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# HYDROGEOMORPHIC PROCESSES AFFECTING RIPARIAN HABITAT WITHIN ALLUVIAL CHANNEL–FLOODPLAIN RIVER SYSTEMS: A REVIEW FOR THE TEMPERATE ZONE

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## ABSTRACT

Hydrogeomorphic processes within alluvial river systems create, maintain and degrade riparian habitat. The dynamic interactions between water, sediment, aquatic–terrestrial landforms and biotic elements control the functional processes and biodiversity patterns within the riparian zone and, thus, contribute directly to their ecological integrity and societal value. Numerous researchers from different disciplines publish work on the physical, biological, economic and societal functions of the riparian zone within various physiographic areas. The present paper aims to review the hydrogeomorphic processes of unconfined alluvial channel–floodplain rivers within the temperate zone. These processes and their interactions with the biotic environment provide the basis for understanding the physical as well as the ecological functioning of fluvial hydrosystems. The review focuses mainly on the European context, but major advances in riparian research from other continents are also considered. Rehabilitation and management strategies for the riparian zone are summarized and recommendations for further research conclude this review. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: riparian habitat; riparian vegetation; hydrogeomorphic processes; channel degradation and aggradation; sedimentation; river management

## INTRODUCTION

The riparian zone provides many societal benefits, which include flood mitigation, aquifer recharge, maintenance of water quality in surface and groundwater and recreation (e.g. Maltby *et al.*, 1996; Fustec and Lefeuvre, 2000; Freeman and Ray, 2001). The high ecological value of the riparian zone is recognized as central to sustainable river management approaches (e.g. Amoros *et al.*, 1987; Petts and Amoros, 1996; Naiman and Décamps, 1990; Naiman and Bilby, 1998). Within this context, an emphasis has to be put on the understanding of hydrogeomorphic processes that are fundamental to sustaining habitat diversity within riparian environments (Salo, 1990).

Habitat diversity within riparian and floodplain environments is related to the regular and repeated rejuvenation of successions associated with disturbance (Petts, 1990a). The main hydrogeomorphic processes related to the disturbance regime are flooding, erosion, accumulation and reworking of sediment along the fluvial corridor. These processes are generating for example various channel patterns, channel migration, avulsion, bar and island formation, and floodplain deposition. Hydrogeomorphic processes also interact with vegetation dynamics and create the geomorphic template for riparian habitat according to different physiographic contexts, valley forms and river styles. In certain regions, wildlife may also interact with hydrogeomorphic processes (Butler, 1995; Naiman *et al.*, 1999).

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Within high gradient systems, hillslope erosion processes such as landslides and debris flows determine the rate of supply of sediment to the channel and, hence, the temporal evolution of riparian habitat (e.g. Swanson *et al.*, 1982; Gregory *et al.*, 1991; Montgomery, 1999). However, larger alluvial low gradient river systems with extensive floodplains are located further downstream in the longitudinal river continuum; and they are most strongly influenced by hydrogeomorphic processes of fluvial origin. They may contain riparian zones primarily reflecting species-specific responses to soil moisture/oxygenation, sediment deposition, the frequency and duration of inundation, and the erosive action of flooding along a lateral gradient (Ward *et al.*, 2002).

In order to contribute to the understanding of the riparian zone, this review focuses on alluvial channel–floodplain rivers within the temperate zone where disturbance processes of fluvial origin affect the riparian zone more than hillslope processes. The purposes of this paper are: (1) to review hydrogeomorphic processes interacting with biotic processes creating, maintaining and degrading riparian habitat within unconfined alluvial floodplain rivers; (2) to discuss human impacts modifying hydrogeomorphic processes and, in turn, riparian habitat diversity; (3) to consider different ecological effects of riparian habitat modifications; (4) to present prevailing river rehabilitation and management approaches with respect to riparian habitat; and (5) to provide recommendations for further research to fully understand natural and anthropogenic factors influences upon hydrogeomorphic processes controlling riparian habitat at the catchment scale and at the reach scale.

## DEFINITION AND CHARACTERISTICS OF THE RIPARIAN ZONE

The terms riparian zone and riparian area are used as synonyms in this review. Gregory *et al.* (1991) presented the definition of the riparian zone (Figure 1) from an ecosystem perspective. This definition presents a functional view, which focuses on the linkages between terrestrial and aquatic ecosystems within the context of fluvial landforms and the hydrogeomorphic processes that create them. Examples of critical functions of vegetated riparian zones for stream ecosystems include shading, bank stabilization, uptake and recycling of nutrients, input of organic matter (leaves, needles, small and large woody debris), and retention of particulate organic and inorganic matter during high flows (Gregory *et al.*, 1989). However, within larger alluvial rivers with extensive floodplains, functions such as shading and input of organic matter will have lesser importance for the aquatic ecosystem processes than within small headwater streams (Vannote *et al*., 1980).

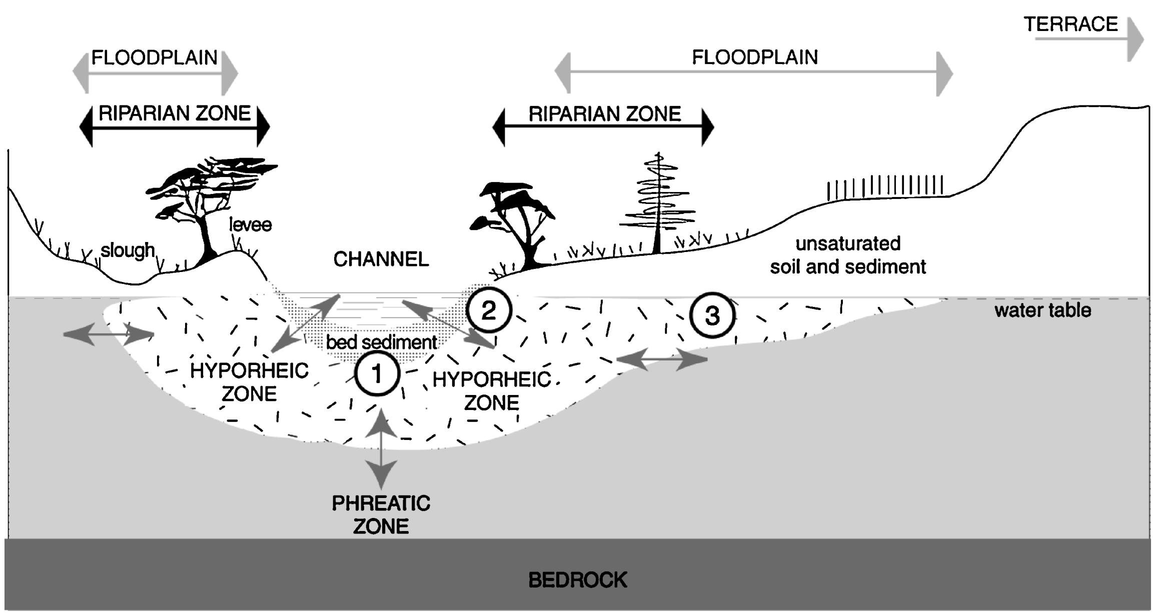


Figure 1. Schematic diagram of the vertical and lateral structure of a channel–floodplain–aquifer system. (1) Wetted channel hyporheic, (2) parafluvial hyporheic and (3) floodplain hyporheic according to Naiman *et al*. (2000) (modified from Ward, 1998)

 

The riparian zone can be viewed as a four-dimensional sub-system of fluvial hydrosystems (*sensu* Amoros *et al.*, 1987; Petts and Amoros, 1996). It may be several tens of kilometres wide, as in the Orinoco and Amazon River basins (Rosales-Godoy *et al.*, 1999) or a narrow strip of streambank vegetation as in canyons and V-shaped valleys (Malanson, 1993) or in arid and semi-arid regions (Salinas *et al.*, 2000). Two main conceptual frameworks delimiting the riparian zone co-exist with intermediate positions according to the authors' conception and the geographical region studied. The first framework considers the riparian zone in a more spatially restrictive sense of within bank and around bankfull discharge (e.g. Hupp and Osterkamp, 1996). The second, which views the riparian zone in a broader sense, includes the ecosystem adjacent to the river channel (Malanson, 1993) which may include the entire floodplain, and, according to Stanford *et al.* (1996) also terraces, i.e. former floodplains. In any case, Malanson (1993) points out that the use of the term floodplain as a synonym for riparian zone would be misleading because the riparian zone also includes narrow strips along downcutting rivers, islands, and channel landforms.

In unmanaged fluvial systems, the riparian zone constitutes highly dynamic areas within the fluvial landscape. The banks of alluvial rivers are less permanent than most other aspects of the landscape (Schumm and Winkley, 1994); and highly dynamic tributary junctions are also recognized to play a major role in providing riparian habitat diversity (Benda *et al.*, 2004). However, under increased human pressure, the riparian zone is coveted by numerous and often conflicting activities (e.g. agriculture, fishing, tourism, urbanization, sediment mining), leading often to significant modification of riparian zone structure and functioning by riverine societies.

Stream structure, habitat and function can be influenced by patch characteristics within fluvial systems which in turn determine biotic and abiotic processes at different spatio-temporal scales (Pringle *et al.*, 1988). Patch characteristics also reflect the dynamic mosaic of resource and disturbance patches of different age and successional stages (Petts, 1990a). A disturbance occurs when potentially damaging forces (e.g. high-flow or low-flow events) are applied to a habitat space occupied by a population, community, or ecosystem (Lake, 2000). Lateral instability, avulsion and variations in hydrogeomorphic conditions in temperate fluvial systems create patches of fluvial landforms that normally exert a profound influence on the vegetation patterns (Hupp and Bornette, 2003) and lead to a particularly diverse range of habitats at different spatial and temporal scales. Thus, hydrogeomorphic processes affect aquatic and riparian ecosystems through their influence on physical and biotic habitat structure, although biological processes can, in turn, influence physical processes (Montgomery, 1999).

The range of riparian habitats includes localized micro-habitats formed of sediment, rocks and dead wood; meso-habitats formed of geomorphic landforms (e.g. bars, natural levees, sloughs, side and abandoned channels) and riverine vegetation; and macro-habitats formed of riparian forests and entire reaches and sections of the river corridor. The ratio between each habitat scale and the river section observes changes according to stream order from headwater streams to the river mouth and also depends on the river style (e.g. braided, anastomosed, meandering). Richards *et al.* (2002) suggest that the reach scale is the most intimate with mutual association between channel and vegetation (patch) dynamics, and the greatest potential for biogeomorphological management (Figure 2).

Within floodplain rivers, riparian habitat quality is determined by mineral substrate, aquatic plants, riparian forests, water depth (instream and overbank) and current velocity (lentic or lotic), and habitat diversity (e.g. islands, cutoffs, benches). Riparian habitat functions as a food source, refugia (e.g. shelter from fast currents, hiding from predators) and reproduction site (e.g. spawning, nursery) for aquatic, amphibian and terrestrial organisms and communities. It plays a key role in providing refugia for recovery from natural (e.g. floods, droughts) and anthropogenic (e.g. accidental pollution) disturbances in river systems. Refugia are defined as habitats or environmental factors that convey spatial and temporal resistance and/or resilience to biotic communities impacted by biophysical disturbances (Sedell *et al.*, 1990). According to these authors most refugia in rivers are characterized by extensive coupling of the main channel with adjacent streamside forests, floodplain features and groundwater. Ward *et al.* (1998) note that the generally high resilience of lotic ecosystems to disturbance is attributable, in part, to high spatio-temporal heterogeneity; and also because habitat patches less affected by a particular perturbation may serve as refugia from which survivors may recolonize more severely affected areas.

The riparian zone does not necessarily have to be characterized by woodlands. Poplar plantations, agriculture, or spontaneous grass and shrubby vegetation also occupy the riparian zone. Geomorphic (e.g. rocky substrate) or climatic (e.g. semiarid regions) conditions may also constrain the theoretically older woody successional stages to herbaceous or shrubby stands. However, at a certain successional stage mature riparian vegetation will establish

 

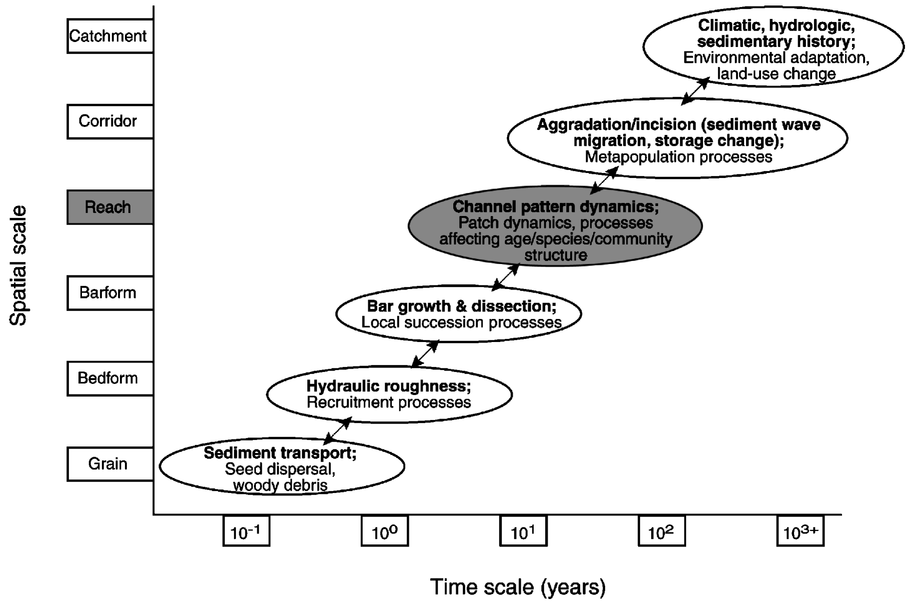


Figure 2. A hierarchical representation of the interrelated fluvial (bold) and ecological (normal text) processes at different scales in the fluvial environment, that determine the habitat diversity of channel–riparian–floodplain environments at various spatio-temporal scales (from Richards *et al.* (2002), reproduced with permission from Blackwell Publishing)

within riparian areas (e.g. Chauvet and Décamps, 1989; Hupp, 1992) and, thus, riparian woodlands are a major biological and structural component of the riparian zone (Figure 3).

Riparian forests in Europe used to be a major element of fluvial landscapes. Throughout Europe, despite early floodplain deforestation from about 2500 BP (Wiltshire and Moore, 1983) along many rivers, the margins remained as seasonally flooded forests until the mid-18th century (Petts, 1997). In France, important floodplain deforestation starts during the Medieval Age (<1000 BP). Between the 16th and 19th century, within the alpine and pre-alpine area that is characterized by very active braiding, forests are non-existent, or are only represented by a few pioneer patches (Piégay *et al*., 2003). River regulation between 1750 and 1850, fixing the location of river channels (e.g. for flood control, land drainage and navigation), has involved the clearance of riparian trees from most streams and rivers throughout Europe (Petts *et al.*, 1989; Petts, 1990b). As a result, the riparian zone today comprises natural and semi-natural habitats within an agricultural landscape, dominated by arable fields, improved pasture and poplar plantations (Petts, 1997).

However, since the end of the 20th century the geomorphic and ecological value of riparian forests has been widely recognized (e.g. Gregory *et al.*, 1991). They influence channel form (Gregory, 1992), bank stability (Kondolf and Curry, 1984) and sediment transfer through the river system (Steiger and Gurnell, 2003). Stream function is influenced by contributing particulate organic matter and large woody debris (Gurnell *et al.*, 2002), by providing shade (Pusey and Arthington, 2003), by retaining organic matter (Tockner *et al.*, 1999) and flood water volumes (Archer, 1989), and by regulating the movement and cycling of nutrients (Pinay *et al.*, 1999). Habitat for birds (Décamps *et al.*, 1987), small mammals (Mason, 1995), beaver (Fustec *et al.*, 2001) or otter (Prenda and Granado-Lorencio, 1996) is provided by the forest structure itself. The production of leaf litter and woody debris supplies food and habitat for fungal (Laitung *et al.*, 2002) and invertebrate communities (Dobson, 1991). The importance of the riparian zone to the conservation and management of freshwater fish is reviewed by Schiemer *et al.* (1995) and Thevenet and Statzner (1999).

These very diverse studies all show that woodland within European riparian areas plays a central role for the functioning of the river system. A reduction of riparian forest diversity may result in an impoverishment, or even a collapse, of riparian ecosystems (Décamps, 1996). Based on this understanding, riparian woodlands are currently taken into account for environmentally sensitive river management (Brown *et al.*, 1997; Piégay and Landon, 1997; Sterba *et al.*, 1997).

 

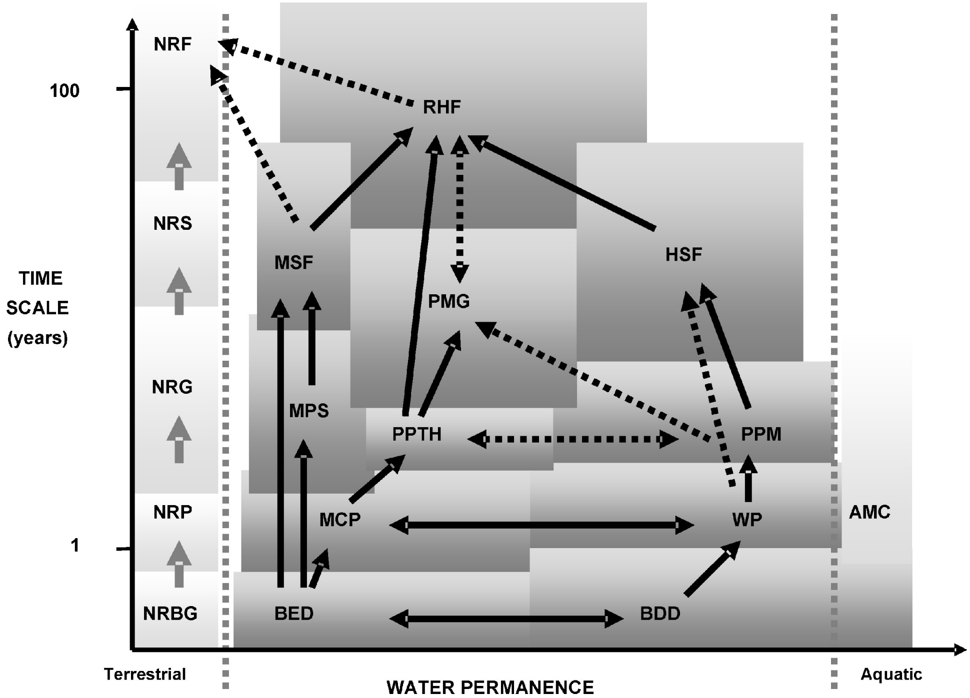


Figure 3. Schematic representation of vegetation succession stages within the riparian corridor of the Middle Garonne River, southwest France (solid arrows indicate most probable pathways, dotted arrows indicate less probable pathways)

Non-riparian external edge: NRBG: Non-riparian bare ground. NRP: Non-riparian pioneer communities. NRG: Non-riparian grassland (*Arrhenatherum elatius, Poa pratensis, Dactylis glomerata, Elytrigia campestris, Brachypodium pinnatum*, . . . ). NRB: Non-riparian shrubland (*Salix caprea, Rosa gr. canina, Crataegus laevigata, Ulmus minor, Viburnum lantana*, . . . ). NRF: Non-riparian forest (*Quercus pubescens, Sorbus torminalis, Castanea sativa*, . . . )

Permanent aquatic habitats of the active channel AMC: Aquatic macrophytes communities (*Batrachium fluitans, Potamogeton pectinatus, Ceratophyllum demersum, Myriophyllum spicatum, Nuphar luteum, Vallisneria spirallis*, . . . ).

Moist habitats BDD: Bare sediment in depositional zone (fine grain size dominant). WP: Wet pioneer communities (*Phalaris arundinacea, Veronica anagallis-aquatica, Bidens frondosa, Cyperus eragrostis, Echinocloa crus-galli, Chenopodium ambrosioides, Polygunum hydropiper, P. lapathifolium, Paspalum paspaloides, Ludwigia grandiflora*,). PPM: Post-pioneer marshy vegetation (*Phragmites australis, Lycopus europaeus, Lythrum salicaria, Cyperus esculentus, Leersia oryzoides, Shoenoplectus lacustris, Typha latifolia*, . . . ). HSF: Hygrophilic softwood forest (*Alnus glutinosa, Salix atrocinerea, Salix fragilis*, . . . ).

Dry habitats frequently flooded: BED: Bare sediment in erosional zone (coarse grain size dominant). MCP: Main channel pioneer communities (annual ruderals dominated). MPS: Mesic pioneer shrubland (*Populus gr. nigra, Salix eleagnos, S. purpurea, Budleja davidii, Artemisia vulgaris, A. verlotiorum*, . . . ). MSF: Mesic softwood forest (*Populus nigra, Salix alba, Acer negundo, Ulmus minor, Robinia pseudacacia, Urtica dioica, Impatiens glandulifera, I. balfouri*, . . . ).

Mesic habitats infrequently flooded: PPTH: Post-pioneer tall herbs (*Urtica dioica, Sambucus ebulus, Dipsacus fullonum, Fallopia* × *bohemica, Helianthus rigigus, Verbascum thapsus, Artemisia verlotiorum, Rubus ulmifolius*, . . . ). PMG: Post-pioneer mesic grasslands (*Arrhenatherum elatius, Elytrigia repens, Dactylis glomerata, Saponaria officinalis, Senecio inaequidens, Rubus caesius*, . . . ). RHF: Riparian hardwood forest (*Fraxinus excelsior, Fraxinus angustifolia, Acer pseudoplatanus, Quercus robur, Querqus pubescens, Ulmus laevis, Carex maxima, Hedera helix, Impatiens parviflora*, . . . )

However, a better understanding of interactions between vegetation and morphodynamics at the local, reach and catchment scale is still needed to manage, restore and rehabilitate riparian woodland within Europe's impacted river systems.

## HYDROGEOMORPHIC PROCESSES CREATING, MAINTAINING AND DEGRADING RIPARIAN HABITAT

### *The role of hydrological variability*

Water volumes as well as the temporal distribution of floods and low flows, reflect the natural and anthropogenic flow regime of the river section studied. The hydrologic variability not only determines erosion and sedimentation rates, but is also particularly important for riparian species (e.g. Naiman and Décamps, 1997), which in turn will generate positive or negative feedback loops for erosional and depositional processes.

The importance of flood magnitude for spatial patterns of maximum flood deposition rates has been illustrated for the meandering River Severn, UK. Steiger *et al.* (2001a) observed that maximum sedimentation during flooding occurred at the interface between the long-duration higher energy and short-duration lower energy flood inundation zones. These patterns persisted through zones of distinctly different sediments associated with geomorphological setting and vegetation cover type. The position of the level of peak sedimentation shifted vertically up and down the river bank according to the magnitude of the flood discharge. Mean submersion time seemed to be more influential than peak discharge in influencing sedimentation rates.

High and rare flood events may be crucial to generating riparian/floodplain habitat diversity (Sparks, 1995). However, extreme floods do not exclusively shape channel and floodplain morphology. Even smaller water level fluctuations ('flow pulses', *sensu* Tockner *et al.*, 2000), over short timescales, can lead to major aquatic riparian/floodplain habitat changes with important consequences for the fauna and flora (van der Nat *et al.*, 2003). Furthermore, bankfull discharge with low magnitude discharges and high frequencies as proposed by the dominant discharge concept (Wolman and Miller, 1960; Leopold *et al.*, 1964) may also lead to riparian habitat changes.

### *Sediment retention within the riparian zone*

The riparian zone may function as an important sediment (clay, silt and sand) sink during flood events (Hupp *et al.*, 1993; Kleiss, 1996; Steiger and Gurnell, 2003) and may buffer rivers from washload produced within uplands (e.g. Lowrance *et al.*, 1985). Nevertheless, erosion processes counterbalance sediment retention and active riparian zones are not permanent sediment sinks. In mobile meandering rivers, point bar accretion in inner bends is in balance with bank erosion at outer bends (Wolman and Leopold, 1957). According to Harvey and Schumm (1994) the lateral migration of the channel ultimately controls overbank deposition on the floodplain and affects bank height because sedimentation rates are highest at the channel margin, and decrease with distance from the channel on the floodplain (Walling and He, 1998). However, many other factors at different spatial-temporal scales control riparian sedimentation (Figure 4).

Several sediment accretion processes are at the origin of the construction and maintenance of riparian environments, which vary according to: (i) river style, (ii) transversal or vertical location of the riparian element considered (e.g. islands, point bars, cutoffs), and (iii) flow regime responsible for sediment deposition events during high flows. Six main processes of floodplain formation were summarized by Nanson and Croke (1992): lateral point bar accretion, overbank vertical accretion, braided channel accretion, oblique accretion, counter point accretion, and abandoned channel accretion.

Riparian landforms undergo different stages during their construction linked to different sedimentation processes. These processes control, to some extent, the deposition of different sediment sizes determining, in turn, habitat conditions (e.g. pore sizes, moisture content and cohesiveness). Many studies indicate a upward fining sequence for both channel bar and overbank facies (Wolman and Leopold, 1957; Nanson and Young, 1981; Magilligan, 1992). Significant differences between coarse-grained low-lying areas (e.g. point bars) and fine-grained high overbank deposits are also frequently and widely observed. However, even though Steiger and Gurnell (2003) find significant differences in sedimentation rates according to different riparian landform features, a clear spatial pattern for sediment grain sizes among single flood event deposits is not observed (unpublished data). It is suggested that grain sizes of single flood deposits may vary significantly during different flood stages of the same flood event and, thus, cause a mixture of coarser and finer sediment. As a result, the observed spatial pattern for sediment grain sizes is less distinct than the spatial accumulation pattern.

### *Erosion processes altering the riparian zone*

Bank erosion (Lawler *et al.*, 1997) is certainly among the most common erosion processes contributing to the destruction of riparian habitat. Accelerated channel entrenchment is observed in many rivers following major human impacts, such as dam construction and river channelization (Petts, 1984; Darby and Simon, 1999). Channel entrenchment favours erosion of oversteepened banks during the degradation and widening of the river channel (Hupp and Simon, 1991) if sediment characteristics and cohesiveness are vulnerable to erosion.

 

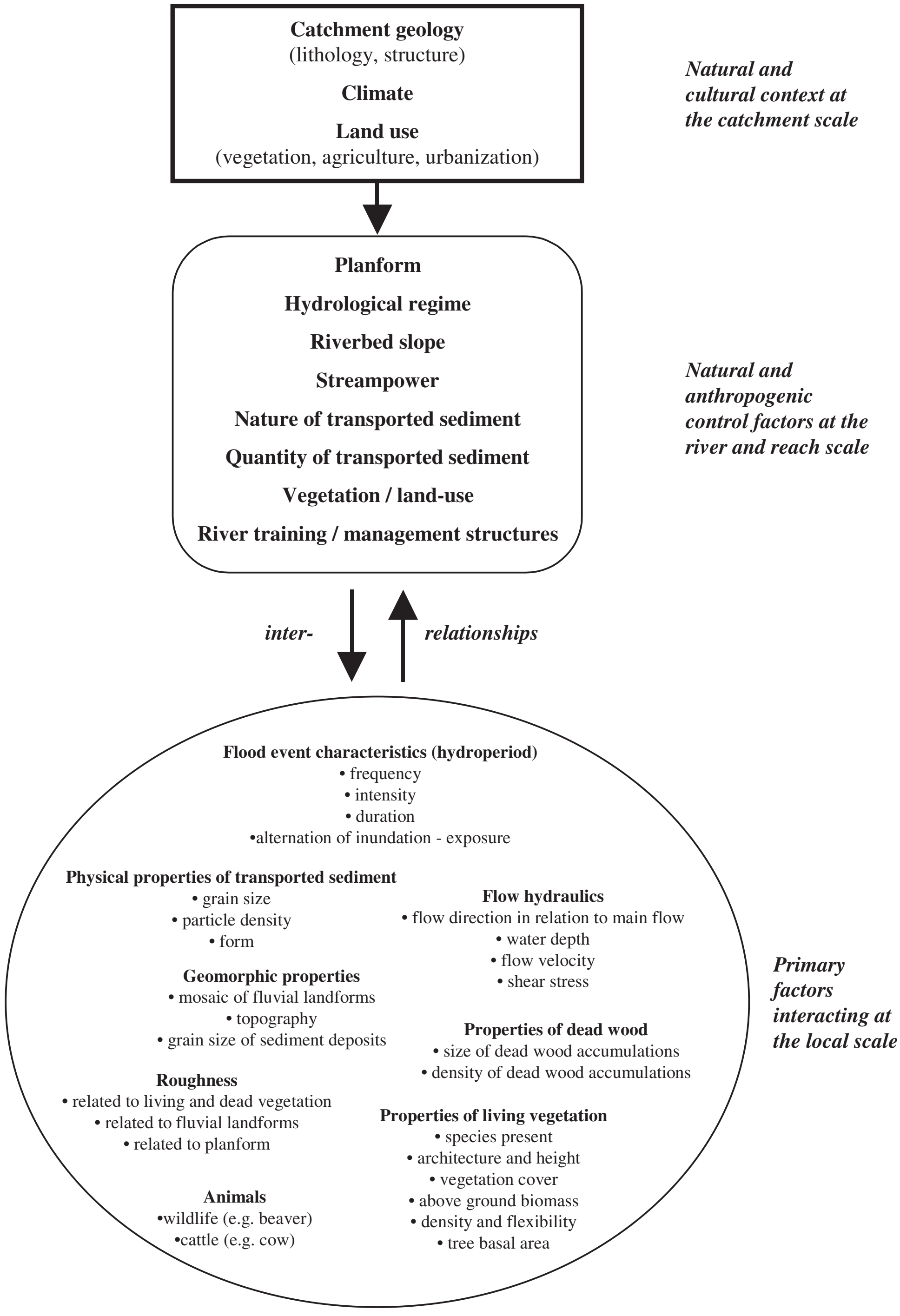


Figure 4. Factors controlling riparian mineral and organic matter deposition, which contribute to the construction and evolution of riparian habitat (modified from Steiger *et al.*, in press)

In river systems where vertical accretion (Allen, 1965) is the dominant floodplain process, periodic floodplain stripping can lead to complex cut-and-fill structures (Nanson, 1986). Since the riparian zone includes low-lying areas, erosion of river banks, islands etc. also contributes to the riparian zone sediment budget, and complicates the quantification of retention time of sediment in fluvial hydrosystems (Hupp, 2000).

 

Another dynamic geomorphic process that forms, modifies and creates variability in riparian zone and floodplain topography is related to sand-splay and channel complexes, often called crevasse splays. Crevasse splays occur by cutting channels during avulsion at natural levee breaches in anabranching rivers and subsequent deposition of sediment that is related to sand-splay processes (Richards *et al.*, 1993). Florsheim and Mount (2002) report from successful intentional levee breaches for riparian habitat restoration by recreating a lost variability in physical structure due to floodplain areas previously levelled for agriculture where lateral connectivity between the channel and floodplain was lacking.

### *Hydraulic effects of riparian vegetation*

Riparian trees and shrubs are particularly important in enhancing flow resistance and sediment cohesion within the riparian zone and, thus, in actively influencing rates of aggradation and degradation (Gurnell *et al.*, 2004). Theoretically, the extent to which vegetation affects Manning's roughness coefficient ($n$) for a particular river section, depends on the depth of flow, the percentage of the wetted perimeter covered by the vegetation, the density of vegetation below the high-water line, the degree to which the vegetation is flattened by the flowing water, and the alignment of vegetation relative to the flow (Arcement and Schneider, 1989). However, these impacts of vegetation must be placed within a geomorphological context.

The significance of both geomorphology and hydrology as controls on sedimentation, which may moderate or override the impact of vegetation, are identified (Hupp *et al.*, 1993; Kleiss, 1996; Steiger *et al.*, 2001a). For example, according to Chow (1959), meanders and, therefore, river planform can increase Manning's $n$ by as much as 30% where flow is confined within the river channel. From a study on the meandering River Severn, UK, Steiger *et al.* (2001a) conclude that flood event characteristics (i.e. peak discharge, shape and duration of the flood event affecting the number of submergence–emergence cycles and the duration of inundation) interact with the morphology of the riparian corridor to produce the distinctive patterns of sedimentation observed. The contrasts in the vegetation structure of the three land-use types investigated (pasture, mixed riparian woodland, poplar plantation) were insufficient to counterbalance the reach-scale importance of hydrological and geomorphological factors.

## HUMAN IMPACTS MODIFYING HYDROGEOMORPHIC PROCESSES AND ALTERING RIPARIAN HABITAT

Habitat alterations within riparian corridors are caused by cumulative effects modifying the two main driving variables: (i) the flow/flood pulse (Tockner *et al.*, 2000); and (ii) the sediment dynamics produced through river engineering (Petts *et al.*, 1989), land-use changes (Walling, 1999) and global climate change (Brown and Quine, 1999). Stream ecosystems are also at risk from changes due to natural or human-induced climate change because hydrogeomorphic and ecological processes are strongly influenced by seasonal patterns of precipitation, runoff and temperature (Carpenter *et al.*, 1992; Poff *et al.*, 1996).

The geomorphic effects of the manifold anthropogenic disturbances on river systems vary according to: (i) their multiple possible combinations, (ii) the mutual adjustments of the dependent variables, and (iii) the physiographic context. Morphological response to river engineering and management, flow regulation and land-use changes in the catchment directly control riparian habitat structure. For example, bedload decreases following dam construction and gravel mining during the 20th century within many European rivers (e.g. Peiry, 1987; Bravard *et al*., 1997; Steiger *et al*., 1998; Surian and Rinaldi, 2003) may directly reduce meso-habitat diversity (e.g. gravel bars, islands), the interstitial micro-habitat, and reduce the variability in hydraulic flow conditions necessary for the maintenance of diverse living organisms communities within the three-dimensional river bed (Statzner *et al.*, 1988).

Channel adjustments to human-induced changes of control variables are widely studied (e.g. Darby and Simon, 1999). Significant progress in understanding these channel responses are achieved through the development of channel evolution models (CEMs) based on research on channelized streams in loess-derived alluvium in the southeastern USA (e.g. Schumm *et al*., 1984; Hupp and Simon, 1991). In respect to riparian habitat, Hupp and Simon (1991) explain that aggradation processes within formerly severely degraded river channels (incised and widened) can lead to the creation of bars and berms, thus constituting newly created riparian zones.

 

Recent research by Rinaldi (2003) and Surian and Rinaldi (2003) on alluvial rivers in Italy confirm the drastic channel adjustments observed on rivers in industrialized countries during the 20th century but show some limitations of the CEMs proposed for incised rivers in loess-derived alluvium in southeastern USA (Schumm *et al.*, 1984; Hupp and Simon, 1991) when trying to transfer it to rivers within different physiographic contexts. Thus, Rinaldi (2003) and Surian and Rinaldi (2003) observe (i) a channel narrowing of many Italian river channels rather than channel widening, and (ii) the lack of an aggradational phase following a phase of incision. Braided rivers adjust predominantly to a drastic reduction of in-channel sediment supply due to dams and sediment mining through important channel narrowing but less severe incision, while single-thread rivers adjust mainly through bed-level lowering accompanied to a greater or less degree by narrowing (Surian and Rinaldi, 2003). A general classification scheme of channel evolution of Italian rivers which clearly distinguishes three channel types (single-thread, transitional, braided) is presented by Surian and Rinaldi (2003).

These new insights in possible channel adjustment mechanisms of different alluvial river types have to be considered and further developed to predict, at least qualitatively, riparian habitat creation, degradation and destruction as a function of the geomorphic setting, hydrological regime and major anthropogenic disturbances to the river system.

## ECOLOGICAL EFFECTS OF EROSION AND SEDIMENTATION WITHIN THE RIPARIAN ZONE

Deposition and reworking of sediment within the riparian zone can be considered as an integral part of the natural disturbance regime (Pickett and White, 1985) affecting species community composition and diversity. The intermediate disturbance hypothesis (IDH) proposed by Connell (1978) predicts highest specific richness within habitats where disturbance is intermediate. When disturbances are too intense and/or too frequent, competing species are not able to colonize. Conversely, when they are too low and infrequent, the absence of sufficient areas for regeneration limits the survival of colonizing species. The IDH has been confirmed when geomorphic processes influence the diversity of whole river corridors (e.g. Gilvear *et al.*, 2000), as well as at more local scales (e.g. Bornette *et al.*, 1998). Bornette *et al.* (1998) observe a higher specific diversity and a higher number of rare species of aquatic macrophytes within disturbed dead arms.

It is the dynamic interaction between water, sediment and aquatic–terrestrial landforms that creates and maintains riparian areas and controls their characteristic functional processes and biodiversity patterns (e.g. Junk *et al.*, 1989; Bayley, 1995; Bornette *et al.*, 1998; Tabacchi *et al.*, 1998). In return, the structure of vegetation mosaics affects hydrology, erosion, sediment transport and deposition processes (e.g. Gurnell 1997; Tabacchi *et al.*, 2000; Hupp and Bornette, 2003).

The riparian zone is characterized by sharp environmental gradients which determine the structure of riparian plant communities (Hughes, 1997). The gradients within localized areas are related to fluvial dynamics, floods (disturbance regime), soil moisture and nutrients, which are all interrelated (Gregory *et al.*, 1991, Naiman and Décamps, 1997). Any changes of the flow or sediment regime affecting the environmental gradients will inevitably alter riparian plant communities. However, natural variations in flood duration and frequency, and concomitant changes in water table depth and plant succession create an environment of complex, shifting habitats that are created and destroyed on different spatio-temporal scales (Malanson, 1993).

### *Interactions between sediment and propagule deposition*

A further important property of riparian sedimentation is the associated deposition of biological materials such as seeds and plant propagules (Goodson *et al.*, 2001). Deposited sediments can contain large numbers of seeds and vegetative fragments (Nilsson and Grelsson, 1990). Gurnell *et al.* (2001) and Gurnell and Petts (2002) illustrate the importance of propagule, dead wood and sediment transport and deposition dynamics in the establishment of wooded islands along the Tagliamento River, Italy. They highlight the significance of changes in sediment calibre in controlling tree establishment along the river. Similarly, Tabacchi *et al.* (2005) demonstrate that along the Garonne River, France, seed inputs under hydrological and geomorphological controls in the innermost zone of the riparian corridor (i.e. at the interface between the active channel and riparian zone) results in a seedbank that appears as very different from the above extant vegetation. Hydrological events of the Garonne River responsible for major sediment deposition also induce peaks in seed diversity inputs (up to 100 distinct species per square metres). However, some ecological processes, such as biological invasions, result more from airborne dispersal as fructification of introduced species mainly occurred during the low-flow season (Tabacchi *et al*., 2005).

Seeds and propagules concentrate in micro-depressions following depositional processes (Abernethy and Wilby, 1999; Goodson *et al.*, 2001; Andersson and Nilsson, 2002; Tabacchi *et al.*, 2005). In addition, such depressions can provide suitable environmental conditions (nutrients, moisture, etc.) for germination and, hence, microtopography is a major factor for determining earlier successional processes and plant diversity (Pollock *et al.*, 1998; Middleton, 1999; Barsoum, 2001; Guilloy-Froget *et al.*, 2002).

Deposition of mineral sediment can have adverse effects on the recruitment of buried seedlings from the underlying soil. For example, Jurik *et al.* (1994) find that deposition of a 10 mm thickness of sediment severely restricts seedling recruitment and favours recruitment from larger-seeded species, implying a significant impact on the structure of the developing plant community. These observations also indicate that if sedimentation depth exceeds a few centimetres, the establishment of a vegetation cover is largely dependent upon the sexual and vegetative propagules that are deposited on or with the sediment. Interactions between sediment and propagule deposition drive much of the observed vegetation diversity of the riparian zone, as well as supporting the dispersal of alien species (Tickner *et al.*, 2001).

### *Hydrogeomorphic processes interaction with riparian plant community dynamics*

As outlined above, river adjustments to changes in the flow and sediment regime depend on a multitude of variables and may result in various river patterns. However, two main geomorphic adjustment modes predominate: (i) channel incision, or (ii) channel aggradation. Riparian plant communities may be adversely affected according to the prevailing geomorphic processes. Channel incision may lead to an increase of bankfull discharge and, thus, a decrease in overbank flooding so altering hydrological connectivity within the river corridor and riparian sedimentation as observed on the Garonne River, France (Steiger *et al.*, 2000, 2001b). Indeed, a widely observed example of human triggered changes is channel incision lowering water tables around the river, with consequences for riparian vegetation that feed back to affect river communities through changes in organic matter input and the fragmentation of the riparian corridor, which is used for migration and dispersal (Naiman and Décamps, 1997).

It was suggested that channel incision on the Garonne River, was one of the main causes which led to a sharp increase of riparian wood dieback after 1980 owing to the subsequent lowering of the groundwater table and a decrease in hydrological connectivity between the river channel and the fringing floodplain (James, 1996; Steiger *et al.*, 1998). According to studies from west Tennessee, USA, Hupp (1992) observed that riparian vegetation recovery after stream channelization and degradation could be related to subsequent channel bed aggradation, woody vegetation establishment and bank accretion over a period of 65 years. Surprisingly, the consequences of channel degradation and high flow frequency decrease on the overall structure of the riparian zone can also result in an increase in biological connectivity between the river channel and its terrestrial surroundings owing to the fragmentation of the external edge of the riparian corridor, which becomes more ‘porous’ to invasion by external species. As reported by Tabacchi and Planty-Tabacchi (2003) from studies of lowland rivers in southwestern France, high flow frequency decrease is expected to promote the invasion of riparian communities by exotic and native species from the adjacent cultivated landscape, and to create a depletion in the contribution of marshy plants to the total diversity. In turn, biological invasions by exotic (Tabacchi and Planty-Tabacchi, 2003) or by native (Johnson, 1994) species can constrain channel dynamics and biogeochemical in-stream processes, such as leaf litter and large woody debris decomposition.

Conversely, channel aggradation may lead to an increase in overbank flooding and hydrological and sedimentary connectivity. Within meander cutoffs of the Ain River, France, isolated on average four decades ago, species richness remains very high owing to a high connectivity during flood pulses that maintains high propagule dispersal compared with less well-connected and older meander channels along the Rhône or the Saône Rivers, France (Piégay *et al.*, 2000). Thus, riparian plant species recruitment is highly dependent upon sedimentation processes.

### *Ecological significance of the interstitial riparian sediment habitat*

The vertical dimension of the riparian zone, the hyporheic zone, extends into the subsurface domain and provides the hyporheic habitat (Stanford and Ward, 1988) (Figure 1). Naiman *et al.* (2000) distinguish the (i) wetted

 

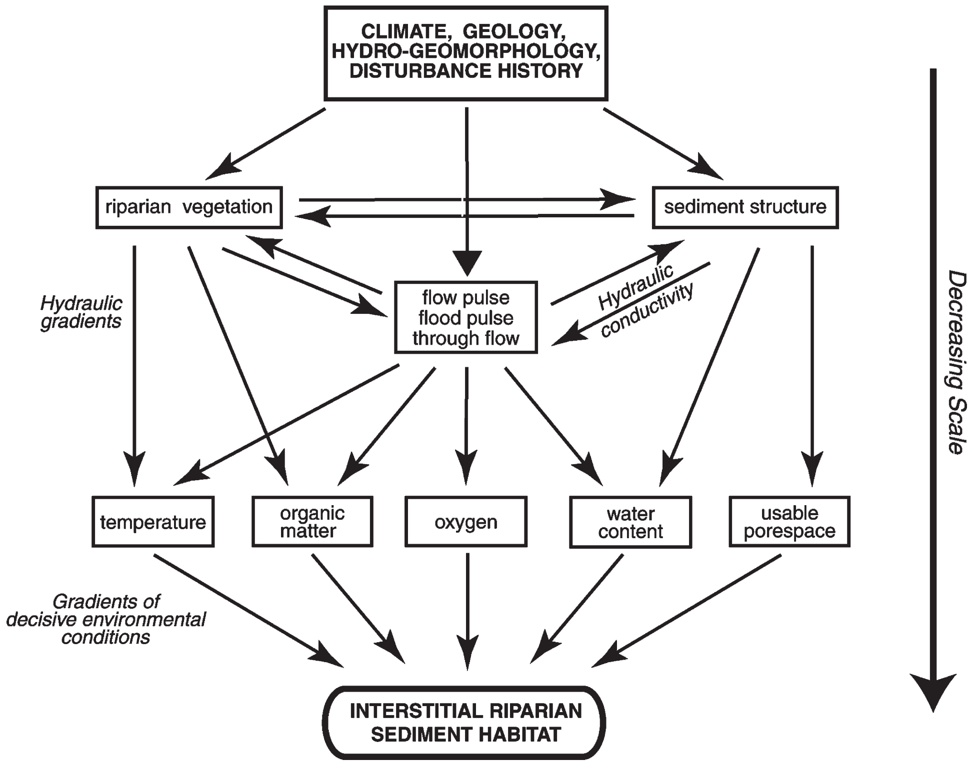


Figure 5. Factors controlling riparian interstitial (subsurface) sediment habitat conditions (modified from Ward *et al.*, 1998).

channel hyporheic, (ii) parafluvial hyporheic and (iii) floodplain hyporheic. The existence and interconnection of these three major types of hyporheic zones beneath a floodplain-river vary regionally and locally with sediment characteristics of the river-floodplain alluvium. The contribution of the hyporheic zone to stream ecosystem function is determined by the rate of subsurface biogeochemical processes and the groundwater–surface water interactions flowing through hyporheic sediments (Jones and Holmes, 1996).

Furthermore, subsurface sediments and associated interstices at the surface water/groundwater interface provide important habitat and refuge for metazoans (major division that comprises all multicellular animals other than protozoans and sponges) within the river bed and in alluvial aquifers beneath the floodplain (Ward *et al.*, 1998). Since hydrogeomorphic processes are creating and maintaining the alluvial environment, these processes also determine hydraulic conductivity, oxygen levels, pore space, particle size heterogeneity, the mechanisms of particulate and dissolved organic matter retention, and other interstitial riparian habitat conditions (Figure 5). Hence, changes in the hydrological and sedimentological regime induced through natural (e.g. climate change) or anthropogenic (e.g. climate change, land use, flow regulation) impacts will ultimately modify subsurface habitat conditions. For example, fine sediment deposition within river channels can cause clogging of subsurface interstices and alter physical habitat characteristics within and below the river bed (Wondzell and Swanson, 1999).

However, basic environmental requirements of the majority of groundwater metazoans remain uninvestigated (Ward *et al.*, 1998). Predictions of changes in interstitial metazoan communities and their contribution to the total productivity and energy flow of the biosphere caused by hydrogeomorphic changes are difficult to estimate. Further research to assess interstitial subsurface and groundwater biodiversity is needed to provide guidelines for the sustainable management of these important water resource systems (e.g. Gibert and Steiger, 2002).

### *Ecological significance of the buffering function of the riparian zone*

The buffer function of riparian areas in retaining sediment and associated nutrients, pollutants and propagules from through-flowing water is considered to be a major benefit to the aquatic ecosystem (e.g. Johnston, 1991;

 

Haycock *et al.*, 1997). Sediment conveyance losses induced by the buffer function of the riparian zone between upstream and downstream river sections will exert an important influence on sediment-associated contaminant loads and budgets (Walling and Owens, 2003) and may enhance water and ecological quality. Nevertheless, in the long term, sediment storage within a river basin can give rise to environmental problems where sediment-associated pollutants accumulate in depositional locations.

To positively effect a reduction in suspended sediment transported by the river, sediment retention within the riparian zone has to be significantly higher than sediment production through bank or floodplain erosion. This will depend on the functioning of the riparian system within its specific catchment context. But, even in the case where riparian areas do not substantially decrease or increase river sediment loads on a local or watershed scale, riparian zones may function to maintain water quality by transforming or retaining nutrients, contaminants and other compounds during temporary (annual, decades, to centuries) periods of sediment storage (Arp and Cooper, 2004).

The riparian zone, their sedimentary characteristics and alluvial soil texture also play an important role for self-purification processes within river systems. Thus, Pinay *et al.* (2000) find a significant relationship between denitrification rates in riparian soils and their texture. Below a threshold of 65% of silt and clay content, riparian and floodplain soils of the Garonne River do not present any significant denitrification rates, while above that threshold denitrification increases linearly (Pinay *et al.*, 2000). These authors suggest that the indirect relationship they find between landscape patterns and denitrifying microbial processes opens new possibilities to evaluate denitrification rates of alluvial soils according to a given geomorphic feature which is measurable at a larger scale.

## RIPARIAN ZONE REHABILITATION AND MANAGEMENT STRATEGIES

Cairns (1990) observes that despite the lack of a robust theoretical support base for lotic ecosystem recovery, there is evidence indicating that lotic ecosystem restoration can both be cost-effective and produce satisfying results relatively rapidly. Whilst freshwater systems may have a high resilience and recover quickly (Milner, 1994), floodplain formation has to be viewed over much longer (geological) timescales and cannot be developed artificially within a short period of time (Kern, 1992; Large and Petts, 1996). Riparian zone rehabilitation may also be more readily achievable than the restoration of large and intensively used (e.g. agriculture) floodplains, and may still be ecologically valuable (Brookes *et al.*, 1996).

Ward *et al.* (2001) promote the landscape approach as a viable strategy for understanding and managing river corridors and point out that established research and management concepts may fail to fully recognize the crucial roles of habitat heterogeneity and fluvial dynamics owing to a lack of fundamental knowledge of the structural and functional features of morphologically intact river corridors. Referring specifically to the restoration of floodplain and riparian woodlands, measures can be taken at different spatial scales: (i) the catchment scale (longitudinal transfers of bed load, hydrological regime), (ii) the reach scale (lateral and vertical connectivity) and (iii) woodland units (forest structure) (Dufour and Piégay, in press).

Riparian woodlands are dependent on fluvial dynamics (flow plus sediment dynamics) and, thus, water allocation decisions targeted at providing natural flow conditions could restore geomorphological processes and benefit riparian woodland restoration as well as in-stream biota. Nevertheless, Hughes *et al.* (2001) argue that it is difficult to predict ecosystem responses to catchment-scale flow allocation measures. Conversely, these authors suggest that site- and reach-scale restoration projects provide reasonably predictable ecological outcomes (see also Figure 2).

The literature review points to the importance of hydrologic connectivity, a key process in riverine floodplains that refers to water-mediated transfer of energy, sediment and organic matter, and organisms within or among elements of riverine corridors (Tockner and Stanford, 2002). The importance of hydrologic connectivity for restoration procedures in order to propose long-term habitat enhancement is also widely recognized (e.g. Henry and Amoros, 1995; Tockner *et al.*, 1998; Piégay *et al.*, 2000).

Tockner *et al.* (1998) conclude after analysing a Danube restoration project that preservation of the high diversity of alluvial floodplains would be more fully realized by the reestablishment of fluvial dynamics and the associated connectivity gradients, rather than by restoration strategies for individual groups or endangered species. Jungwirth *et al.* (2002) also point out that effective management of riverine landscapes should focus on maintaining or restoring interactive pathways and a natural disturbance regime that increases the diversity of habitat patches and successional stages. According to these authors, once the natural disturbance regime is reestablished and self-sustaining ecological processes restored, a minimal maintenance would be required and would result in the enhancement of habitat conditions and species diversity.

A second key point of the geomorphological approach to stream stabilization and restoration is the long-term management of sediment supply/loads within the catchment (Sear *et al.*, 1994). Since sedimentation is one of the major processes creating and maintaining riparian habitat and, thus, contributes to the ecological integrity of fluvial systems, it should receive more attention in the planning process as well as the post-project evaluation phase (Asselman and van Wijngaarden, 2002).

A recent rehabilitation project of side channels of the Rhône River, France, aims to recreate habitat heterogeneity after 150 years of river engineering works by explicitly considering the spatio-temporal variability of erosion and accumulation processes of fine sediment (Amoros *et al.*, in press). The knowledge of these hydrogeomorpholocial processes is fundamental to evaluating temporal durability and, hence, to guaranteeing the success of such rehabilitation projects.

As suggested by Arp and Cooper (2004), previous studies which did not quantify sediment erosion at the same time as sediment accretion have produced incomplete pictures of the sediment budget of riparian sites. To determine whether a riparian site or reach is in equilibrium, surface scour, sediment resuspension and bank erosion processes also have to be monitored.

Sediment budgets provide frameworks for organizing and interpreting information about sediment regimes in fluvial geomorphology (Reid and Dunne, 2003) and they may be used as management tools (Slaymaker, 2003). Sediment management objectives need to be defined in the context of the whole river basin (Naden *et al.*, 2004). These authors point out that monitoring strategies with a high temporal resolution and a spatial coverage are needed to establish a quantitative appreciation of amounts, sources, rates and process interactions. However, the major problem with management applications of sediment budgeting is the long time and costly investment required to produce a reliable data set (Slaymaker, 2003).

Riverine habitat is being assessed for river management purposes to evaluate general river health, to support river rehabilitation projects, to determine environmental flows or to find surrogates for biodiversity assessment since the quantity and quality of available habitats are critical elements of ecological condition (Thomson *et al.*, 2000). Numerous habitat assessment methods have been proposed; but they are mostly concerned with in-stream habitat and not with riparian habitat. However, the River Style framework developed in Australia provides a geomorphic template upon which spatial and temporal linkages of biophysical processes are assessed within a catchment context. Furthermore, the River Style framework proposes to assess riparian habitat patterns and availability along river courses (Brierley and Fryirs, 2000; Brierley *et al.*, 2002). This framework is interesting in respect to the assessment as well as the management of riparian habitat since it is: (i) process-based, including the understanding of the character and behaviour of both channel and floodplain zones and, thus, encompassing the riparian zone; and (ii) catchment-based with respect to water and sediment fluxes and vegetation dispersal (Brierley *et al.*, 2002). A similar approach is proposed by Kondolf *et al.* (2003).

The large, but not exhaustive, array of different approaches and frameworks proposed to effectively manage, rehabilitate and/or restore fluvial systems and riparian habitat presented here reflect the complex multiscale structure of river systems. The different approaches at the catchment and reach scale have to be considered as complementary and both are needed to successfully enhance hydrogeomorphic and ecological functioning of riparian corridors.

## CONCLUDING REMARKS AND FURTHER RESEARCH DIRECTIONS

No other species than humans has a greater impact on the stability, dynamics, diversity, composition, structure, and functioning of Earth's communities and ecosystems (Tilman, 1999, p. 1471) and no ecosystem on Earth's surface is free of pervasive human influence (Vitousek *et al.*, 1997, p. 494). These statements are particularly true for riparian corridors, which form an integral part of fluvial systems and they are the most diverse, dynamic and complex biophysical habitats on the terrestrial portion of the Earth according to Naiman *et al.* (1993). Human impacts on the biotic and abiotic structure and functioning of the riparian zone are manifold since they operate at many spatial (e.g. catchment, reach, site) and temporal (e.g. event to centuries) scales. Human effects on two main driving variables within river systems, the water and sediment regime, alter significantly the structure of riparian habitat in alluvial rivers which in turn threatens the ecological integrity of river systems.

In Europe, river rehabilitation and management including surface (inland, transitional and coastal) and groundwaters, channel, riparian and floodplain environments, will be strongly influenced by the implementation of the European Commission's Water Framework Directive (WFD) (EC, 2000) in 2015. Even though difficulties are arising for achieving the main targets of the WFD and certain shortcomings are recognized (e.g. Ledoux and Burgess, 2002), the Directive has much merit in setting ecological targets for surface waters. In doing so, the European Commission recognizes the need for an integrated approach to managing three of the components of aquatic and riparian habitats: (i) water quality, (ii) water quantity and (iii) geomorphology (Chovanec *et al.*, 2000; Logan and Furse, 2002; Newson, 2002). Hence, the need to consider hydrogeomorphic processes for sustainable river management strategies is acknowledged and taken into account by Europe-wide legislation.

There is a great need for a better appreciation of the fluvial sediment system as whole (sediment transport, deposition, and resuspension), considering jointly the catchment scale and the river reach scale to manage and/or restore hydrogeomorphic processes sustaining riparian ecosystem functions. The effects of anthropogenic controls (e.g. urbanism, agriculture, deforestation, river engineering works) on these temporarily highly variable sediment transfers have to be taken into account according to different physiogeographic contexts. Knowledge of the effects of climatic changes on sediment delivery is also lacking. Long-term studies addressing the dynamic interactions of the physical, chemical and biological processes are still lacking, but will considerably help to understand present, past and future functioning of human impacted river systems.

Answers are needed to questions about the capacity of the riparian zone to buffer anthropogenic impacts at the basin scale by retaining and/or transforming sediment, associated nutrients and pollutants. At the local (reach) scale the understanding of how the form and dynamic structure (abiotic plus biotic) of the riparian zone influence the nature of local sediment depositional and resuspension processes still needs to improve. Further knowledge is needed about the impacts of erosion and sedimentation processes on the specific composition and functional diversity of riparian communities, on the structural organization (density, roughness) of riparian elements and on the physicochemical substrate properties in relation with conditions for riparian vegetation development. *In situ* experiments within diverse riparian environments and different physiographic contexts, based on, for example, the conceptual model proposed by Hupp and Bornette (2003), will help to gather further information to achieve a sustainable management of riparian ecosystems.

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