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Fuzzy rule-based macroinvertebrate habitat suitability models for running waters

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ABSTRACT

A fuzzy rule-based approach was applied to a macroinvertebrate habitat suitability modelling problem. The model design was based on a knowledge base summarising the preferences and tolerances of 86 macroinvertebrate species for four variables describing river sites in springs up to small rivers in the Central and Western Plains of Europe. As the modelling problem asked for a model with an interpretable structure and a shaded indication of the river habitat suitability for a macroinvertebrate species, we opted for fuzzy classifiers. For each species, four different types (A, N, P, C) of habitat suitability models were developed, including ‘ammonium concentration’, ‘nitrate concentration’, ‘phosphate concentration’ or ‘electrical conductivity’, as third input variable in addition to the primary two input variables ‘stream width’ and ‘stream velocity’. The models were evaluated on field data collected at 445 sites in the Province of Overijssel (the Netherlands). For the majority of the 86 species, the significance of the model validation is biased by the highly non-uniform distribution of the data points over the input and output space, due to the fact that sites of high ecological quality are largely outnumbered by sites at deteriorated conditions. The evaluation by the validation data set was regarded objective for 12 species, only one of them being an indicator for reference conditions. Given the present environmental conditions of rivers in EU Member States, shifts in abundance levels of more common species are as such more suitable to detect gradual changes in water quality than shifts in abundance levels of species characterising reference conditions. Good scores were obtained with the performance measure ‘percentage of correctly fuzzy classified instances’ for the 12 corresponding N- and P-models, whereas the A- and C-models showed a low to moderate performance. This work illustrates that fuzzy rule-based models, designed using a comprehensive knowledge base, have properties that are of great interest for river management tools. The main components of a fuzzy rule-based model are the if–then rules, allowing for the expression of non-linear relations and the fuzzy sets, guaranteeing gradual transitions between classes. Due to the fact that these model components can be understood intuitively, the fuzzy rule-based approach results in highly transparant habitat suitability models.

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1. Introduction

According to EU standards and objectives, ecological water quality in EU Member States is still far from satisfactory, both in terms of nutrient management and habitat degradation (Chave, 2001). Within the last decade, the industrial pollution load has significantly decreased, but household and agricultural pollution still cause a high load of organic substances and nutrients (Hering et al., 2004). In contrast to standing waters, the effects of eutrophication and enhanced organic load on running water ecosystems have not been given much attention (Nijboer and Verdonschot, 2004). Nevertheless, water managers need to know the effects of these stressors on the biological communities in streams and rivers. Besides physical–chemical degradation of the watercourses, the habitat quality of running waters is also unsatisfactory due to modifications in channel morphology and hydrology, causing increased discharge fluctuations. These fluctuations alter the natural habitat, causing difficulties for the species to build up a viable population.

Apart from the currently available studies investigating the environmental responses of biological river communities or species to specific conditions, there is a clear need for models quantifying the community or species-environmental relationships to support decision making. The description of species or taxa distributions as a function of the abiotic environment, named habitat suitability modelling, has only recently been recognised as a significant component of conservation planning (Austin, 1998, 2002; Guisan and Zimmerman, 2000) and is now believed to be at the core of predictive ecology. The habitat suitability models aim to link abiotic variables, describing the general habitat in a river, to the presence or abundance of a species at a site, based on known ecological preferences of this species. River management can benefit from such predictive models as decision support tools to improve the efficiency of monitoring and assessment, for example by choosing the most optimal restoration measure from a set of given river restoration scenarios (Guisan and Zimmerman, 2000).

The development of decision support tools in river management is strongly inspired by the introduction of the European Water Framework Directive (WFD) (EU, 2000), in which Member States are hold to reach good ecological quality for their surface waters by 2015 (Chave, 2001). Reaching this good ecological water quality can be guided by tools, such as habitat suitability models, describing the effects of human activities on river ecosystems. When developing ecological models to support decisions in river management, one should compromise between the policy relevance of the variables, the ecological processes incorporated in the model and the accuracy of the model. Moreover, the model structure should be straightforwardly interpretable in order to allow a decision maker to assess the uncertainty associated with the model outputs, and, furthermore, to allow for the incorporation of qualitative data during model development (Ehrlich and Daily, 1993; Ludwig et al., 1993; Parsons and Norris, 1996; Omlin and Reichert, 1999; Elith et al., 2002; Holling and Allen, 2002; Regan, 2002; Borsuk, 2003; Poff and Allan, 1995).

Predictive ecological models to be used in river management can differ in biological endpoint. The choice of the endpoint can both depend on the conservation value of a specific group of organisms as on the functionality as a biological indicator of river conditions. The biological endpoints for rivers as set by the WFD (EU, 2000) include phytoplankton, phytobenthos and macrophytes, macroinvertebrates and fish. Among these groups, macroinvertebrates are highly appropriate to monitor ecological changes caused by human impacts (Karr and Chu, 1999). Macroinvertebrate communities are made up of species that constitute a broad range of trophic levels and pollution tolerances. Furthermore, they show limited migration patterns and are therefore well suited for assessing site-specific impacts, they are abundant in most streams and they are easily sampled. Besides, macroinvertebrates are widely used indicators for assessing the quality of freshwater (Wiederholm, 1980; Sládecek et al., 1982; Metcalfe, 1989; Rosenberg and Resh, 1993).

As fuzzy rule-based models can be designed using qualitative knowledge and have an interpretable structure, they were applied in this study to a habitat suitability modelling problem. The models describe the habitat suitability for macroinvertebrates in springs up to small rivers in the eco-region of the Central and Western Plains of Europe (Illies, 1978). They were built based on expert knowledge and evaluated using field data collected in the Province of Overijssel (the Netherlands). The objective of this study was to evaluate the knowledge-based approach as well as the rule-based modelling technique for the aim of habitat suitability modelling.

2. Material and methods

2.1. *Knowledge base and rule bases*

The knowledge base, used during the model design process, is described in detail in Adriaenssens et al. (2005). It summarises observations of several ecological studies (Mauch, 1976; Moller Pillot and Buskens, 1990; Verdonschot, 1990; Usseglio-Polatera, 1994; De Loose et al., 1995; Bayerisches Landesamt für Wasserwirtschaft, 1996; RIZA, 2000; Verdonschot, 2000a,b; Tachet et al., 2000) regarding preferences as well as tolerances of 86 macroinvertebrate species for a limited set of environmental variables. In Appendix A the names of the 86 macroinvertebrate species are listed. Among them, 30 species are regarded as characteristic for the reference conditions of the river types included in this study (high ecological quality; based on Verdonschot (2000a,b)) and will be referred to as indicator species. The other 56 species are so-called common species, observed at river sites of diverse ecological quality. The information in the knowledge base applies to river sites within the limnological eco-regions Central and Western Plains of Europe as defined by Illies (1978). The considered application area of the developed habitat suitability models ranges from springs and small streams to upper, middle and lower course streams and small rivers according to the typology as published in Verdonschot (2000a,b). The ecological variables addressed in the knowledge base are: river dimension (stream width), stream velocity, saprobic conditions, habitat *sensu stricto* and habitat diversity.