Preservation and restoration of river ecosystems

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Abstract

Recently, physical river restoration and rehabilitation in Europe has become a priority for local, regional, national and international authorities. The key to restoration is the understanding of the complex spatial and temporal interactions between physical, chemical and biological components in a whole catchments scale. The catchment comprises aspects of spatial and temporal scale and hierarchy. Thus, an effective decision support system should include the catchment approach in the restoration plan. Such whole watershed approach can generate solutions which can be more effectively applied to sustainable management that includes both water resources quality, quantity, and biota diversity and abundance. The nowadays restoration approach should prioritize and balance human impacts and develop management tools that increase system resilience to changing human impacts at local and global scales.

Introduction

After decades of adapting rivers to agricultural, domestic and industrial needs, one became aware of the damages these alterations caused to the natural river ecosystem. In the Netherlands, only about 4% of the rivers still has a natural morphology and a (more or less) natural hydrology. In comparison to Denmark, where even only 2% is more or less natural (Brookes, 1987), and in Germany the respective value is between 2 and 5% (current results of the mapping of river morphology in almost half of the country).
Environmental awareness, concern for the loss of river and floodplain habitats and biodiversity provided the (political) route for river rehabilitation and restoration. Recently, physical river restoration has become a priority for local, regional, national and international authorities. River restoration is growing fast in Europe. For example, in the Netherlands in 1991: 70 projects were performed, in 1993: 170, and this number increased in 1998 up to 206 with a total cost of about 1.3 million euro (Verdonschot & Nijboer, 2002). From the scientific and technical point of view, there are many possibilities for physical river restoration, e.g., reforestation of the floodplain, re-meandering, removal of dams and bank fixation. New, innovative approaches include the adding of coarse woody debris (Gerhard & Reich, 2000; Gippel et al., 1996), the removal of sediment deposits in floodplains (approach described in Kern, 1994) and various methods to combat the deep cutting of rivers.
In order to make the proper choices in river restoration, the complex spatial and temporal interactions between physical parameters, habitat diversity and biodiversity have to be understood. When a river has been restored, the success (increase in

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biodiversity) depends on the re-colonisation of the original (indicator) species. Whether these species will be able to re-colonise the restored river depends on the distance to remaining populations, dispersal barriers in between the remaining population and the restored river, and the dispersal ability of the species. Establishment of an invasive or non-native species may also hinder re-colonisation, and biodiversity may in general be threatened by invasive species replacing the native ones.

River restoration ecology: theory

The key to restoration is the understanding of the complex spatial and temporal interactions between physical, chemical and biological components. The success of restoration depends on steering the appropriate key factor(s). Which factor this is, differs for each river and each site.
As most ecosystems, river ecosystems are composed of groups of interacting and interdependent parts (e.g. species, resources) linked to each other by the exchange of energy and matter. Linkage not only occurs between different parts in the transversal profile of a river but also between upriver and downriver parts of a river. For a long time, the longitudinal component of a river was seen as a sequence of inter linked zones (Illies & Botosaneanu, 1963; Hawkes, 1975) or as a longitudinal continuum (Vannote et al., 1980; Wallace et al., 1977). But exchange of energy and matter is not limited to the river itself. Hynes (1975) was the first one who included the catchment. River ecosystems are considered to be complex because their functioning is not limited by the river itself and the banks but it stretches out all over the catchment. Within the catchment as a whole, rivers are characterised by strong interactions between components, feedback loops, significant interdependencies in time and space, discontinuities, thresholds, and limits (Costanza et al., 1993). To entangle this complexity, Ward (1989) introduced the concept of the four dimensional nature of river ecosystems with a longitudinal, lateral, vertical and temporal component (Figure 1). Except from this theory about dimensions a second theory is important. Frissell et al. (1986) ordered the controlling factors from catchment to river habitat in a hierarchical space and time framework. Processes in rivers are important at different scales. The organisms in a river are dependent on habitat characteristics, best reflected in their life-history tactics (Verberk et al., 2008). These characteristics are in their turn dependent on morphology and hydrology of a river. Morphology and hydrology depend on geomorphologic structure and climate in the catchment. Knowledge of this hierarchy allows us to infer the direction and magnitude of potential changes (alteration as well as restoration) due to human activities.

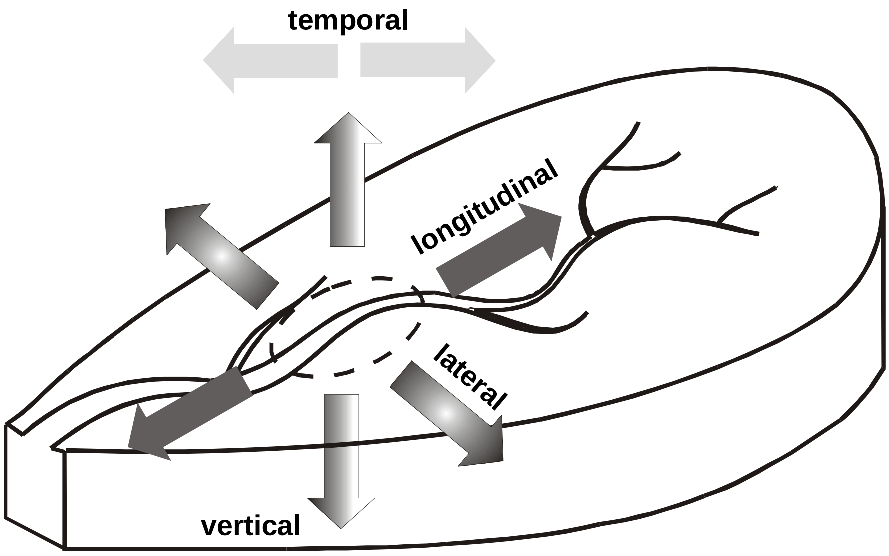

Fig. 1. The four-dimensional nature of river ecosystem (after Ward 1989).The arrows referr to LONGITUDINAL (channel-channel interactions), LATERAL (channel-riparian/floodplain interactions), VERTICAL (channel – aquifer - air interactions) andTEMPORAL (behavioural response-evolutionary change).

The catchment approach

River restoration can only become successful through an integrated catchment approach. The transport property of a river is the most important process and directly depends on the catchment (spatial component). Because of the open character of the river, it reflects the past and present structure and functioning of the whole catchment and thus includes the temporal component. Water that infiltrates in the catchment can have a long retention time before it enters the river. In a catchment approach the longitudinal and transversal components also include the ‘dry’ floodplain and the (infiltration) areas at a higher altitude in the catchment. In fact, infiltration areas affect the river water quality and land use in these areas influence, amongst others, transport of substances towards the river. The deep groundwater flow, which connects infiltration areas to the rivers, is important in lowland rivers and differs in the different reaches. Upper courses often only receive subsurface and less deep flow, middle reaches can receive subsurface flow but are also often infiltrating, lower reaches almost always receive deep, old groundwater. The water enters the river in a more vertical direction as seepage. In conclusion, a river is part of its catchment and can not be studied without looking along all dimensions.

Large catchments are comprised of tributaries and their sub-catchment, tributaries contain multiple river reaches, each reach potentially includes different habitats, and these habitat each contain multiple microhabitats (Frissell et al., 1986; Sedell et al., 1990). The multitude of processes that form river systems exist within a hierarchical framework (Allan & Starr, 1982; Frissell et al., 1986). The catchment comprises aspects of spatial and temporal scale and hierarchy (Figure 2). The temporal component is not always independent from the spatial ones and can be added to each of them.

The longitudinal component stretches out over the whole spatial area of the catchment. It more often concerns processes acting over a long-term period, such as

deep groundwater flow and processes of longitudinal meandering. But there also examples of shorter term like nutrient spiralling and fish migration. The longitudinal component can be related to a coarse spatial and a different temporal scales.
The lateral component interacts at the spatial scale of the flood plain and concerns processes like inundation and (sub-) surface runoff. These interactions more often act over a shorter time period. The lateral components also include the creation and evolution of oxbows or marshes; they act over a long term. Thus, the lateral component can be related to an intermediate spatial and again different temporal scales.
The vertical component includes the riparian zone or the wooded bank as well as the thin more or less oxygenated substrate layer on the river bottom. Its interactions more often cover a short time period such as the exchange of gasses between atmosphere and water column, the emerging and reproduction of adult insects in the overhanging trees or the (bio-) turbation of the river bottom substrate. On the other hand the vertical component is highly influenced by processes that operate at a long temporal scale, such as erosion and deposition resulting from river incision. The vertical component can be related to fine spatial and different temporal scales.

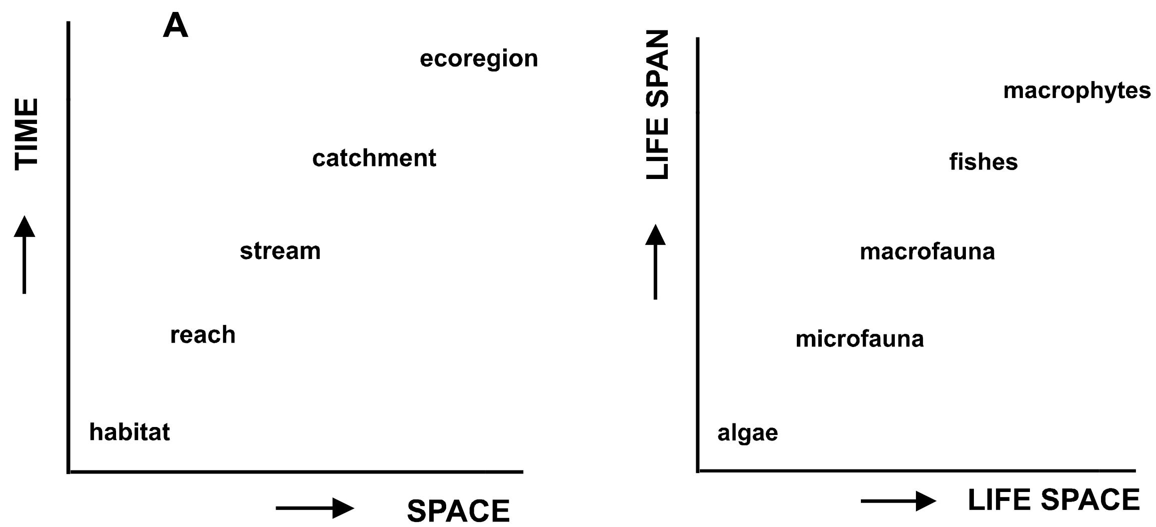

Figure 2. *Spatial and temporal scale and hierarchy (A), and the response scale of different taxonomical groups (B) (after Verdonschot 1999).*

Scale and hierarchy

There is a hierarchy between the three components in space and time whereby the longitudinal component (coarser scale) bounds the range of ecological features of the lateral and vertical ones (finer scales), but also the vertical one (finer scales) affects the lateral and longitudinal components (coarser ones). River functioning acts at multiple spatial and temporal scales with ‘top down’ and ‘bottom up’ controls often termed dominance and feedback.
Integrated ecological approach in river restoration should include more than one spatial (include at least one lower scale) and temporal scale (to include system dynamics) dependent on the objective which is addressed. Looking at river

functioning always should cover a fine, intermediate and coarse scale in space and time.
Including the whole catchment in river ecology and restoration of rivers implies working in hierarchical order. It is no use to start at a small scale (certain habitat in a river) if there are problems on the large scale (in the infiltration area of the catchment). In a catchment approach processes at different scales in the catchment varying from microhabitat to catchment are included.

Solutions

River managers need a simple decision support systems to handle the ecological complexity for an effective restoration plan at a site. It provide the opportunity to go trough the most important steps in river restoration and to extract the factors in the catchment that should be tackled. Each site and each river is different. But the approach of planning a successful restoration should be the same. Such decision support systems should be based on the theories of dimensions, scale and hierarchy and forces a water manager to include the catchment in the restoration plan.

Restoration goals

The success of river restoration depends on the societal and ecological potentials present in the area to be restored. The societal potentials depend on political and management choices. Although, most probably the water managers involved in for example the Vloedgraaf project did know on forehand that the bad water quality could be a problem for ecological rehabilitation. A clear example of lack of power (political) and financial means to also tackle this quality problem at the same time. It shows that political and management choices really are a major bottleneck for an integrated approach of river restoration. Despite this important observation these choices will not be discussed further in this manuscript.
The ecological potentials depend on the conditions in the catchment and the river as well as on the reference condition. For the latter, restoration needs clear goals. Goals defined in terms of reference and target conditions. These reference conditions refer to natural or pristine river ecosystems, which can be accomplished in the long term (period of 25 to 50 years). The target conditions represent conditions in between the present and the reference condition and can be accomplished in a middle-long term (period of 5 to 25 years). From a management point of view, these targets have an important practical use in monitoring and evaluation. Species composition and ranges of abiotic variables describe targets and references. To set management goals it is important to know what the river type is and how it should look like in the most optimal ecological situation. To manage a certain river type it is necessary to identify the key factors that are, or will be, disturbed by human influences. The higher the level of the key factor that will be managed the closer the reference can be approached (Figure 3).

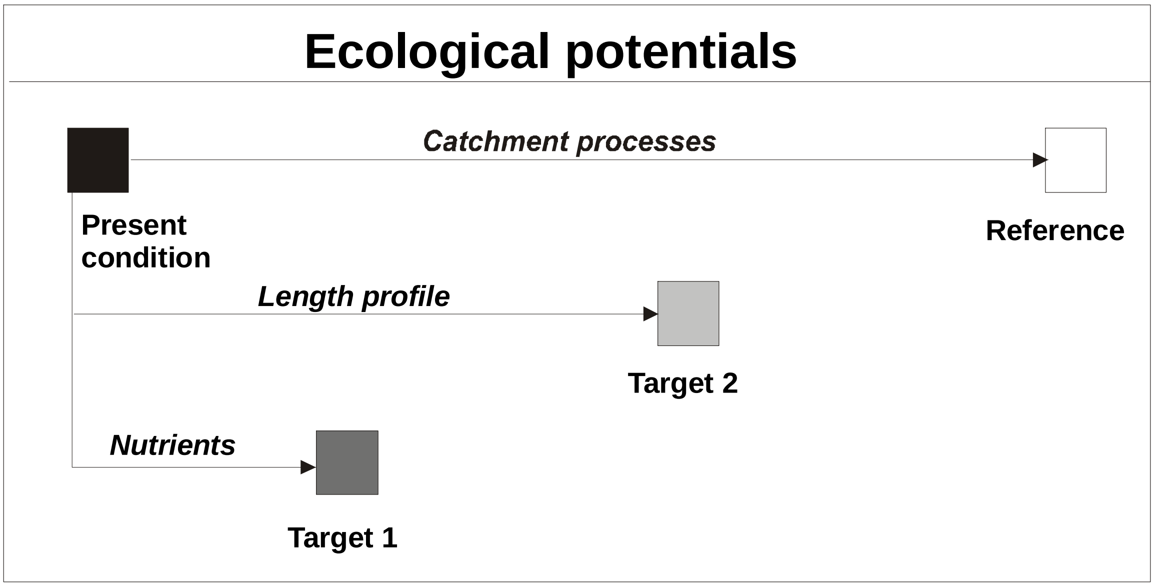

Figure 3. Ecological potentials in river restoration. Management goals set targets and references.

The 5-S-Model

It becomes clear from the second section of this paper that firstly, present river restoration is lacking a catchment perspective. Secondly, measures are often taken because of practical motives such as non-ecological demands, land availability, maintenance of the river channel, et cetera. Therefore, an integrated approach is needed in which ecological concepts; threats and practical experiences are combined with physical measures. This synthesis leads to an appropriate decision support system for river restoration.
The key themes in theoretical river ecology deal with the four dimensions, hierarchy, response of species and human influence (Table 1). A catchment approach includes all themes and can be applied at different scales. When these theoretical considerations are confronted with the practical execution of river restoration a number of problems occur. To improve this practical approach and include all dimensions relevant in a river restoration project from a catchment and landscape ecological point of view the key factors in river restoration were ordered.
In order to make the proper choices in river and catchment management; one has to understand the functioning and interactions (dominance and feed back) of the controlling key factors. To simplify the ecological complexity of the controlling key factors, and the concepts on hierarchy and scale as described in the first section of this paper, the 5-S-Model (Figure 4) was formulated. This conceptual model integrates the four dimensions in rivers, scale and hierarchy and provides guidelines for management (Verdonschot et al., 1998). Aspects of scale and hierarchy between key factors are included in the model. The five main components (from high to low level) are:

1. System conditions comprise the processes related to climate (temperature, rainfall), geology and geomorphology (like slope, soil composition). System conditions are composed of ultimate controlling factors and are boundary conditions for a river. The system conditions set the possibilities and limits for river ecosystem functioning. Ultimate controlling factors

continuously interact with a river at a high hierarchical scale in space (the catchment), as well as in time (± 100 years). Generally, management can not change system conditions. Human activities influence this level through, for example, atmospheric deposition and climate change. River rehabilitation does not focus on these factors but one has to consider the effects of these boundary conditions as well as the long-term effects of change. All system conditions together determine the type of river. A river is seen as a whole and as part of its catchment. The catchment is composed of gradients. But for restoration purposes, it is necessary, one way or another, to identify and arrange river types as discrete entities which can be dealt with. For the water manager, who can not deal with a gradient in environmental circumstances, this more or less arbitrary identification of entities is of high practical value.

2. River hydrology characteristics are set by the system conditions. River hydrology comprises, at the scale level of catchment, the processes, like infiltration, ground water flow, seepage, run off and discharge. At the level of river and habitat, river hydrology comprises hydraulic processes, like current velocity and turbulence. River hydrology refers to the water quantity parameters. The direction of the water flow strongly influences the direction of all other parameters in the system. The two main directions of flow are one running from the boundary of the catchment towards the river (lateral) and one running from the source to the mouth of the river (longitudinal).
3. Structures of the river valley and the river itself are strongly determined by the hydrological and hydraulic processes of river hydrology. Structures imply the morphological features of the longitudinal and transversal shape of the river bottom, banks and bed, as well as the substrate patterns within. Structures also refer to old meanders, terrestrialisation, sand deposits and others in the river valley. The dynamics of these structures directly relate to the dynamics in hydrology and hydraulics. Structures in rivers provide habitats for organisms.
4. Substances include the dissolved components like nutrients, organic matter, oxygen, major ions and contaminants. Substances directly follow the water flow. From the catchment boundary towards the river the amount of dissolved substances increases. Also from source to mouth this increase is visible. Substances refer to the water quality parameters.

River hydrology, structures and substances together compose the group of controlling factors that directly determine how the river community functions. These factors are included in the decision support system (see next paragraph).

5. Species are the response to the functioning of all above-mentioned groups of controlling factors. Species and their communities are the actual goal of ecological river management and rehabilitation.

Controlling and response characteristics are not solely related to one of the mentioned groups of factors. There are mutual interactions. Structures, for example, can respond to the action of river hydrology but in reverse can also reduce discharge fluctuations. Species can be adapted to river hydrology but, for example, trees can steer river flow and bed morphology. Despite a dominant hierarchical effect, a feed back is always present. Thus, factors interact on different hierarchical scales and with different intensity.

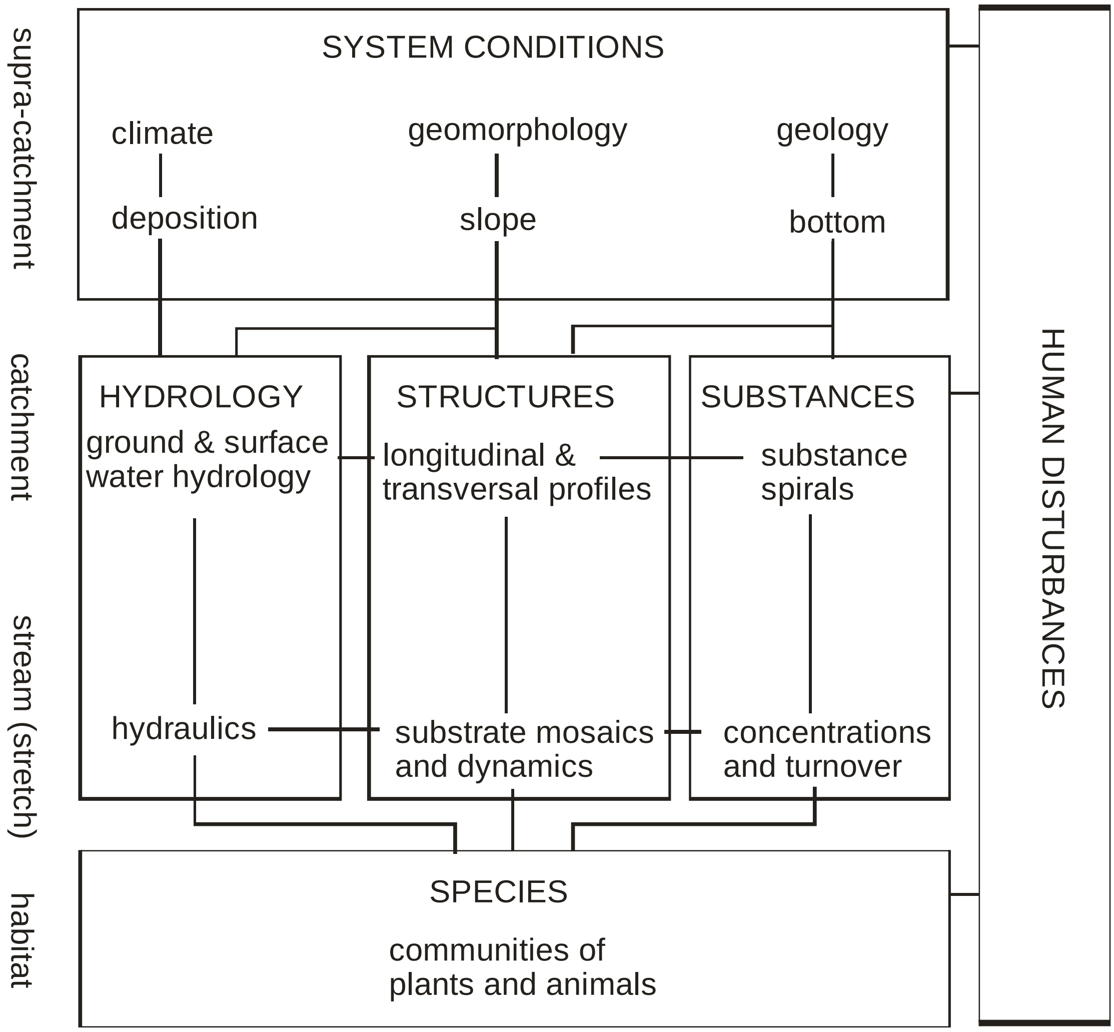

Figure 4. Main structure of the 5-S-model with key factors and functional aspects (after Verdonschot et al. 1998).

Human influences

Knowledge of the hierarchy in factors and processes acting in space and time in rivers, allows also inferring the direction and magnitude of potential changes due to human activities. Changes which refer to alteration as well as to restoration, and the time involved/needed. Human alterations can be seen as a sixth ‘S’; the ‘S’ of Steering. The alteration and restoration of rivers steer the ecosystem in a negative (alteration) or positive (restoration) direction.

Decision support system for river restoration

In Figure 5 and Table 1 the present macrofauna assemblage is taken as a starting point for the decision support system. The macrofauna assemblage is composed of all macro-invertebrate species and their numbers of individuals present at the site or river reach under consideration. From the macrofauna assemblage the required information on the state of the river environment is extracted by using the ecological information of each individual species, such as saprobic valence, current velocity, trophic state, substrate composition et cetera. Verdonschot & Nijboer (2000) give examples of a quantitative approach of this process. When a river suffers from more than one stressor at the same time, more often the assemblage will indicate this possibility, except when the disturbance is too intensive. Severely impacted sites, where stressors are mostly very obvious, need an additional approach. Thus, the macrofauna assemblages tell about the state of the river environment. For the decision support system the following major steps are taken:

1. The macrofauna firstly refers to the four major groups of key factors, as described in the 5-S-model, which compose four decision sub-keys in the decision support system. These major groups of key factors can be specifically managed and refer to; water quantity (river hydrology), water quality (substances), habitat variability (structures), and direct human interference. System conditions mainly act at a coarse spatial and temporal scale, they are not included. River hydrology, structures and substances mainly act at an intermediate scale, and species function at a fine scale though indicates the state of the first three named. Of course, exceptions at this rule show patterns of dominance and reaction whereby even species can dominate system conditions.
2. Within each decision sub-key the macrofauna is related to three items: (a) the controlling processes responsible for the state of the river under study, (b) the specified groups of macrofauna indicative of these processes, and (c) the state of some relevant indicative environmental parameters.
3. The macrofauna composition, environmental parameters and controlling processes lead to the following questions. These questions concern the major human influences. The potential human causes of alteration detected in-river within each decision sub-key, are arranged in a hierarchically. The key starts asking questions at the scale of the catchment as a whole or more specifically at the infiltration area. Then it focuses towards finer scales: surroundings, riparian zone, towards in-river.
4. In the following step the human causes detected are related to major groups of actions to be taken. These are indicated by letters and refer to Table 4.
5. Finally, in Table 4, the actions decided in the decision key (Figure 11) are translated into measures to be taken, dependent on which specific key parameters are disturbed and on the specific causes of alteration.

This decision support system can be used to identify the effect of human influences upon key factors to be steered. Furthermore, the controlling processes are hierarchically ordered. The figure and table translate the 5-S-model, scale and hierarchy and the four dimensions together into a frame that can be used to improve restoration planning.

The decision support system (combined Figure 5 and Table 1) is based on knowledge on the ecology of macrofauna as well as on measures or knowledge of a number of key factors and key parameters, their reference or target value and their present state. The difference between the latter two indicates which processes are important and may be disturbed by the indicated human activities. With this relationship it is possible to choose the relevant actions to be undertaken. In translating species traits into life-history tactics, one can relative easily transplant this knowledge to other systems, by identifying the traits of the local species (Verberk et al., 2008).

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MACROFAUNA ASSEMBLAGE INDICATES :

➔ **WATER QUALITY CHANGES**

strong organic pollution many saprophilics/-bionts high ammonium, low oxygen	*yes* ➔	catchment use urban / industrial ?	*yes* ➔	**A1**
➔ *no*		➔ *no*		
eutrophication algae feeders, ubiquists high nutrient content	*yes* ➔	intensive agricultural use of catchment / infiltration area ?	*yes* ➔	**A2**
➔ *no*		➔ *no*		
moderate chemical pollution saprophilics, eutrophilics present moderate N/P conc.	*yes* ➔	surroundings use urban / agricultural ?	*yes* ➔	**A2**
		➔ *no*		
		point sources of sewage / purification plant ?	*yes* ➔	**A1**

and / or ➔ **WATER QUANTITY CHANGE**

drought and acidification intermittent sp., acidophilics drought > 6 wks., acidity < 5.0	*yes* ➔	catchment drainage and water course alteration ?	*yes* ➔	**B**
➔ *no*		➔ *no*		
irregular discharge patterns few rheophilics, ubiquists flow dynamics	*yes* ➔	catchment / infiltration area drainage ?	*yes* ➔	**B**
➔ *no*		➔ *no*		
moderate discharge disturbance several rheophilics, specialists lack flow irregularities, erosion	*yes* ➔	surroundings drained / paved surfaces ?	*yes* ➔	**C**
➔ *no*		➔ *no*		
no sediment dynamics less common and rare rheophilics lack too regular profile, erosion	*yes* ➔	profile alterations and local drainage ?	*yes* ➔	**C, D**
		➔ *no*		
		local hydrological changes ?	*yes* ➔	**D, E**

and / or ➔ **HABITAT LOSS**

no habitat variety low diversity, only ubiquists homogenic substrates / profile	*yes* ➔	catchment drainage and flow alterations ?	*yes* ➔	**B, C**
➔ *no*		➔ *no*		
siltation moderate diversity, specialists lack silty bottom, low sinuosity	*yes* ➔	channalization / regulation ?	*yes* ➔	**D, E, F**
➔ *no*		➔ *no*		
moderate habitat variety taxa supply from up-river some substrate types, profile altered	*yes* ➔	within reach variety loss / bank and bottom shape alteration ?	*yes* ➔	**E, F, G**

Figure 5. Decision key for river restoration (for letter definitions see Table 1).

Table 1. Actions and river restoration measures.

ACTION	RESTORATION MEASURES
A1 water quality improvement (point sources)	discharge reduction of sewage discharge reduction of effluent improvement purification plants construction of natural purification filters (helophytes) construction of horse-shoe wetlands construction of buffer zones
A2 water quality improvement (non-point sources)	discharge/use reduction of toxic substances discharge reduction of manure and nutrients diversion of polluted flows construction of natural purification filters (helophytes) construction of horse-shoe wetlands construction of buffer zones
B restoration groundwater supply and flow	removal of surface and subsurface drainage improvement of infiltration change of (ground-)water extraction afforestation of the catchment construction of hydrological buffers infiltration of purified effluent creation of inundation areas improvement of water retention reconstruction of natural catchment
C length profile adjustment	natural re-meandering digging new meanders construction of in-channel meanders removal of weirs
D transverse profile restoration	construction of a-symmetric profile creation of overhanging banks profile narrowing and river bottom raising removal of profile consolidation bottom silt removal construction of by-passes and secondary channels create berms to take high flows
E riparian zone restoration	creation of wooded banks digging of pools reconstruction/opening of old meanders lowering of adjacent land establishing agricultural free zone
F habitat improvement	all measures listed under B, C, D and E reconstruct habitats for specific species creation of riffles and pools construction of fish ladders introduction of objects into the channel (trees, stones)
G maintenance adaptation	reduction of maintenance frequency reduction of maintenance intensity spotwise maintenance
H re-introduction/removal of species	removal by fishing re-introduction programmes maintenance adaptation (G)