Ecological Modelling 325 (2016) 1–12

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Species distribution models grounded in ecological theory for decision support in river management

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ARTICLE INFO

Article history:
Received 4 September 2015
Received in revised form
27 December 2015
Accepted 28 December 2015
Available online 21 January 2016

Keywords:
Water Framework Directive
Water quality management
Environmental decision support
Habitat suitability
Aquatic macroinvertebrates

ABSTRACT

Species distribution modelling has gained importance since the introduction of the Water Framework Directive. Several efforts have been made for the development of decision support tools to aid river basin managers. However, there is a mismatch between the available ecological models and stakeholder needs. For example, models can be so complex that they can only be applied on a limited set of species, or models can be so qualitative that they fail to deliver insight in the underlying processes behind changing ecological quality. Yet, much is known already about ecology and ecography, in general and for specific species. To valorize this available knowledge, we have developed species distribution models for macroinvertebrates in Flanders grounded in ecological theories. We introduce a conceptual approach based on niche and landscape filter theories. To apply the concept on many different macroinvertebrate species, the model development uses both data from Flanders, expert knowledge and data from other similar river systems. Implementing these niche and migration models results in a moderate predictive accuracy (average Kappa of 0.19). For sensitive species that are essential for an ecological quality status the approach results in a higher accuracy. Despite the moderate predictive accuracy, the resulting models have a good applicability. The models concur well with ecological knowledge on species preferences. Furthermore, throughout the model development process stakeholders and end users have been involved to discuss model structure and its related assumptions. This ensures that the developed model is credible and acceptable. This model approach has shown to be a way forward for ecological decision support in river management in Flanders, but inclusion of additional knowledge on migration behaviour and species interactions could help to improve the predictive accuracy the models in the future.

1. Introduction

The health of freshwater ecosystems is deteriorating worldwide (Carpenter et al., 2011; Vörösmarty et al., 2010). They are under many pressures, including for example hydrological alteration, eutrophication, organic pollution, etc. (Allan, 2004; Carpenter et al., 2011; Malaj et al., 2014). River managers are faced with the challenge of restoring these ecosystems with limited budgets and conflicting demands. It is thus important to understand which stressors should be addressed first when planning river restoration. In light of this, several efforts have been made for the development of decision support tools for river basin managers (Holguin-Gonzalez et al., 2014; Holzkämper et al., 2012; Klauer et al., 2012; Shaw et al., 2012; Shuker et al., 2012; Turak et al., 2011; Volk et al., 2010).

In the past, the focus often remained on process-based simulation models that simulate the effect of diffuse and point source pollutions on the physical–chemical water quality of the rivers (Chapra et al., 2004; Cools et al., 2011). Since the introduction of the European Water Framework Directive (WFD), more effort has been put into the development of ecological models (Everaert et al., 2010; Feio and Poquet, 2011). Often these ecological models are no species distribution models, but rather models related to the ecological quality indices (Klauer et al., 2012; Mouton et al., 2009b; Van Der Most et al., 2006). Unfortunately this approach fails to deliver a thorough ecological insight and it is difficult to incorporate any ecosystem dynamics in the stressor analysis (Stephens et al., 2015). Furthermore, hydromorphology is rarely considered in these efforts, since limited data were available up until recently (Vaughan and Ormerod, 2010; Verdonschot, 2009).

Species Distribution Models (SDMs) are a way forward to evaluate the effect of changing abiotic variables on the ecological status of a river more explicitly (Domisch et al., 2013; Funk et al., 2013).

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http://dx.doi.org/10.1016/j.ecolmodel.2015.12.016

SDMs are often used as a tool to assess impacts of environmental stressors on the species community and therefore the health of the ecological system. The aim of SDMs is to predict the distribution of a single species in a study area given a set of factors constraining the presence of the individuals (Guisan and Thuiller, 2005). Typically, these are empirical models which relate field observations to environmental predictor variables, based on statistically or theoretically derived response surfaces (Guisan and Zimmermann, 2000). In recent years SDMs have gained predictive power. Not only novel statistical techniques related to machine learning have improved SDM performance (Elith and Graham, 2009; Elith et al., 2006; Van Echelpoel et al., 2015), there are also several applications for individual species where conceptual approaches have been successful. An important field where advances have been made is the inclusion of species migration in the models (Boets et al., 2014; Dedecker et al., 2007, 2006; Pauwels et al., 2013; Radinger et al., 2014).

Still, it seems that the application of SDMs in river basin management is limited (Funk et al., 2013; Marsili-Libelli et al., 2013). The reasons for this are threefold. First, the advances in predictive accuracy for one species cannot always be translated to many species at once. Since ecological goals often are defined as a suit of species, for example for WFD applications, having techniques that are applicable for many species is important. Data availability is another limiting factor. Model complexity can introduce many parameters that are hard to estimate, either because the dataset is too small or because the dataset is not suitable for testing the model structures (Guisan and Thuiller, 2005). This means that, for example, interactions between variables often are not included, since testing these interactions increases the parameter space considerably. Third, the usefulness of a decision support system in environmental management also depends on its deemed validity by stakeholders (Junier and Mostert, 2014; Van der Molen and Boers, 2002; Voinov and Bousquet, 2010; Volk et al., 2010). Flexible modelling systems and the inclusion of expert knowledge can increase the trust of end users in the models, as this allows clear communication of assumptions made in the model development (Guisan and Thuiller, 2005; Krueger et al., 2012; Voinov and Bousquet, 2010). To be acceptable for stakeholders, SDMs should consider appropriate spatial scales (Austin, 2002; Jepsen et al., 2005), have a clear indication of sources of uncertainty (Beale and Lennon, 2012; Van der Lee et al., 2006) and allow for the involvement of stakeholders during model development (Voinov and Bousquet, 2010; Volk et al., 2010).

Grounding SDMs in ecological concepts, such as the Spatially Explicit Species Assemblage Modelling (SESAM) concept as presented by Guisan and Rahbek (2011) could overcome some of these hurdles. Not only could such approaches advance scientific understanding (Austin, 2007), they also provide a pragmatic method for the development of SDMs for many species at once and allow the inclusion of expert knowledge.

We have developed and implemented a model approach to predict aquatic macroinvertebrate assemblages based on the SESAM concept using both data and expert knowledge. The approach is grounded in two ecological theories: the niche theory (Hirzel and Le Lay, 2008), specifically the niche characteristics, and the landscape filter theory (Poff, 1997). In this paper, we present the model approach, the model development process and its implementation for aquatic macroinvertebrates in Flanders. We have implemented the method for many species simultaneously and have selected the most optimal model structure based on the overall highest performance for all species. The method is validated in terms of its accuracy by using statistical criteria and its ecological validity by using expert knowledge. Advantages and drawbacks of the used methodology for freshwater ecosystem management are assessed in the discussion.

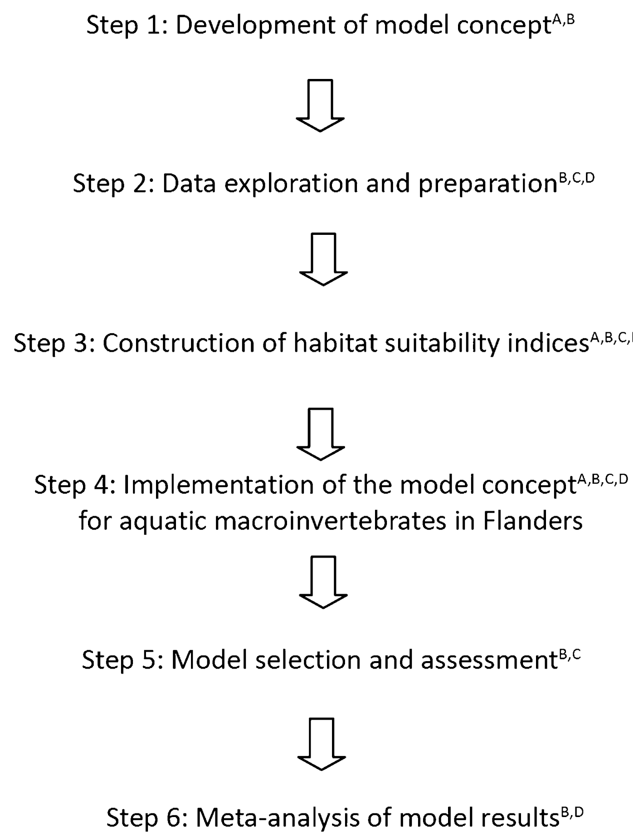

Fig. 1. Overview of the 6 steps in the research outlined in this paper. In subscript to each step is indicated what input was used for this step, with (A) general ecological theory, (B) expert judgment and stakeholder consultation, (C) data from the Flemish monitoring programme and (D) other databases on ecological preferences of macroinvertebrate species.

2. Materials and methods

2.1. Overview of model development process

The research presented in this paper existed of 6 steps (Fig. 1). In a first step, the general model concept was developed based on general ecological theory and stakeholder consultation (Section 2.2). Second, all Flemish monitoring datasets of macroinvertebrate species and abiotic variables were combined and explored (Section 2.3). Stakeholder needs were taken into account for the variable selection and the data preparation. In the third step, the method for the construction of the individual habitat suitability indices was developed (Section 2.4) based on general ecological concepts and using both Flemish data as data on ecological preferences. The method was evaluated with expert consultation. Next, the specific details for the implementation of the full model concept resulting from step 1 were decided upon with consideration for the available data and stakeholder needs (Section 2.5). In step 5 (Section 2.6), we performed model selection and calibration of the final model structure using cross-validation. Model selection criteria were decided upon after stakeholder consultation. A performance assessment of the final model structure was done with an independent test set. In a final step (Section 2.7), we performed a meta-analysis of the model validation results in terms of their ecological validity.

2.2. Model concept

The general model concept is based on the landscape filter theory (Poff, 1997) and niche theory (Hirzel and Le Lay, 2008). The