Concepts of Decision Support for River Rehabilitation

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Abstract:

River rehabilitation decisions, like other decisions in environmental management, are often taken by authorities without sufficient transparency about how different goals, predictions, and concerns were considered during the decision making process. This can lead to lack of acceptance or even opposition by stakeholders. In this paper, a concept is outlined for the use of techniques of decision analysis to structure scientist and stakeholder involvement in river rehabilitation decisions. The main elements of this structure are (i) an objectives hierarchy that facilitates and stimulates explicit discussion of goals, (ii) an integrative probability network model for the prediction of the consequences of rehabilitation alternatives, and (iii) a mathematical representation of preferences for possible outcomes elicited from important stakeholders. This structure leads to transparency about expectations of outcomes by scientists and valuations of these outcomes by stakeholders and decision makers. It can be used (i) to analyze synergies and conflict potential between stakeholders, (ii) to analyze the sensitivity of alternative-rankings to uncertainty in prediction and valuation, and (iii) as a basis for communicating the reasons for the decision. These analyses can be expected to support consensus-building among stakeholders and stimulate the creation of alternatives with a greater degree of consensus. The paper concentrates on the overall concept, the objectives hierarchy and the design of the integrative model. More details about the integrative model, the stakeholder involvement process, and the assessment of results are being published separately. Because most decisions in environmental management are characterized by similarly complex scientific problems and diverse stakeholders, the outlined methodology will be easily transferable to other settings.

Keywords: decision analysis; stakeholder involvement; decision support; probability network; river rehabilitation; ecological prediction.

1. Introduction

In many industrialized countries, river ecosystems have been strongly impacted over the past centuries, mainly by constraining their widths to gain agricultural and urban land and improve flood protection of cultivated and urban land. River rehabilitation has the goal of re-establishing parts of these ecosystems. Decisions about river rehabilitation measures are difficult because of the uncertainty about the outcomes, the number of stakeholders with partially conflicting objectives, and the difficult and time-consuming governmental decision procedure.

Decisions about river rehabilitation are societal decisions. They have always to take into account trade-offs between ecological goals, ecosystem services, competing land uses, and costs. To better prepare authorities and politicians to make and communicate such a decision, a procedure for using scientific knowledge and structuring the different viewpoints and attitudes could be extremely useful.

Decision analysis techniques (von Winterfeldt and Edwards, 1986; Clemen, 1996; Eisenführ and Weber, 2003) were originally developed to support individual decision makers in carefully considering all aspects of their decisions. However, because these techniques are used to structure the decision problem and to make explicit the expectations about outcomes and preferences, they can also be used to support group decisions or to structure stakeholder involvement and communication (Marttunen and Hämäläinen, 1995; Keeney and McDaniels, 1999; Ananda and Herath, 2003).

In this paper, we describe a general procedure of how decision analysis techniques can be used to support river rehabilitation decisions. The procedure is divided into seven steps.

Step 1: Definition of the decision problem

Step 2: Identification of objectives and attributes

Step 3: Identification and pre-selection of alternatives

Step 4: Prediction of outcomes

Step 5: Quantification of preferences of stakeholders and decision makers for outcomes

Step 6: Ranking of alternatives

Step 7: Assessment of results

These steps are mainly derived from the existing decision analysis literature. However, as described in more detail below, we will integrate a stakeholder involvement procedure with the primary goals of consultation and consensus-building. The stakeholder involvement aspects are mainly dealt with in steps 1-3, 5 and 7, whereas step 4 is based on scientific analysis and step 6 is a technical integration step, the results of which are interpreted in step 7.

The seven steps outlined above form the structure of the paper. They are briefly described in the following sections in the context of decisions about river rehabilitation measures for a particular river reach. The problem of integrative planning of river rehabilitation in the context of the whole river basin is not addressed in this paper. However, a similar approach could be used to address this problem.

The approach discussed in this paper can be seen as a further concretization of previously suggested concepts of decision support in river rehabilitation (Llewellyn et al. 1995; Qureshi and Harrison, 2001; Pieterse et al. 2002; Verdonschot and Nijboer, 2002). Similar approaches have been proposed in other fields of water management (Hämäläinen et al. 2001) and, more generally, environmental decision making (Lahdelma et al., 2000). The emphasis of this article is on the development of an exhaustive objectives hierarchy, on the concepts of a predictive model to estimate the consequences of decision alternatives, and on the use of valuation techniques. More details on elicitation of stakeholder values and on implementation of the procedure for conflict resolution is given elsewhere (Hostmann et al., 2005a,b).

2. Step 1: Definition of the Decision Problem

Defining the decision problem is an important first step to set the framework for the subsequent steps of the decision support procedure. Two aspects of the decision problem are important to address: the scientific or technical part of the problem and the socio-economic part which, for public sector decisions, is intimately linked to the stakeholders involved in, or affected by, the decision.

In environmental management, the core of the scientific part of the problem is often a sustainability deficit of material flows or a disruption of habitats in ecosystems. The description of this part of the problem can be difficult because of lack of precise knowledge about the relevant mechanisms in the ecosystem. River degradation is often caused by

- loss of habitats for aquatic organisms, shoreline fauna, and birds by straightening and narrowing the river bed, thereby decreasing the variability of water flow and depth, the shoreline variability and length, and the diversity of the floodplain area (side channels, pools, gravel bars, pioneer vegetation and floodplain forests);

- water pollution from point and diffuse sources;
- change in flow velocities and the hydraulic regime by damming, water abstraction and water release from power plants with unnatural short- and long-term dynamics.

The perceived severity of a degradation problem depends on the desired state to be achieved. The definition of this state links the natural scientific part of the problem to the socio-economic part, as it is a political issue to decide in which environment a certain community would like to live.

A handle to the socio-economic part of the problem is obtained by performing a stakeholder analysis with the goal of eliciting their preferences and supporting consensus-building for a rehabilitation project (Grimble and Wellard, 1997; World Bank, 1996). Stakeholders are any group of people, organized or unorganized, who share a common interest or stake in a particular issue or system (Grimble and Wellard, 1997). Stakeholders can be identified by analyzing who affects the decision (active stakeholders) and who is affected by the decision (passive stakeholders). Both assessments should be made at different spatial and administrative levels and confirmed or extended by the identified stakeholders. Table 1 lists groups of organized stakeholders identified by Hostmann et al. (2005a) for a river rehabilitation project in Switzerland.

3. Step 2: Identification of Objectives and Attributes

An objective is something a decision maker (or stakeholder) would like to achieve, and attributes are measurable system properties that can be used to quantify the degree of fulfilment of the objectives. Identification of objectives and attributes is the second step of the decision support procedure to ensure that the goals are laid out explicitly and that the correct and complete objectives are addressed by the alternatives, model and valuation processes. When combining decision analysis with stakeholder involvement, as suggested in this paper, objectives and attributes should be assessed from representatives of all considered stakeholder groups (traditionally they have been elicited from the single decision maker). This can best be done as a first part of the interview for the elicitation of stakeholder preferences in step 5. An objectives hierarchy developed initially by scientists, such as that described below, can be useful to reduce the elicitation process and to serve as a check for completeness and adequate complexity.

3.1 Objectives

Objectives can be divided into fundamental objectives (directly related to what a decision maker would like to achieve) and means objectives (that lead to the accomplishment of fundamental objectives). Fundamental objectives are usually structured hierarchically according to their degree of concreteness (Clemen, 1996; Eisenführ and Weber, 2003). The objectives at each level of such a hierarchy should be mutually exclusive and collectively exhaustive (Keeney, 1992). When applied to ecological goals, exhaustive means that all the most relevant aspects of ecosystem structure and function are represented. At lower levels of the objectives hierarchy, this needs a selection of sub-objectives that are indicative of the objective at the higher level; however, in this context, exhaustive cannot mean describing all aspects of the higher objective. For example, in the context of prediction of a future state of the system, biodiversity cannot be represented by the densities of all species. Instead, indicator organisms or functional groups must be used.

Figure 1 provides a proposed hierarchy of fundamental objectives for a rehabilitated river reach. This hierarchy can serve as a guideline for other river rehabilitation projects. It was developed by scientists involved in the multidisciplinary Rhone-Thur project for support of river rehabilitation projects in Switzerland (Peter et al., 2005). It served as a basis for subsequent value assessments by all stakeholder groups, who did not request additional objectives when using a simplified version of this hierarchy (Hostmann et al. 2005a). In another sub-project of the Rhone-Thur project (Woolsey et al., 2005), a slightly modified version of this objectives hierarchy was used as a basis for quantifying the assessment of success of implemented projects. The major difference between these two uses was in the rightmost branch of the hierarchy shown in Figure 1 which, for the assessment of success, was replaced by objectives focused on the implementation process itself (e.g. meeting the budget, involving stakeholders).

At the highest level of the objectives hierarchy, the overall objective of achieving a *rehabilitated river section* is divided into the objectives of achieving high levels of ecological integrity and socio-economic integrity.

Achieving a *high level of ecological integrity* is further divided into achieving high levels of physical, chemical and biological integrity. It is obvious that, due to the important influence of the physical aspects of river hydrology and morphology and the chemical aspects of water quality on the development of biology, we already run into difficulty distinguishing means objectives from fundamental objectives and with having mutually exclusive objectives. Possibilities would be to either concentrate on biological integrity and treat physical and chemical integrity as means objectives to achieve biological integrity, or concentrate on physical and chemical integrity and assume that this is sufficient to guarantee biological integrity. Neither of these approaches is satisfying. The first does not account for the achievement of physical and chemical integrity as fundamental objectives, while the second omits biological integrity as an important (or even the most important) fundamental objective. To account for the difficulties above, we decided to use physical, chemical and biological integrity all as fundamental objectives. This does not imply that physical and chemical attributes are not useful as proxies for quantifying the objective of achieving biological integrity. However, the difficulty is that when characterizing the preference structure, we have to assign values to physical and chemical integrity that exclude its benefits to biological integrity. This is necessary to keep the valuation of objectives mutually exclusive (otherwise the value of ecosystem integrity would be double counted).

The objective of achieving a *high level of physical integrity* of the ecosystem is divided into achieving natural river morphology and hydraulics, a natural discharge regime, a natural temperature regime, a natural level of suspended solids, and a high longitudinal, lateral and vertical connectivity.

The objective of achieving a *high level of chemical integrity* is divided into achieving a high dissolved oxygen concentration, natural nutrient concentrations, and low pollutant concentrations.

The objective of achieving a *high level of biological integrity* is divided into natural ecosystem function and natural species diversity and abundance. At this level we again have problems of specifying mutually exclusive objectives, as species are a determinant of ecosystem function. Still, it seems necessary to distinguish whether a function is provided by a small number of species or by a diverse ecosystem.

The branch of achieving a *high level of socio-economic integrity* of the objectives hierarchy is divided into ensuring good ecosystem services and achieving low monetary and other costs. These have generally fell within the realm of cost-benefit analysis, but within the decision analysis framework they can be addressed without having to express all attributes in monetary units (Hanley and Spash, 1993). Major *ecosystem services* of the river ecosystem are identified to be high flood protection, good groundwater supply, high self-purification capacity, high recreational value, and high aesthetic value. The objective of achieving *low monetary and other costs* helps society to afford implementation of the measures. It is divided into low implementation costs, low maintenance costs, and low loss of agricultural workplaces. The latter is often a major concern by local farmers, when agricultural land is converted to natural floodplains.

3.2 Attributes

Careful selection of attributes is often overlooked in the rush to quantitative analysis. However, this is an important step as it provides the link between social objectives and scientific predictions. The lowest level objectives of the hierarchy shown in Figure 1 can be characterized by the attributes listed in Table 2. In some cases, these attributes can easily be used to quantify the degree of fulfilment of the corresponding objective. However, in other cases, the chosen attributes reflect a compromise between the goals of achieving a good characterization of the objective and making it possible to get reasonable prediction accuracy. Care should be given to the problem that the attributes which are easier to predict not lead to too large an increase in the uncertainty of the value assessment step.

4. Step 3: Identification and Pre-Selection of Alternatives

To make the analysis concrete and limit the required effort of the analysis procedure, the next step of the decision support procedure is to identify and pre-select decision alternatives. Important options for rehabilitation of river sections include (Woolsey et al., 2005):

- local river widenings,
- removal of culverts,
- structuring of the river bed,
- improving the river bank,
- removal of barriers,
- creation or reconnection of side channels,
- reconnection of oxbows,
- reconnection of floodplains,
- construction of fish ladders.

Decision alternatives typically consist of combinations of some of these measures with flood protection measures for cultivated or urban land. Some flood protection measures, such as retention basins, may increase the area of occasionally flooded terrestrial habitat. In many cases, relieving river width constraints is the most important measure for rehabilitation. Allowing low intensity use of occasionally flooded land, such as by extensive agriculture or recreation, may be an option to increase consensus among stakeholders while still keeping a significant fraction of the ecological benefits. An assessment of the results of step 7 can help to derive new compromise alternatives. This leads then to an iterative use of the outlined procedure.

5. Step 4: Prediction of Outcomes

Once the alternatives to be included in the analysis process have been identified, their consequences must be predicted. This is done in step 4 of our decision support procedure. Predicting ecological consequences of rehabilitation measures is a difficult task. However, it is important to explicitly pursue this task as legislation in many countries states good ecological status to be a major goal to be achieved for all water bodies (an important example is the European Water Framework Directive; European Parliament, 2000). As rehabilitation measures usually directly affect the shape of the river bed, the most direct consequences consist of hydraulic and morphological changes. The discharge regime and water quality are usually not significantly affected by local rehabilitation measures. Therefore, the most relevant predictive task is to estimate hydraulic and morphological changes and their consequences for the ecological state of the river section. According to the objectives hierarchy in Figure 1 and the corresponding list of attributes in Table 2, this state is characterized by attributes that are indicators for vegetation, benthic population, shoreline community, and fish population. These groups of species were selected because they are significantly influenced by river construction and rehabilitation, they seem to be adequate as indicators for ecosystem integrity and they are less dependent on neighbouring ecosystems that are not affected by river rehabilitation measures compared to birds, mammals or reptiles. The last property makes it less difficult to predict the expected changes in abundance due to the implementation of rehabilitation measures. In addition, we consider social and economic consequences. The major relationships between these general fields of indicators are represented in Fig. 2.

Prediction of the consequences of rehabilitation measures requires a model of cause-effect relationships. Such a model must combine knowledge from all available sources, such as basic scientific knowledge, specialized literature, more detailed models, measured data, and expert knowledge. Probability network models provide a very useful model structure to combine different types of knowledge, divide a model into more easily tractable sub-models, and explicitly consider prediction uncertainty (Pearl, 1988; Charniak, 1991; Reckhow, 1999; Borsuk et al., 2004). They consist of two components: (1) a graphical depiction of the most important cause-and-effect relationships among variables in the system, and (2) conditional probability distributions describing how each variable changes in response to changes in its causal parents. Because of the advantages described above, we decided to build the first integrative model of rehabilitation measures as a probability network.

The graphical model in Figure 2 shows the causal relationships between the main variables describing the rehabilitation project and some of the decision attributes. This formed the starting point of model construction. More detail was then added by resolving the dominant relationships, adding important influence factors and identifying the boxes in Figure 2 as sub-models of an integrative model to predict the consequences of the rehabilitation measures. This resulted in the diagram shown in Figure 3. Note that several of the fields of assessment will be inputs to the model for the river reach, as they are not affected by the local rehabilitation measures (left column of assessment fields). Morphological and hydraulic assessment fields are intermediate nodes predicted by the hydraulics sub-model and used as input to the biological models. The structures of the six sub-models of hydraulics, vegetation, benthic population, shoreline community, fish, and economics identified in Figure 3 at the final resolution level of attributes (see Table 2) corresponding to the fields of assessment shown in Figure 3 (or to the lowest level objectives shown in Figure 1) will be discussed briefly in the following sub-sections. These sub-models are currently at different stages of development. The hydraulics, fish and economics sub-models are complete, the benthic population sub-model is in development, the vegetation sub-model has been initiated, and the shoreline community model is still at a preliminary stage of conceptual discussion. Further model development as well as changes in attributes may lead to changes in the structure of the sub-models. However, the conceptual diagrams discussed below are representative enough to stimulate discussion about their structure, the equations used for their quantification, and linkage of the sub-models to the comprehensive integrative model of the effects of rehabilitation measures.

In the diagrams shown in Figures 4a to 4f giving more details about the relationships considered in the sub-models, green nodes refer to model inputs, yellow nodes to intermediate nodes, and red nodes to model outputs used as inputs to another sub-model (these nodes are also red in the sub-models to which they are input) or for valuation. The nodes used for valuation are indicated by a rhombic shape. These nodes for valuation do not cover all attributes listed in Table 2. Some of the attributes can be directly determined from the specification of the alternative, while for some of the others we have not yet derived a predictive model.

5.1 Hydraulics Sub-Model

Because all biotic endpoints of interest are influenced by hydraulics and river morphology (see Figs. 2 and 3), model development started with this critical sub-model. The focus was on predicting variables that would be required as inputs to the other sub-models, including channel morphology, velocity and water depth distributions, and river bed clogging. A special challenge for the hydraulics sub-model is the difference of time scales between tens of years for the development of channel morphology and hardwood floodplain forests and hours for spatial velocity distributions. This was solved by using long-term hydrograph information for estimating the morphological type of the river and by calculating velocity distribution for a typical (e.g. mean) discharge only. In the following paragraphs, we give a brief overview of the model shown in Figure 4a. More details can be found in Schweizer et al. (2004).

River morphology is an important attribute on its own and is also a fundamental determinant of hydraulic habitat characteristics. Whether a river will be single- or multi-threaded depends on the balance between local gravel transport capacity and upstream gravel supply with consideration of width constraints. Van den Berg (1995) developed a predictive method for distinguishing between multi- and single-thread rivers using annual discharge, gravel size, and valley slope. Bledsoe and Watson (2001) made this approach probabilistic by fitting a logistic regression model to a data set from 270 streams. We used their results to predict the natural tendency of a river in the absence of width constraints. The effect of width constraints was then determined by applying the pattern diagram of da Silva (1991).

The spatial distribution of velocity can be estimated for given discharge using the method of Lamouroux et al. (1995). In a statistical analysis of data collected from a diversity of streams, they found that the spatial frequency distribution of relative velocity could be modelled as a mixture of a centred (Gaussian) and a decentred (mixture of exponential and Gaussian) distribution with fixed distributional parameters. A parameter describing the mixture between the centred and decentred distributions could then be expressed as a linear function of the relative roughness and the logarithm of the Froude number. An increasing relative roughness leads to a more decentred distribution, while an increasing Froude number leads to a more centred distribution.

Clogging and clearance of the bed matrix are crucial ecological processes because fish and benthic species depend on the interstitial gravel zones. Additionally, the content of fine particles in the river bed influences water exchange between surface and ground water, thus affecting groundwater regeneration. Conceptually, we model gravel bed clogging as a process that occurs over time at a rate which depends on hydraulic and bed characteristics. The clogging process is disrupted by the occurrence of high floods which are accompanied by high bottom shear stress. This disturbs the gravel bed matrix and clears it of fines. When having estimated the threshold shear stress for bed movement according to Günther (1971) and having converted it to a critical discharge using Strickler's formula, the frequency of clearance of the river bed can be derived from the hydrograph. This frequency together with the rate of clogging will determine temporal extent and severity of clogging. The temporal progression of the build-up of fines between floods can be estimated from a calculation of the volume of water filtered through the gravel bed, according to a simplified version of the formula given by Schälchli (1993). The mass of fine particles retained in the bed matrix is calculated as the product of the volume of filtered water and concentration of suspended particles. The average percentage of fines can then be used as a measure of the degree of river bed clogging.

5.2 Vegetation Sub-Model

The vegetation sub-model has the goal of predicting long-term averages of various floodplain vegetation types. It is constructed as a response surface representation of the results of a mechanistic, distribution-based floodplain vegetation model. This model is based on a previously developed stochastic forest succession model (Lischke et al., 1998; Botkin, 1993; Bugmann, 2001) which has been adapted to floodplain forest dynamics (Glenz, not yet published). As an additional element of the model, Central European tree and shrub species had to be classified according to their response to flooding stress (Glenz et al. 2005a,b). Figure 4b shows the structure of response surface probability network model approximating the behaviour of this model. The main determinants of floodplain vegetation characteristics, represented in the model by the areas of gravel bars, pioneer vegetation, softwood vegetation and hardwood vegetation, are the occurrence of bed building floods and floodplain flooding, floodplain geometry, climatic conditions, and soil moisture. Soil moisture is determined by climatic conditions, groundwater level, and soil properties. As probability networks do not allow an explicit representation of feedback loops, the feedback loops of humus build-up by organic matter from the forest and forest self-shading are implicitly included in the dependence of vegetation structure on external influence factors. The end nodes for vegetation structure are used to derive the additional end nodes of organic matter input into the river, and river shading, which are used as inputs to other sub-models.

5.3 Benthic Population Sub-Model

The benthic population sub-model has the goal of predicting seasonally averaged density of algae, macrophytes, and functional feeding groups of invertebrates (grazers, collector-gatherers, collector-filterers, predators and shredders). These functional groups build a food web with primary producers, primary consumers, secondary consumers, and consumers growing on organic material from external sources. This food web obviously implies a cause-effect structure for short-term development of the functional groups. This structure is the basis for mechanistic benthic population models which follow the temporal evolution of the functional groups in detail (McIntire, 1973; Rutherford, 1999). However, when focusing on seasonal averages, this cause-effect structure is lost by omitting the shorter time scales in the model. For this reason, at our time scale, the external driving forces directly determine most of the functional groups (at this time scale, more nutrients lead to more consumers even if primary producer densities are kept small by those consumers). This leads to a somewhat awkward network with a large number of links to the functional groups (Fig. 4c). The major environmental factors influencing the benthic population are available irradiation, nutrient concentration, water temperature, velocity and water depth distribution, organic matter input and floods with gravel movement. The structure of the community is also affected by suspended sediments and gravel size. The predictions of benthic populations are used to derive benthic turnover rates which are important indicators of ecosystem function.

5.4 Shoreline Community Sub-Model

The shoreline community model has the goal of predicting the density of spiders, rove beetles and ground beetles as important indicators of the shoreline fauna (under natural conditions densities can be up to 200 spiders, 370 ground beetles and 900 rove beetles per m^2; Schatz et al., 2003; Paetzold et al., 2005; Sadler et al., 2004). Figure 4d shows a simple representation of the major causal relationships determining the shoreline community. The main direct influence factors are high flow refugia, area of gravel bars, short-term discharge variations (e.g. due to hydropeaking), river bed clogging, and food availability. Loss of habitat due to straightening the river bed and short-term discharge variations are major factors that can lead to a drastic reduction in the density of shoreline populations (Boscaini et al., 2000; Sadler et al., 2004; Paetzold and

Tockner, unpublished data). This is considered in the model through the presence of high flow refugia estimated from the morphological type of the river (predicted by the hydraulics sub-model) and by the influence of short-term discharge variations derived directly from the discharge regime. A decline in shoreline diversity is believed to affect the energy transfer across aquatic and terrestrial boundaries, thereby reducing the functional integrity of entire river corridors. To consider this effect, the ratio of bank to river length is used in the model as an indicator for shoreline diversity (Tockner and Stanford, 2002).

5.5 Fish Sub-Model

Figure 4e shows a probability network representing the influence of river rehabilitation measures on brown trout populations. At the heart of the network is a dynamic representation of the fish life cycle with five major life stages. The number of individuals in each life stage is influenced by the number in the previous life stage, as well as relevant population parameters, such as survival and reproductive rates (Lee and Riemann, 1997). These parameters are influenced, in turn, by intermediate variables, such as growth rate, or by external controls, including habitat and water quality, stocking practices, angling, and prey abundance.

The exact choice of environmental variables included in the model, and the nature of their influence on the population, will depend on the fish species of interest. In rivers that are candidates for rehabilitation in Switzerland, for example, salmonids, such as brown trout, and rheophilic cyprinids, such as nase, are of primary interest. The probability network developed for brown trout emphasizes the influence of gravel bed conditions, water quality, temperature, habitat conditions, and flood frequency (Figure 4e). Quantification of these influences was based on experimental and field results, literature reports, and the elicited judgment of scientists (Borsuk et al., 2005). For cyprinids, which are found in larger rivers, different components of habitat, such as the presence of migration barriers, are more important.

Probability networks are required to be acyclic. However, dynamic population models require a cycle linking adults back to eggs. This can be handled by creating a dynamic network, so that the values of life stage variables at one time step depend on the values of other, down-arrow variables at a previous time step. In this way, cycles are avoided (Haas et al., 1994).

5.6 Economics Sub-Model

The economics sub-model quantifies the effects of the rehabilitation work on the local economy using changes in the number of jobs as an endpoint. It was built as an input-output model (Miller and Blair, 1985) that was integrated into the probability network model formalism (Figure 4f). This type of model uses an input-output table of the goods and service flows (expressed in monetary value) between different sectors of the economy to derive technical coefficients by dividing these transactions by the corresponding sectoral output. It is then used to calculate the change in output and jobs per industry for the demand change in the construction and other involved industries during implementation of the rehabilitation measures, assuming the technical coefficients do not change. The underlying local input-output table can be constructed by adapting the national input-output table based on local employment statistics (location quotient method; Isard et al., 1998). A possible reduction in agricultural land area due to the rehabilitation project is accounted for by modifying the standard input-output model. It is assumed that the agricultural sector is constrained by the land available and that the residual of the local demand for agricultural goods is compensated by imports.

The same model can also be used to estimate the (small) longer-term effects on the local economy of increases in tourism resulting from rehabilitation. This effect depends on the size of the rehabilitated river reach; if a critical length is not reached (e.g. 5 km) then the attraction outside the region is likely to be very small and the additional demand in the local economy is also likely to be very small. If a longer stretch is rehabilitated (e.g. 60 km in the case of the Danube floodplains; see http://www.donauauen.at) then one might expect additional tourists to stay overnight in hotels and add to demand in the local economy.

5.7 Integrated Model

Once all the relations in all the sub-models of the integrated probability network have been quantified, probabilistic predictions of model endpoints can be generated based on probability distributions of input variables. The predicted endpoint probabilities, and the relative change in probabilities between alternative scenarios (represented by probability distributions of input variables), convey the magnitude of system response to proposed management measures, accounting for predictive uncertainties. These results can be used for further evaluation of different decision alternatives. For detailed planning of river construction, such as would be required to implement the chosen alternative, more detailed investigations will be necessary.

6. Step 5: Quantification of Preferences of Stakeholders for Outcomes

After having estimated the attribute ranges characterizing the outcomes of all decision alternatives, the preferences of decision makers or stakeholders for possible outcomes are elicited in step 5 of the decision support procedure.

There exist several approaches for the quantitative representation of preferences of decision makers or stakeholders (Belton and Stewart, 2002). The most frequently applied approaches are value or utility functions (von Winterfeldt and Edwards, 1986; Eisenführ und Weber, 2003), the analytic hierarchy process (Saaty, 1980; Schmoldt et al., 2001), and outranking (Vincke, 1999; Brans et al., 1986). We prefer the value and utility function approaches of decision analysis because (i) they have sound underlying theoretical concepts which prove the existence of these functions based on a minimum of "rationality" assumptions, (ii) preferences are elicited for outcomes and not for alternatives what is conceptually more satisfying and makes it easier to consider additional alternatives at a later stage of the analysis process, (iii) preferences rankings of alternatives derived from predictions and valuations of outcomes are independent of the considered alternatives, implying that the preferred alternative does not depend on the consideration of irrelevant alternatives, and (iv) the utility function approach naturally considers uncertainty in outcome prediction and risk attitudes of the decision makers or stakeholders. The independence of the valuation step on alternatives is important because it allows the analyst to apply the elicitation results to alternatives developed during the subsequent analysis process without having to redo preference elicitation (if the new alternative does not lead to predictions that are significantly outside the outcome attribute ranges considered in the valuation). Note that most of the other decision support techniques violate at least one of the four criteria mentioned above.

A value function is used to characterize an individual's preferences for outcomes by assigning a higher value to a more preferred outcome. Value functions are usually normalized to provide outputs between zero and unity for the least and most preferred combination of attributes, respectively. Such value functions have been proven to exist under very general assumptions of consistency and completeness of preferences (von Winterfeldt and Edwards, 1986; Eisenführ und Weber, 2003). As the value function is a mathematical construct that does not have its counterpart in the mind of the individual, elicitation should be done by asking the individual for preference orders or indifference between attribute combinations characterizing different possible outcomes and not by asking the person to specify values for outcomes directly. The value function is then constructed as a mathematical representation of these preferences. To facilitate the elicitation process, it is often assumed that the multi-attribute value function has the form of a weighted sum of single-attribute value functions. It should be realized, however, that the use of such additive value functions strongly limits the types of preference structures that can be represented.

The use of additive value functions may be a less severe restriction at higher levels of aggregation of the objectives hierarchy as they can represent trade-offs that have to be made between ecological and social goals. However, within the branch of ecosystem integrity there are certainly branches that cannot be represented by an additive function. Examples include abundances of species within different functional groups that can only be substituted by other species to a limited degree. In this case, achieving a reasonable ratio of species within different groups may be more important than maximizing the abundance of species within a particular functional group. Such preferences have to be represented by non-additive value functions or by using ecosystem diversity indices.

Value functions do not include information about risk attitudes of individuals or groups. Such risk attitudes can be considered by using utility functions instead of value functions (von Winterfeldt and Edwards, 1986; Eisenführ und Weber, 2003). Elicitation of utility functions, however, is much more difficult then elicitation of value functions because individuals have to be asked to express their preferences between probabilistic outcomes (typically lotteries of two different outcomes). Furthermore, utility functions alone do not allow the analyst to distinguish between non-constant marginal value and risk attitudes (Dyer and Sarin, 1982; Eisenführ and Weber, 2003). For this reason, it may be desirable to elicit value functions first and then consider risk attitudes by asking a second set of questions based on a small subset of attributes. This procedure would be much easier but is based on the assumption that risk attitudes are independent of the attribute for which they are elicited (Dyer and Sarin, 1982).

When eliciting values or utilities of stakeholders for the attributes corresponding to the lowest level objectives in the objective hierarchy for river rehabilitation, two main problems may arise. First, the stakeholders may not be able to specify their preferences at such a detailed level of ecosystem description because they do not have sufficient knowledge of the importance of the different sub-objectives to overall ecosystem structure and function. Second, the elicitation process takes much time because of the large number of attributes. There are two options to overcome this problem. First, the objective hierarchy could be simplified by using objectives and corresponding attributes at a higher level of the objective hierarchy. The problem with this approach is that it is more difficult to find good attributes at higher hierarchical levels. Hostmann et al. (2005a) used visualization of a semi-quantitative scale of ecological integrity to overcome this problem. An alternative would be to elicit value functions for detailed attributes related to ecosystem integrity from scientists and then let the stakeholders only assess the weights of these objectives relative to others based on a description of the range of possible outcomes. This procedure would facilitate the use of an additive value function at the higher aggregation level of the objectives hierarchy with weights provided by the stakeholders while still being able to switch to other forms of value functions within the ecosystem integrity branch.

7. Step 6: Ranking of Alternatives

After having carefully predicted the outcomes of all alternatives and their associated uncertainties based on the scientific analysis in step 4 and having quantified the preferences of stakeholders and decision makers for the outcomes in step 5, these two aspects of the decision problem are merged to result in rankings of alternatives. Depending on the consideration of risk attitudes in the elicitation of preferences, we must distinguish two cases. When utility functions are elicited, a unique ranking can be derived for each decision maker or stakeholder group based on decreasing values of expected utilities calculated using the probability distributions of outcomes. As value functions do not contain information on risk attitudes, only probability distributions of rankings of the alternatives can be derived using probability distributions of outcomes and value functions. These probability distributions must be discussed with the stakeholders or decision makers to find the preferred alternative that also considers the risk attitude. Note that high prediction uncertainty of attributes does not necessarily lead to wide distributions of rankings of alternatives, as probability distributions of differences in predicted attributes may be much narrower than the distributions of the attributes themselves (Reichert and Borsuk, 2005).

Figure 5 summarizes the results of rankings based on preliminary outcome predictions for five river rehabilitation decision alternatives and elicited values from eight stakeholder groups for a case study in Switzerland (Hostmann et al., 2005a). This figure illustrates that some alternatives are inferior to others for all stakeholder groups but that there is also a set of alternatives within which the preference is controversial between stakeholder groups (more discussion of this figure will be given in the next section).

8. Step 7: Assessment of Results

The preference rankings in step 6 summarizing the results of steps 1 to 5 are useful results for the decision maker. However, even more useful are the insights gained by the application of the procedure and subsequent analysis of the results. This is the task of step 7 of our decision support procedure. Of special importance are the analysis of the conflict potential of the alternatives, the use of the results for the derivation of compromise alternatives with a lower conflict potential, and various types of sensitivity analyses that can be performed to assess the robustness of the results.

An alternative has a high conflict potential if it is highly ranked for some stakeholders and poorly ranked for others. The transparency of the outlined procedure allows the analyst to identify the causes of poor ranking of such an alternative for some stakeholder groups and to suggest improvements based on alternatives that lead to a higher rank for these stakeholder groups. This can lead to the development of alternatives that have high rankings for most stakeholder groups and avoid very poor rankings by others. Figure 5 illustrates the development of such a compromise or negotiation alternative based on an analysis of the rankings of four river rehabilitation alternatives considered in the analysis process (Hostmann et al., 2005a). Out of the top four alternatives, the administration alternative is clearly superior to all the other three for most of the stakeholder groups. An analysis of the causes for the poor performance of this alternative for the forest rangers and farmers led to the development of the fifth negotiation alternative that performs well, though perhaps not optimally, for all stakeholder groups (see Hostmann, 2005a for more details).

The rankings derived in step 6 of the decision support procedure should be tested for their robustness by sensitivity analysis. It is useful to do sensitivity analysis with respect to the uncertainty in model predictions (input uncertainty, parameter uncertainty, model structure uncertainty) and with respect to the uncertainty in the quantification of preferences.

The final results can then be used to stimulate and guide stakeholder discussions, to develop compromise alternatives together with stakeholders, and to make the basis for decisions transparent (Hostmann et al., 2005a,b).

9. Conclusions

River rehabilitation decisions can be controversial due to uncertain outcomes and conflicting interests of stakeholders. This article demonstrates how decision analysis techniques can provide support by structuring the decision and stakeholder involvement processes and by making scientific assumptions, their consequences, and social preferences explicit.

The application of decision analysis techniques leads to rankings of the alternatives or probability distributions of these rankings for all decision makers or stakeholders who provided their values. While these rankings are an important result of the application of decision analysis techniques, we are convinced that there are many more benefits resulting from the application of the proposed procedure. For example:

- Extensive discussion and valuation of objectives and careful consideration of cause-effect relationships in the predictive model lead to improved insights into social and scientific aspects of the decision problem and to confidence that all relevant aspects of the decision have been taken into account.
- Documentation of the prediction of effects, elicitation of values and resulting rankings increases the transparency of the decision making process.
- Analysis of the conflict potential of alternatives can stimulate the development of compromise alternatives with a lower conflict potential.
- Analysis of the sensitivity of rankings to important sources of uncertainty, such as input, parameter and model structure uncertainty of predictions and uncertainty in value elicitation demonstrates the robustness with which decisions can be made.

Results from previous studies support the statements above on the usefulness of such procedures for gaining insight and providing better informed recommendations (McDaniels et al., 1999). Despite these advantages, controversial results have been reported about the acceptance of decision support techniques by involved stakeholders. There are cases in which application of these techniques has been found to be poorly accepted (Hobbs et al., 1992). However, in other studies, the involved stakeholders stated a fairly good acceptance (Hobbs and Horn, 1997; McDaniels et al., 1999; Hostmann et al., 2005b). We interpret these contradicting results as an indication of the importance of the implementation aspects of the procedure. This may be an area that requires further research.

Acknowledgements

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Water and Geology (BWG), the Swiss Federal Institute for Environmental Science and Technology (EAWAG) and the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) (Peter et al., 2005). In addition, many project partners contributed through stimulating discussions, comments, and suggestions to this paper. Contributions of specific importance were made by Armin Peter, Sharon Woolsey, Hans-Joachim Mosler, Jon Sadler and Achim Paetzold.

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Figure Captions

Figure 1: Objectives hierarchy of a river rehabilitation project. Colours are used to facilitate the identification of corresponding fields of assessment in Figure 3.

Figure 2: Important relationships between consequences of river rehabilitation measures.

Figure 3: Overview of the integrative model for the prediction of outcomes of decision alternatives for river rehabilitation. The rectangular nodes represent fields of assessment corresponding to objectives listed in Figure 1 (note that the colours are chosen to support a quick identification of the corresponding objectives), the round nodes represent additional required inputs used to characterize the decision alternatives. Nodes in the left column represent model inputs (some of them influenced by the decision alternative), nodes in the central column intermediate nodes, and nodes in the right column model outputs.

Figure 4: Simplified graphical representation of the major causal relationships considered in the sub-models of the integrative model. Green nodes refer to model inputs, yellow nodes to intermediate nodes, and red nodes to model outputs used as inputs to another sub-model (these nodes are also red in the sub-models to which they are input) or for valuation (represented by a rhombic shape). Sub-models: a) hydraulics sub-model, b) vegetation sub-model, c) benthic population sub-model, d) shoreline community sub-model, e) fish sub-model, f) economics sub-model.

Figure 5: Example of rankings of five river rehabilitation decision alternatives for different stakeholder groups according to Hostmann et al. (2005a). Note that the fifth alternative (negotiation option) was derived during the analysis process based on the results for the other four alternatives.

Figure 1:

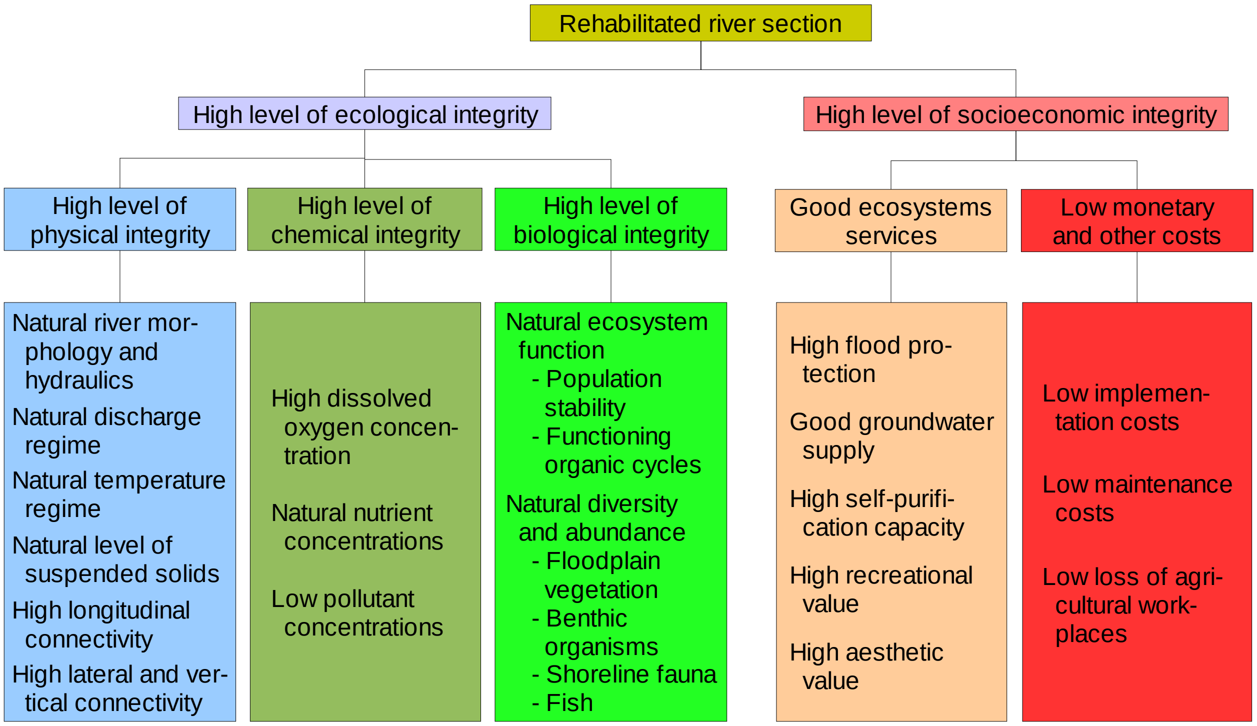
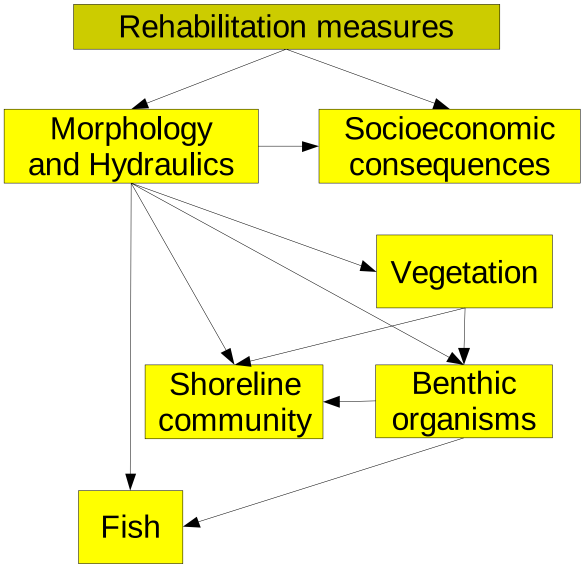
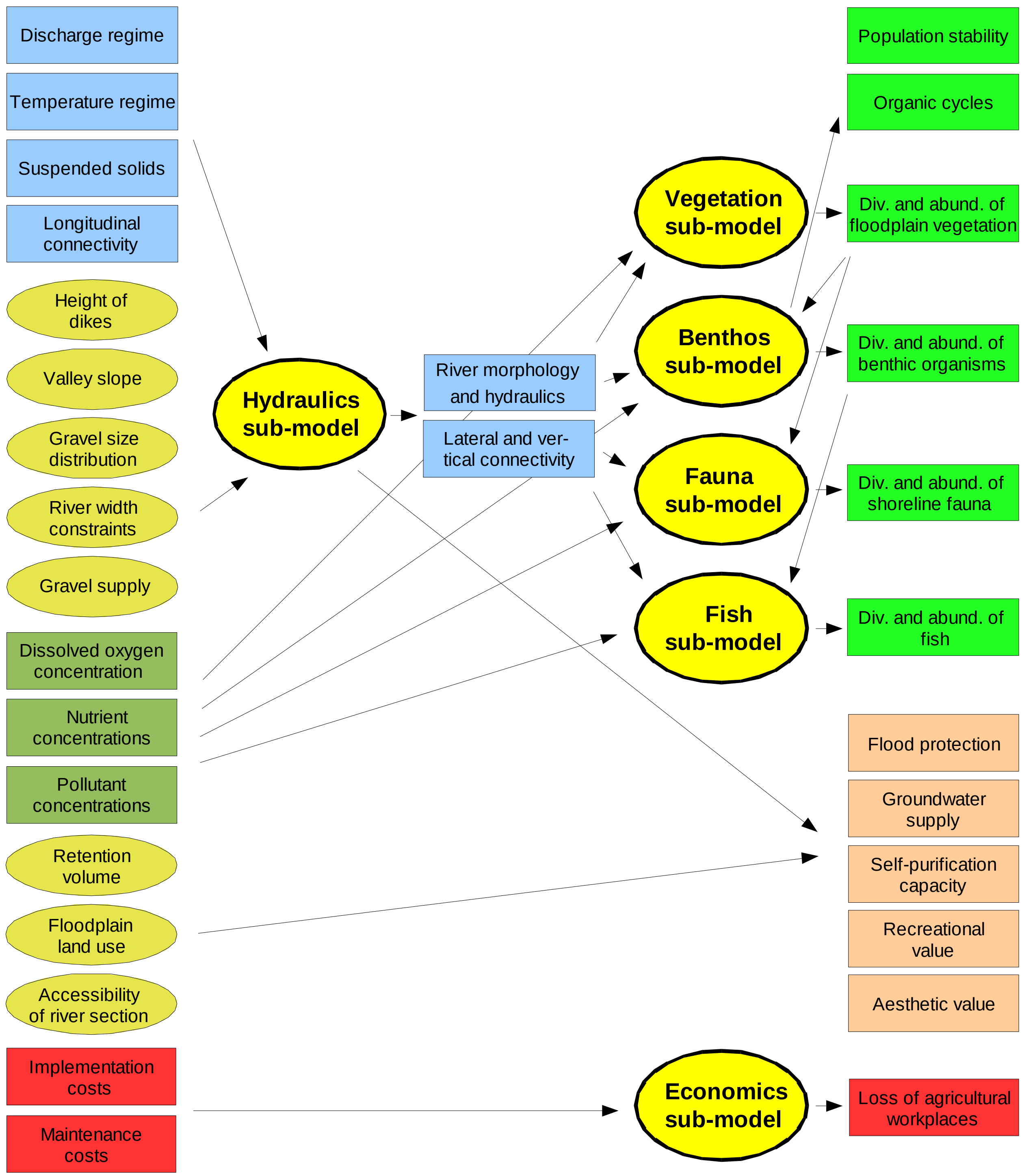

Rehabilitated river section
High level of ecological integrity
High level of socioeconomic integrity
High level of physical integrity
High level of chemical integrity
High level of biological integrity
Good ecosystems services
Low monetary and other costs
Natural river morphology and hydraulics
Natural discharge regime
Natural temperature regime
Natural level of suspended solids
High longitudinal connectivity
High lateral and vertical connectivity
High dissolved oxygen concentration
Natural nutrient concentrations
Low pollutant concentrations
Natural ecosystem function
- Population stability
- Functioning organic cycles
Natural diversity and abundance
- Floodplain vegetation
- Benthic organisms
- Shoreline fauna
- Fish
High flood protection
Good groundwater supply
High self-purification capacity
High recreational value
High aesthetic value
Low implementation costs
Low maintenance costs
Low loss of agricultural workplaces

Figure 2:



Rehabilitation measures
Morphology and Hydraulics
Socioeconomic consequences
Vegetation
Shoreline community
Benthic organisms
Fish

Figure 3:



Discharge regime
Temperature regime
Suspended solids
Longitudinal connectivity
Height of dikes
Valley slope
Gravel size distribution
River width constraints
Gravel supply
Dissolved oxygen concentration
Nutrient concentrations
Pollutant concentrations
Retention volume
Floodplain land use
Accessibility of river section
Implementation costs
Maintenance costs
Hydraulics sub-model
River morphology and hydraulics
Lateral and vertical connectivity
Vegetation sub-model
Benthos sub-model
Fauna sub-model
Fish sub-model
Economics sub-model
Population stability
Organic cycles
Div. and abund. of floodplain vegetation
Div. and abund. of benthic organisms
Div. and abund. of shoreline fauna
Div. and abund. of fish
Flood protection
Groundwater supply
Self-purification capacity
Recreational value
Aesthetic value
Loss of agricultural workplaces

Figure 4a:

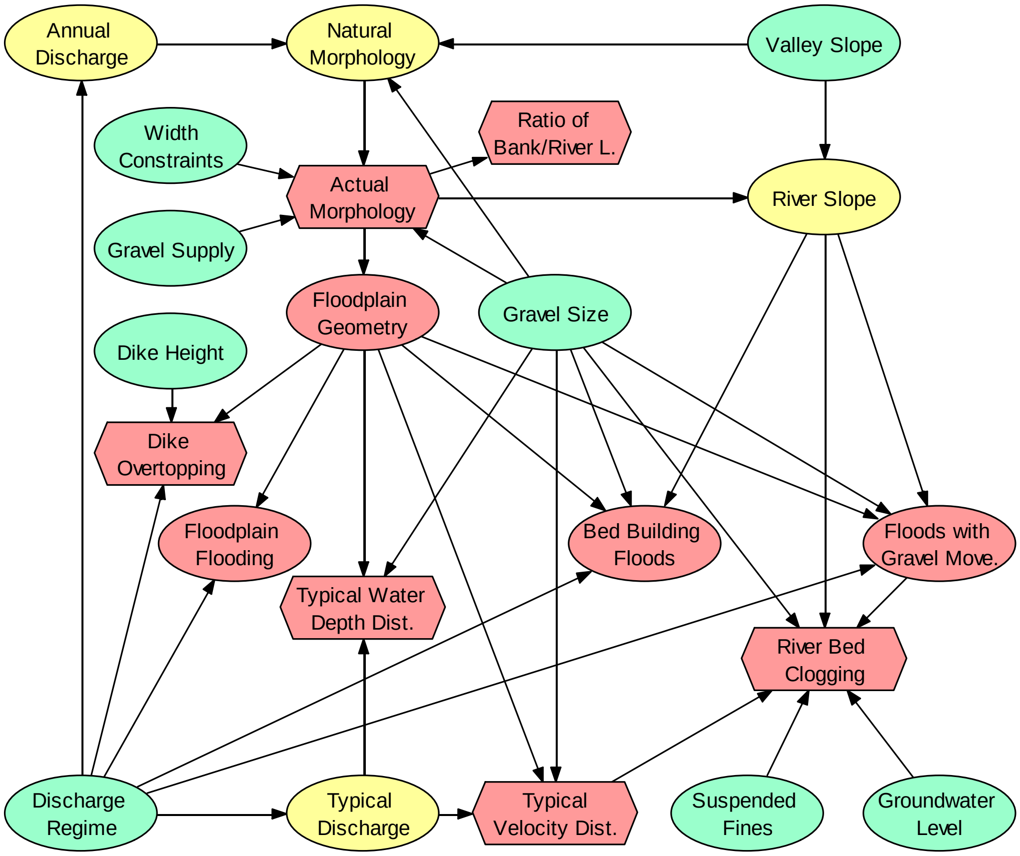

Annual Discharge
Natural Morphology
Valley Slope
Width Constraints
Ratio of Bank/River L.
Actual Morphology
River Slope
Gravel Supply
Floodplain Geometry
Gravel Size
Dike Height
Dike Overtopping
Floodplain Flooding
Bed Building Floods
Floods with Gravel Move.
Typical Water Depth Dist.
River Bed Clogging
Discharge Regime
Typical Discharge
Typical Velocity Dist.
Suspended Fines
Groundwater Level

Figure 4b:

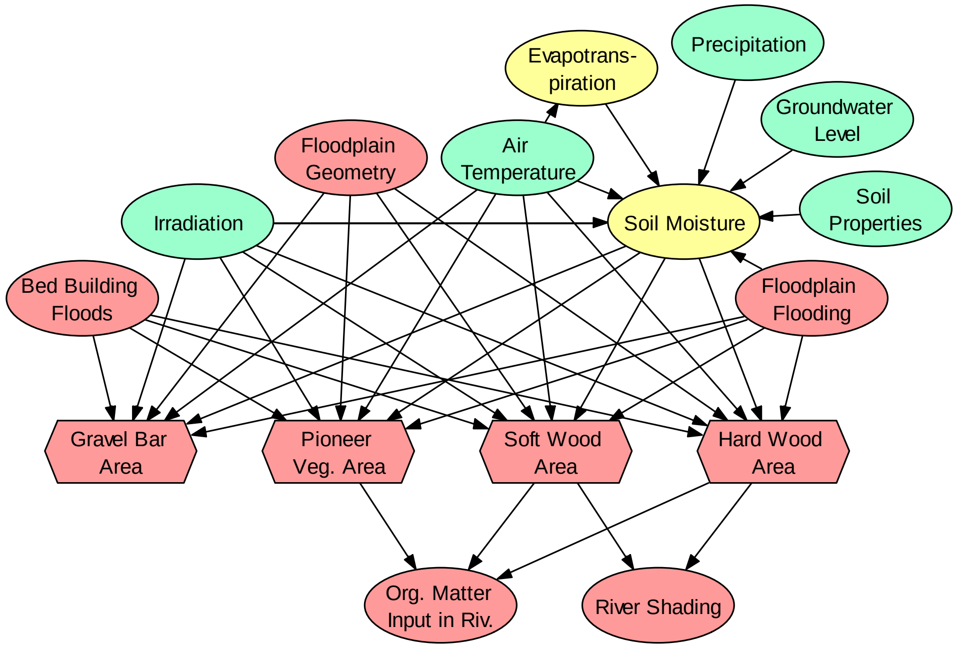
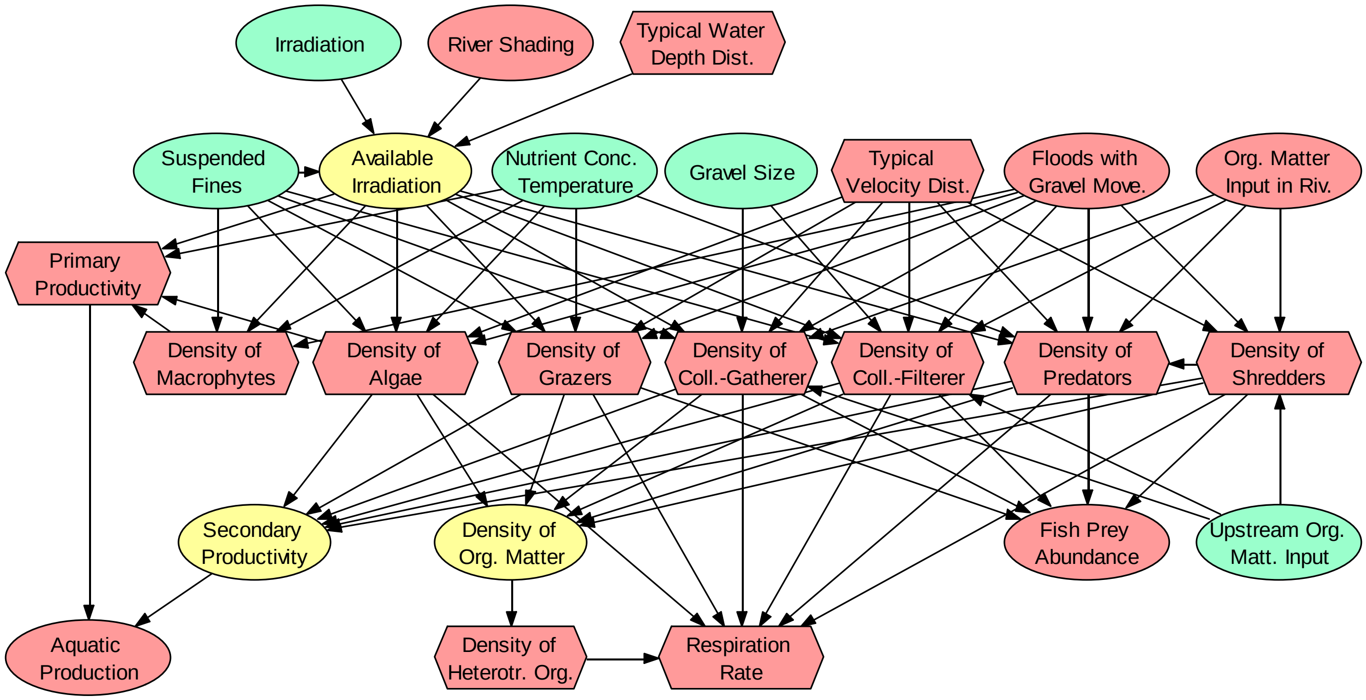

Evapotrans-
piration
Precipitation
Groundwater
Level
Floodplain
Geometry
Air
Temperature
Irradiation
Soil Moisture
Soil
Properties
Bed Building
Floods
Floodplain
Flooding
Gravel Bar
Area
Pioneer
Veg. Area
Soft Wood
Area
Hard Wood
Area
Org. Matter
Input in Riv.
River Shading

Figure 4c:



Irradiation
River Shading
Typical Water Depth Dist.
Suspended Fines
Available Irradiation
Nutrient Conc. Temperature
Gravel Size
Typical Velocity Dist.
Floods with Gravel Move.
Org. Matter Input in Riv.
Primary Productivity
Density of Macrophytes
Density of Algae
Density of Grazers
Density of Coll.-Gatherer
Density of Coll.-Filterer
Density of Predators
Density of Shredders
Secondary Productivity
Density of Org. Matter
Fish Prey Abundance
Upstream Org. Matt. Input
Aquatic Production
Density of Heterotr. Org.
Respiration Rate

Figure 4d:

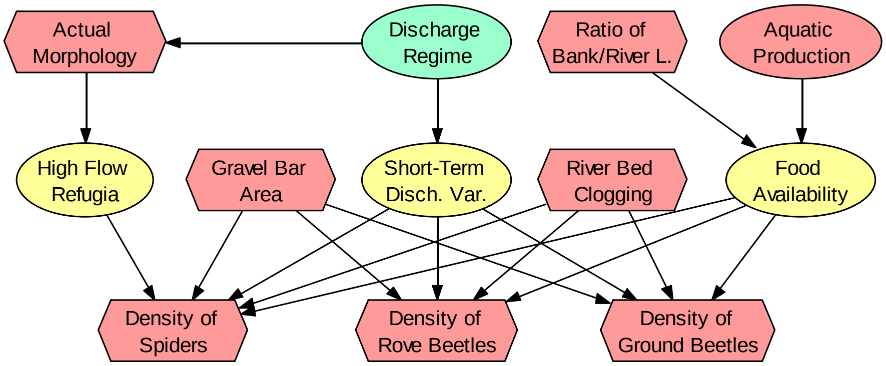
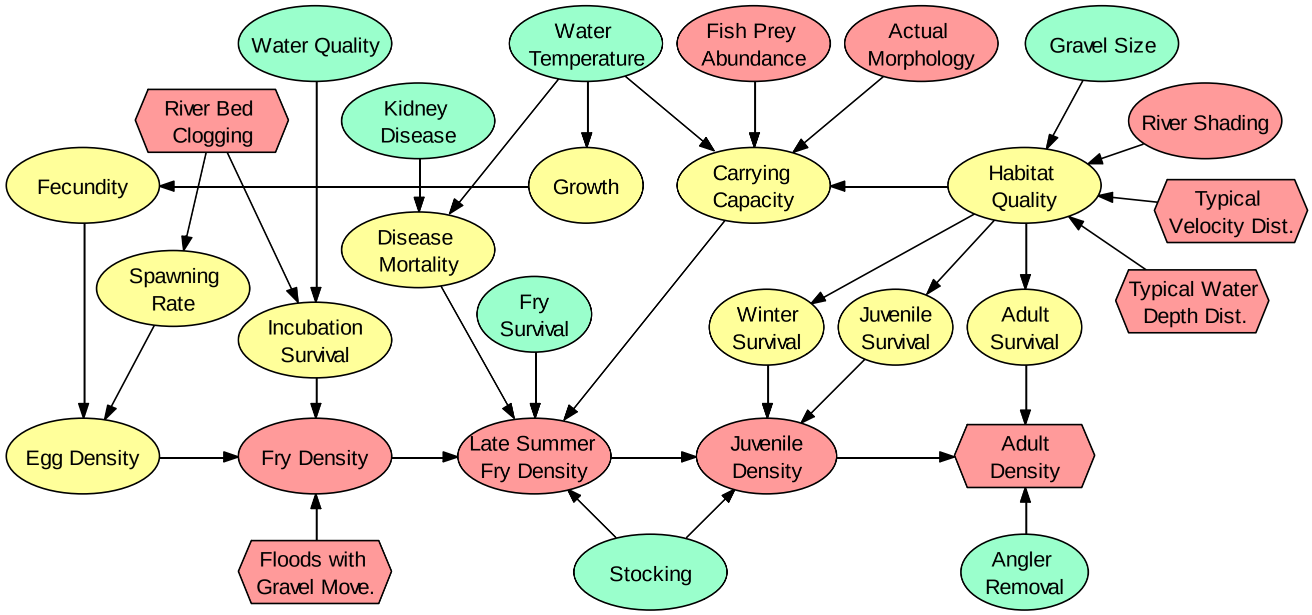

Actual Morphology
Discharge Regime
Ratio of Bank/River L.
Aquatic Production
High Flow Refugia
Gravel Bar Area
Short-Term Disch. Var.
River Bed Clogging
Food Availability
Density of Spiders
Density of Rove Beetles
Density of Ground Beetles

Figure 4e:



Water Quality
Water Temperature
Fish Prey Abundance
Actual Morphology
Gravel Size
River Bed Clogging
Kidney Disease
River Shading
Fecundity
Growth
Carrying Capacity
Habitat Quality
Typical Velocity Dist.
Disease Mortality
Spawning Rate
Incubation Survival
Fry Survival
Winter Survival
Juvenile Survival
Adult Survival
Typical Water Depth Dist.
Egg Density
Fry Density
Late Summer Fry Density
Juvenile Density
Adult Density
Floods with Gravel Move.
Stocking
Angler Removal

Figure 4f:

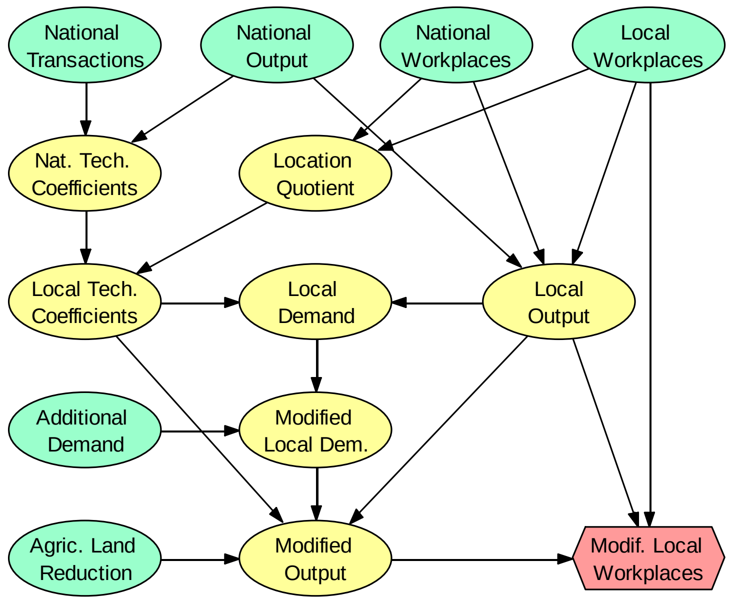

National Transactions
National Output
National Workplaces
Local Workplaces
Nat. Tech. Coefficients
Location Quotient
Local Tech. Coefficients
Local Demand
Local Output
Additional Demand
Modified Local Dem.
Agric. Land Reduction
Modified Output
Modif. Local Workplaces

Figure 5:

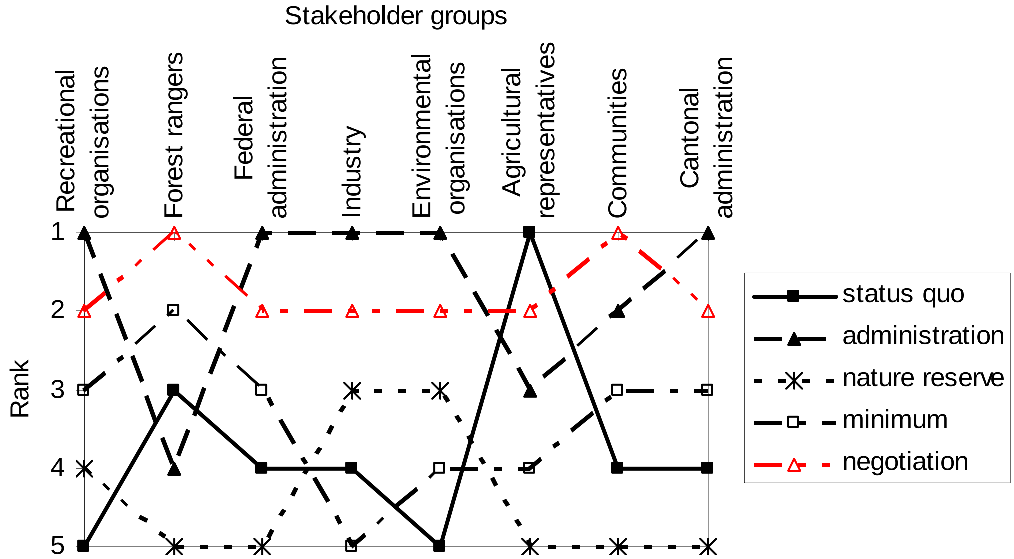

Stakeholder groups
Recreational organisations
Forest rangers
Federal administration
Industry
Environmental organisations
Agricultural representatives
Communities
Cantonal administration
Rank
1
2
3
4
5
status quo
administration
nature reserve
minimum
negotiation

Table Captions:

Table 1: Organized stakeholder groups for a river rehabilitation project in Switzerland, as identified by Hostmann et al. (2004a). The groups are listed in the order of increasing ability to influence the selection of the rehabilitation alternative.

Table 2: Attributes to characterize the degree of fulfilment of the most detailed objectives shown in Figure 1.

Table 1

Recreational organizations
Forest rangers
Federal administration
Industry
Environmental organizations
Agricultural representatives
Communities
Regional or state administrations

Table 2

Objective	Attributes
High Level of Physical Integrity	
Natural river morphology and hydraulics	Morphological type
	Coefficient of variation of water depth
	Coefficient of variation of flow velocity
Natural discharge regime	Seasonally averaged discharge
	Discharge of annual flood
	Number of delaminating floods per season
	5^{th} percentile of discharge distribution
	Amplitude of artificial flow variation
	Rate of increase/decrease of artificial flow variation
Natural temperature regime	Seasonally averaged temperature
	Amplitude of artificial temperature variation
Natural level of suspended solids	Mean suspended solid concentration at low discharge
High longitudinal connectivity	Length of connected reach
High lateral and vertical connectivity	Fraction of natural river banks
	Ratio of bank to river length
	Fraction of fine sediments
High Level of Chemical Integrity	
High dissolved oxygen concentration	Seasonally averaged dissolved oxygen concentration
	Minimum dissolved oxygen concentration
	Amplitude of daily variation in dissolved oxygen
Natural nutrient concentrations	Mean phosphate concentration
	Mean inorganic nitrogen concentration
Low pollutant concentrations	Mean metal concentrations
	Mean organic pollutant concentrations
High Level of Biological Integrity	
Natural ecosystem function	
Population stability	Density of refugia
	Number of natural tributarities per river length
Functioning organic cycles	Mean primary productivity
	Mean whole ecosystem respiration rate
	Mean leaf decomposition rate
Natural diversity and abundance	
Floodplain vegetation	Area of hard wood vegetation per river length
	Area of soft wood vegetation per river length
	Area of pioneer vegetation per river length
	Area of gravel bars per river length
Benthic organisms	Seasonally averaged density of macrophytes
	Seasonally averaged density of algae
	Seasonally averaged density of grazers
	Seasonally averaged density of collectors-gatherers
	Seasonally averaged density of collectors-filterers
	Seasonally averaged density of shredders
	Seasonally averaged density of predators
	Seasonally averaged density of heterotrophic microorganisms
Shoreline fauna	Mean density of shore beetles
	Mean density of spiders
	Mean density of ants
Fish	Total fish abundance
	Abundance of salmonids (or another relevant indicator)
	Abundance of cyprinids (or another relevant indicator)
Good Ecosystem Services	
High flood protection	Expected frequency of dike overtopping
	Average expected damage cost per year
Good groundwater supply	Groundwater recharge rate
	Groundwater infiltration/transport time to well
High self-purification capacity	Reaeration coefficient
High recreational value	Area of accessible gravel bars per unit river length
High aesthetic value	Rating by the public
Low Monetary and Other Costs	
Low implementation costs	Implementation costs per river length
Low maintenance costs	Maintenance costs per river length per year
Low loss of agricultural workplaces	Number of agricultural workplaces lost per river length