Predicting the Hydraulic and Morphological Consequences of River Rehabilitation

S. Schweizer, M. E. Borsuk, and P. Reichert
Swiss Federal Institute for Environmental Science and Technology (EAWAG)
P.O. Box 611, 8600 Dübendorf, Switzerland. Email: steffen.schweizer@eawag.ch

Abstract: Decisions about flood protection and river rehabilitation require prediction of the consequences of each possible management alternative. To provide such predictions, an integrative model is required that represents the cause-effect relations between revitalisation measures and morphologic, hydraulic and ecological consequences. This paper describes the hydraulics submodel of such an integrative model. This submodel is subdivided into four modules predicting channel morphology, gravel transport, velocity distribution, and riverbed clogging. The channel morphology module predicts natural channel form based on a simple regression model of its dependence on easily available influence factors (valley slope, annual discharge, and median gravel size). Morphology predictions are then corrected by considering width constraints. The gravel transport module tests whether sufficient gravel is available for the development of gravel bar features or if a straight, incising river will result. A parameter describing the spatial velocity distribution is again estimated with a simple regression on relevant influence factors. Finally, estimates of the extent and severity of bed clogging are based on a model estimating the retention of fine particles carried by water infiltrating the gravel bed. This estimate is currently very uncertain as it depends on a number of uncertain input parameters. A preliminary application of the hydraulics submodel to a reach of the Thur River in Switzerland demonstrates its utility for predicting important consequences of river channel widening. The full integrative model will be used, together with quantitative assessments of stakeholder preferences, for decision support concerning revitalisation alternatives.

Keywords: hydraulics; channel morphology; probability network; integrative modelling; velocity distribution, clogging; bed load

1. INTRODUCTION

In the last 200 years, many river systems throughout the world have been regulated and channelised. These alterations have been conducted mainly to enhance agricultural and urban areas, to enable or facilitate river navigation, and to reduce flooding risk. This has resulted in a dramatic reduction of river floodplain area and loss of hydraulic and morphological variability. This uniformity decreases the habitat quality for organisms living in or near a regulated river (including algae and macrophytes, meio- and makro-zoobenthos, fish, and terrestrial flora and fauna). Thus, the biodiversity, abundance, and biomass of organisms are reduced and the functionality of the river ecosystem is impaired.

In Switzerland, only about 10% of all rivers remain in a natural or near natural state [BUWAL 1997]. Therefore, there is a high need for ecological rehabilitation, although most funding for river construction has been granted for the purposes of additional flood control. However, a recent federal requirement to include ecological rehabilitation measures in flood control projects has provided new opportunities. To understand the ecological and socio-economical consequences of river construction projects and provide advice for future efforts, the interdisciplinary “Rhone/Thur River Rehabilitation Project” was recently initiated [Peter et al. 2004]. One subproject of this research program is the development of an integrative model (IM) predicting the hydraulic-morphological situation after river rehabilitation and the resulting changes in the ecosystem. The IM is in the form of a probability network [Pearl 1988] and represents the relevant cause-effect-relations within and among the relevant biotic and abiotic factors, leading to attributes of concern to the river system’s stakeholders (Figure 1). Together with a model of the preference structure for different levels of these attributes, the IM provides a comprehensive basis for decision support [Reichert et al. 2004].

In this paper, we describe the hydraulic and morphological submodel that provides the foundation for predicting all the biotic and abiotic attributes of interest. We begin by outlining the model approach, then describe the model equations and implementation, and finally demonstrate application to a section of the Thur River, Switzerland.

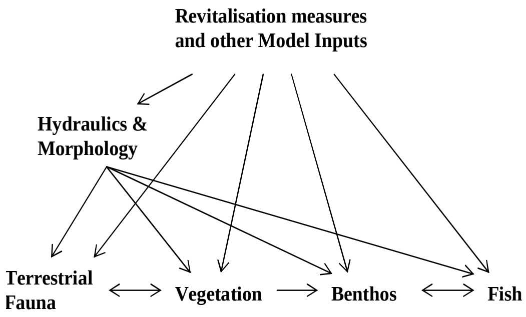

Figure 1. Submodels and structure of the integrative river rehabilitation model

2. MODEL DESCRIPTION

The development of an IM requires scientific knowledge in a variety of forms including literature findings, experimental and field data, other models, and, in the absence of other information, expert assessment. The principal motivations for implementing the IM as a probability network are the simplicity of combining different sources of information to represent cause-effect relations, the ability to simultaneously consider different spatial and temporal scales, and the ability to explicitly include uncertainties in model inputs, structure and outcomes [Borsuk et al. 2004].

Because all biotic endpoints of interest (including terrestrial fauna, riparian vegetation, aquatic benthos, and fish) are influenced by hydraulics and river morphology (see Fig. 1), model construction began with this abiotic submodel. The focus was on predicting variables that would be required as inputs for the biotic submodels including channel morphology, gravel transport, velocity distribution, and gravel bed clogging. These modules are described in the following subsections.

2.1 Channel Morphology

River channel planform is an important model endpoint 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 stream power, bed composition, and artificial width constraints [van den Berg 1995]. While a number of researchers have developed diagrams separating channel patterns based on flow-related parameters [e.g. da Silva 1991], these have generally been descriptive, in that they require advance knowledge of the channel geometry, which is pattern-dependent. Van den Berg [1995] developed a truly predictive method for distinguishing between multi- and single-thread rivers that requires only the pattern-independent properties of annual discharge, gravel size, and valley slope. Bledsoe and Watson [2001] made this approach probabilistic by fitting a logistic regression to data from 127 unconstrained, gravel-bed rivers. Of the several fitted relationships, we chose one which gives the probability, p_m, of a multi-thread pattern as,

$$p_m = \frac{\exp\left[10.35 + 5.71\cdot\log_{10}\left(J_V\sqrt{\frac{Q_a}{d_{50}}}\right)\right]}{1+\exp\left[10.35 + 5.71\cdot\log_{10}\left(J_V\sqrt{\frac{Q_a}{d_{50}}}\right)\right]} \qquad (1)$$

where J_V is valley slope, Q_a is annual discharge (m^3s^{-1}), and d_{50} is median gravel diameter (m) [Bledsoe and Watson 2001].

We used equation (1) to predict the natural tendency of a river in the absence of width constraints, such as along-channel dikes. To determine the effect of constraints, the hypothetical unconstrained width was first estimated for each channel pattern from a regression on discharge, valley slope, and gravel diameter using the data of Bledsoe and Watson [2001]. The resulting model (n=153) yielded, for multi-thread rivers,

$$w_{bf} = 2.61\cdot Q_a^{0.49}\cdot d_{50}^{-0.76}\cdot\varepsilon_w$$

and, for single-thread rivers, (2)

$$w_{bf} = 1.85\cdot Q_a^{0.49}\cdot\varepsilon_w$$

where w_{bf} is bankfull width (m), assumed to occur at annual discharge, and ε_w is a lognormally-distributed error term with median zero and geometric standard deviation of 1.75. Valley slope was not a significant predictor for either river pattern, and gravel size was only significant for multi-thread rivers. The exponent on discharge was not significantly different for the two river patterns (all at the 0.01 significance level).

Single-thread rivers may be either straight, meandering, or sinuous with alternating side bars. In most locations, the space required to restore a meandering pattern is impractical given present land use. Therefore, we expect that rivers predicted to be single-threaded according to equation (1) will be sinuous with alternating side bars unless the constrained width is narrower than the width predicted by equation (2), in which case the river will be straight.

Rivers predicted to be multi-threaded according to equation (1) might yet be single-threaded if width constraints are too severe. This can be checked using the pattern diagram of da Silva [1991] for a known gravel size, channel geometry and mean depth at annual discharge. Width at annual discharge is estimated from equation (2), accounting for width constraints, and mean depth is estimated using the equation of Strickler [1923],

$$J = \frac{1}{k_{st}^2}\left(\frac{P}{A}\right)^{4/3}\left(\frac{Q}{A}\right)^2 \quad (3)$$

where J is channel slope (assumed here to equal valley slope, J_v), k_{st} is Strickler's coefficient ($m^{1/3}s^{-1}$), P is wetted perimeter (m), A is cross-sectional area (m^2), and Q is discharge (m^3s^{-1}). In applying equation (3) we assumed that each channel of a multi-thread river carries an equal amount of the total flow and has a triangular cross-section that is filled at annual discharge. For a single-thread river, we assumed a trapezoidal cross-section with a known angle of repose. Strickler's coefficient, k_{st}, is calculated as,

$$k_{st} = \frac{A_{st}}{\sqrt[6]{d_{90}}} \quad (4)$$

where A_{st} is a constant with values reported in the literature between 21 and 26 $m^{1/2}s^{-1}$.

The number of channels expected in an unconstrained multi-thread river was predicted using the relation identified by Robertson-Rintoul and Richards [1993] in an analysis of 21 braided rivers,

$$n_b = round[1 + 5.52 \cdot (Q_a J_v)^{0.40} d_{84}^{-0.14}] \quad (5)$$

where n_b is the number of braids and d_{84} (m) is the 84th percentile of gravel size. To account for width constraints, we multiply the number of channels by the ratio of the constrained width to the natural width predicted by equation (2).

Regardless of predicted morphology, mid- or side-channel bars will not develop if gravel transport out of the reach exceeds upstream gravel supply. In such cases, we assume that an incising, single-thread channel will eventually result. Incision may, however, be prevented by the installation of weirs and other bed stabilization measures or the reduction of upstream gravel retainment.

2.2 Gravel Transport

As mentioned above, the formation of gravel structures in a widened river reach depends on net deposition of gravel. The upstream input is treated as known, while the transport capacity within the reach, Q_b (m^3s^{-1}), is calculated as the product of a specific transport capacity, q_b (m^2s^{-1}), and the width, w (m),

$$Q_b = w \cdot q_b \quad (6).$$

The specific transport capacity is estimated [Meyer-Peter and Müller 1948] as,

$$q_b = \Phi\sqrt{(s-1)gd_{50}^3} \quad (7)$$

where Φ is a dimensionless transport capacity, s is the ratio of sediment to water density, and g is the gravitational constant 9.81 $m \cdot s^{-2}$.

The dimensionless transport capacity Φ can be estimated from the bed load formula of Meyer-Peter and Müller [1948],

$$\Phi = 8 \cdot (\theta - 0.047)^{1.5} \quad (8)$$

where θ is the dimensionless bottom shear stress,

$$\theta = \frac{h \cdot J}{(s-1) \cdot d_{50}} \quad (9)$$

and h is water depth (m), which can be estimated for a given discharge from equation (3) with an assumed channel geometry. To derive the annual gravel input, we cumulate the daily inputs estimated using daily discharge.

2.3 Velocity Distribution

The quality of habitat for aquatic biota is strongly influenced by velocity characteristics. Both average and spatially distributed velocities are of relevance. Spatial mean velocity, v_m is calculated from discharge and cross-sectional area as $v_m=Q/A$. The spatial distribution of velocity can then be estimated for a given mean velocity 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 measured relative velocity (v/v_m) 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 (d_{50}/h) and the logarithm of the Froude number ($v_m/(gh)^{1/2}$). An increasing relative roughness leads to a more decentred distribution, while an increasing Froude number leads to a more centred distribution. The accuracy and robustness of the analysis of Lamouroux *et al.* [1995] give us confidence in directly applying their results to our model.

2.4 River Bed Clogging

Fish and benthic species depend on the interstitial gravel zones. Therefore clogging and clearance of the bed matrix are crucial ecological processes. Additionally, the content of fine particles in the riverbed 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. This flushing occurs with a calculable frequency for a particular river, and the 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],

$$V_A = \sqrt{\frac{\Delta h_w \cdot g \cdot \left(\frac{d_{10}}{d_{50}}\right)^3 \cdot \mathrm{Re}^{1.5} \cdot i \cdot t}{2.5 \cdot 10^{12} m^2 kg^{-1} \cdot \nu \cdot \theta^{0.5} \cdot C}} \tag{10}$$

where V_A is the volume of filtered water per unit area ($m3 \cdot m^{-2}$), Δh_w is the pressure head between channel and groundwater level (m), *Re* is the Reynold's Number, *i* is the hydraulic gradient, *t* is the time since the last flushing event (s), ν is kinematic viscosity ($m2 \cdot s^{-1}$), and *C* is the concentration of suspended particles ($kg \cdot m^{-3}$).

The mass of fine particles retained in the bed matrix, m_{fines}, is calculated as the product of the volume of filtered water and concentration of suspended particles. The fraction of fines, f_{fines}, in the riverbed is then calculated as,

$$f_{fines} = \frac{m_{fine}}{m_{fines} + m_{coarse}} = \frac{V_A C}{V_A C + (1-\phi) H \rho_{sed}} \tag{11}$$

where m_{coarse} is the mass of coarse bed material (kg), ϕ is porosity, *H* is the depth of the bed layer (m) (usually 0.1 to 0.3m, see Schälchli 1993), and ρ_{sed} is the gravel density ($kg \cdot m^{-3}$). The percentage of fines can be used as a measure of the degree of gravel bed clogging.

A bottom shear stress of sufficient magnitude to initiate bed disturbance and gravel flushing, θ_D, is calculated according to Günther [1971] as,

$$\theta_D = \theta_{Cr} \cdot \left(\frac{d_{50D}}{d_{50}}\right)^{2/3} \tag{12}$$

where d_{50D} is the median diameter of the upper gravel bed layer (m), d_{50} is the median diameter of particles lying on the river bed (m), and θ_{Cr} is the critical shear stress, assumed to equal 0.05 [Meyer-Peter and Müller 1948].

The water depth associated with a bottom shear stress value of θ_D can be calculated from equation (9) and then related to a critical discharge using Strickler's formula (equation 3).

2.5 Model Implementation

The model described above was implemented using a software program for evaluating probability network models, e.g. Analytica [Lumina, 1997]. A sample of one thousand realizations was drawn for each probability distribution representing uncertainty using Latin hypercube sampling. The major inputs to the model (Figure 2) can be derived from historical data for the river system of interest, and the decision variables can be set to values corresponding to current conditions, decision alternatives, or scenarios used for sensitivity analysis.

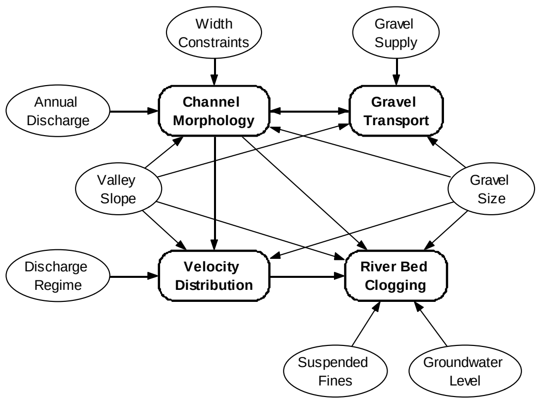

Figure 2. The hydraulic and morphologic submodel as implemented in Analytica. Round nodes indicate important input variables and bold nodes indicate submodel components.

3. FIRST RESULTS OF A CASE STUDY

A case study at the Thur River between the towns of Weinfelden and Bürglen, Switzerland, demonstrates an application of the hydraulic submodel. Two scenarios are considered: (i) the present conditions (leave the straight river width at 50m) and (ii) possible river widening up to 200m. Table 1 summarises the principal site characteristics for these scenarios (model inputs) and their uncertainties.

Table 1: Mean, standard deviation and distribution of model inputs at Weinfelden-Bürglen

Model input	Mean	Std. Dev.	Distribution
Slope J [‰]	2.0	0.2	Lognormal
1-year flood Q_a [m^3/s]	410	40	Normal
d_{50} [cm]	2.9	0.5	Lognormal
d_{90} [cm]	6.8	1	Lognormal
Porosity ϕ [%]	25	2	Lognormal
Bankfull width w_{bf} [m]	50 / 200	-	-
Angle of repose γ (single-thread) [°]	45	-	-

As the logistic regression approach for predicting river form (equation 1) assumes no width constraints, predictions of the natural river form tendency is the same for all possible alternatives: a 24% probability of a multi-thread river and corresponding 76% probability of a single-thread. While, in general, the final channel morphology additionally may depend on channel width constraints, in this case the probabilities above are maintained after considering a 200m constraint (Figure 3).

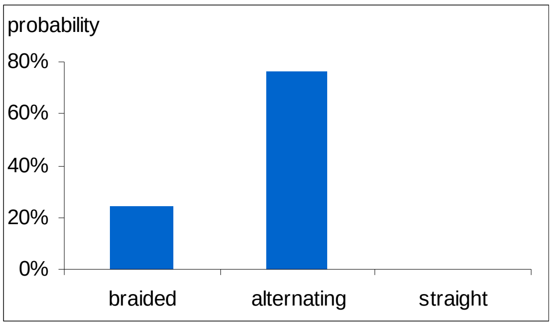

Figure 3: Probability distribution of possible river forms for a 200m river-widening.

Compared to the present state, the alternating river reach would respond to an annual flood regarding mean width and depth and dimensionless bottom shear stress nearly identically (Table 2). However, if a braided river reach were to develop, major differences with respect to these hydraulic quantities can be expected.

Table 2: Predicted hydraulic properties for the present state and the two possible outcomes of the widening alternative at a one-year flood (Q_a=410m^3/s), assuming sufficient gravel supply.

	Present State (50m)	**Widening Alternative (200m)**	
	Straight	**Alternating**	**Braided**
Probability	-	76%	24%
Mean Width	36m	38m	200m
Mean Depth	4.6m	4.5m	1.2m
Mean θ	0.2	0.19	0.05
# of Braids	-	-	2 - 3

Mean water depth, mean velocity and its spatial distribution can also be calculated for discharges below the annual flood, such as the mean discharge (Q_m=40m^3/s) or dry weather discharge (Q_{347}=8m^3/s). For flows equal to or lower than mean discharge no differences in mean velocity and depth between the present state and a widening with the consequence of alternating gravel bars will occur (Table 3). This applies also for the spatial distribution of velocity (Figure 4a,b). If a braided river reach develops, significant distinctions in comparison to the present state can be expected for flows similar to mean discharge, whereas for low stages the differences become indistinct.

Finally, it should be stated that some important differences between the two morphologies straight and alternating exist: alternating gravel bars provide some refuges for benthic organisms (this can be important during floods) and serve as important pioneer areas for terrestrial flora and fauna. This information will be propagated to the biological models.

Table 3: Predicted hydraulic properties for the present state and the two possible outcomes of the widening alternative for mean and dry weather discharge, Q_m= 40m^3/s and Q_{347}=8m^3/s, respectively.

	Present State (50m)	**Widening Alternative (200m)**	
	Straight	**Alternating**	**Straight**
mean depth (Q=40m^3/s)	1.0m	1.0m	0.5m
mean velocity (Q=40m^3/s)	1.5m/s	1.5m/s	1.0m/s
mean depth (Q=8m^3/s)	0.4m	0.4m	0.3m
mean velocity (Q=8m^3/s)	0.8m/s	0.8m/s	0.7m/s

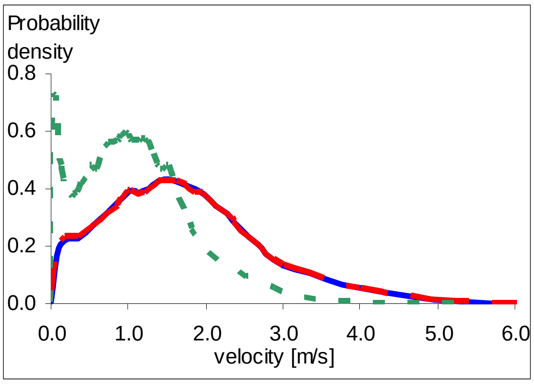

Figure 4a: Spatial velocity distribution for Q=40 m^3/s (solid line=present state; dashed line=200m widening single-thread (almost identical to solid line); dotted line=200m widening, multi-thread).

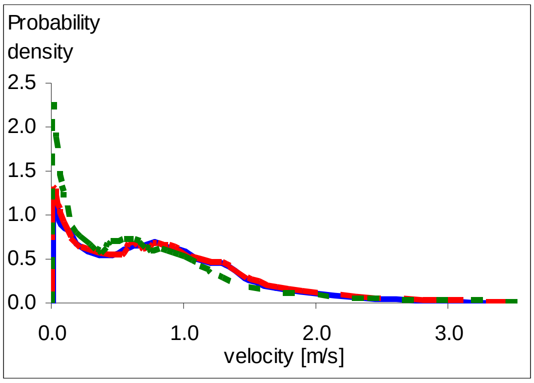

Figure 4b: Spatial velocity distribution for Q=8m^3/s (solid line=present state; dashed line=200m-widening,single-thread (almost identical to solid line); dotted line=200m-widening, multi-thread).

4. DISCUSSION AND CONCLUSIONS

The submodel presented in this paper predicts the morphological and hydraulic changes resulting from rehabilitation alternatives. In addition these predictions will be used in a next step as inputs to the other submodels of an integrated river rehabilitation model of benthic and fish populations, terrestrial vegetation, and shoreline fauna. Reichert et al. (2004) describe how the results of that integrated model, together with value assessments of possible outcomes of rehabilitation measures, will support decision making. The validation of this hydraulics submodel with real data will be started in summer 2004 by another group of the "Rhone/Thur River Rehabilitation Project" at both the studied reach and at an adjacent reach of the river Thur. For detailed planning of construction work, a more detailed hydraulic study is required.

5. ACKNOWLEDGEMENTS

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