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Abstract: We have previously reported on a variety of modelling methods and decision support concepts that can assist with various aspects of river rehabilitation planning and management. Here, we bring all of these tools together into an Integrative River Rehabilitation Model (IRRM) that links management actions, through morphological and hydraulic changes, to the final ecological and economic consequences. The IRRM is formulated as a probability network and represents the relevant cause-effect relations among important biotic and abiotic factors, leading to attributes (model endpoints) of concern to river system stakeholders. Together with a model of the stakeholders' preference structure for different levels of these attributes, the IRRM is intended to provide a comprehensive basis for supporting river rehabilitation decisions. While many opportunities for further model improvement and uncertainty reduction exist, we believe that the present version of the model provides a flexible framework that can be adapted and refined according to local project-specific needs and data availability. We exemplify model application to three large planned or recently completed rehabilitation projects in Switzerland.

Keywords: Bayesian Network; Uncertainty; Decision Analysis; Stakeholders; Integrated Assessment; Restoration; Morphology and Hydraulics; Benthos; Fish; Economics

1. INTRODUCTION

In recent years, rehabilitation of channelized river systems has become increasingly common, with some countries spending billions of dollars to improve flood protection for adjacent land uses while enhancing ecological condition. Often, rehabilitation involves the creation of localized 'river widenings' in which levees are moved back to allow a more natural channel movement within a limited area [Rohde *et al.*, 2005]. Within the widened reach, the river might shift and adjust, possibly re-establishing the range of riparian habitats that were found prior to channelization.

As rehabilitation becomes more common, integrative modelling tools are essential to help stakeholders understand the morphological, economic, and ecological consequences of the rehabilitation activities. Such predictions can provide the basis for planning and management efforts that attempt to balance diverse interests [Reichert *et al.*, 2007]. In previous publications, we have described a variety of submodels and decision support concepts applicable to river rehabilitation planning and management. Here, we bring all of these tools together in the form of a probability network [Pearl, 1988]. The resulting Integrative River Rehabilitation Model (IRRM) links management actions, through morphological and hydraulic changes, to the final ecological and economic consequences. Together with a preliminary model of the stakeholders' preference structure for different levels of these attributes [Hostmann et al, 2005], the IRRM is intended to provide a comprehensive basis for supporting river rehabilitation decisions.

2. PROBABILITY NETWORKS

Probability (or belief) networks have been used in a variety of settings to compile knowledge from multiple sources to generate probabilistic predictions. A key element in their use is a graphical representation of the causal relationships described by the model. The interesting feature that is made explicit by the graph is the conditional independence implied by the absence of connecting arrows between some nodes. These independences allow the complex network of interactions from primary cause to final effect to be broken down into sets of relations which can each be characterized independently [Pearl, 1988]. This aspect of belief networks significantly facilitates their use for representing multi-disciplinary models such as the IRRM.

Characterization of the relationships in a probability network consists of constructing conditional distributions that reflect the aggregate response of each variable to changes in its immediate "up-arrow" predecessor, together with the uncertainty in that response. It is often convenient to write these conditional relationships in a functional form that includes uncertainty in the model's parameters and an error term capturing unexplained variability. This method of expressing conditional probabilities is consistent with the perspective of most process-based modeling and facilitates computer simulation. Once all relationships in a network are characterized, probabilistic predictions of model endpoints can be generated conditional on values (or distributions) of any "up-arrow" causal variables. These predicted endpoint probabilities, and the relative change in probabilities between decision alternatives, convey the magnitude of expected system response to management while accounting for predictive uncertainties.

3. MODEL DESCRIPTION

3.1 Model Endpoints

A model designed to support rehabilitation management decisions should have endpoints that address the key concerns of system stakeholders. Therefore, our model development started with the identification of river stakeholders and their rehabilitation objectives. Key stakeholder groups include recreational organizations, forest managers, industry representatives, environmental organizations, farmers, local communities, and federal or regional administrations [Hostmann et al, 2005]. A stakeholder elicitation exercise in Switzerland found that the objectives held by these groups could be organized into broad classes related to physical river integrity, chemical water quality, biological integrity, and economic value, including minimization of project cost and maximization of ecosystem services [Hostmann et al, 2005; Reichert *et al.*, 2007]. Some objectives, such as those related to water quality, are usually not strongly impacted by local rehabilitation actions and were therefore not considered further in our project. The remaining objectives were assigned attributes, which are measurable variables that can be used to assess attainment of objectives (Table 1). These attributes, which were understood to represent long-term steady state conditions over a reach scale, were used as endpoints of the predictive model.

Table 1: Key stakeholder objectives and corresponding attributes used as model endpoints.

Category	Objective	Attributes
Physical River Objectives	Natural river morphology	Morphological type (braided, alternating, or straight)
	Natural river hydraulics	Joint distribution of velocity and depth Percent area riffles, runs, and pools Gravel movement and siltation
Biological Objectives	Abundant benthic organisms	Summer density of periphyton Summer density of invertebrates
	Abundant shoreline fauna	Summer density of beetles Summer density of spiders
	Abundant fish	Density of salmonids Density of cyprinids
Economic Objectives	High flood protection	Estimated flood frequency
	Low project costs	Implementation costs Maintenance costs
	Positive impact on local employment	Net change in short-term service and construction jobs due to project implementation Net change in long-term agricultural and service jobs due to changes in land and recreational use

3.2 Physical River Objectives

The physical characteristics of a river reach are important stakeholder concerns on their own and are also fundamental factors influencing most biological and economic attributes. To predict how these characteristics would change as a function of local river widening, we developed a synthesis model based to a large degree on the results of work published by other research groups [see Schweitzer *et al.* 2007a for details].

3.2.2. River Morphology

To predict whether a river will tend towards a braided or single-threaded morphology after the release of lateral constraints, we used the logistic regression model of Bledsoe and Watson [2001], in which the probability, p_m, of a multi-thread pattern can be estimated as,

$$p_m = \frac{\exp\left[3.00 + 5.71 \cdot \log_{10}\left(J_V \cdot \sqrt{Q_a}\right) - 2.45 \cdot \log_{10}\left(d_{50}\right)\right]}{1 + \exp\left[3.00 + 5.71 \cdot \log_{10}\left(J_V \cdot \sqrt{Q_a}\right) - 2.45 \cdot \log_{10}\left(d_{50}\right)\right]} \qquad (1)$$

where J_V is valley slope (-), Q_a is mean annual flood discharge (m^3s^{-1}), and d_{50} is median gravel diameter (m). This probabilistic expression could be used directly as a conditional distribution in the probability network model.

To determine the effects of any remaining width constraints on final morphology, we used the pattern diagram of da Silva [1991] which predicts whether a river section will be braided, meandering, alternating or straight, conditional on gravel size, width constraints, and mean depth at bankfull discharge. Finally, gravel transport calculations based on Meyer-Peter and Müller [1948] (for a single-threaded morphology) and Zarn [1997] (for a braided river morphology) were implemented to determine whether there is sufficient deposition in the widened reach to form the gravel structures required for a braided or alternating gravel bar morphology.

Gravel movement and substrate siltation is a crucial ecological attribute because fish and benthic species depend on the interstitial gravel zones for shelter and egg development. We modeled siltation as a process of fine sediment accumulation that occurs over time at a rate which depends on hydraulic and bed characteristics [Schälchli 1995]. This process is disrupted by high floods accompanied by high bottom shear stress. This disturbs the gravel bed matrix and clears it of fines. The threshold shear stress for bed movement can be calculated according to Günther [1971] and converted to a critical discharge using Strickler's formula for single-thread rivers and Zarn's (1997) formula for braided rivers. The frequency of river bed clearance can then be determined from the hydrograph. This frequency together with the rate of fine sediment buildup determines the temporal extent and severity of clogging.

3.2.2. River Hydraulics

To predict the joint distribution of flow velocity and depth in a rehabilitated reach after widening, we developed a statistical model based on point data from 92 stream reaches [see Schweitzer *et al.* 2007b for details]. We found that, for reaches with a braided or gravel bar morphology, the bivariate distribution of relative velocity and relative depth could be described by a mixture of two end-member distributions, one normal and the other lognormal, each with fixed parameters. The contribution of each shape for a particular reach at a particular discharge could then be related to the reach mean Froude number, the reach mean relative roughness, and the ratio of the survey discharge to the mean discharge. For straight morphologies, we found that the joint distribution of relative velocity and relative depth could be described by fixed beta-distributed marginals correlated with a rank correlation coefficient of 0.94.

The proportions of a reach consisting of pools, runs, and riffles can be calculated directly from the predicted bivariate distributions, using quantitative definitions of these hydraulic units in terms of point depth and velocity. Following Jowett [1993], we defined pools as having values of the Froude number less than 0.18 and a velocity/depth ratio less than 1.24 s^{-1}, riffles as having Froude numbers greater than 0.41 and a velocity/depth ratio greater than 3.20 s^{-1}, and runs as having intermediate values.

3.3 Biological Objectives

3.3.1 Benthic Organism Abundance

Periphyton and invertebrates dominate the first levels of the trophic pyramid in many small and intermediate size rivers and therefore can influence the complete ecosystem of running waters. They also influence water colour, clarity and odour by utilizing nutrients and organic material. Finally, anglers also rely on macroinvertebrates as the main source of food for sport fish.

To predict periphyton and invertebrate density in rehabilitated rivers, we used simple models that were mechanistically motivated but have lower data requirements than detailed simulations [see Schweizer *et al.* in review for details]. They describe the density of periphyton and various invertebrate functional feeding groups based on days since the last bed-moving flood, mean water depth, substrate size, mean flow velocity, and day of the year. Model parameters were estimated using a combination of literature results and statistical fit to survey data from a set of Swiss and French rivers (Figure 1). Considering their simplicity, the models show a remarkably good fit to time series measurements. For periphyton, total invertebrates, collector-gatherers, and predators, R^2 values ranged from 0.52 to 0.71. Scrappers were modelled less well (R^2=0.26), and shredders and filterers were too scarce in our data sets to be modelled.

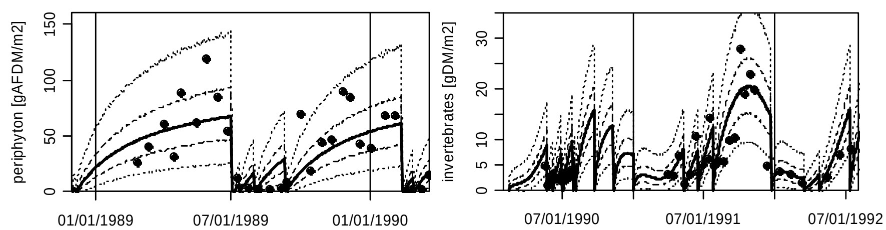

Figure 1. Example fits of benthic model to data on periphyton (left) and total invertebrates (right). Solid lines represent best estimates, dashed lines bound the 50% predictive intervals, and dotted lines bound the 90% predictive intervals. Solid circles represent measured data. Data from the Necker Aachsäge (left) [Uehlinger 1991] and Sihl (right) Rivers [Elber et al. 1996].

3.3.2 Shoreline Fauna Abundance

Riparian arthropod density is an important indicator of shoreline fauna abundance. Arthropods contribute significantly to overall riverine biodiversity and represent a functionally important component of river ecosystems. Our model focuses on predicting the abundance of three major arthropod groups (spiders, ground beetles, and rove beetles) as well as total arthropod abundance

We used multiple regression analyses to relate the variation in each species' abundance to the river morphology and shoreline embeddedness (Figure 2) using data from twelve, differently-impacted, river sections of seven, mid-size to large, rivers in Switzerland and Northern Italy [Paetzold and Tockner, in review]. We used a backward stepwise regression procedure to assess which variables and interactions explain most of the variation. All regressions were performed using the square root transformation of abundance data to improve the normality of model residuals.

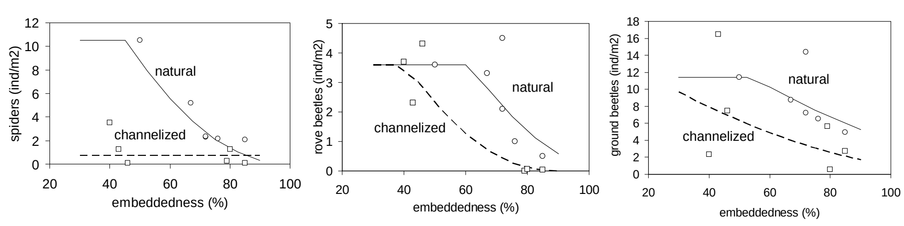

Figure 2. The dependence of arthropod density on shoreline embeddedness and river morphology. Circles and solid lines represent the data and model fit, respectively, for natural (braided or gravel bar) rivers. Squares and dashed lines represent the data and model fit for channelized rivers. Data from [Paetzold and Tockner, in review].

We found that for all species there were significant differences between natural and channelized river sections. Additionally, embeddedness reduced the abundance of all species similarly in both types of morphologies, except for spiders at channelized sites which were already so low that embeddedness had no further effect. Rove beetles were the most precisely predicted, with an R_{adj}^2 value of 0.80, and ground beetles were the least precise with an R_{adj}^2 of 0.29.

3.3.3 Fish Abundance

Salmonids and cyprinids are two key families of fish in many large rivers. They are fished and farmed for food across Eurasia and are the major species of fish eaten in many land-locked countries. Salmonids are also an important recreational species for anglers.

To model an important salmonid, brown trout, we started with a dynamic, age-structured population model [see Borsuk *et al.* 2006 for details]. This model is characterized by population parameters, such as growth, survival, and reproductive rates, which were linked to external indicators of habitat quality and anthropogenic influence using experimental and field data, literature reports, and the elicited judgment of scientists. Important influences relevant to river rehabilitation included physical habitat conditions (e.g. % riffles, depth and velocity variability, and substrate size), flood frequency, stocking practices, and angler catch. Effect strength and associated uncertainty were described by conditional distributions directly encoded in the probability network model. The model was tested using data from populations at twelve locations in four Swiss river basins. First applications of the model involved predicting the effect of candidate rehabilitation measures at these twelve sites.

A model for cyprinids is still being developed. Because this family is less well studied than salmonids, it is likely that this model will be more empirical than mechanistic in its structure. We anticipate using habitat suitability data as the basis for model relations.

3.4 Economic Objectives

3.4.1 Flood Protection and Project Costs

In most river rehabilitation projects, flood protection level is specified as a constraint on the minimal expected return period of a flood for which adequate protection must be provided. Project costs then follow from this flood protection level as well as the project design. Costs include both the initial construction cost, as well as ongoing costs for maintenance.

3.4.2 Local Employment Impacts

To estimate the impact of river rehabilitation on short-term employment in the construction sector and long-term employment in the service and agricultural sectors, we used an input-output model parameterized for the local economy [see Spörri *et al.* 2007 for details]. This type of model uses an input-output table of the goods and service flows between different sectors of the economy to calculate the change in output and jobs per sector resulting from a specified demand change (in the construction or service industries, for example) [Miller and Blair 1985]. Reductions in agricultural employment caused by changes in land use are accounted for by assuming that the agricultural sector is constrained by the land available and that the residual local demand for agricultural goods is compensated by imports.

3.5 Model Implementation

The submodels described in the above sections were implemented using the software package Analytica (Figure 3), a commercially available program for evaluating probability network models [Lumina, 1997]. The inputs to the model can be determined for a river system of interest from historical data, and the decision variables can be set to values corresponding to various rehabilitation alternatives. A large sample of realizations is then drawn for each marginal and conditional probability distribution using random Latin hypercube sampling. These samples are propagated to model endpoints to generate distributions of results which represent uncertainty and natural variability. When combined with a model of stakeholder preferences, these endpoint distributions provide a rational basis for stakeholders to decide among rehabilitation alternatives or to improve a certain alternative. [Reichert *et al.* 2007].

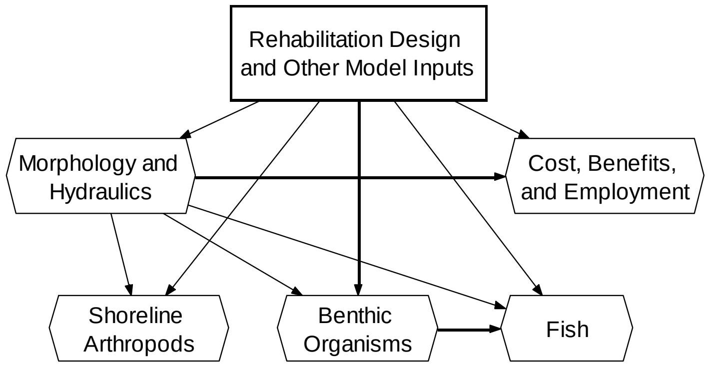

Figure 3. Schematic of the Integrative River Rehabilitation Model. The rectangular box represents rehabilitation design variables (e.g., river width constraints, flood plain and levee height, distance between levee) and other model inputs (e.g., slope, gravel size). Hexagons represent submodels predicting key endpoints. Arrows represent causal influences.

4. CASE STUDIES

4.1 Site Descriptions

We present three case studies to demonstrate application of the IRRM to different locations. The first is a rehabilitated section of the Moesa River in the Swiss canton of Graubünden. This section was originally channelized in the years 1896-1912 to protect the Rhätischen train line and to provide agricultural area. After the region was listed as an area of national importance, a rehabilitation project was financed in 1999. Along a section where it would not present an immediate risk to adjacent populated areas, the river was relieved of its side constraints for 600m along the right bank and 280m along the left bank. The river is now free to expand and run its natural course along this section. We will use the model to generate predictions of the current rehabilitated status and compare these predictions against actual conditions.

The second and third case studies concern two rehabilitation projects (one accomplished and one planned) along the Thur River in the Swiss canton Thurgau. Historically, annual floods of the Thur prevented settlement along its banks. In 1890, a first correction of the river involved straightening meanders and building levees on either side. However, occasional large floods continued, and riverbed erosion worsened on the majority of the river course. The monotonous channel also impaired breeding grounds for birds, fish and other aquatic organisms. To overcome these problems, the Thur has been rehabilitated in some places over the past 10 years. In 2004, a widening was conducted near Niederneunforn at the border with the canton of Zürich. In this 1.5 km section, where mean discharge is 49 m^3s^{-1}, the river was widened from 50 m to 120 m. For this location we will also compare model predictions to actual conditions.

Finally, we will generate predictions for a planned widening of the Thur between the towns of Weinfelden and Bürglen. This is a 4 km long, 30 m wide section, with an average discharge of 41 m^3s^{-1}. It is being proposed to widen this section to up to 200 m. We will evaluate the potential of such a widening to meet stakeholder objectives.

4.2 Model Predictions

Model results show very different predicted outcomes of widening at the three locations (Table 2). The Moesa is most likely to take on a braided or alternating gravel bar form, with a mix of riffles, runs, and pools and an associated variety in velocity and depth. This is predicted to support abundant periphyton, invertebrates, and arthropods, as well as an abundant brown trout population. For comparison, after rehabilitation this section of the Moesa has indeed taken on a blend of braided and alternating gravel bar morphologies, with about 33% of the area classified as riffles, 33% as runs and 33% as pools. Unfortunately, there have not been measurements of periphyton, invertebrate, or arthropod densities, however brown trout surveys have revealed densities between 123 and 192 ind/ha.

The Thur at Niederneunforn is predicted to be alternating or straight, with a predominance of runs and a less diverse depth structure. The resulting high frequency of bed-moving floods leads to a low predicted periphyton density, although invertebrate and arthropod densities are predicted to be fairly high. The river at this location is too large and warm to support brown trout. Observations show that this section actually has an alternating gravel bar morphology and has about 25% riffles, 60% runs and 15% pools. There are no post-rehabilitation measurements of periphyton, invertebrate, or arthropod densities against which to compare predictions. Fish population surveys have found maximum brown trout densities of only 19 ind/ha.

After widening, the Thur at Weinfelden is predicted to remain straight, primarily because there seems to be insufficient gravel input to develop braided or alternating gravel bar structures. Therefore, velocity and depth are expected to stay fairly monotonous dominated by runs. Construction costs of 31 million CHF are expected to lead to short-term employment of about 49 full time equivalents (fte), while changes in land and recreation use will only add about 1 or 2 long-term fte. The Thur at Weinfelden in not expected to support brown trout after rehabilitation.

Table 2. Summary of model predicted outcomes for three implemented or planned river rehabilitation projects.

Attribute	Moesa	Thur - Niederneunforn	Thur - Weinfelden
Morphological type (probability of braided, alternating gravel bar, or straight)	<u>0.46 braided</u>, 0.34 alternating, 0.20 straight	0.0 braided, <u>0.56 alternating</u>, 0.44 straight	0.29 braided, 0.08 alternating, <u>0.63 straight</u>
Coefficient of variation of velocity and depth[a]	0.7 velocity, 1.0 depth	0.7 velocity, 0.7 depth	0.38 velocity, 0.55 depth
Percent riffles, runs, and pools	43% riffles, 45% runs, 12% pools	12% riffles, 63% runs, 25% pools	4% riffles, 96% runs, 0% pools
Summer density of periphyton (g AFDM m^{-2})	26.0 $\pm$ 18.5	7.5 $\pm$ 3.8	6.5 $\pm$ 9.1
Summer density of total invertebrates (g dry wt m^{-2})	20.9 $\pm$ 7.8	18.6 $\pm$ 7.2	7.4 $\pm$ 4.3
Summer density of arthropods (beetles+spiders, ind m^{-2})	26.5 $\pm$ 5.7	26.5 $\pm$ 7.4	14.1 $\pm$ 7.0
Density of adult brown trout	180 $\pm$ 132	0	0
Implementation costs (million CHF)	0.8	9.9	31[b]
Net change in short term employment (fte)	NA[c]	16.1 $\pm$ 0.8[d]	49 $\pm$ 2.6
Net change in long-term employment (fte)	NA[c]	-3 $\pm$ 0.5[d]	1 $\pm$ 1.3

[a] this result and those for all lower rows are reported for the most likely morphology only
[b] rough cost estimation for demonstration purposes only
[c] relevant economic data not readily available as model input for region surrounding Moesa
[d] employment predictions made using economic data from the region surrounding Weinfelden

5. CONCLUSIONS

Additions and improvements are still being made to the IRRM, however the present version provides a coherent and flexible framework for predicting the ability of river rehabilitation projects to meet many important stakeholder objectives. Because of its modular structure, the model can be easily adapted as necessary for project-specific needs. Unfortunately, very few data are available to test the model's predictive accuracy. Collection of such data is recognized to be an important need for assessing rehabilitation project success [Woolsey *et al.* 2007].

To form a more complete and quantitative basis for rational decision making, probabilistic model predictions can be combined with a formal description of stakeholder preferences in the form of multiattribute utility functions [Keeney and Raiffa, 1993]. Preliminary such functions are reported by Hostmann et al. [2005], and we are currently working to elicit more detailed preference structures from stakeholders and scientists.

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