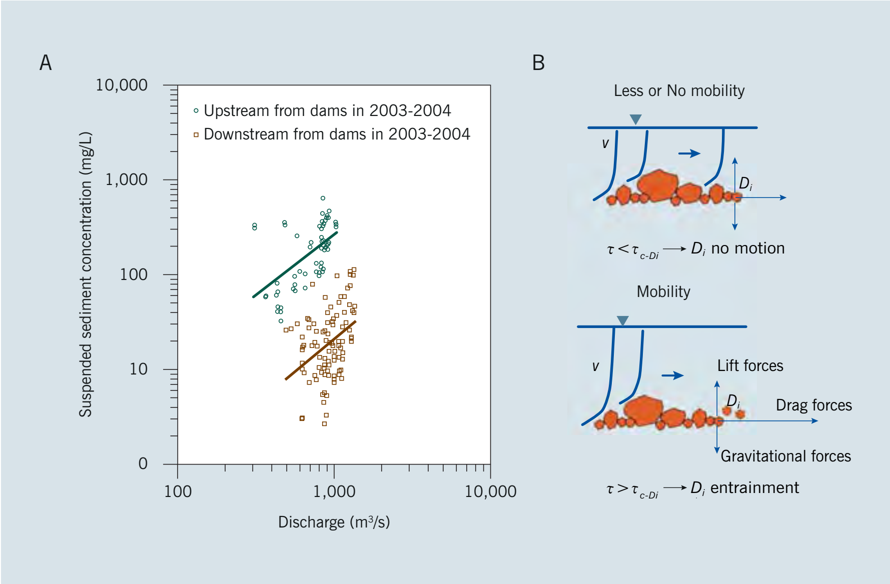
	Local ⟶		General
	Riverchannel	***Floodplain***	*Basin*
Short-term *from year to decade*	• Gravel mining • Rip-rapping • Channelization	• Gravel mining • Channelization	• Land use changes (i.e. forest fires, urbanization)
↓ **Long-term** *… decades to centuries*	• Gravel Mining • Rip-rapping • Channelization	• Gravel Mining • Rip-rapping • Channelization	• Dams • Land use changes (i.e. afforestation, deforestation)

[2] See International Commission of Large Dams at http://www.icold-cigb.net for more details.

Figure 3.5:
Examples of morphological impacts on rivers. A1) Incision and A2) disruption of channel form in the Ribera Salada (Southern Pyrenees) as a consequence of gravel mining. B1) Alteration of river continuity by damming, and B2) sediments retained in Barasona Reservoir, Ésera River, Southern Pyrenees). C) Rip-rapping in the Ribera Salada (Southern Pyrenees)

Overall, dams reduce flood magnitude and frequency (Batalla et al. 2004) and block sediment transport (Figure 3.6A) (Vericat and Batalla 2006), altogether reducing flow energy and sediment mobility (Figure 3.6B). The effects of dams are relatively larger on rivers in dry climates, both through reductions in high flows (reduced disturbance) and extended baseflows, making these environments more suitable for exotic species not adapted to seasonal drought (e.g. Batalla and Vericat 2009). Sediment transfer to downstream reaches is also altered. Virtually all bedload, and much of the suspended load are trapped into reservoirs. This sediment deficit generates a series of impacts on channel morphology and sediment characteristics. Loss of bars and other areas with bare sediments, intrusion

Figure 3.6:
A) Suspended sediment transport upstream and downstream from the dams in the lower Ebro River (data from Vericat and Batalla 2006). B) Conceptual model of bed mobility. Bed material entrains when the flow exceeds the critical strength for mobility. In the case of river channels downstream from dams, if flood magnitude is reduced, energy expenditure is less over river bottom sediments, hence reducing bed mobility and, with it, the natural perturbations basic to maintaining fluvial ecosystem functioning



Note: v = flow velocity, D_i = particle of an i diameter, τ = shear stress, t_{c-Di} = critical shear stress for a given particle size i.

of terrestrial vegetation in formerly open areas (Williams and Wolman 1984, Figure 3.7), channel narrowing and associated changes in river flow conditions, are amongst the most pronounced physical effects downstream from dams. Water released by dams is often called *hungry water* (as per Kondolf 1997), as it leaves the reservoir with almost no sediment, and so, erodes sediments from the river bed without replacing them with new sediments from upstream. This fact creates a disequilibrium that may produce armouring of the river bed (i.e. only the largest particles stay in place; Williams and Wolman 1984) and incision of the channel (i.e. deepening, Kondolf 1997). These changes in flow and flood regimes and in channel form and sediments have important effects on the river ecosystem (Ligon et al. 1995). The modified regime exacerbates species with life history characteristics atypical of the pre-dam environment, including non-native species, resulting in altered species composition and vegetation dynamics (Cowell and Dyer 2002).

River sediments are naturally sorted and often close to markets, and thus, they have been widely used as a source of construction materials. Sediment mining affects streams and floodplains and it is severe in countries subjected to a rapid urban growth, where the availability of aggregate (sediment mixtures i.e. sand, gravels, used for construction) is key to maintaining economic activity (Kondolf 1997). Additionally, sediments are also extracted from highly dynamic rivers where sediments tend to accumulate in the channel, with the aim of

Figure 3.7: *Channel narrowing and vegetation encroachment as a consequence of dams in Segre River near the Alcarràs (Ebro basin, NE Spain). A) Segre River, 1956; B) Segre River, 2009*

maintaining flood capacity (e.g. the Lower Waimakariri, New Zealand, Griffiths 1979). In other places (e.g. the River Platte, USA) sediments have been removed from islands to improve bird nesting habitat (Kinzel 2009). Sediment mining represents a non-natural stressor which profoundly modifies physical and ecological processes and dynamics. In contrast to dams, whose effects extend progressively over space and time, mining is a localized intensive impact. Once mining ceases, recovery of ecological diversity may require more time than after natural perturbations, even large catastrophic floods. The recovery time depends on the channel condition (physical and biological) after the impact, the flood and sediment transport regimes, including sediment availability and supply, and the distribution and dispersal ability of potential colonists.

Thus, both physical and ecological impacts of sediment mining leave short- and long-term signatures (Erskine 1997). Short-term impacts are those related directly to the mining activity, such as a turbidity plume or water barriers to fish migration. Long-term morphological effects include channel deepening and instability, and coarsening of the riverbed surface. Ecological effects including habitat homogenisation (e.g. Wyzga et al. 2001), result in decreased diversity and changes in species composition of invertebrates, biofilm and fish communities (Brown et al. 1998).

3.5. Floods: When the water dances with sediments. Opportunities for restoration

Floods are the most common form of natural disturbance in rivers. They constitute an essential element of the fluvial dynamics and, although sometimes may be the cause of economic damages, they are indispensable for the river's normal functioning (Chapter 2). Dams are the elements that most directly alter the flow regime, mostly by absorbing flood flows and collecting almost all the sediment carried down in the river basin. Floods and sediments are key elements for the good functioning of river ecosystems.

Sound management of available water in the catchment may return a certain degree of naturalness to a river. Conserving and/or restoring the natural variability of the river flow is a worthwhile way to progress towards that goal. In particular, artificial flow releases from dams, known as *flushing flows*, provide an interesting opportunity to restore river processes in altered streamchannels. They can be designed to modify or maintain the channel sediment and geometry (Kondolf and Wilcock 1996) or the riverine ecosystem as a whole (Arthington and Pusey 2003). Milhous (1990) provided some rules to estimate the flushing flow needed to keep the substrate in a condition that will support a desired aquatic ecosystem. For instance, and in order to remove interstitial fine sediment from gravels, we can calculate, based on the median size of the gravel, the critical shear stress necessary to set gravels in motion; once gravel particles are entrained into motion, sand beneath them may be entrained and removed from the bed. However, the use of hydro-geomorphological criteria both fixed (i.e. river-bed grain-size distribution) and dynamic (i.e. sediment transport) is still not very common (e.g. Kondolf and Wilcock 1996, Batalla and Vericat 2009). Despite several constraints, if carefully designed and implemented, flushing flows may play an important role in enhancing physical habitat in the river. Flushing flows can also be suitable in rivers affected by hydropower production, and may actually result in a positive trade-off due to vegetation removal and reduced clogging of water intakes (Batalla and Vericat 2009). It is, however, necessary to reassess their effectiveness regularly and monitor adverse physical effects like riverbed erosion. Flushing flows are an important instrument of river management, but one that must be employed as part of a spectrum of approaches to enhance physical habitat conditions and restore basic river functions.

Complementarily, sediment extracted from reservoirs or debris-control basins has been utilized to enhance fish habitats. This practice is known as *gravel replenishment* and has been implemented in Sacramento River, California, downstream from the Keswick dam (Buer 1994). This type of actions provide short-term habitat, since the amount of gravel added is but a small fraction of the bedload deficit, and gravels placed in the main river can be typically washed out during high flows, requiring continued addition of more gravel (Kondolf 1997). In the Rhine River sediment injection has been implemented downstream of the Iffezheim dam. This approach has proved successful in preventing further incision of the riverbed downstream and to protect river infrastructure (Kuhl 1992).

Riverchannel instability maintains streams alive and must form the core of conservation and restoration practices

3.6. Maintaining river form and processes: A way to keep rivers active

Most rivers are not and will no longer be pristine anymore. All societal bodies (i.e. authorities, scientists, environmentalists, company managers and, overall, citizens as end-users) must accept and agree on this fact. The question arises of how to make compatible the use of natural resources (surface waters, in this case) and the conservation of river integrity as its most important element. Recipes are not universal and must be kept simple to guarantee probabilities of success. A few final remarks and recommendations encompassing the main concepts outlined in this chapter can be drawn as follows:

— Physical and biological processes in rivers must be seen as inseparable. Water and sediment dynamism constitute the bases to maintain the ecological integrity of a river system.
— Rivers need to maintain physical disturbance (i.e. floods). Physical instability keeps streamcourses active and must form the core of conservation and restoration plans, if accompanied by evaluation programmes based on monitoring, sampling and modelling.
— Available scientific and technical expertise is already sufficient and ready to inform river management practices. Continuous reassessment of renaturalization and restoration practices is a key factor to keep work in progress and updated. Twenty-first century technical developments support the implementation of sound guidelines to the fields of river science and engineering.

In spite of being governed by universal factors, rivers are complex and distinct, and no universal solutions exist to face environmental problems in the whole variety of contrasted socioeconomic and climatic environments on Earth. Indeed, extrapolation between river basins is a smart way to progress, but local *ad hoc* actions (both short and long-term) such as, (i) flushing flows, (ii) sediment injection downstream from dams, (iii) sediment pass-through reservoirs, (iv) periodical reservoir drawdown and sediment dredging, (v) restoring of abandoned channels, (vi) decommissioning levees and re-introducing sediments into streams, among others, shall be put on the agenda and progressively implemented.

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