Fuzzy based Models for the Evaluation of Fish Habitat Quality and Instream Flow Assessment

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Abstract

To improve the performance of the habitat simulation model CASIMIR, fuzzy rules are applied to describe habitat preferences of fish species during their different life stages. Fuzzy rules turned out to be more effective to develop because they can be derived from experts' knowledge that is often readily available. Common preference function based approaches mostly consider parameters separated from each other or in combination with one or two other parameters. Opposite to that, fuzzy rules allow to include large numbers of combinations of physical parameters into habitat simulation tools and it is easy to implement more parameters if they turn out to be relevant.The results gained with fuzzy rules clearly differ from those gained with traditional preference functions. Comparisons of actual fish findings in several rivers show a higher correlation with habitat prediction for fuzzy based simulations than for those based on preference functions. Methods and results from studies in Swiss alpine rivers affected by hydropower operation are presented.

Introduction

In European mountain regions where electricity is generated from hydropower and flood protection has high priority, nearly all running waters are influenced in their morphological state and their hydrological regime. The consequence of these complex physical changes in river systems is a degradation of biological integrity of running waters. As public awareness of the value of natural river systems is increasing and the European Water Framework Directive is demanding restoration measures for ecologically disturbed rivers, actions are required for a sustainable management of rivers and catchments. In that context, habitat simulation models for fish and other species are a highly developed tool to evaluate the present state of a river, to define deficits in morphology, hydraulic patterns and the hydrological regime and to predict the ecological consequences of certain restoration measures or management strategies.

The Simulation Model CASIMIR

CASIMIR (Computer Aided Simulation Model for Instream Flow Requirements) is a Toolbox for habitat simulation in rivers. It has been developed at the Stuttgart Institute of Hydraulic Engineering since the beginning of the 1990's [1]. The simulation model comprises modules with individual computing programmes which can be combined to suit a particular case in question. Three main areas of simulation are implied in the current version. The flow regime module includes programs to simulate hydropower plants, including energy generation, reservoir operation and instream flow regulations. The river bed module calculates statistical distributions of near bed flow forces derived from field measurements [2]. The aquatic zone module simulates and analyses hydraulic and morphologic patterns. The latter two modules are complemented with biological components that contain data about habitat preferences and simulation tools for habitat quality and availability. This modular structure has the advantage that further parameters can be adopted at any time, should they prove to be ecologically relevant. Thus very differing data sets can be evaluated. CASIMIR has been applied to examine the consequences of various types of human activities or natural processes in river systems.

Fish Habitat Simulation

The traditional approach for a qualification of fish habitats are local depths, depth averaged velocities, and substratum. Each of the criteria was treated seperately and the final habitat quality of a certain area was defined by multiplying single criteria results or taking the minimum or average of single criteria results. Preference data sets used in these models are obtained by snorkeling and/or electrofishing. Newer approaches for preference functions are based on multivariate statistics [4] and results reveal a higher correlation between fish findings and predicted habitat quality in some cases. This approach takes into account that physical parameters cannot be considered as isolated from each other. However, preference functions generally neglect the plenty of possible physical parameter combinations. Another lack of preference based methods is that spatial connectivity and the networking of habitats is not considered. Therefore, so called „Individual fish based models“ and bioenergetic models [3] were developped and successfully applied for large drift feeding salmonids.

Another new approach to evaluate habitat quality is fuzzy rule-based modelling [5,6]. Fuzzy models allow to work with imprecise or „fuzzy“ information. They have the significant advantage that expert knowledge readily available from experienced fish biologists can easily be transferred into preference data sets by setting up check-lists with possible combinations of relevant physical criteria and let experts define if habitat quality is e.g. good, medium or low. Table 1 shows an extract of a set of fuzzy rules for brown trouts in alpine regions.

Table 1: Fuzzy rules for brown trout in alpine region (extract). Example line 2: If velocity is “medium” AND depth is “high” AND substrate is “large” AND cover type is 2 THEN suitability is “high”.

velocity	local depth	substratum	cover type	suitability index
medium	high	large	0	low
medium	high	large	2	high
medium	high	large	3,4,5	high
medium	high	large	6,9	high
medium	high	medium	0	low
medium	high	medium	2	high

The parameters, that are contained in the criteria combinations are categorized by so called fuzzy sets (fig. 1). These sets defined by membership functions enable a fuzzy formulation of rules (table 1) close to human way of communication. The rules define the relation between input or explanatory variables and consequence, in our case the output or habitat suitability.

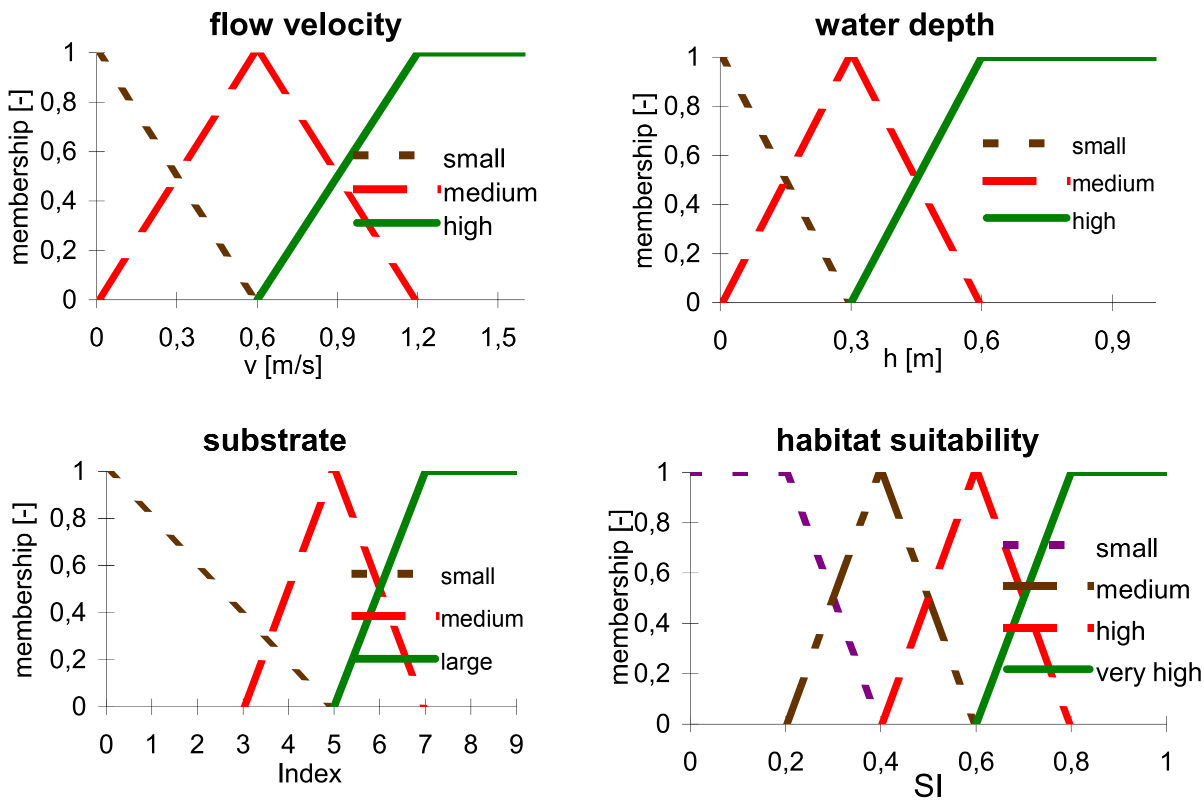

Fig. 1: : Fuzzy sets describing degrees of membership (membership functions) for input (velocity, depth, substratum) and output (suitability index)

Not only the input but also the output is „fuzzy“. The output of the fuzzy model is derived by calculating the degrees of fulfillment of all the rules in a whole rule system. These degrees of fullfillment are then used for a „defuzzyfication“. Thus the result, which is still in the form of a fuzzy set is transformed back into a standardized number to describe habitat quality. The approach described here was developped within the Swiss Oekostrom Projekt.

"Oekostrom" Pilot Project

In Switzerland, the Swiss Federal Institution for Environmental Science and Technology (EAWAG) started a pilot project named "Oekostrom" to generate criteria for ecologically sustainable hydropower use with an emphasis on local aspects concerning the affected river systems, not global ones such as greenhouse gas emissions. One of the important aspects of that study are instream flow regulations downstream of dams, diversion weirs or water intakes. The pilot study was performed in the Val Blenio in the Southern Alps of Switzerland [7]. The main river is the Brenno, it has a catchment of appr. 400 km^2 and the system is influenced by 22 intakes at 3 different altitude levels, 3 large dams and reservoirs for annual storage and/or compensation, and 3 hydropower plants. Within the instream flow program fish habitats were invesitgated in several reaches of the Brenno di Lucomagno and the Brenno. The reaches were considered to be representative for certain larger longitudinal stretches of the river.

Field measurements for the hydraulic and morphologic simulation consist of cross section survey data with additional monitoring of substratum and choriotopes including accessabilities, types and availability of different cover categories, shadowing, pool types, single rocks and bank structure. The data are processed within CASIMIR and a 3-dimensional digital river bed model is generated. Additional informations are stored as index figures with each bottom element. Water tables can be either measured, which is often more effective and accurate especially under low flow conditions, or calculated from a 1-D hydraulic model. In this case, a CASIMIR module was applied that utilizes simple rule based methods to derive local depth averaged velocities from mean cross section velocities and cross section geometry.

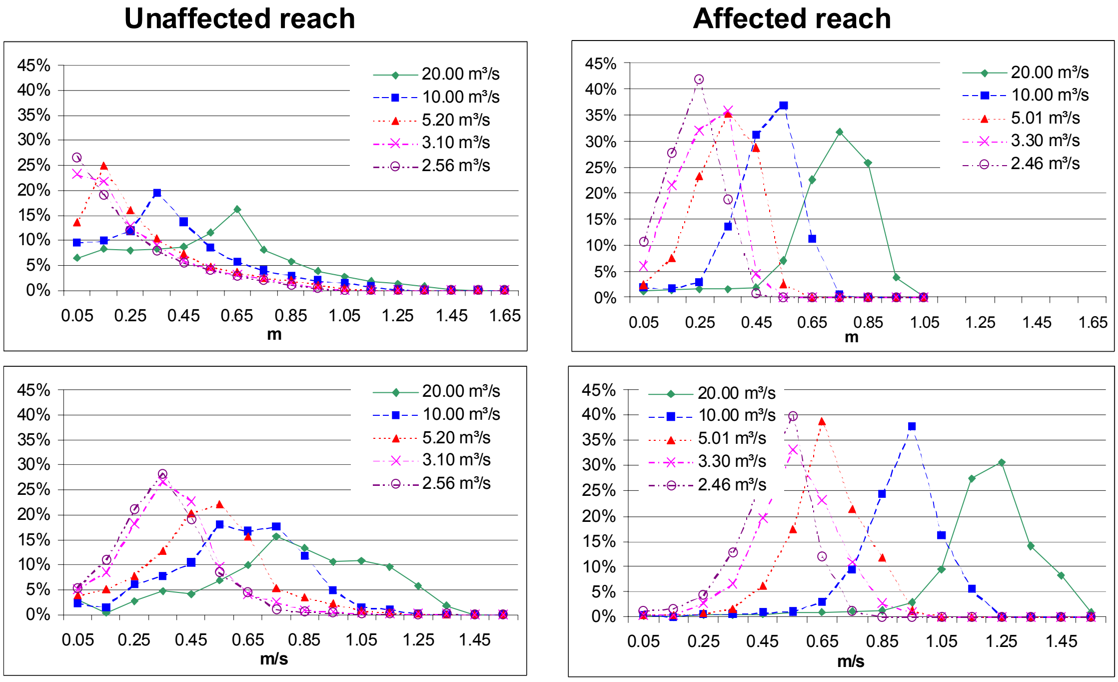

Fig. 2: Distribution of water depths and local flow velocities in two structural different river reaches for various discharges

Fig. 2 shows frequency distributions of local flow velocities and water depths of two investigation sites, “Floodplain Loderio” and “Channel Loderio”, at the river Brenno, which are both influenced by water diversions reaching about 75% of the annual flow. The reaches are in totally different morphological condition, the “Floodplain” (unaffected reach) is in fairly natural morphological state whereas the”Channel” (affected reach), just 1 km upstream, has a rectangular cross section with very low spatial variability and levees on both sides. The distributions werde derived from digital maps of depth and flow velocity calculated for different flows and indicate differences in the spatial variability of both parameters.

The results of this abiotic modelling are consequently combined with the preference functions or with fuzzy rules that describe habitat quality. A comparison between both simulation results for the Loderio Floodplain and Channel reach is given in fig. 3 (fuzzy method) and fig. 4 (preference method). It is evident that results differ significantly in qualities as well as in locations.

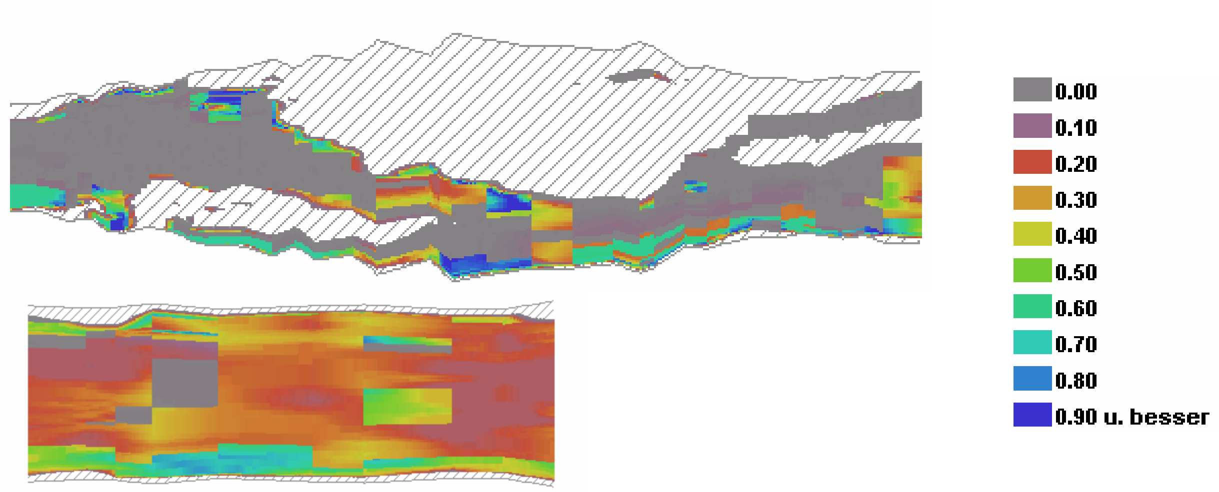

Fig. 3: Habitat suitability maps for brown trout (*Salmo trutta*) in Loderio Floodplain and Loderio Channel, 5200 l/s, derived by fuzzy approach

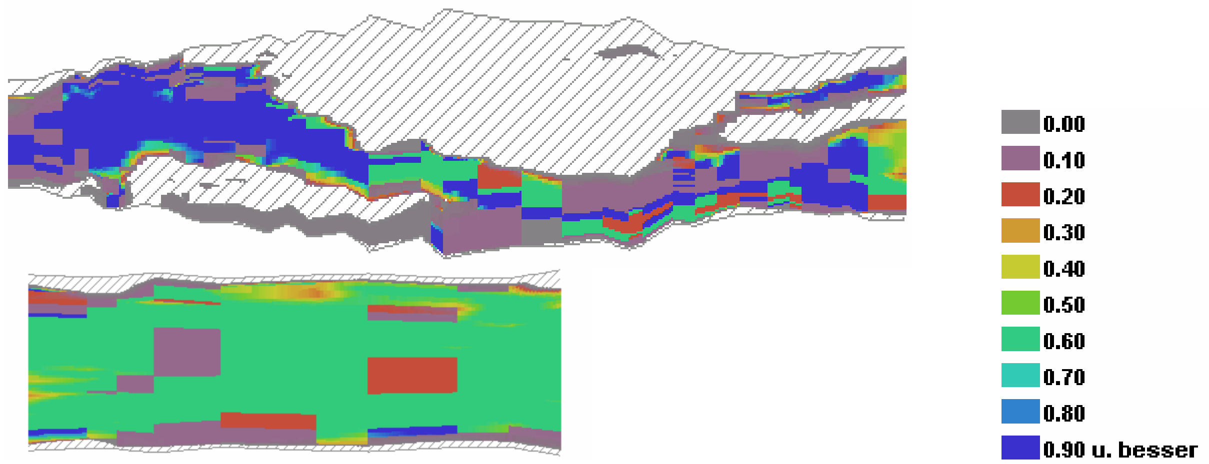

Fig. 4: Habitat suitability maps for brown trout (*Salmo trutta*) in Loderio Floodplain and Loderio Channel, 5200 l/s, derived by preference functions

In a next step, Weighted Usable Areas (WUA) can be calculated from the habitat quality maps as an integral value. Fig. 5 shows the comparative results of WUA for Brown Trout with increasing discharges and with preference vs. fuzzy approach.

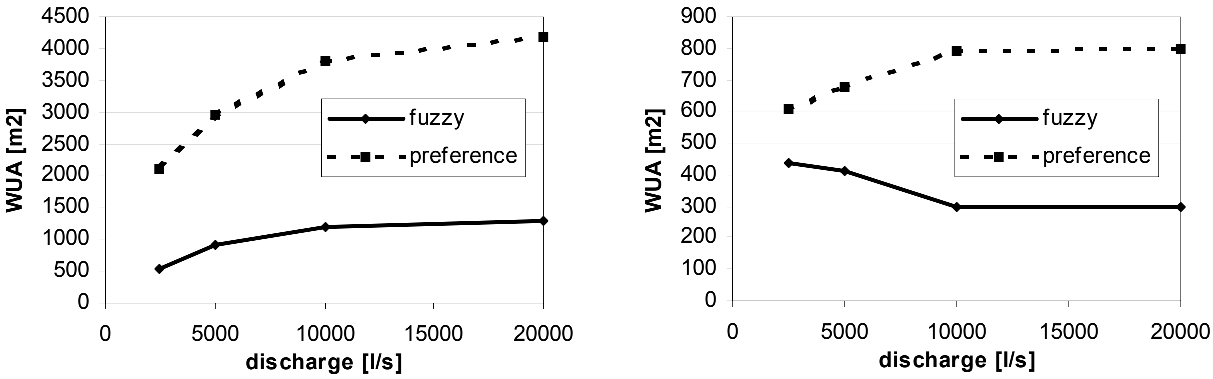

Fig. 5: Integrated habitat availability for adult brown trout (S*almo Trutta*), Floodplain (left) and Channel (right)

To include temporal information, hydrographs of the river reach are integrated into the model to indicate seasonal aspects that might be of major importance, such as spawning periods of certain species. This allows to adapt flow regulations or limitate abstraction of water to fulfill certain criteria and thus ensure ecological sustainability of a river reach.

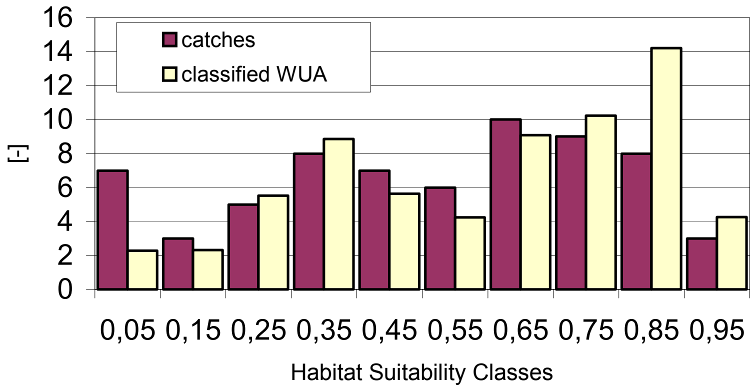

Fig. 6: Comparison between classified WUA (equivalent to predicted fish findings) to actual catches for model validation

Validation of Models

The validation of habitat simulation models is more difficult than the validation of the hydraulic or morphologic part which can easily be verified by field measurements. It is well known, that only a certain share of suitable habitat is actually occupied by individuals. So the availability of suitable hydraulic habitat is necessary, but not sufficient as a prerequisite. Habitat simulation models are therefore not able to predict population dynamics. However, for a validation it is meaningful how predicted habitat quality corresponds with actual fish observations. Fig. 6 shows an example from the Olivone reach of the River Brenno where sufficient fish data were available for a validation. The comparison is based on the asumption that observed fish per unit area should correspond linearly with the suitability index of the area. The results show good correlation for all suitability classes except the lowest and second highest class where further interpretation was required [6].

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