Meso-scale habitat modeling for river macroinvertebrate communities
Modélisation de l'habitat à méso-échelle pour les communautés de macro-invertébrés des rivières

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RÉSUMÉ
Les communautés de macroinvertébrés sont rarement considérées comme des cibles écologiques dans les modèles d'habitat fluvial, qui se concentrent souvent sur une seule espèce de poisson. Cette étude propose une nouvelle approche pour modéliser la réponse de l'ensemble de la communauté de macroinvertébrés à la modification du régime d'écoulement. Le modèle utilise l'indice Flow-T combiné à la régression Random Forest (RF) pour évaluer la disponibilité de l'habitat à l'échelle méso. Mené dans trois rivières italiennes avec une morphologie en tresse, des lits de rivière en gravier et des débits estivaux faibles, le modèle a été calibré dans la rivière Trebbia (en utilisant les données de terrain collectées en 2019) et validé à travers les rivières Trebbia, Taro et Enza (avec des données collectées en 2020). Le modèle RF identifie comme les plus importants 12 descripteurs de mésohabitat, y compris la profondeur de l'eau, la vitesse d'écoulement, la taille du substrat et la connectivité du canal, avec une validation croisée (R^2 = 0,71) et des tests (R^2 = 0,63) montrant une grande précision. Le modèle prédit efficacement les réponses des communautés de macroinvertébrés aux changements de régime d'écoulement et étend la méthodologie MesoHABSIM à une nouvelle cible écologique. Cette approche offre des applications potentielles pour la conception de débits écologiques (e-flows) dans les rivières pérennes et non pérennes, y compris les systèmes fluviaux sans populations de poissons.

ABSTRACT
Macroinvertebrate communities are rarely considered as ecological targets in river habitat models, which often focus on single species of fish. This study provides a novel approach to model the whole macroinvertebrate community response to flow regime alteration. The model uses the Flow-T index combined with Random Forest (RF) regression to assess habitat availability at the meso-scale. Conducted in three Italian rivers with braided morphology, gravel riverbeds, and summer low flows, the model was calibrated in the Trebbia River (using the field data collected in 2019) and validated across the Trebbia, Taro, and Enza Rivers (with data collected in 2020). The RF model identifies as most important 12 mesohabitat descriptors, including water depth, flow velocity, substrate size, and channel connectivity, with cross-validation (R^2 = 0.71) and testing (R^2 = 0.63) showing high accuracy. The model effectively predicts macroinvertebrate community responses to flow regime changes and extends the MesoHABSIM methodology to a new ecological target. This approach offers potential applications for ecological flow (e-flows) design in perennial and non-perennial rivers, including river systems without fish populations.

KEYWORDS

Ecological flows, Ecological responses, Macroinvertebrate communities, Mesoscale habitat modelling, Random Forest. Flux écologiques, Réponses écologiques, Communautés de macro-invertébrés, Modélisation de l'habitat à méso-échelle, Random Forest.

1 INTRODUCTION

Macroinvertebrates are vital for river ecosystems, playing a crucial role in the food chain and serving as bioindicators of ecological status (Melcher et al., 2018). Although flow alterations affect macroinvertebrate communities, especially during high and low flow events, their habitat needs are often overlooked in habitat modeling. Existing models such as MesoHABSIM (Meso-HABitat Simulation Model, Parasiewicz et al., 2001) have been primarily used for fish species, with limited applications for macroinvertebrates (Vezza et al., 2016). Burgazzi et al. (2021) emphasize that the mesohabitat scale has potential to represent the distribution of macroinvertebrate communities and supports its application in macroinvertebrate habitat modeling. To characterize the community response to flow variation, several indices have been developed in the last years. Among them, the Flow-T index (Laini et al., 2022) was shown to effectively describe the community's response to flow variations and the assemblage of taxa across different mesohabitat types.

This study aims to fill this gap by developing a meso-scale habitat model for the whole macroinvertebrate community, using the trait-based Flow-T index. A machine learning technique was employed to calibrate and validate the model in three Italian rivers (Trebbia, Taro, and Enza). The main research objectives are to extend the MesoHABSIM methodology to a new ecological target and to provide a new module for the application in the SimStream-Web service.

2 MATERIAL AND METHODS

2.1 Study area

This study was conducted in three rivers (Trebbia, Taro, and Enza) located in Northern Italy, characterized by braiding morphology and gravel riverbeds. The study focused on low-flow conditions, which are critical for aquatic biota due to reduced wetted area and low flow velocities. Field campaigns were conducted in the summer of 2019 and 2020. The model was trained using data collected in the Trebbia River in the field campaign of 2019 and tested in Trebbia, Taro, and Enza Rivers with data collected in the year 2020.

2.2 Methodological Steps

The system description is based on a multidisciplinary approach involving topographic and hydromorphological characterization, and macroinvertebrate sampling and analysis. Uncrewed Aerial Vehicle (UAV, DJI Mavic 2 Pro) was used for photogrammetry, providing high-resolution RGB orthomosaics and Digital Terrain Models (DTMs) of the river reaches. Macroinvertebrate samples were collected using a surber net simultaneously to the physical habitat description. The replicates were distributed along the river reaches, in order to ensure representative sampling of all the mesohabitat types.

Bathymetric surveys were conducted with an Acoustic Doppler Current Profiler (ADCP) and GNSS to map the riverbed elevation. A bathymetric linear model was calibrated to reduce errors in shallow water depths. Hydrodynamic simulations were carried out using the HEC-RAS software, obtaining the distribution of water depth and flow velocity along the river reaches. The riverbed substrate composition was classified following what the MesoHABSIM approach (Vezza et al., 2017).

Random Forest (RF) regression was then applied to model macroinvertebrate community responses to mesohabitat physical characteristics, using the Flow-T index as dependent variable. Developed in R (randomForest package), the model was trained using the dataset built in Trebbia river (2019) and validated on the Trebbia, Taro, and Enza (2020) dataset. Predictor importance was assessed using Mean Decrease in Accuracy (MDA), selecting significant variables, while a correlation matrix minimized collinearity. Partial Dependence Plots (PDPs) visualized relationships between predictors and the Flow-T index.

The Random Forest (RF) model was integrated into the SimStream-Web platform (https://mesohabsim.isprambiente.it/), provided by the Italian Institute for Environmental Protection and Research (ISPRA) to extend the MesoHABSIM methodology for macroinvertebrate communities. This web service allows users to input hydromorphological data and generates geo-referenced habitat maps, habitat-flow rating curves, and time series for the Habitat Integrity Index (IH) calculation. Adapted for the Flow-T index, SimStream-Web enables two analyses: (i) creating Flow-T maps in GIS format to visualize index values at the mesohabitat scale and (ii) generating Flow-T rating curves, showing Flow-T variation with discharge and wetted area at the reach scale.

3 RESULTS

A total of 360 macroinvertebrate samples were collected across 3 studied rivers. Overall, 317 mesohabitats were identified and categorized into 5 types: *glide, riffle, pool, backwater,* and *isolated pond*. The photogrammetric surveys provided 4 high-resolution orthomosaics and 4 DTMs, with bathymetric data collected through ADCP. The hydrodynamic simulations were performed with a mesh size of 1 m, and provided raster maps of flow velocity and water depth with a ground resolution of 10 cm.

The Random Forest (RF) model identified 12 variables, among substrate type, water depth, flow velocity and connectivity, as significant predictors of the Flow-T index. The model showed that higher velocities and certain substrate types (e.g., *microlithal*) positively influenced the Flow-T index, while finer substrates (i.e., *pelal*) had a negative impact. Connectivity to the main channel was also a crucial factor, with mesohabitats connected to the main channel having higher Flow-T values. The model's predictive accuracy was high, with R^2 values of 0.71 for calibration and 0.63 for validation.

The SimStream-Web platform now supports macroinvertebrate community modeling using the Flow-T index. Users can obtain Flow-T maps and Flow-T rating curves as results of the application.

4 DISCUSSIONS AND CONCLUSION

This research contributes to developing a mesohabitat model focused on the trait-based Flow-T index (Laini et al., 2022), able to evaluate the effects of hydromorphological changes on macroinvertebrate communities. It may broaden the range of ecological targets used by the MesoHABSIM methodology and results in a specific module for macroinvertebrates in the SimStream-Web service. The model demonstrated satisfactory predictive power and reliability during summer low flows, but requires further validation for other flow conditions. The approach, accessible via SimStream-Web, allows for the assessment of macroinvertebrate spatial distribution and ecological responses to flow and morphological changes at both mesohabitat and reach scales.

Although based on a limited number of watercourses and requiring further validation across diverse morphological and seasonal contexts, the approach has proved robust and has potential for applications. These findings may contribute to an ecologically integrated forecasting framework applicable for e-flows design, able to consider different ecological targets (fish and macroinvertebrates), in perennial and non-perennial rivers.

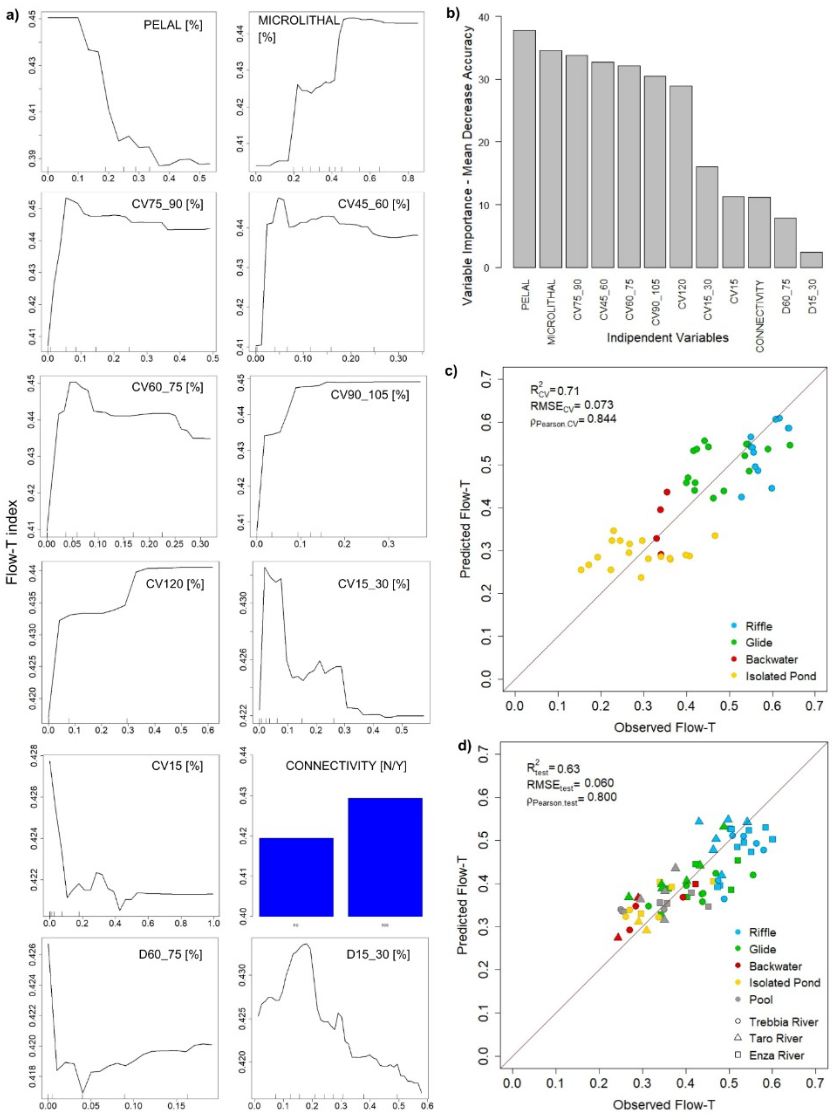

Figure 1. a) RF Partial Dependence Plots of the most important mesohabitat descriptors, b) variable importance ranking, c) scatter-plot of observed vs predicted Flow-T in cross-validation, and d) in true validation using the independent data collected in 2020.

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