HABITAT SUITABILITY MODELS AS TOOLS FOR IMPLEMENTING THE "ECOHYDRAULIC TRINITY"

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Habitat suitability models are being widely used for the simulation, under different spatial and temporal scales, of the instream habitat availability for aquatic and riparian species or communities. Their great potential can be also exploited for designing natural like fish-passes in the implementation of the so-called "ecohydraulic trinity": environmental flows (e-flows) assessment, re-establishing river continuity and designing river restoration measures. Indeed, nature-like fish passes can provide both e-flow releases and suitable habitat not only for fish, but for the entire aquatic community. We discuss from a theoretical point of view the potential of the integrated application of these modelling tools with particular regard to the microhabitat and mesohabitat scale approaches (e.g., PHABSIM, Bovee et al., 1982, MesoHABSIM, Parasiewicz et al., 2013). Advantages and limitations of each approach are highlighted and the application domain of each modeling approach is assessed. Results show, on the one hand, the advantages of the mesohabitat scale when channel slope and morphological complexity increase. Whereas, on the other hand, the microhabitat scale demonstrates effectiveness to evaluate potential habitat for motionless organisms, such as, freshwater pearl mussels. Limitations are related to the application of established hydraulic simulation models in the case of coarse substrate, limited water depth and gradient higher than 2%.

1 HABITAT SUITABILITY MODELS (HSMs): MICRO- AND MESO-SCALE APPROACHES

Modeling the watercourse hydro-morphology and its relations with stream biota allows us to quantify and evaluate the suitability of the available habitat for aquatic organisms under specific environmental conditions [1;2]. Habitat suitability models (HSMs) provide biophysical templates [3;4] assuming correspondence between the physical settings and the biological community structure [5] by statistically relating physical variables (flow, geomorphology, chemical parameters, etc.) to a biological response found by field observations of the organisms, providing in this way a prediction of the locations that have potential (suitability) for use by the targeted species [6].

HSMs based on micro-habitat scale level such as the physical habitat simulation model (PHABSIM [7,8]) are the most common and widely used techniques to evaluate habitat suitability related to streamflow alterations. Micro-habitat scale HSMs are focused on small spatial scales and use univariate habitat suitability curves, taking into account habitat variables such as water depth, velocity and substrate separately [9]. Their approach emphasizes cross-sectional over longitudinal variations, requiring a time-consuming data collection procedure [10] and data interpolation between consecutive cross-sections, which is representative mainly for perennial low/moderate-gradient streams [11] with regular morphology. Furthermore, for streams with gradients higher than 2% or with a varied morphology (i.e. pluricursal or with macro-roughness elements with height comparable to the water depth) the use of 1D hydraulic models or the calibration of 2-3D ones becomes critical, thus limiting their application range; in any case these models need detailed bed topography surveys which may lead to extensive efforts for field data collection [12] even for very short stream reaches, severely affecting the representativeness of the analysed study site.

Meso-habitat scale HSMs have been recently developed, showing a considerable potential requiring less extrapolation to provide output at larger spatial scales [13]. This approach considers hydromorphological units (HMUs e.g. pools, riffles and rapids) and mesohabitats as functional habitats, i.e. areas where animals can be observed for a significant portion of their diurnal routine. Meso-habitat scale resolution of freshwater fish habitat changes the methodological approach and the analytical procedures compared to the traditional micro-habitat ones, allowing longer length of surveyed rivers, involving a larger range of habitat variables (e.g. by multivariate statistical techniques such as Random Forests (RF) and Logistic Regressions (LR), see [14]) and enabling understanding of fish behaviour at larger spatial scales. Furthermore, significant ecological variables such as cover types, water surface gradient in the HMU, interactions among species (and even among different life stages and with other taxonomic and functional groups) can be included in the evaluation with the meso-scale approach. Meso-habitat scale HSMs require a river to be mapped at several discharges and can avoid the use of hydraulic models for discharge simulation, representing the best choice available in high-gradient [15] and/or morphologically complex streams.

2 IMPLEMENTING THE "ECOHYDRAULIC TRINITY"

HSMs can be used for the simulation, under different spatial and temporal scales, of the instream habitat availability for aquatic and riparian species or communities. Their great potential can be also exploited in the implementation of the so-called "ecohydraulic trinity": environmental flows (e-flows) assessment, re-establishing river continuity with natural like fish passes and designing river restoration measures. In the following sections the possible approach for this implementation is briefly discussed from a theoretical point of view.

2.1 HSMs for e-flows assessment

The use of HSMs is generally aimed at identifying a relationship between streamflow and physical habitat for targeted species (from a single species life stage to a whole fish community) which allows us to determine and evaluate the e-flow to be released at water abstraction sites.

As a standard reference [13;15], the sequence of the main steps of the MesoHABSIM methodology can be outlined:

- Habitat description: representative site selection and habitat survey (river morphology and physical attributes collection) at different discharges (3-4 flow condition over the range of investigated flows); creation of mesohabitat maps and geodatabase of habitat features (depth, velocity, substrate, cover, etc.) for each discharge
- Biological model: mesohabitat sampling and biological models construction (and) or identification of validated (multivariate) habitat suitability models available in literature applicable to the reference fish community/target species
- Habitat-flow rating curve and habitat time series: application of the biological models to the habitat features geodatabase; identification and weighting of the area of HMUs with suitable (or optimal) habitats and plot against the channel area; construction of the habitat-flow rating curve for each target species and/or fish community; analysis of flow time series and identification of habitat stressor thresholds (HST)

The outcomes of this procedure (habitat-flow rating curves and habitat time series) can then be used during the decision making process for water resources planning to define the flow values to be released at the investigated site (new or existing water abstractions).

2.2 HSMs for nature-like fish pass design/evaluation

When planning the restoration of fish migration routes through the construction of fish pass at man-made obstacles (dams, weirs, etc.) the feasibility of providing a nature-like bypass channel should be the first option to be investigated. Such devices usually require the availability of large areas along the river bank due to their limited mean slope (0,3-3%) and should be designed mimicking the natural characteristics of streams of the same or neighboring watersheds [16;17]. Besides restoring the river continuity for fish, these type of devices can provide suitable habitats and spawning grounds for some species and therefore, can act as a river restoration measure. Furthermore, nature-like fish pass can be used for passing a large proportion, in some cases up to 100%, of the total flow to be released, becoming the main technical element to be introduced for complying with e-flow legal requirements. Therefore, in this way, a nature-like fish pass by itself encompass the three pillars of the "ecohydraulic trinity".

HSMs can have a significant potential both for the design and for the evaluation of nature-like fish pass. Since they should mimick local streams with regards to slope, geometry and morphology, hydrodynamic patterns, structures, substrate and materials [16], the approach of habitat mapping proposed by MesoHABSIM can be used to identify common features and sequences of mesohabitats of representative tributaries or small streams of the considered watershed, to be adopted as reference templates for the design of the fish pass; by coupling them with biological models validated for targeted species, the course of the fish pass can be designed providing adequate physical attributes that can maximize the areas with availability of optimal or suitable habitats at varying discharges (according to the reservoir and tailrace level fluctuations). This innovative approach can provide an added value to the traditional design procedure, usually just focused at keeping flow velocities, water depths and energy dissipation values within acceptable ranges defined for the targeted species/families. The micro-scale HSMs can be used when the by-pass channel is designed with a regular morphology and low or almost constant slope, exploiting the potential of 1 or 2D hydraulic models; however, because of the need for (i) mimicking the natural heterogeneity of the watercourse, (ii) inserting boulders and other structures to provide energy dissipation and resting areas and (iii) introducing high-gradient portions along the fish pass to comply with usual space limitations (i.e. limiting the total length of the device), the meso-scale approach can be generally considered more appropriate. HSMs can also be used in evaluating existing nature-like by-pass channels, identifying possible improvements to be introduced (e.g. modifying the channel morphology; e.g. [18]) aimed at increasing the availability of suitable habitats, thus maximizing the use of these devices not only for passage but also like a real river restoration measure (even though just at a limited local scale).

2.3 HSMs for river restoration design/evaluation

River restoration planning frequently lacks the identification of benchmarks for evaluating the success of the introduced measures [19]; these targets should consist of quantitative descriptions of expected ecological benefits and should allow the analysis of alternatives using adequate metrics [5]. To quantify the improvement of the status of the concerned aquatic communities through biological observations can be very complex (temporal scale for recovery of populations, influence of biological and hydrological variability, limited efficiency of monitoring techniques, etc.); therefore, Parasiewicz *et al.* [5] proposed an alternative quantitative approach using the spatial unit of physical habitat suitable for the reference aquatic community as a more pragmatic metric in describing current and expected status [5]. By using meso-scale HSMs (MesoHABSIM), the procedure consists of developing suitability criteria for the target reference aquatic community structure, mapping the current instream habitat conditions of the watercourse and identifying the biophysical templates to be adjusted to reflect reference hydro-geomorphological characteristics; through this approach the possible adjustments to the physical attributes of the stream can be identified in order to create a hydrogeomorphic structure matching the desired biological requirements for the reference target community [20]. Reference flow patterns must be investigated and the analysis of habitat time series can allow the identification of habitat stressor thresholds (duration and frequency of non-exceedance events) in order to provide adequate input, where applicable, for e-flow management at local and/or watershed scale. Under this scenario, two habitat indices were recently proposed [21] to quantify the impact of hydro-morphological alterations on the aquatic communities, assessing the spatial and temporal variation of instream habitat resources: the Index of Spatial Habitat availability (ISH), used to describe the relative amount of habitat loss due to a specific pressure (e.g., water withdrawals, hydropeaking, sediment releases from dams), and the Index of Temporal Habitat availability (ITH), used to measure the increase of continuous duration of events when habitat bottlenecks create stress to the fauna. These indices are currently under development and are showing a great potential also for the assessment of the ecological status when biological indicators cannot be applied (e.g., when fish community indices are affected by massive re-stocking and artificial management of local populations)

3 CONCLUSIONS

HSMs quantitatively relate the physical patterns of a watercourse to an expected biological response and can predict locations that have potential for use by targeted species or aquatic communities. These models, in their traditional setup (micro-habitat scale) have already found a wide use, while the more recent meso-habitat scale approach is being increasingly studied, showing a great potential for a wider application range. Main advantages and limitations of each approach have been highlighted in this paper, showing the advantages of the meso-habitat scale HSMs (MesoHABSIM) when channel slope and morphological complexity increase, whereas the micro-habitat scale HSMs demonstrate effectiveness to evaluate potential habitat for motionless organisms, such as, freshwater pearl mussels, or for applications in low-gradient watercourses of more regular morphology, being their main limitations related to the application of established hydraulic simulation models in the case of coarse substrate, limited water depth and gradient higher than 2%.

Applications of the HSMs as tools for the implementation of the “ecohydraulic trinity” (e-flows, fish pass, river restoration) have been briefly discussed from a theoretical point of view, outlining the potential for the innovative use of these tools for designing and evaluating nature-like fish pass and river restoration measures. While for the e-flows evaluation, which is their current main field of application, examples of successful implementation are already available in the scientific literature, further research is certainly needed for testing and validating their effectiveness for designing and evaluating nature-like fish passes and providing a framework for quantitatively assess river restoration measures even at watershed level.

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