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Short communication

Univariate functions versus fuzzy logic: Implications for fish habitat modeling

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ABSTRACT

Univariate functions, like the Habitat Suitability Criteria (HSC) for each species life-stage, consider separate effects of individual parameters. Other than using independent univariate functions, knowledge-based models as the fuzzy logic approach are based in the establishment of fuzzy sets and rules for each species life-stage built on a fish biologists' expert judgment. Nonetheless, results from HSC and fuzzy logic may differ significantly and, thus increase the difficulty to choose between these two approaches. With the aim to compare and assess differences from using HSC and fuzzy logic methodologies, the habitat requirements for the Southwestern arched-mouth nase (*Iberochondrostoma almacai*), partitioned by life-stages, were set based on data collection and on expert judgment. The Weighted Usable Area (WUA) and Hydraulic Habitat Suitability (HHS) were calculated by means of a two dimensional model using the HSC and considering three different mathematical combinations of the independent parameters (i.e. product, arithmetic mean and geometric mean) and using the fuzzy logic approach. Simulations yielded different results, especially for the young-of-year (YOY), therefore affecting the final profile habitat versus discharge curves. Knowledge on species requirements proved to be scarce, thus, preventing the attainment of conclusive results. The product combination of the HSC returned the lowest habitat values, whereas the arithmetic mean stepped closer to the fuzzy logic habitat results. Discharge thresholds obtained were substantially different among the different mathematical combinations of HSC and fuzzy logic. Habitat outputs translated in HHS exhibited a clear maximum value of habitat for a specific discharge, whereas the WUA versus discharge curves performed an asymptotical trend disabling the selection of a discharge threshold. Results from this study suggest the use of HHS as the habitat output and the use of HSC when expert knowledge over a species is scarce.

1. Introduction

The Habitat Suitability Index (HSI) is a data-driven approach to analyze the habitat preference that describes the frequency of an individual of a specific species or life-stage occupying a microhabitat compared to the relative frequency of that microhabitat in the environment. The HSI can be represented as a function of the univariate Habitat Suitability Curves (HSC) that represent the degree of preference displayed by the fish over the abiotic variables of depth, velocity, substrate and cover. HSI obtained for each physical factor can be combined by means of the product, the arithmetic mean and the geometric mean. The former is based on the assumption that fish select each particular variable independently of other (Bovee, 1986), thus, the product approach assumes that unsuitable habitat conditions based on one variable cannot be compensated by good conditions on the basis of others (e.g. Lee et al., 2010). This method returns the lowest habitat values. The geometric mean assumes that each environmental variable is equally important (e.g. Yi et al., 2014). It can represent the nth root of the product of n individual indices (e.g. the fourth root of the product of four indices; Boavida et al., 2013). This approach also implies some compensation (Korman et al., 1994), yet like the product equation, it yields zero suitability for any zero-valued HSI. In contrast, the arithmetic mean assumes that good habitat conditions based on one variable can compensate for poor conditions of another. This spectrum of mathematical calculations will inevitably return different

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habitat values which should be accurately assessed. Furthermore the univariate functions (i.e. HSC) have been criticized over the years because results are user dependent and the habitat preferences applied need to be developed for a specific reach and thus, not easily transferable to other rivers (e.g. Freeman et al., 1997; Moir et al., 2005).

The fuzzy logic (Zadeh, 1965), a knowledge-based method, applied to the habitat requirements of aquatic species appears to overcome these issues. Expert judgment from experienced rivers biologists is translated into linguistic categories instead of precise numbers, disabling uncertainty that often exists in ecological modeling. Furthermore it can consider multivariate effects of variables without the assumption of independence of the input parameters. Finally, new parameters can be added and it is relatively easy to use (Jorde et al., 2001). Moreover, when data on species requirements is scarce or requires time-consuming data collection, the fuzzy logic approach arises as the best methodology (e.g. Adriaenssens et al., 2004).

Normally, outputs from habitat models are expressed as Weighted Usable Area (WUA) (Bovee, 1986) – the area that can potentially be used by a given fish life-stage, but they can also be set as the Hydraulic Habitat Suitability (HHS) (Stalnaker et al., 1995) – the ratio between the WUA and the total wetted area (defined between 0 and 1). These two variables integrate the overall habitat suitability on a reach considering a steady state. As habitat modeling tools are applied in a wide range of water management actions, key topics are the formulation of habitat requirements and the adaptability of a model for the specific objectives of the habitat study. In fact, the habitat output and their interpretation can be highly different whether we consider univariate preference functions or fuzzy logic, or even when we choose to interpret results based on WUA or HHS, leading to misleading conclusions.

In this paper we compare univariate preference functions and fuzzy logic while assessing the habitat suitability for the Southwestern arched-mouth nase. Our specific objectives were: (1) to use fuzzy rules set by expert knowledge and HSC generated from in situ data collection to evaluate the habitat suitability for the nase; (2) to compare habitat suitability considering the HSC different calculation methods of variables and considering the fuzzy-logic; and (3) to assess differences in habitat outputs (namely whether to consider WUA or HHS).

2. Materials and methods

2.1. Data collection

The study was carried out in the Odelouca River (987 km^2 and 80 km long), the largest tributary of the Arade Basin, Southwest Portugal. A typical native species of the basin is the Southwestern arched-mouth nase (*Iberochondrostoma almacai*) (hereafter 'nase'). However this species is now scarce in the lower part of the basin as a result of habitat alteration and, therefore, is considered critically endangered (Cabral et al., 2006). A study site representative of the river segment was selected in the lower course of the Odelouca River, with a modular discharge of 4.05 m^3/s. Riverbed topography was surveyed at the study site by sampling 4129 spots. To calibrate the model, a series of points were located along cross-sections where significant alterations in depth, water velocity, substrate composition and slope were noted. Water velocity and depth were measured at these series of points. Additionally, substrate composition was visually assessed using a modified Wentworth scale (Bovee, 1986) [(0) organic material detritus; (1) silt, clay, loam; (2) sand < 2 mm; (3) fine gravel 2–6 mm; (4) medium gravel 6–20 mm; (5) large gravel 2–6 cm (6) small stones 6–12 cm; (7) large stones 12–20 cm; (8) boulders > 20 cm; and (9) rock].

Nase populations were sampled at four undisturbed or minimally disturbed sites (mean water depth: 32.1 ± 1.4 cm SD; mean water velocity: 5.2 ± 0.8 cm/s SD) in the Odelouca catchment in order to reflect the optimal habitat of species and not an externally imposed displacement toward sub-optimal situations. Species stratification was made into three size-classes based on reported differences in length and age structure: <5, 5–7 and >7 cm, roughly corresponding to the fish life-stages young-of-year (YOY, 0+), juveniles (1+), and adults (>1+). Further details about site locations, sampling procedures and microhabitat measurements are given in Santos and Ferreira (2008).

2.2. Data analysis

HSC were developed for the three target fish-size classes. Microhabitat variables (depth, velocity and substrate) were divided into classes and histograms of frequencies of use and availability were built. The HSI was calculated as the ratio between proportional use and availability, and then normalized, dividing by the maximum suitability value so that the minimum value was 0 and the maximum was 1. Data on depth, velocity and substrate availability of the river reach was translated into fuzzy sets in order to develop the fuzzy model. Expert knowledge from experienced fisheries ecologists with the target species defined the fuzzy rules with no data collection information. The river expertise was supported by past field experience and available literature (Coelho et al., 2005; Santos and Ferreira, 2008).

The River2D model (Steffler and Blackburn, 2002) was applied to simulate the hydraulic conditions in the river reach. The boundary conditions were established with field data (discharge and water surface elevations) and HEC–RAS simulations. Discharge was assumed to be constant, as no tributaries joined the study reach. Different bed roughness coefficients were estimated in accordance with observations of bed material and bedform size. The final values were obtained by calibrating the model results to the measured water surface elevations and the water velocity profile in different cross-sections. The CASiMiR Fish 2D model (Schneider et al., 2010) was used to model the habitat availability, by integrating biological preference data – either by using the HSC or the fuzzy sets and rules – with the River2D outputs – depth, velocity and substrate maps – to calculate the WUA and the HHS. Integration of HSC was made considering different mathematical combinations of depth (DSI), velocity (VSI) and substrate (SSI) – product, arithmetic mean and geometric mean – to calculate the composite habitat suitability index (HSI_i). Habitat availability considering the fuzzy sets and rules was also made in the CASiMiR Fish 2D model. For each cell, the membership degree of these values to the fuzzy sets of the corresponding variable defined the degree of fulfillment of each rule. Then, the fuzzy sets of the habitat suitability are weighted with degree of fulfillment and combined to a final fuzzy set. At the end, this final fuzzy set is transformed back into a standardized crisp number expressed as HSI, between 0 and 1 representing unsuitable and the most suitable habitat respectively. This last step, known as defuzzification, is made considering the Center of Gravity of the possibility distribution (area under the combined fuzzy set) of the inferred fuzzy output which is the most commonly used approach (Mocq et al., 2013; Ahmadi-Nedushan et al., 2008).

The WUA was than calculated multiplying the dimensionless HSI by the contributing area (i.e. the local area surrounding each model node) (Eq. (1)). To eliminate the influence of the wetted area in order to facilitate model comparisons between sites, the