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Ecohydrology, key-concept for large river restoration*

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Abstract

Successful restoration requires clear goals and objectives to succeed. Possibilities for and constraints of rehabilitation - both from a process-oriented view as well as from the nature conservation perspective differ strongly according to the landscape setting of a particular river segment and to the degree of anthropogenic changes. Large river restoration requires the development of an integrative scientific approach between ecology, hydrology and river engineering. For defining ecological targets and long-term sustainability of restoration programmes two aspects are particularly relevant. First, reference standards must be applied. Reference standards have to be based on the original landscape dynamics as defined by hydrology and bedload transport which resulted in a dynamic equilibrium of fluvial processes, habitat composition and consequently characteristic patterns of biodiversity and biogeochemical processes. The application of reference standards has to follow this cause-effect sequence. A second major requirement, dependent on this cause-effect chain between fluvial dynamics, habitat composition and ecology is the development of a prognostic ecohydrological parameter set which allows an evaluation of restoration scenarios and a prediction of their effects at a range of temporal and spatial scales.

Key words: sustainability, reference standards, biodiversity, ecological integrity, hydrological dynamics, ecohydrology.

1. Emerging concepts for understanding the ecology of large rivers

Over the past 10 years a sound conceptual basis has been developed for understanding functional processes and biodiversity patterns of large rivers (Thorp *et al.* 2006). It is well understood that the key factors are the flood-controlled geomorphologic processes which create the characteristic patch dynamics, spatial heterogeneity, the mosaic structure of densely packed ecotones and patterns of successions over a range of scales. The ecological significance of a dynamic habitat equilibrium in floodplains as expressed in disturbance and succession theory is a continuous rejuvenation process. In turn, this provides the habitat diversity and the specific habitat conditions for characteristic floodplain species and results in high levels of local species richness, habitat diversity and between-habitat differences (Ward *et al.*1999). The flood pulse concept (Junk *et al.* 1989; Junk, Wantzen 2004) also pinpoints to the enhancement of productivity and functional processes by flood events.

The ecotone concept (Naiman, Decamps 1990; Decamps *et al.* 2004) emphasises that riparian ecosystems are strongly structured by transi-

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tion zones. Such ecotones are usually characterized by high biodiversity and high process rates. The importance of ecotones is generally high in the low order reaches, declines with increasing distance from the river source and increases again at high order braided and meandering zones and their flood plains (Schiemer, Zalewski 1992). Ecotones have to be viewed hierarchically. Within the floodplains a multitude and hierarchy of transition zones exists. Density and configuration result in the high biodiversity and the characteristic process levels.

A further significant aspect of floodplain ecology refers to the spatial and temporal connectivity of the different habitat elements (Amoros, Roux 1988; Heiler *et al.* 1995; Schiemer 1999). Connectivity links to the term "ecological integrity" which provides a good focus for river ecology and river conservation (Karr 1991; Schiemer 2000). Ecological integrity can be described by its physical correlates, for example hydrological connectivity of the river, the ground water table and backwaters with regard to characteristic nutrient and carbon routing. Ecological integrity has a significant conservation meaning which has to be set in relation to the compound habitat requirements of characteristic species. All of these concepts are based on a combination between hydrology and ecology, which provides the interdisciplinary framework of ecohydrology. Ecohydrology is an interdisciplinary framework focusing on the functional response of ecological phenomena to hydrological conditions at the range of scales.

It is developing as a guiding research program to obtain management tools in order to improve the quality of freshwater resources (Zalewski 2000).

2. Large river restoration: experiences and learnings from the Austrian Danube

Anthropogenic alterations in the catchment, pollution, river regulation and damming have affected almost all large river ecosystems in Europe and North America (Petts *et al.* 1989; Dynesius, Nilsson 1994). The most destructive impacts are due to river engineering which has disrupted ecological integrity with regard to the longitudinal continuity, the lateral interactions with the bordering riparian zones, and the structure of the in-stream channel. This has led to deficiencies in functional processes, in the diversity of habitats and characteristic biota and has reduced the "ecological services" of river systems. In order to restore the ecological integrity, restoration has become an important issue during the past 20 years (Amoros *et al.* 1987; Boon *et al.* 1992; Stanford *et al.* 1996; Schiemer *et al.*1999; Buijse *et al.* 2005).

The experiences on restoration programmes this paper is based on refer to a sequence of guiding mitigation programmes in the free flowing section of the Austrian Danube between Vienna and Bratislava which have been carried out or are in the phase of implementation. The Austrian Danube is characterized by high and highly variable flow from the Alps with large seasonal changes in the river stage (Liepolt 1967). The dynamic hydrology and high gravel transport historically created large alluvial fans in the unconstrained sections with floodplains of several kilometre width and a braided river course. Over the past 50 years more than 90% of the Upper Danube and its major tributaries have been dammed for hydropower production. The remaining few stretches have been affected by major regulation schemes starting in the second half of the 19th century (Schiemer *et al.* 1999). The river reach of approximately 45 km downstream of Vienna to Bratislava - although strongly impacted by regulations - represents the largest remnant of a river floodplain system in Europe where the key functional attributes - the hydrological dynamics, and floodpulses - are partially operative and the high potential for re-establishing hydrological dynamics remains. Therefore this stretch was declared an Alluvial Forest National Park in 1996 and gained IUCN status in 1998.

The present conditions are determined by a major regulation scheme starting in 1875. It represented a major engineering feat at its time, however did not take ecological aspects into consideration. The main engineering approach was to change the braided course into a single, straightened channel, stabilized by riverside embankments and ripraps. The former arms of the braided system were cut off. Transverse check dams had to be built in order to retain the water level in the floodplain. The riverside embankments reduced the hydrological interaction with the floodplain and large levees completely cut off parts of the former floodplains from erosive, scouring flood flow (Fig. 1).

The immediate effects were:

- a loss of riverine inshore habitat, which had strong impacts on inshore retention characteristics and on habitat value for rheophilic organisms, eg. as nurseries for riverine fish
- a reduction of the lateral floodplain extent
- reduced hydrological connectivity both of groundwater exchange and open surface water connections between river and floodplains
- strongly reduced geomorphic processes in the floodplain and complete change of cut and fill
- a concentration of the erosive forces on the main channel bed.

This initiated :

- a deepening of the channel
- a lowered groundwater table
- isolation of backwaters
- sediment accumulation and terrestrialization in the isolated water bodies

Fig. 1. River regulation, starting in 1875, of the Danube at Vienna. The graph shows the original braided river system and the constructed single channel.

- and in sum an ongoing fragmentation and separation of river and floodplains.

With lateral distance from the main channel sedimentation and water retention increase, while erosive processes, hydrological connectivity and the amplitude of the hydrograph decrease. Outside the levees these trends are strongly enhanced.

The loss of "ecological integrity" is expressed in a reduction of inshore habitat with its high significance ("Inshore Retention Concept", Schiemer *et al.* 2001, Reckendorfer *et al.* 1999) and by reduced lateral connectivity both via surface and ground water and by a reduction of fluvial morphological processes and habitat renewal rates. The fluvial morphological equilibrium between erosion and terrestrification processes which has been initiated by the regulation programme has not yet reached a new equilibrium. A deepening of the river bed (Fig. 2), terrestrialisation processes within the floodplain and a clogging of the aquifer continually increases the separation between the river and its former floodplains. Fig. 3 illustrates the dramatic reduction in floodplain extent. Fig. 4 exhibits the dramatic reduction in the extent of the aquatic area. The reduction in ecological integrity due to engineering is expressed in a considerable loss of biodiversity and endangerment of a large number of characteristic river-floodplain species. Many species characteristic for river-floodplain landscapes are on the Red List of rare, vulnerable and endangered taxa (Fig. 5). This is illustrated in two groups of organisms with completely different requirements, aquatic and semi-aquatic macrophytes and fish.

Different stakeholders e.g. the River - and National Park authorities as well as conservationists have - for various reasons - been interested in mitigation programmes.

Pilot programmes have been carried out and an overall concept for improvement of the whole 45 km stretch between Vienna and Bratislava has been worked out by a team of ecologists, hydrologists and engineers compromising between the interests of navigation and ecology (Reckendorfer *et al.* 2005). The main focus is to stop the deepening of the channel and to improve the nature of the inshore structure and the lateral integration of river and floodplain. These are, from a conservation point of view, the most important aspects.

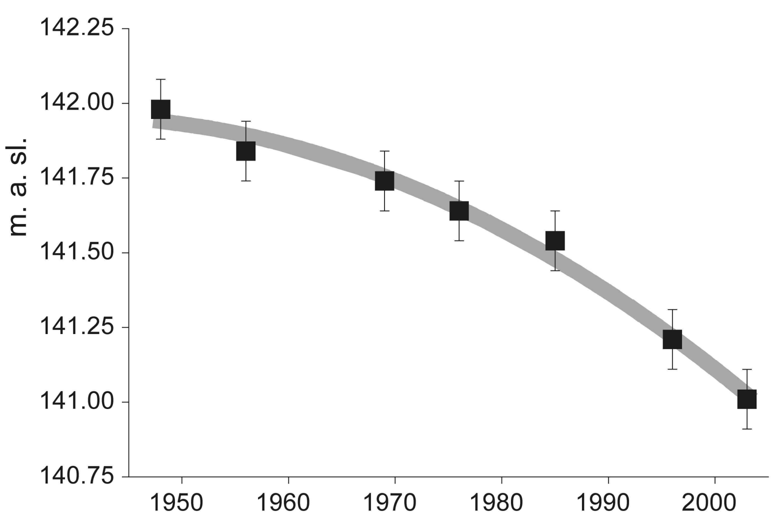

Fig. 2. River bed incision of the free flowing Danube downstream of Vienna. The graph shows the decrease in the low water table over the past 60 years (from Reckendorfer *et al.* 2005).

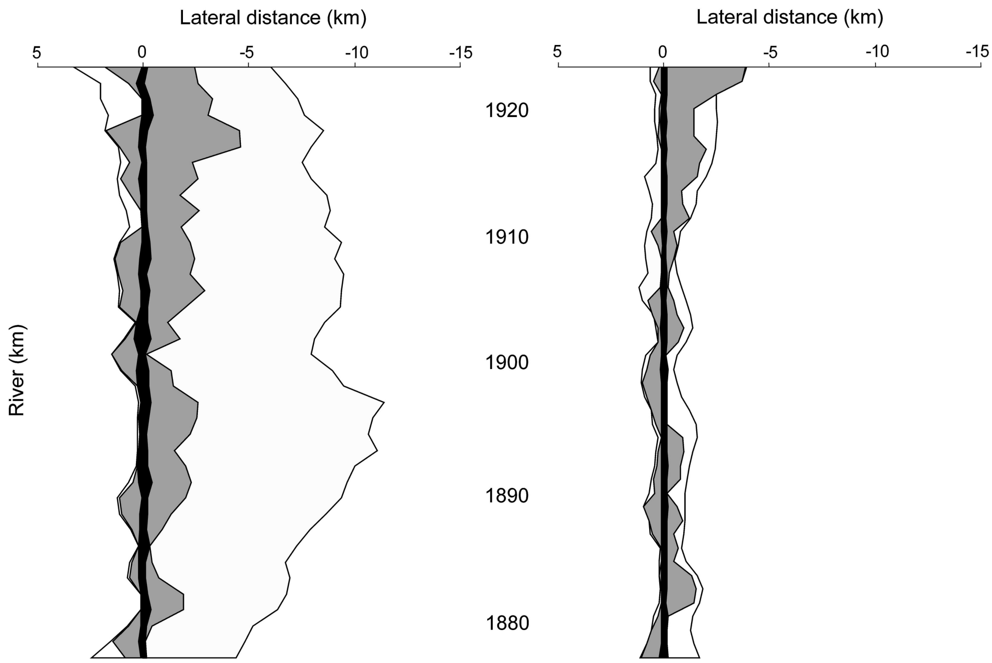

Fig. 3. Effects of the Danube regulation scheme on the lateral extension (orographic left and right) of the main river (black), the active floodplain (shaded) and the inundation area (white) downstream of Vienna: The position is given in river kilometres.

The stretch consists of segments (Fig. 6) differing strongly with regard to

a) the deviation from original (reference) conditions
b) reversibility towards the original conditions
c) existing connectivity and technical potential for improvement.

They range for example from strongly disconnected former floodplain areas within the municipality of Vienna (Lobau) where over the last 120 years strong terrestrialisation processes have taken place and for which the potential of ecological restoration is strongly constrained by requirements of flood control and drinking water supply of Vienna. On the other end of the scale are segments with a continued more dynamic integration between the regulated river and its floodplain although even in such cases the continuous habitat change in direction of a loss of aquatic habitats and an increase of terrestrial habitats has been dramatic.

These segments can be considered as units for which individual restoration schemes have to be developed. This offers the opportunity to develop and improve restoration programs step by step and develop restoration strategies and skills. It represents a large scale experimentation field in landscape ecology, where the master factor - hydrology and flow diversion is controlled, and various ecological properties, limnological processes, biodiversity pattern etc, geomorphology are the dependent variables. The

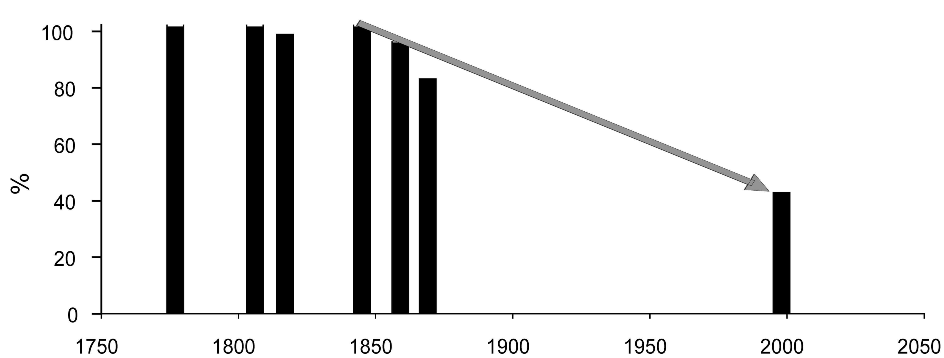

Fig. 4. Loss of aquatic habitat of the Regelsbrunn section following the Danube regulation.

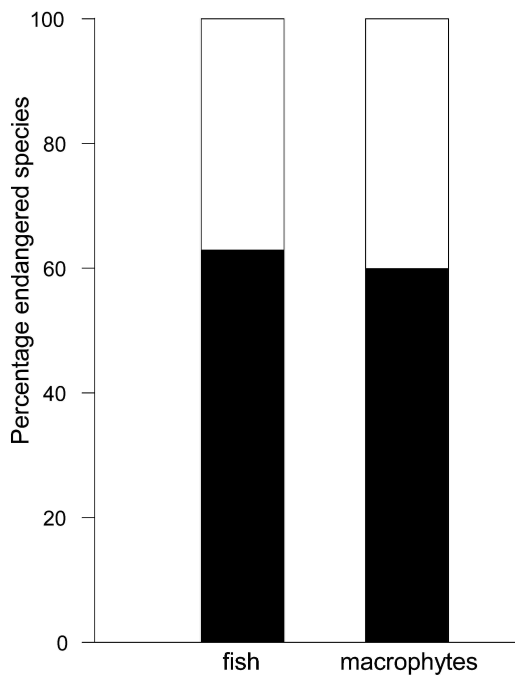

Fig. 5. Endangerment of biota; the black part of the column represents the percentage of "Red List" species among the fish and the aquatic macrophyte community.

planning and monitoring of these restoration programmes provides a unique opportunity to execute large scale experiments in river ecology. The experiences gained allow guidelines to be drawn for conservation management.

The formulation of restoration programmes is in a learning phase considering the limited international experience so far made. This necessitates long-term monitoring of pre- and post-restoration conditions in order to resolve questions on feasibility, time scales, sustainability, and to document and analyse the various stages of recovery. An important goal in this respect is the formulation of appropriate ecohydrological parameters.

A first major restoration programme with exclusively ecological orientation was planned and implemented formulated and executed on one of the segments at Regelsbrunn (Schiemer *et al.* 1999). It was conceived as a large-scale pilot programme in floodplain restoration. It was a very significant first step to start the wheels going, to develop monitoring skills and in the communication between the various stakeholders. This programme has been of tremendous significance and an eye opener with respect to the cooperation required between engineers, ecologists and conservationists with regard to the methodology for assessment required. The engineering measures essentially increased the connectivity between the river and the floodplain area by lowering the riverside embankments at 5 positions to mean water level as well by constructing lateral weirs (Fig. 7.). In order to allow a faster through-flow in the backwater chain dams had to be lowered and the capa-city of the existing weirs had to be increased. These technical measures of flow diversion resulted in a connectance between the river and the sidearms of approx. 200 days per year and a strongly enhanced water exchange.

We expected major ecological improvements with respect to intensified limnological processes, strongly improved habitat conditions for a rheophilic fauna and enhanced geomorphic processes. The actual findings after a five years monitoring programme was that geomorphic dynamics were in some parts higher than expected while changes in limnological parameters and habitat improvement were below expectation (see below). The discrepancies between expectations and actual changes forced us to develop a stringent approach of the application of reference standards and prognostic mechanistic models of the functional response of key ecological processes and hydrology.

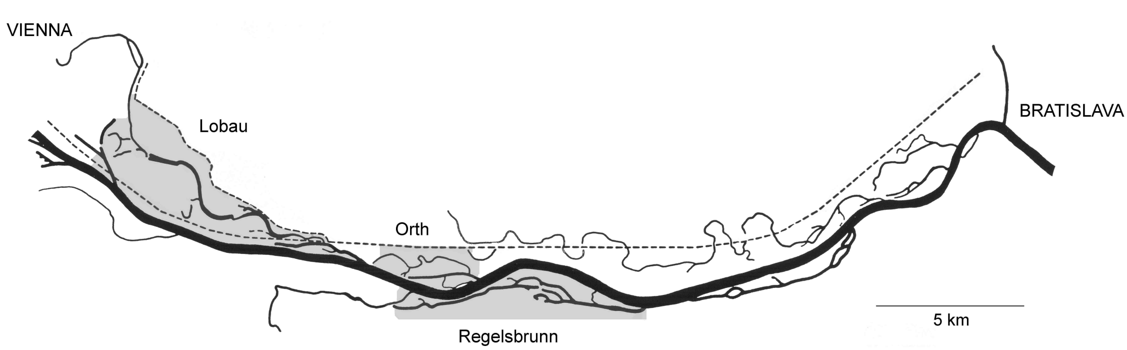

Fig. 6. The Danube and its floodplains from Vienna to Bratislava. The broken line shows the existing flood protection levees. Different segments have been identified for individual restoration programmes, e.g. Regelsbrunn, Orth and Lobau.

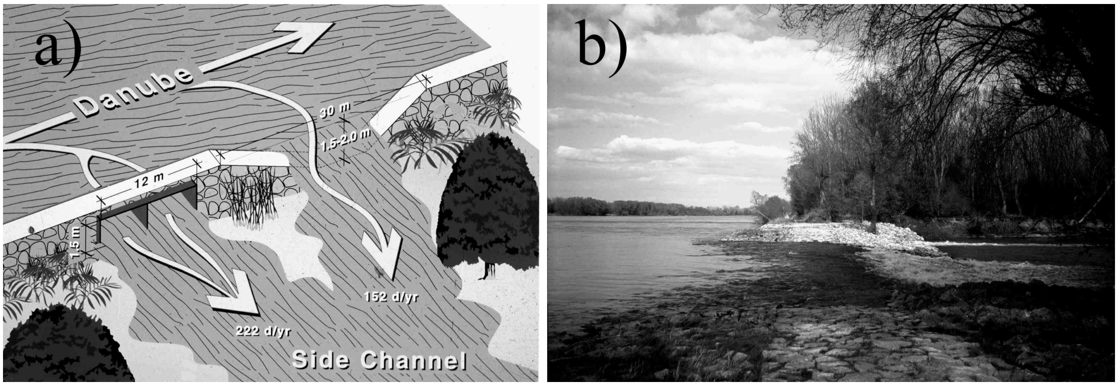

Fig. 7. The Danube restoration programme at Regelsbrunn, a first decisive step. Restoring the lateral connectivity between the river and the floodplains by lowering the inflow areas, construction of lateral weirs and enhancing the longitudinal through-flow in the side arm system (a). A photograph of an inflow area (b). After Schiemer *et al.* 2006

3. Reference standards: a hierarchical approach in its application

In theory we can conceive restoration as management measures to allow the "return of an ecosystem to a close approximation of its conditions prior to anthropogenic disturbance", or promote the "re-establishment of predisturbance aquatic functions and related physical, chemical and biological characteristics". This is rarely a realistic goal. However for defining the realistic goals - the ecological targets, their end-points and long-term sustainability - and for the evaluation of alternative management measures, it is imperative to refer to the original conditions as reference standards. These reference standards, the original landscape pattern as the dynamic equilibrium of fluvial processes, defined by hydrology, bed-load transport and geomorphology, has to be derived from historical maps and descriptions and analytical procedures using undisturbed reference sites. In applying reference standards in the definition of targets and the evaluation of management alternatives it is of paramount importance to follow the hierarchy of cause effects relationships (Fig. 8.): Key factors within a specific topographic and geological setting are hydrology and bedload transport. The resulting geomorphic dynamics lead to a dynamic equilibrium of habitat composition and connectivity which finally is the arena upon which the ecological processes and the characteristic biotic diversity depend. This hierarchical framework resolves the controversy between a system vs. a species centred approach. Different groups of bioindicators from plants to mammals have to be integrated. In managing "riverscapes" the key factors of hydrology and bed-load transport form the screw which have to be used ("let the river work" principle). In order to attain a dynamic habitat equilibrium with appropriate functions, hydrology and bedload transport have to reach and maintain a dynamic geomorphic equilibrium resulting in a characteristic habitat pattern, Such endpoints should be sustainable without further management.

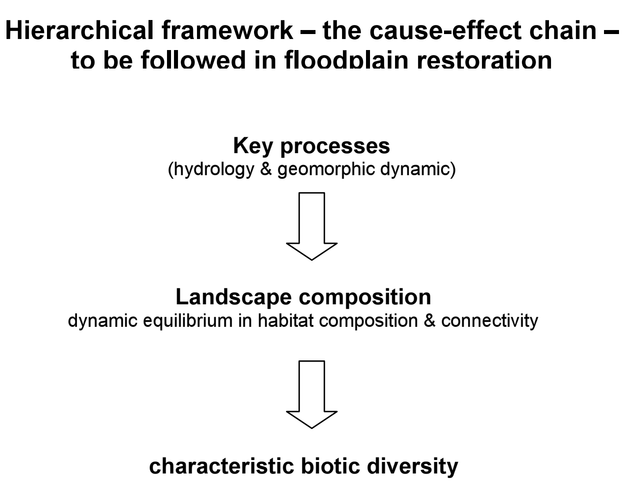

Fig. 8. Hierarchical framework - the cause effect chain - to be followed in the application of reference standards.

4. The need for prognostic ecohydrological parameters

Success in terms of improvements of the ecological quality as well as failures in terms of a falsification of prognoses and hypotheses have both been highly educative for the formulation of further programmes which have been executed or are planned as a second and a third step.

From the limnological perspective in the formulation of the goals of restoration programmes the following aspects have to be distinguished:

1. limnological processes with regard to water chemistry, seston transport and "pelagic

processes" linking to the integration between the river and the backwaters
2. the biodiversity and the representation of various ecological guilds, from stagnotopic to rheotopic with respect to connectivity
3. the extent of channel trans port processes and geomorphic processes within the floodplains with respect to habitat dynamics, and
4. exchange processes between the groundwater and the river.

For all those 4 aspects different ecohydrological parameters have to be formulated and their significance calibrated by a bioindication. Ecohydrological parameters should be immediately understandable for ecologists, hydrologists, and engineers. In the course of the Danube Restoration Programme we have gained experiences in this respect mainly with regard to the above formulated aspects 1, 2, and 3.

With regard to limnological processes a functional model connecting hydrological parameters and functions with ecological time series analysis was used to formulate prognosis and predictions on short-term limnological processes as well as on formulating parameters for biodiversity levels of various groups of organisms from macrophytes to fish and amphibians.

The formulation of water age the main parameter in understanding processes of floodplain lakes approaches the phenomenon of water exchange rates between different pools and the river. Fig. 9 illustrates the change in average water age at two positions for the Regelsbrunn floodplain system calculated for the average hydrological cycle. Water age highlights the significance of different flow pathways for the short-term biogeochemical and biological processes in the water body. The relationship between water age and nutrient chlorophyll and seston concentrations as well as the composition of the planktonic biocoenosis are shown in Fig. 10 (for a detailed explanation see Schiemer *et al.* 2006). In this functional response between water age and limnology the average change achieved by the restoration scheme at the two localities identified in Fig. 9 are inserted. It is apparent, that on an average annual basis the limnological effects are comparatively small. This finding emphasizes the significance of prognostic ecohydrological tools already applied in the restoration planning.

For organisms with longer life spans, e.g. molluscs (Reckendorfer *et al.* 2006), macrophytes or fish, a significant ecohydrological parameter which can be derived from geo-morphological data of the floodplain area is the extent of connectivity between the river and individual floodplains. The principal value of this parameter is outlined in Fig. 11, which also demonstrates why the success of the initial Regelsbrunn programme with regard to rheophilic species was lower than expected. The habitat shift in direction of long term connectivity is not reaching the scale required by strictly rheophilic forms.

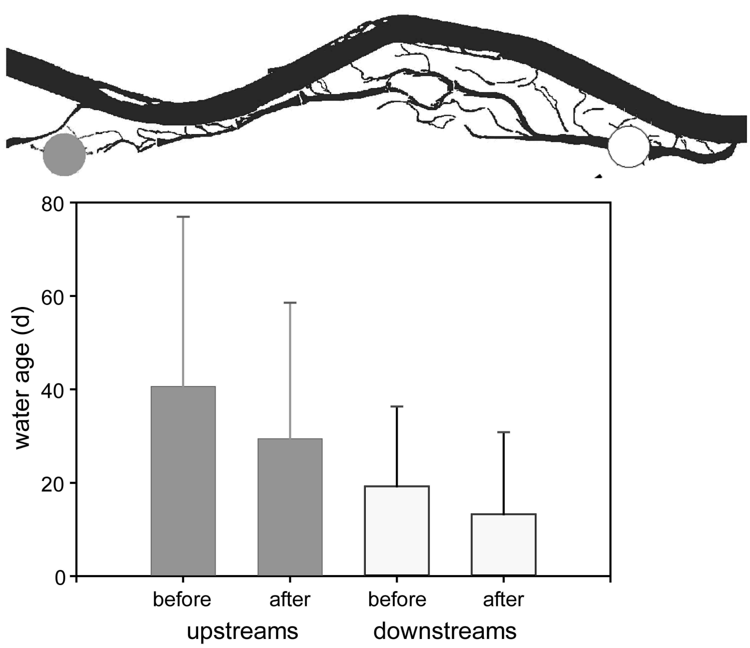

Fig. 9. Change in the average water age over the annual hydrological cycle at two positions of the Regelsbrunn floodplain system. The values are calculated by a hydrologic model relating floodplain flow to the river stage of the Danube and considering the different inflow routes and backwater capacities. Water retention is expressed as water age taking the river water as age zero.

5. A summary of management directives and guidelines

From our experiences it is apparent that the development of management criteria has to be based on insight into the ecological functioning and also the knowledge of short- and long-term effects of the various forms of human utilisation and engineering.

The goal of restoration is to retain and regain the functions of the rivers and their riparian zones in respect to
- the water budget of the whole landscape,
- their value for natural purification processes,
- the significance of wetlands as focal points - as hotspots - of biodiversity and
- the significance of riparian wetlands as a resource for human recreation and enjoyment.

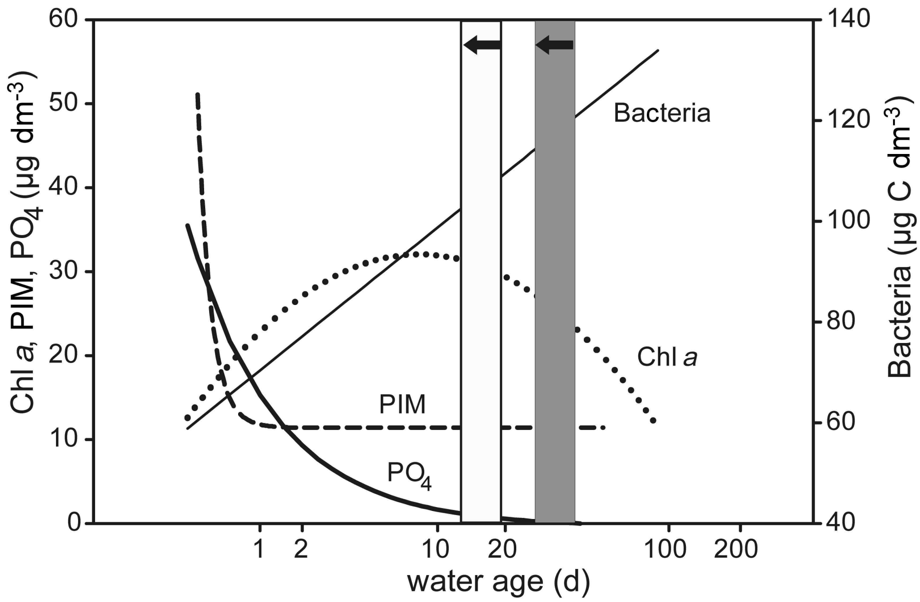

Fig. 10. Relationship between water age and various limnological parameters: particulate inorganic matter (PIM), phosphorous content, phytoplankton concentration expressed as chlorophyll a and bacterial densities (according to Schiemer *et al.* 2006). The vertical segments represent the water age before and after the regulation scheme (indicated by the arrows). The graph indicates the comparatively small effects on limnological parameters achieved by the restoration programme.

Management directives have to be primarily conceived at a catchment scale: this holds especially good with regard to the hydrology and runoff-patterns, the sediment transport processes and the pollution and nutrient levels of the rivers. However plans for restoration will have to be considered at the local scale identifying local potentials and constraints.

In the formulation of the management strategy for a particular wetland area several questions have to be addressed and constraints identified especially with regard to

a) the reversibility, i.e. to what extent under the present day constraints is it possible to turn back the clock in the direction of the original conditions prior to river regulation and damming
b) the ecological target conditions ("reference standard")
c) long-term sustainability with regard to a dynamic equilibrium of hydrology and fluvial geomorphic processes.

Reversibility addresses the questions to what extent - quantitatively and qualitatively - the original conditions prior to regulation can be regained taking into account that regulation has initiated a change in landscape processes in direction to terrestrification. A second aspect to be considered is the drastic change in the pattern of hydrology, sediment transport processes and nutrient loads of the rivers. Another important aspect is the potential conflict between human requirements e.g. for flood control, shipping and drinking water supply versus conservation interests. Restoration planning thus becomes a political issue very much influenced by local decisions and the general acceptance of conservation goals.

An important aspect concerns sustainability: what development in the riparian landscape will take place? To what extent is it possible to achieve a new level of hydrological integrity and fluvial dynamics without continuous management.

In summing up we can define some guidelines for an ecologically orientated management strategy of large rivers and their wetlands:

- **Ecosystem-centred (not a species-centred) approach**

In all scenarios conservation management should be conceived and formulated at the system level (Lubchenco *et al.* 1991). This means that protocols have to be based on functional properties in order to achieve compound effects for the restoration of biodiversity. The broad range and often strongly divergent requirements of individual species, guilds or higher taxonomic units such as fish or macrophytes, have to be integrated into a holistic, system-orientated view. On the other hand, detailed protocols have to be developed and calibrated on the demands of target species whose biology and ecophysiology should be well known. This means that the development of conservation requires a system-oriented approach which is supported by experimental autecology and ecophysiology of characteristic target species.

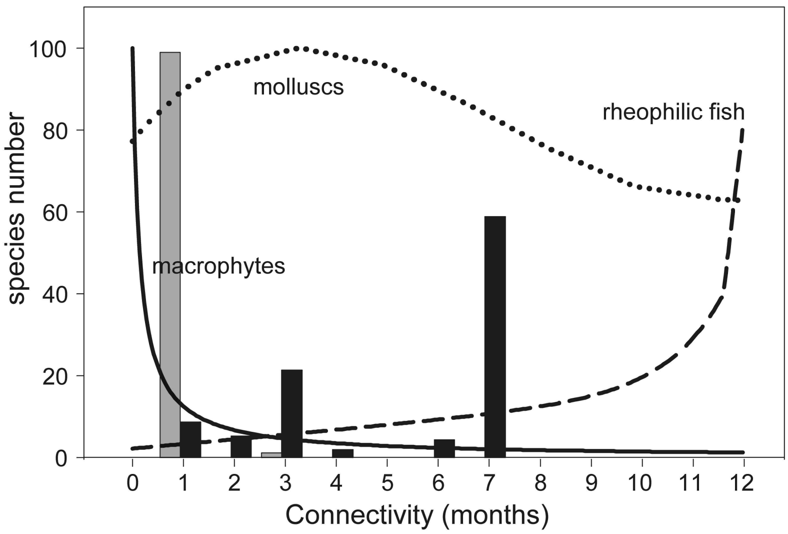

Fig. 11. The graph represents a second important ecohydrological parameter for the evaluation of floodplain restoration programmes. This is the temporal extent of upstream connectance of a backwater to the river. Expressed on an annual basis it relates to the habitat value of backwaters for the different groups of organisms. The graph shows the percentage distribution based on the whole species set of aquatic macrophytes, aquatic molluscs and rheophilic fish of the area in a sequence from low to high connectance. Into this functional response curve the habitat type distribution of backwater at Regelsbrunn before (grey) and after (black) restoration is inserted. The graph demonstrates that although a strong shift was achieved, it was not sufficient to meet the necessary habitat requirements of the rheophilic community.

- **Bioindicators**

In order to understand the meaning of functional properties of floodplains a detailed assessment of the requirements of individual key species, well adapted to floodplain situations, has to be established. These key requirements have to be defined for the various guilds and floodplain habitat types.

- **Biodiversity**

Biodiversity by itself cannot be a scientifically sound conservation goal. Although the success of a management or restoration concept will ultimately be measured by biodiversity patterns without knowledge of the ecological requirements of the contributing species, it will not provide insight into the actual degree of success of the restoration programme.

- **"Let the river work" Concept**

- **Orientation towards a "reference standard" ("guiding image")**

Biodiversity levels have to be evaluated with reference to the original conditions and their characteristic biota. The deviation from the original conditions in terms of habitat diversity and in loss and endangerment of the original biota defines the restoration potential. The restoration aims are towards the original conditions by restoring the fluvial regime. In situations where reversibility is low (see below) the "ecological target" has to be well defined, based on an interdisciplinary, system-oriented discussion process.

- **Reversibility and sustainability**

A significant question in planning restoration is to what extent under the present day constraints is it possible to turn back the clock in the direction of the "reference standard" of conditions prior to regulation, keeping in mind major changes in the ecological situation of an area (Henry, Amoros 1995; Sparks 1995; Stanford *et al.* 1996; Schiemer *et al.* 1999).

A further important issue concerns the sustainability of management and restoration measures because the goal of restoration has to be to achieve a sustainable ecological status, i.e. a new dynamic equilibrium that does not require continuous management.

- **Adaptive Management Concept**

Since available experience about restoration is very limited it is necessary to use an "adaptive management" concept, i.e. operate in small steps and analyse continuously the reaction of the complex wetland systems. This requires detailed studies and long-term monitoring!

- **Multidisciplinary planning and responsibility**

Further recommendations are that the planning process should be multidisciplinary, involving ecologists, hydrologists and engineers. It is a challenge to develop management and engineering concepts guided by ecological principles in order to harmonize ecological functions and human requirements.

The recent development in this field gives reason for hope that we are on the right track and I express my hope that your conference contributes significantly towards this goal.

These points suggest that for development of management procedures for floodplain rivers it is necessary to merge a system-orientated view with detailed autecological and experimental analysis of characteristic floodplain organisms. It is very important that the planning of restoration schemes is based on interdisciplinary teams including, ecologists, hydrologists and civil engineers. Long-term pre- and post-implementation assessments of ecological conditions and the composition of the flora and fauna are necessary in order to gain insight into the progress of the restoration and it is very important that adaptive management is applied, that is we have to return to the original dynamics in small steps and learn by doing.

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