Restoration strategies for river floodplains along large lowland rivers in Europe


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SUMMARY

1. Most temperate rivers are heavily regulated and characterised by incised channels, aggradated floodplains and modified hydroperiods. As a consequence, former extensive aquatic/terrestrial transition zones lack most of their basic ecological functions.

2. Along large rivers in Europe and North America, various floodplain restoration or rehabilitation projects have been planned or realised in recent years. However, restoration ecology is still in its infancy and the literature pertinent to river restoration is rather fragmented. (Semi-) aquatic components of floodplains, including secondary channels, disconnected and temporary waters as well as marshes, have received little attention, despite their significant contribution to biological diversity.

3. Many rehabilitation projects were planned or realised without prior knowledge of their potential for success or failure, although, these projects greatly contributed to our present understanding of river–floodplain systems.

4. River rehabilitation benefits from a consideration of river ecosystem concepts in quantitative terms, comparison with reference conditions, historical or others, and the establishment of interdisciplinary partnerships.

5. We present examples from two large European rivers, the Danube and the Rhine, in which the role of aquatic connectivity has been extensively studied. The Danube delta with its diversity of floodplain lakes across an immense transversal gradient (up to 10 km) serves as a reference system for restoration projects along lowland sections of large rivers such as the Rhine in the Netherlands.

Keywords: biodiversity, Danube, flood pulse, Rhine, secondary channel

Importance of river floodplain connectivity

During the last decades, our perception of river–floodplain systems has been significantly improved by the application of new theoretical concepts (Ward et al., 2001). The ‘river continuum concept’ addresses the longitudinal linkages within rivers (Vannote et al., 1980), while the ‘flood pulse concept’ integrates the lateral river–floodplain connections in both tropical (Junk, Bayley & Sparks, 1989) and temperate climates (Bayley, 1991; Junk, 1999). ‘Flood pulses’ predominantly address effects of flood predictability, duration and extent (Junk et al., 1989), while ‘flow pulses’ (Tockner, Malard & Ward, 2000b) refer to processes below overbank flow. Despite the benefits of ecological concepts for understanding large rivers, more multidisciplinary empirical studies are needed to
assess the ecological state of river–floodplain systems, so as to facilitate restoration planning (Henry & Amoros, 1995; Lorenz et al., 1997) and challenge existing conceptual constructs (Galat & Zweimüller, 2001). Information on habitat diversity, biological production and the source and flow of energy is especially important (e.g. Johnson, Richardson & Naimo, 1995). Other important issues that need to be resolved include the questions of whether hydro- and morpho-dynamics should be increased or decreased, and to what extent floodplain succession can be reset by integrating conflicting interests of ecological needs, safety and navigation.

**The need for rehabilitation**

The majority of large temperate rivers has been strongly regulated during the past few centuries (Petts, Möller & Roux, 1989; Dynesius & Nilsson, 1994). In North America, Europe and the former Soviet Union, 71% of the large rivers (premanipulation mean annual discharge >350 m³ s⁻¹) are affected by dams and reservoirs, interbasin diversion and water abstraction (Dynesius & Nilsson, 1994). Nowadays, large pristine rivers are restricted to remote boreal and arctic regions. In headwaters, the construction of dams caused most damage (Ward & Stanford, 1995), whereas lowland sections were most affected by floodplain reclamation and channelisation. In addition, dams were constructed to facilitate navigation during low flow. Channels were shortened, their beds incised and aquatic/terrestrial transition zones drastically reduced (e.g. Lelek, 1989; Van Urk & Smit, 1989; Dister, 1994; Gore & Shields, 1995; Sparks, 1995; Galat et al., 1998; Dohle, Bornkamm & Weigmann, 1999; Günther-Diringer, 2001). As a consequence, riverine floodplains are among the most endangered landscapes worldwide (Olson & Dinerstein, 1998; Tockner, Ward & Stanford, 2002). In Germany (Junk, 1999) and along the Mississippi (Gore & Shields, 1995), for example, only about 10% of the former floodplains are in a near natural state (cf. Jungwirth, Muhar & Schmutz, 2002).

In most riverine systems, hydrological connectivity between the river and its floodplain is restricted to groundwater pathways; geomorphological dynamics are mostly absent (Marchand, 1993; Heiler et al., 1995). Migration of permanent aquatic organisms such as fish or aquatic molluscs ceased, affecting overall biodiversity (Grift, 2001; Robinson, Tockner & Ward, 2002). Studies of endangered fish species show that both species preferring flowing water (rheophilic species) and still-water (limnophilic) species are at risk (Lelek, 1987; Schiemer & Spindler, 1989; Schiemer & Waidbacher, 1992; Guti, 1995; IUCN, 2000; Wolter et al., 1999). A recent assessment of eight European and North American large rivers indicated that the fish species that depend for all or some of their life stages on fluvial conditions are most imperilled (Galat & Zweimüller, 2001). Therefore, restoration must focus on the dynamic interplay among the main channel, the floodplain, and the tributaries.

**Present state of floodplain rehabilitation**

Examples of river–floodplain restoration and rehabilitation in Europe and North America are few and recent (e.g. De Waal et al., 1995; Brookes, Baker & Redmond, 1996; Galat et al., 1998; Toth et al., 1998; Schiemer, Baumgartner & Tockner, 1999; Simons et al., 2001; Zöckler, Wenger & Madwick, 2001; and reference therein). Many more are at the planning stage (WWF, 1999; ICPR, 2001). However, most of these projects focus narrowly on permanent aquatic habitats, with only few including the riparian zone and floodplain (e.g. Schiemer, 1995; Adams & Perrow, 1999).

Restoration and rehabilitation projects are long-term undertakings. The Kissimmee River project (Florida), for example, took more than two decades of iterative planning, including a demonstration project, before a pilot de-channelisation project became a reality (Toth et al., 1998). The inherent complexity of floodplain ecosystems and our limited scientific understanding of their spatio-temporal dynamics significantly constrain planning (Henry & Amoros, 1995; Brookes et al., 1996; Adams & Perrow, 1999). An important aspect to consider is the hydrological regime also from an ecological perspective (Junk et al., 1989; Bayley, 1991; Haueber & Michener, 1998). For medium-sized rivers such as the Kissimmee River it may be feasible to restore the natural flow regime, while for large rivers (e.g. the Rhine, Danube, Missouri or Mississippi) flow only can be managed locally, at the scale of a tributary or of a section between two dams (Stanford et al., 1996; Poff et al., 1997; Galat et al., 1998; Sparks, Nelson & Yin, 1998; Toth et al., 1998; Tockner et al., 2000a).
Restoring large rivers with extensive floodplains and complex inundation patterns is exceedingly difficult. Conflicting interests among statutory bodies and other stakeholders complicates the process further (Zöckler et al., 2001). Restoration often suffers from a fundamental problem of perception. Many technically trained river managers, as well as the public, have little understanding of what a floodplain is and how it functions. Socio-economic factors can place severe limitations on how far a natural flow regime can be restored (De Waal et al., 1995). Thus, major constraints of floodplain restoration include scientific complexity, technological limitation and management (Adams & Perrow, 1999), and understanding of floodplains needs careful integration of different disciplinary knowledge and perspectives. In many cases, rehabilitation projects are the result of a compromise between natural and engineering solutions (Cowx & Welcomme, 1998).

**Objectives of the paper**

This paper illustrates how river rehabilitation schemes will benefit from a multidisciplinary approach including three main components: (1) consideration of river ecosystem concepts in quantitative terms, (2) comparison with reference conditions and (3) establishment of interdisciplinary partnerships. We attempt to link examples on research priorities, initiatives and co-operation as the basis for protecting and rehabilitating river systems (cf. Naiman et al., 1995). The first two topics (concepts and references) are illustrated by studies of patterns (present-day active floodplains), processes (flood pulses) and biota (e.g. fish communities) along two large European rivers, the Rhine and the Danube. Environmental non-governmental organisations (NGOs) and the International Commission for the Protection of the Rhine (ICPR) are used as examples of successful partnerships. The paper focuses on (semi) aquatic components of large lowland rivers, thus broadening the present discussion on river restoration (Naiman et al., 1992; Allan & Flecker, 1993; Gore & Shields, 1995; Brookes et al., 1996; Stanford et al., 1996; Poff et al., 1997; Jungwirth et al., 2002).

**Flood pulses of the Rhine and Danube**

The flow regime of rivers needs to be quantified in terms of magnitude, frequency, duration, timing and rate of change – seasonally and interannually (Figs 1 and 2; Poff et al., 1997; Richter et al., 1997). This information is required to assess the potential in restoring a more natural flow regime. Here, we compare the flow regimes of the Danube and Rhine. Flow dynamics in the lower reaches of these rivers show both differences and similarities. Average monthly flow is highest in the first half of the year, that is in late winter and early spring in the Rhine and in mid-spring in the Danube, although floods may occur at any time. In the second half of the year, flow patterns are quite similar in both rivers, with a decrease from June through October and a subsequent increase thereafter. Flood events on the Rhine today are more sudden and amplified compared with the situation before river regulation. In the Danube, the magnitude, duration and timing of the flood pulse are stronger, longer and more predictable compared with the Rhine. This is mainly because the Danube is longer (2860 versus 1320 km) and has a larger catchment (817 000 versus 185 000 km$^2$). The Danube’s discharge is more predictable (CV = 31%) and constant throughout the year, whereas discharge of the Rhine fluctuates more strongly, especially in winter (May–October: CV = 37%; November–April: CV = 54%) (Fig. 1).

**The Danube delta and its floodplain lakes**

The Danube delta is still in a rather pristine state despite significant human impact during the
The main human impacts on the system include engineering to enhance navigation and fish production, already envisioned by Antipa (1932), and the reclamation of some 20% of the area for agriculture and fish ponds (Fig. 3). A network of river branches and man-made canals interconnect the hundreds of lakes in the delta. By the early 1980s, the total length of man-made canals equalled the length of natural or partially modified water courses. As a result, the inflow of water into the delta floodplain increased from approximately 160 m$^3$ s$^{-1}$ around 1900, to 620 m$^3$ s$^{-1}$ in the 1990s (Table 1). In addition, recent eutrophication of the Danube River has led to substantial changes in fish composition and aquatic vegetation (Bacalbasa-Dobrovici, Nicolau & Nitu, 1990; Coops et al., 1999; Staras, 1999; Navodaru, Buijse & Staras, 2002). Average P and N concentrations increased 6- and 3.7-fold, respectively, during the last decades. However, the immense size (5800 km$^2$) of the

delta and the large number of lakes (>300) have ensured that despite these impacts the delta still harbours the full range of natural habitats.
In the mid-1990s, a study was initiated to assess the present state of delta lakes (Oosterberg et al., 2000). Classification of the lakes forms the scientific basis for managing the delta in the future and provides a reference for heavily degraded systems elsewhere in Europe (e.g. Lower Rhine, see below). Five main criteria were used to classify the Danube delta lakes. Hydrogeomorphology and water quality were considered the main controlling factors for aquatic communities, and the composition and abundance of plankton, aquatic vegetation and the fish community served as indicators of the trophic state. A similar set of variables was applied to the Kissimmee restoration project in Florida, U.S.A. (Dahm et al., 1995). Based on these criteria, three principal lake types were identified in the Danube delta (Fig. 4, Table 2): (1) large turbid lakes located at the deeper parts of the former marine lagoon, characterised by a co-dominance of both still-water fish and fish species occurring in both standing and running water (cf. Fig. 6); (2) mostly clear lakes of medium size strongly influenced by river flow, colonised by dense stands of Potamogeton

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
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<th>1960s</th>
<th>1997</th>
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<td></td>
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<td>Inflow</td>
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<td>120</td>
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<td>mg L⁻¹</td>
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<td>260</td>
<td>130</td>
</tr>
<tr>
<td>Flux</td>
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<td>2.5</td>
<td>2.5</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>0.01</td>
<td>0.06</td>
</tr>
<tr>
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<td>mg P L⁻¹</td>
<td></td>
<td></td>
<td>0.16</td>
</tr>
<tr>
<td>Flux of P-total</td>
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<td>0.4</td>
<td>3.2</td>
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<tr>
<td>Nitrogen</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inflow concentration</td>
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<td>0.4</td>
<td>1.5</td>
</tr>
<tr>
<td>N-total</td>
<td>mg N L⁻¹</td>
<td></td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>Loading of N-total</td>
<td>10⁶ kg N year⁻¹</td>
<td>4</td>
<td>8</td>
<td>59</td>
</tr>
</tbody>
</table>

**Fig. 4** Cross-section through the Danube delta and the relative position of lake types (see Table 2 for further characterisation). Arrows indicate direction of water flow.

trichoides Cham. & Schlecht and filamentous algae, and characterised by a fish community indifferent to flow velocity; (3) isolated and shallow lakes with floating reed beds and peat accumulations, dense carpets of *Nitellopsis obtusa* (Desv.) J. Groves, and a ‘black fish’ (*sensu* Regier et al., 1989) community (e.g. the tench, *Tinca tinca* L., and crucian carp, *Carassius carassius* L.). Increased inputs of nutrients and sediments to the delta lakes have recently shifted the relative proportion of lake types, with types 1 and 3 being more severely affected (Oosterberg et al., 2000).

The small tidal amplitude of the Black Sea (20 cm) limits the marine influence on the Danube delta. Therefore, the species composition in the delta is quite similar to that of upstream floodplain lakes along large European rivers. This similarity and the region’s high biodiversity makes the Danube a reference for many other European rivers (see also Krogulec, 2001).

Options for the ecological recovery of delta lakes include blocking artificial canals that do not support any significant economic function, thereby reducing direct inputs of eutrophic river water (Fig. 3). Improving the water quality in the Danube is another option, which will benefit both the delta and the Black Sea. Finally, the re-opening of unprofitable polders (embanked and reclaimed in previous decades for agriculture, forestry or fish culture) may help to restore river–floodplain interactions and enlarge the delta wetland area (Staras, 1999; Zöckler, 2000; Schmidt 2001).

### The Lower Rhine: patterns and processes

After entering the Netherlands at Lobith, the Rhine River splits into three branches. The two southern arms merge with the River Meuse and form a complex estuary before discharging into the North Sea. Both the Rhine and the Meuse are important for navigation, with 160 000 and 56 000 ship passages each year (Middelkoop & Van Haselen, 1999). At present, floodplains along the Lower Rhine are lined by high embankments, which prevent flooding of the densely populated hinterland. Additional low embankments separate the main channel from the present active (i.e. hydrologically although not morphologically dynamic) floodplain, allowing intensive agriculture for most of the year. The high embankments were completed as early as the fifteenth century, isolating large parts of the former floodplain, which was up to 10 km wide (Van Urk & Smit, 1989; Middelkoop, 1997; Schoor et al., 1999). The average width of the remaining active floodplain is only 1 km (Fig. 5, Table 3). The main stem of the Lower Rhine was channelised during the nineteenth and early twentieth century. These works initiated an incision of the river bed and an aggradation of the floodplain. At present, the

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type 2</th>
<th>Type 1</th>
<th>Type 3</th>
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</thead>
<tbody>
<tr>
<td>Dominant fish</td>
<td>Species indifferent to flow velocities</td>
<td>Indifferent and still-water species</td>
<td>Still-water species ('black fish')</td>
</tr>
<tr>
<td>Zooplankton abundance</td>
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<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Cladocera abundance</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Macrophyte abundance</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Dominant macrophyte species</td>
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<td>None</td>
<td><em>Nitellopsis obtusa</em></td>
</tr>
<tr>
<td>Abundance of filamentous algae</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Phytoplankton abundance</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Abundance of cyanobacteria</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Phosphorus concentration</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Nitrogen concentration</td>
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<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Turbidity</td>
<td>Clear</td>
<td>Turbid</td>
<td>Clear</td>
</tr>
<tr>
<td>Level amplitude</td>
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<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Water travel time</td>
<td>Small</td>
<td>Intermediate</td>
<td>Large</td>
</tr>
<tr>
<td>Size</td>
<td>Intermediate</td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td>Area of aquatic reed belt</td>
<td>Small</td>
<td>Varying</td>
<td>Large</td>
</tr>
<tr>
<td>Water depth</td>
<td>Shallow</td>
<td>Deep</td>
<td>Shallow</td>
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<tr>
<td>Substratum</td>
<td>Clay</td>
<td>Sand-silt</td>
<td>Organic</td>
</tr>
</tbody>
</table>

Table 2 Typology of Danube delta lakes. ‘Low’, ‘intermediate’ and ‘high’ represent relative values (after Oosterberg et al., 2000).
majority of the numerous floodplain lakes are sand- and clay-mining pits (Jongman, 1992).

The floodplain-to-channel-width ratio ranges from 3.85 along the Waal branch to 8.27 along the Ijssel branch (Table 3). Only major floods (>4300 m$^3$ s$^{-1}$; <20 days year$^{-1}$) inundate the remaining active floodplain, and only 1% of the area is flooded for more than 150 days per year, and 5 and 9% for 50 and
20 days, respectively (Table 3, Fig. 5). Thus, the river—floodplain system is characterised by two dominant landscape elements, permanent water (31% of the area) and an aquatic-terrestrial transition zone that is dry for most of the time. An overview of the most important characteristics and the natural and socio-economic functions of the Lower Rhine is given by Middelkoop & van Haselen (1999) and by Marteijn et al. (1999).

**Biodiversity**

To assess the success of restoration and rehabilitation projects, biological patterns need to be linked to abiotic patterns and processes at various spatial and temporal scales (Roux et al., 1989; Petts et al., 1992; Henry & Amoros, 1995). A special issue of the journal *Restoration Ecology*, dedicated to the restoration of the Kissimmee River (FL, U.S.A.), stresses the importance of such a multidisciplinary approach that considers hydrology, vegetation, macroinvertebrates, fish and waterfowl in evaluating the success of restoration projects (e.g. Dahm et al., 1995; Toth et al., 1995). For evaluating biodiversity of the (semi)aquatic components of river—floodplain complexes, a number of species groups that differ in their responses to hydrological connectivity, water quality and habitat heterogeneity need to be considered (e.g. Tockner et al., 1999). Various groups of organisms, including benthic invertebrates, fish, plankton, birds, amphibians and aquatic and terrestrial plants, have been used as ecological indicators along the Soane River in France (Godreau et al., 1999), the Austrian Danube (Tockner, Schiemer & Ward, 1998), the lower Rhine and Meuse in the Netherlands (Van Den Brink et al., 1996), and the Danube delta in Romania (Coops et al., 1999; Oosterberg et al., 2000; Navodaru et al., 2002). Benthic invertebrates, fish and aquatic macrophytes are most frequently used and were selected as indicators of the ecological status of rivers in the EU Water Framework Directive (EU, 2000). Components of diversity such as alpha-, beta- and gamma-diversity have been used to identify the hierarchical structure of floodplain biodiversity (Tockner et al., 1999; Ward & Tockner, 2001).

The absence of certain species may be a good indication of ecological deterioration, as acknowledged by the EU Water Framework Directive (EU, 2000). For example, the loss of many long-distance migratory fish species such as salmonids, coregonids,
shads and sturgeons, indicates a disruption of longitudinal connectivity or a deterioration of spawning and nursery areas (IUCN, 2000). At large scales (e.g. at the catchment scale), species richness is probably an adequate evaluation criterion. Assessing the effectiveness of small-scale restoration projects may nevertheless require determination of qualitative (i.e. presence or absence of species) and quantitative biological parameters (see below).

**Fish composition in floodplain lakes**

Intact river–floodplain systems are important for fish, as many species require several habitats during their life cycle (Bayley, 1991; Schlosser, 1991; Jungwirth, Muhar & Schmutz, 2000; Schiemer, 2000). Floodplain lakes in the deltas of the Rhine (52° N, 5° E) and the Danube (45° N, 29° E), contain similar species although the two locations are more than 1800 km apart. Fish community composition changes, however, from dominance of lotic to lentic species along the hydrological gradient across the Danube floodplain, whereas similar shifts do not occur on the Lower Rhine (Fig. 6).

The hydrological connectivity of Danube delta lakes can be expressed by travel time, an estimate of river water reaching a lake (Oosterberg et al., 2000). For 11 lakes, travel times ranged from 1 to 91 days. Vegetation cover was high (>70%) in 10 of the lakes. The composition of the fish community displayed the full range of lentic components associated with an intact floodplain system, and biomass was rather evenly distributed over the nine most dominant species. The white or silver bream, Abramis bjoerkna L., indicates permanent connections to the river, whereas still-water species such as tench and crucian carp dominate in more remote lakes.

Along the Lower Rhine, the smaller variation in hydrological connectivity (lakes fall into two classes depending on inundation times, which range from 50 to 150 and 2–20 days year⁻¹, respectively) is reflected in the fish community. While vegetation cover ranged from 0 to 100%, the fish communities varied little. Both still-water species and species indifferent to current conditions were present, but 15 of the 20 investigated lakes were dominated by a single species, A. brama L.

Galat & Zweimüller (2001) concluded that in large European and North-American rivers, rheophilic fish species are most imperilled. This finding matches our experience. However, Galat & Zweimüller (2001) grouped still-water species and species indifferent to flow conditions in the same category. This pooling would obscure the endangered status of still-water species, which throughout their life cycle are fully dependent on intact floodplains (Lelek, 1987; IUCN, 2000).

**Secondary channels: recovery of the river–floodplain interaction**

The present-day planform of regulated rivers is the result of former hydrogeomorphological processes and recent regulation (Brookes et al., 1996). A stream power of 35 W m⁻² is considered as the threshold below which straightened channels cannot recover to a natural planform without human intervention (Brookes & Sear, 1996). Based on historical maps and present geomorphological data (e.g. width-to-depth ratios and Shield parameters), Schoor et al. (1999) assessed the potential for floodplain rehabilitation along the Lower Rhine in the Netherlands. Because of the low stream power, and hence limited potential for morphodynamics, ‘assisted’ recovery (sensu Brookes et al., 1996) is suggested as the preferable approach to rehabilitation.

In regulated rivers, rheophilic organisms are mostly restricted to the channelized main stem. Secondary and tertiary channels, which play major roles (e.g. as flow refugia) for sustaining endangered lotic communities, are generally missing along large European rivers. Consequently, several projects were initiated to restore river–floodplain interactions by re-opening or artificially creating secondary channels (Table 4). These measures help to re-establish a flow gradient across the river–floodplain system – from the main channel to shallow side arms, to permanent and ephemeral floodplain lakes and ponds. Within the existing limits because of flood control requirements, navigation and space restrictions, these projects should also support natural disturbance regimes and interrupt succession trajectories towards terrestrial conditions.

Along the Lower Rhine and Meuse, aquatic communities reflect the sharp transition in environmental conditions between the main river channel and the floodplain lakes (Van den Brink et al., 1996). First attempts at restoring river–floodplain interactions aimed at reconnecting water bodies to the main...
channel at the downstream end before creating new secondary channels (Cals et al., 1998; Schropp & Bakker, 1998). Re-opening of old channels would normally be preferred (WWF, 1993), but the digging of new channels is often required because of safety reasons and the lack of sufficient stream power (Barneveld, Nieuwkamer & Klaassen, 1994; Schropp, 1995). Oxbow lakes and disconnected side arms are often located too close to high embankments (so-called winter dikes), which increases the risk of hinterland flooding. Therefore, new secondary channels are projected at least 100 m distance from the embankment (Schropp & Bakker, 1998). From an ecological point of view, permanently flowing

Fig. 6 Fish community composition and aquatic vegetation cover along gradients of hydrological connectivity. Still-water species and species indifferent to current velocities are presented as stacked from the bottom and hanging from the top, respectively. Blank areas refer to non-specified species. (a) Danube Delta lakes are ranked by travel time [see Navodaru et al. (2002) for further explanation]. (b) Floodplain lakes along the River Rhine in the Netherlands (Grift, 2001) are separated into two inundation classes (duration of inundation: 50–150 and 2–20 days year⁻¹, respectively). Within each class, lakes are ranked by aquatic vegetation coverage. CP and SP: clay- and sand-mining pits. OX: natural oxbow lake.
conditions are preferable in secondary channels. In many cases, however, only controlled inflows via artificial openings above mean water level (Danube at Regelsbrunn, Austria) or above the level required for navigation (Vén Duna, Hungary) are allowed. This leads to stagnant conditions in secondary and side channels for 40 and 5% of the year, respectively (Marchand, 1993; Schiemer et al., 1999). On the other hand, the diversion of too much water into side arms may cause transversal currents and sandbank development in the main channel (Barneveld et al., 1994; Schropp, 1995). At mean flow, the through-flow capacity of recently realised secondary channels varies between 0.3 and 3.0% of the total river discharge. No major negative side-effects of such newly created secondary channels have been reported to date (Simons et al., 2001).

Along the Rhine in the Netherlands, five secondary channels have been created in the last 2–7 years, all of which are still functional. These rehabilitation projects took advantage of sand-mining pits located at the upstream end of the secondary channels. The pits act as sediment traps that prolong the lifespan of the secondary channels. The drawbacks of this approach are that pits may prove as effective at trapping macroinvertebrates and fish larvae as they are in trapping sediment and that low sediment inputs may result in scouring. However, no quantitative data have yet been reported that would allow evaluation of these possible scenarios.

Although restoration along the Rhine in the Netherlands is still at an early stage, some preliminary results have been reported. For example, the constructed secondary channel near Beneden–Leeuwen shows a less specific rheophilic community than those near Opinjen and Gameren (Grift, 2001; Simons et al., 2001). After 7 years, the high spatial heterogeneity in flow velocity, sediment type, bank slope and bank vegetation cover resulting from the restoration of secondary channels has created a broad range of habitats suitable for a variety of aquatic and riparian species (Grift, 2001; Grift et al., 2001; Simons et al., 2001). From the Danube floodplain at Regelsbrunn in Austria (Hein et al., 1999; Schiemer et al., 1999) and the Hungarian Vén Duna floodplain (Csányi, Gulyás & Németh, 1994) only pre-restoration conditions have been reported. More recent initiatives for secondary channel restoration have been started along the Loire (Belleudy, 2000) and Rhône (Amoros, 2001) in France.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>River</th>
<th>Country</th>
<th>Restoration measure</th>
<th>Discharge (% of flow in main channel)</th>
<th>Width (m)</th>
<th>Length (km)</th>
<th>Sediment trap</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ven Duna</td>
<td>1998</td>
<td>Danube</td>
<td>Hungary</td>
<td>Re-opening</td>
<td>3</td>
<td>50–100</td>
<td>2</td>
<td>Permanent</td>
<td>No</td>
</tr>
<tr>
<td>Regelsbrunn</td>
<td>1998</td>
<td>Danube</td>
<td>Austria</td>
<td>Re-opening</td>
<td>2</td>
<td>10–100</td>
<td>No</td>
<td>Permanent</td>
<td>Marcellini et al. (1999)</td>
</tr>
<tr>
<td>Opijnen</td>
<td>1994</td>
<td>Rhine</td>
<td>the Netherlands</td>
<td>Re-opening</td>
<td>0.5</td>
<td>1</td>
<td>10–150</td>
<td>Permanent</td>
<td>No</td>
</tr>
<tr>
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<td>1995</td>
<td>Rhine</td>
<td>the Netherlands</td>
<td>Connection</td>
<td>2.5</td>
<td>10–30</td>
<td>No</td>
<td>Permanent</td>
<td>No</td>
</tr>
<tr>
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<td>Rhine</td>
<td>the Netherlands</td>
<td>Creation</td>
<td>0.8</td>
<td>40–80</td>
<td>No</td>
<td>Permanent</td>
<td>Jans (unpubl. data)</td>
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<td>1996</td>
<td>Rhine</td>
<td>the Netherlands</td>
<td>Creation</td>
<td>0.5</td>
<td>20–60</td>
<td>No</td>
<td>Permanent</td>
<td>Jans (unpubl. data)</td>
</tr>
<tr>
<td>Gameren 3</td>
<td>1999</td>
<td>Rhine</td>
<td>the Netherlands</td>
<td>Connection</td>
<td>1.5</td>
<td>40–150</td>
<td>No</td>
<td>Permanent</td>
<td>Jans (unpubl. data)</td>
</tr>
</tbody>
</table>
Rhine: transboundary co-operation

Over the past 50 years, the ICPR has become the main forum for European restoration activities at the catchment level (Wieriks & Schulte-Wülfwer-Leidig, 1997). Other transboundary river commissions in Europe exist for the rivers Danube (since 1999; www.icpdr.org), Elbe (since 1990; www.ikse.de), Meuse (since 1994; www.cipm-icbm.be), Mosel and Saar (since 1956; www.iksms-cipms.org), Oder (since 1999) and Scheldt (since 1995; www.icbs-cipe.com).

Along the Rhine, the ‘Rhine Action Programme’ (RAP) and the ‘Salmon 2000’ programme were among the first transboundary restoration efforts, both launched as a consequence of a severe pollution incident caused in 1986 by a pharmaceutical company in Basel, Switzerland (Schulte-Wülfwer-Leidig, 1999). The programmes’ specific ecological goal, the return of higher trophic level species (benthic invertebrates, fish) to the river (Marteijn et al., 1999), was partly met (Schulte-Wülfwer-Leidig, 1999). Several serious floods along the rivers Rhine and Meuse in 1993 and 1995 prompted the programme ‘Room for Rivers’ in 1996 (Ministry of Transport, Public Works & Water Management, 2000), and in 1998 the ICPR published its flood defence action plan (ICPR, 1998) intending to combine flood protection with ecological improvements similar to action plans along the Missouri and Mississippi (U.S.A.; Haeuber & Michener, 1998; Galat et al., 1998; Sparks et al., 1998). In January 2001, the Conference of Rhine Ministers identified focal points for the river by the year 2020, as well as a short-term action programme for 2005. The establishment of ecological networks (see below), free fish migration routes, high water quality, flood protection, and the maintenance of groundwater quality and quantity (ICPR, 2001) are the major goals. Ecological networks will be strengthened by the protection, enlargement and restoration of floodplains, the re-connection of backwaters, and the re-establishment of hydrological and ecological interactions between the river and the floodplain. Realisation of these plans will require a shift to less intense use of agricultural land (1900 km²), afforestation (1200 km²), re-activation of floodplains (300 km²) and restoration of running waters in the river basin (3500 km). Calculated costs until 2005 are 5.5 billion Euro. Factors considered important to the effectiveness of the ICPR are the establishment of mutual confidence, necessity to co-operate and adoption of a holistic and pragmatic approach (Wieriks & Schulte-Wülfwer-Leidig, 1997).

Input from environmental NGOs and the private sector

Current river restoration programmes are based on both scientific insights and empirical knowledge gained in former restoration projects. Unfortunately, much restoration work is not well documented in the scientific literature (De Waal et al., 1995). The details of many projects have not been published in peer-reviewed journals, either because the studies lacked scientific rigour or because such journals are not routinely accessible to river managers. Both NGOs and the private sector nevertheless contributed significantly to river and floodplain restoration over the past two decades. The WWF-Institute in Rastatt (Germany), for example, is specialised in floodplain studies (e.g. Dister, 1994; Günther-Diringer & Weller, 1999). Recently, for example, this institute inventoried the extent of natural floodplains along the Danube and its major tributaries to assess the potential for environmental improvements within the entire catchment (Günther-Diringer & Weller, 1999; Günther-Diringer, 2001).

In the Netherlands, several important contributions have been made by NGOs and the private sector during the last 15 years. Among the first were the plan ‘Ooievaar’ (De Bruin et al., 1987) and the WWF’s vision on ‘Living Rivers’ (WWF, 1993). The plan ‘Ooievaar’ (the name refers to the black stork, Ciconia nigra, a typical occupant of extensive floodplain forests) won the first prize in a contest for spatial planning of riverine landscapes. Both programmes promote natural floodplain conditions and a shift of agriculture from floodplains to the hinterland. The WWF (1993) envisages win–win situations with benefits for nature, safety, the brick-building industry and recreation. The private sector (i.e. mining industries) may serve as the financial engine for restoration. Both the plan ‘Ooievaar’ and the vision ‘Living Rivers’ have influenced policy decisions. In 1993, it was decided to create 70 km² of ‘new nature’ along the Lower Rhine and Meuse (Pruissen, 1999). In 1998, the private sector, that is WL/Delft Hydraulics, launched its vision ‘The Rhine in the long term’ by looking
ahead to the year 2100 (WL/Delft Hydraulics, 1998). Three themes were advanced, namely sustainable safety, quality of life and accessibility. A worst-case scenario induced by possible climate change on water storage and discharge was developed. The vision proposes an approach to safety from flooding in which river dyamics rather than human land use is the structuring force of the landscape. Accordingly, floodplain management strategies need to move from a notion of resistance to one of resilience. Former flood regimes in the eighteenth and nineteenth centuries should be restored, thus creating opportunities for ‘green rivers’. In 1999, the WWF and Staatsbosbeheer, the largest land-owner and manager of natural areas in the Netherlands, published an updated vision entitled ‘Natural Safety Through Flow Retention’ (SBB, 1999). This report advocates a whole-basin approach for river management, based on the insight that many environmental problems in riverine floodplain originate outside the Netherlands. The report recommends an increased water retention through a delayed discharge regime and a reduced desiccation during low flow periods (i.e. the so-called sponge function). Proposed measures include setting back major embankments, lowering or removing groynes and minor embankments, and extracting aggradated sediments from floodplains (Fig. 7).

Other initiatives are the WWF’s efforts to protect and restore European rivers (WWF, 1999), including the ambitious joint initiatives with the Ministries of Environment of Bulgaria, Romania, Moldavia and Ukraine, aiming at the restoration and sustainable development of 7000 km$^2$ of floodplains along the lower Danube (WWF, 2000). The WWF’s Europe-wide initiative encompasses 65 demonstration projects in 25 countries.

All these activities, feasible or not, have contributed to reinforce thoughts on how to reconcile socio-economic requirements (predominantly in relation to safety and navigation) with ecological functions. For the Netherlands, Pruijssen (1999) provides an overview of 27 floodplain realised or ongoing restoration projects along the Rhine and the Meuse. Pruijssen (1999) highlights the importance of collaboration between national, regional and local authorities, together with environmental NGOs, landowners and the private sector in realising restoration plans. Furthermore, Holmes & Nielsen (1998) reported on restoration along the English rivers Cole and Skerne, and the Danish river Brede. These demonstration projects, supported by the EU-LIFE programme, are characterised by an intensive environmental monitoring, international co-operation, sound design and professional project management.

Restoration projects require a thorough scientific documentation to be useful in the future. Good examples are the Regelsbrunn floodplain along the Danube in Austria (Tockner & Schiemer, 1997;...
Schiemer, 1999; Schiemer et al., 1999; Tockner et al., 1999, 2000a), the Kissimmee River in Florida (U.S.A.) (Toth et al., 1998), the rivers Brede (Denmark), Cole and Skerne (U.K.) (Biggs et al., 1998; Kronvang et al., 1998). In assessing 12 projects, Zöckler et al. (2001) concluded that all were a success to some extent, although only one-third (four) were monitored in sufficient detail to enable full postproject appraisal. Key criteria of the analysis Zöckler et al. (2001) included were thorough project planning, long-term commitment of partners, a shared vision, public awareness activities, an experimental approach and the incorporation of socio-economic aspects from the beginning.

Landscape design measures supporting ecological restoration

Brookes et al. (1996) identified five types of restoration activities from an ecological point of view: (I) restoration of riparian strips, (II) restoration of small but ecologically valuable patches, (III) less intensive restoration of larger floodplain areas, (IV) restoration of the original hydrograph, and (V) relaxing constraints on lateral river channel migrations so that natural processes recreate a mixture of floodplain features. Priorities may vary among river systems. In a schematic cross-section of a highly developed large lowland river, 16 landscape design measures have been identified to accommodate the various functions (flood protection, shipping, natural development) (Fig. 7; Middelkoop & van Haselen, 1999). Ecological restoration may be achieved by measures 6–10, 13 and 14. The linkage with Brookes et al. (1996) is I–6; II–8, 9; III–7, 10, 13, 14; V–8. Natural banks (6) could replace rip-rap constructions, which would increase the shore length and re-establish inshore zones (Schiemer, 2000). Removal of minor embankments (7) will increase the frequency and duration of flooding of the embanked area, in particular if at the same time the terrain is lowered (9).

Floodplain embankment accelerates sedimentation and consequently promotes the transformation of aquatic into terrestrial ecosystems (Marchand, 1993; Schiemer et al., 1999; Zsuffa, 2001). Removal of sediments can reposition the floodplain surface relative to the incised main channel. Dredging of aggradated channels followed by monitoring was carried out along the Rhône floodplains (Henry, Amoros & Giuliani, 1995; Henry & Amoros, 1996) and the Meuse (Pedroli & Dijkman, 1998). In the Netherlands, this approach is often used to create room for the river, as the hinterland offers only limited space for water retention or for setting back embankments (Coops et al., 2000; Silva, Klijn & Dijkman, 2001). Secondary channels (8) contribute to the river–floodplain interaction and re-install lotic conditions in the floodplains during high flow (see above). Asselman (1999) addressed the sustainability of several of these interventions (removal of minor embankments, creation of secondary channel, floodplain lowering) and concluded that they will even accelerate floodplain sedimentation because inundations are more frequent and prolonged. Thus, management through cyclic floodplain rejuvenation through human intervention is proposed to compensate the lack of natural erosion by the river (Smits, Havinga & Marteijn, 2000). We propose that interventions need to be repeated periodically (e.g. once every decade for secondary channels to once every century for aggradated floodplains).

Floodplain areas with low hydro- and morphodynamics may benefit from setting back embankments (13) (Jahrling, 1995) and increasing water retention (14) (Siepe, 1994; Vieser, 1999). Flood retention areas could become beneficial for nature when ecological requirements such as a prolonged water retention and minor flood events are considered (Galat et al., 1998; Dohle, 1999; Vieser, 1999). Traditional water management in floodplains such as the ‘fok’-system in Hungary (Zsuffa, 2001) illustrate this point. Small artificial channels are cut through natural levees, connecting floodplain lakes and depressions to the river, thereby supplying even remote areas with water. This is essentially a passive method adapted to an unrestricted flood regime.

Synthesis

In Europe and North America, the extent of riverine floodplains has dramatically declined as a result of river regulation and embankment. River–floodplain transition zones including areas at some distance from the active channel (e.g. marshes) were most affected. Rehabilitation projects need to focus primarily on the transition zones and distant wetland habitats. A classification of the existing and potential hydrogeomorphological conditions, the position (height and
width) of the floodplain relative to the river, and selected indicators of biodiversity (e.g. fish, aquatic macrophytes and invertebrates) are required to assess the ecological state of river–floodplain systems and to direct restoration schemes.

Many river and floodplain restoration projects in the past lacked a sound scientific underpinning. More recent projects are being increasingly conceived as meso- to macro-scale scientific experiments designed to document the success or failure of restoration measures. Important factors influencing the success of projects also include communication and co-operation among river managers, environmental NGOs and scientists, and a rigorous interdisciplinary approach.

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Restoring aquatic components in lowland river floodplains


