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Research article

Physical habitat modeling for river macroinvertebrate communities

Beatrice Pinna[a,*], Alex Laini[b,1], Giovanni Negro[a], Gemma Burgazzi[b,1], Pierluigi Viaroli[b], Paolo Vezza[a]

[a] Department of Environment, Land and Infrastructure Engineering, Polytechnic University of Turin, Turin, Italy
[b] Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parma, Italy

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ABSTRACT

Habitat models rarely consider macroinvertebrate communities as ecological targets in rivers. Available approaches mainly focus on single macroinvertebrate species, not addressing the ecological needs and functionality of the whole community.

This research aimed at providing an approach to model the habitat of the macroinvertebrate communities. The study was carried out in three rivers, located in Italy and characterized by a braiding morphology, gravel riverbeds, and low flows during the summer period. The approach is based on the recently developed Flow-T index, together with a Random Forest (RF) regression, which is employed to apply the Flow-T index at the mesohabitat scale. Using different datasets gathered from field data collection and 2D hydrodynamic simulations, the model was calibrated in the Trebbia River (2019 field campaign) and validated in the Trebbia, Taro, and Enza rivers (2020 field campaign).

The RF model selected 12 mesohabitat descriptors as important for the macroinvertebrate community. These descriptors belong to different frequency classes of water depth, flow velocity, substrate grain size, and connectivity to the main river channel. The cross-validation R^2 coefficient (R^2_{cv}) of the training dataset was 0.71, whereas the R^2 coefficient (R^2_{test}) for the validation dataset was 0.63. The agreement between the simulated results and the experimental data shows sufficient accuracy and reliability. The outcomes of the study reveal that the model can identify the ecological response of the macroinvertebrate community to possible flow regime alterations and river morphological modifications.

Lastly, the proposed approach allowed to extend the MesoHABSIM methodology, widely used for the fish habitat assessment, to a different ecological target community. Further applications of the approach can be related to ecological flows design in both perennial and non-perennial rivers, including river reaches in which fish fauna is absent.

1. Introduction

Rivers are increasingly subject to hydromorphological pressures and are among the most endangered ecosystems in the world (Dudgeon et al., 2006; Van Rees et al., 2021). Dams and barriers on rivers, pollution, and overwhelming water consumption are among the most threatening factors. European rivers are highly fragmented by artificial structures (Belletti et al., 2020) resulting in altered flow regimes, that may be further impacted by climate changes and increasing water demand (Schneider et al., 2013).

Macroinvertebrates are fundamental for the functioning of river ecosystems because they play an essential role in the entire food chain, being secondary producers and consumers at an intermediate trophic level. They are the main source of food for fish, amphibians, and aquatic birds (Melcher et al., 2018). Important processes like nutrient cycles, decomposition, or primary production are influenced by macroinvertebrates and their conservation must be kept into account for effective river management (Carter et al., 2017; López-López and Sedeño-Díaz, 2015; Wallace and Webster, 1996). Macroinvertebrate community structure is sensitive to flow regime alteration, and it is affected by the occurrence of high and low flows (Doretto et al., 2019; Wood et al., 2000). Macroinvertebrates can be easily found in most

* Corresponding author. Department of Environment, Land and Infrastructure Engineering, Polytechnic University of Turin, Corso Duca degli Abruzzi 24, 10129, Turin, Italy.
E-mail address: beatrice.pinna@polito.it (B. Pinna).
[1] Present address: Department of Life Sciences and Systems Biology, University of Turin, Turin, Italy.

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aquatic systems, and their role as bioindicators of ecological status is largely supported in Europe and all over the world (Bonada et al., 2006; Gresens et al., 2010; Melcher et al., 2018).

River habitat modeling rarely considers macroinvertebrates as ecological targets for analyses. The lack of consistency about their response to flow alteration (Poff and Zimmerman, 2010) complicated their use in ecological flows (eflows) design or river restoration actions (Mérigoux et al., 2009). Available approaches mainly focus on single species, not addressing the ecological needs and functioning of the whole community. Macroinvertebrate habitat models for single species were developed at the micro and mesohabitat scales. At the microscale, Li et al. (2009), Mérigoux et al. (2009), and Shearer et al. (2015) developed different types of models for one or more macroinvertebrate taxa. As a supplement of the IFIM (Instream Flow Incremental Methodology, Bovee & Milhous, 1978), Gore (1977, 1978) attempted to use one species or group of species as indicator for instream flow assessment. At the mesoscale, Parasiewicz et al. (2012) developed a meso-scale habitat model (using the MesoHABSIM approach) for the dwarf wedgemussel (*Alasmidonta heterodon*), whereas Vezza et al. (2016) proposed a meso-scale habitat approach for the endangered European crayfish (*Austropotamobius pallipes*). Parasiewicz et al. (2008) selected one of the most flow-sensitive orders of benthic macroinvertebrates (*Odonata*) as a target of a habitat model on the Lamprey River (USA).

Given the large number of taxa and the complexity of their spatial distribution, it becomes of crucial importance to develop approaches able to capture the ecological functionality of the whole macroinvertebrate community. Few studies discussed the appropriate spatial scale to explain the linkage between the physical habitat's conditions and the community assemblage. Burgazzi et al. (2021) highlight that the mesohabitat scale (i.e., the geomorphic unit scale) has the potential to describe the distribution of the whole macroinvertebrate community and support the use of the mesohabitat scale for macroinvertebrate habitat modeling. Indeed, the mesohabitat scale allows building biological models with a wider variety of hydromorphological variables, evaluating the community composition at a larger spatial scale (Parasiewicz et al., 2013; Burgazzi et al., 2021). However, all the meso-scale habitat models available in literature (Mesohabitat Evaluation Model – MEM, Hauer et al., 2009, 2011; MesoCASiMiR, Noack et al., 2013; and MesoHABSIM, Parasiewicz, 2007) are mostly focused on fish as ecological targets and just very few applications of the MesoHABSIM model are currently available for macroinvertebrates (Parasiewicz et al., 2013; Vezza et al., 2016).

To characterize the macroinvertebrate response to flow regulation several biological indices have been developed in the last decade, mostly considering the linkages between community composition and flow velocity (Rheoindex, Banning, 1990; LIFE index, Extence et al., 1999; ELF index, Theodoropoulos et al., 2020; MESH index, Timm et al., 2011). Indeed, flow velocity strongly shapes macroinvertebrate community functions (Poff et al., 2010), such as respiration and feeding (Petts, 1984; Wright et al., 1994). Interestingly, the recently proposed Flow-T index (Laini et al., 2022) has been based on the *'current velocity'* ecological trait (Tachet et al., 2010) and tested with an international dataset (from Italy, UK, Cyprus), demonstrating good transferability performance (Laini et al., 2022). The Flow-T index was also revealed to be effective in describing the community response to flow variation and the assemblage of taxa in different types of mesohabitats (Laini et al., 2022).

The main aim of the present study was to develop a mesohabitat model for the whole macroinvertebrate community, focused on the trait-based Flow-T index. A machine learning approach was employed to calibrate and validate the model in three Italian Rivers (Trebbia, Taro, and Enza Rivers, Northern Italy), characterized by braiding morphology, gravel riverbeds, and summer low flows. The main research objectives were: i) to provide a novel approach to model the habitat of the whole macroinvertebrate community, ii) to extend the MesoHABSIM methodology to a different ecological target community, iii) to implement a new module for the whole macroinvertebrate community in the SimStream-Web service.

2. Material and methods

2.1. Study area

The present study was conducted in three rivers (Trebbia, Taro, and Enza Rivers, Table 1) located in Northern Italy. These rivers originate in the Northern Apennines and are important right-bank tributaries of the Po River (Fig. 1). For much of their lengths, they run through mountain zones, then they widen at the foot of the Apennines to become multi-thread systems with active channel widths ranging from 300 m to 500 m wide. This area of the Po Plain is characterized by a temperate climate, with 800 mm mean annual precipitation and 13 °C mean annual temperature (Peel et al., 2007). The considered river reaches are characterized by a braiding morphology and gravel riverbeds. The longitudinal extension of the reaches ranged between 600 m (Enza River) and 1200 m (Trebbia River). Two different field campaigns were performed in the summer of 2019 and 2020. The model was trained in Trebbia River (2019 campaign) and tested in Trebbia, Taro, and Enza Rivers (2020 campaign), during low flow periods, which correspond to the most critical bioperiod for the aquatic biota (Dewson et al., 2007; Dunbar et al., 2010; Wood and Armitage, 2004). During the low flow period, the aquatic habitat availability is reduced by the limited submerged area, which negatively affects the functionality of the macroinvertebrate community due to the reduced flow velocities and increased water temperatures.

2.2. Methodological steps

To resume the four methodological steps, a flowchart is provided (Fig. 2). Step 1 was represented by the hydromorphological description of rivers, and macroinvertebrate data collection. Step 2 was dedicated to the 2D hydrodynamic modeling and mesohabitat characterization of the analyzed rivers. In Step 3, the functionality of the macroinvertebrate community was modeled, and the Flow-T index calculated. In step 4, the developed model was implemented in the SimStream-Web service, an online service used for the MesoHABSIM model application.

2.2.1. Hydromorphological description and macroinvertebrate data

The description of the system involved a multidisciplinary approach based on two different techniques: (i) topographic and hydromorphological description of the river reaches and (ii) macroinvertebrate sampling and analysis. In this specific study, high-resolution orthophotos supported the classification of mesohabitats and substrates remotely, in a synergic combination with the field surveys, as recommended by Rinaldi et al. (2016).

An Uncrewed Aerial Vehicle (UAV, DJI Mavic 2 Pro) was employed for the photogrammetric surveys of the areas of interest. A Structure-from-Motion (SfM) solution was applied to obtain RGB orthomosaics (spatial ground resolution <5 cm) and the corresponding Digital Terrain Models (DTM, spatial ground resolution 10 cm) of the three river reaches. The survey period was selected to produce the most accurate DTM during the lowest flow conditions and to avoid bad weather issues (rain or clouds). The bathymetry and the flow field were investigated by

Table 1
Mean Annual Discharge (MAD), reach length, river width, catchment area of Trebbia, Taro, and Enza Rivers.

River	Municipality	MAD (m^3/s)	Reach length (m)	River width (m)	Catchment area (km^2)
Trebbia	Rivergaro	23.6	1200	500	1070
Taro	S. Secondo	40.6	1000	450	2030
Enza	Cedogno	9.74	600	300	890

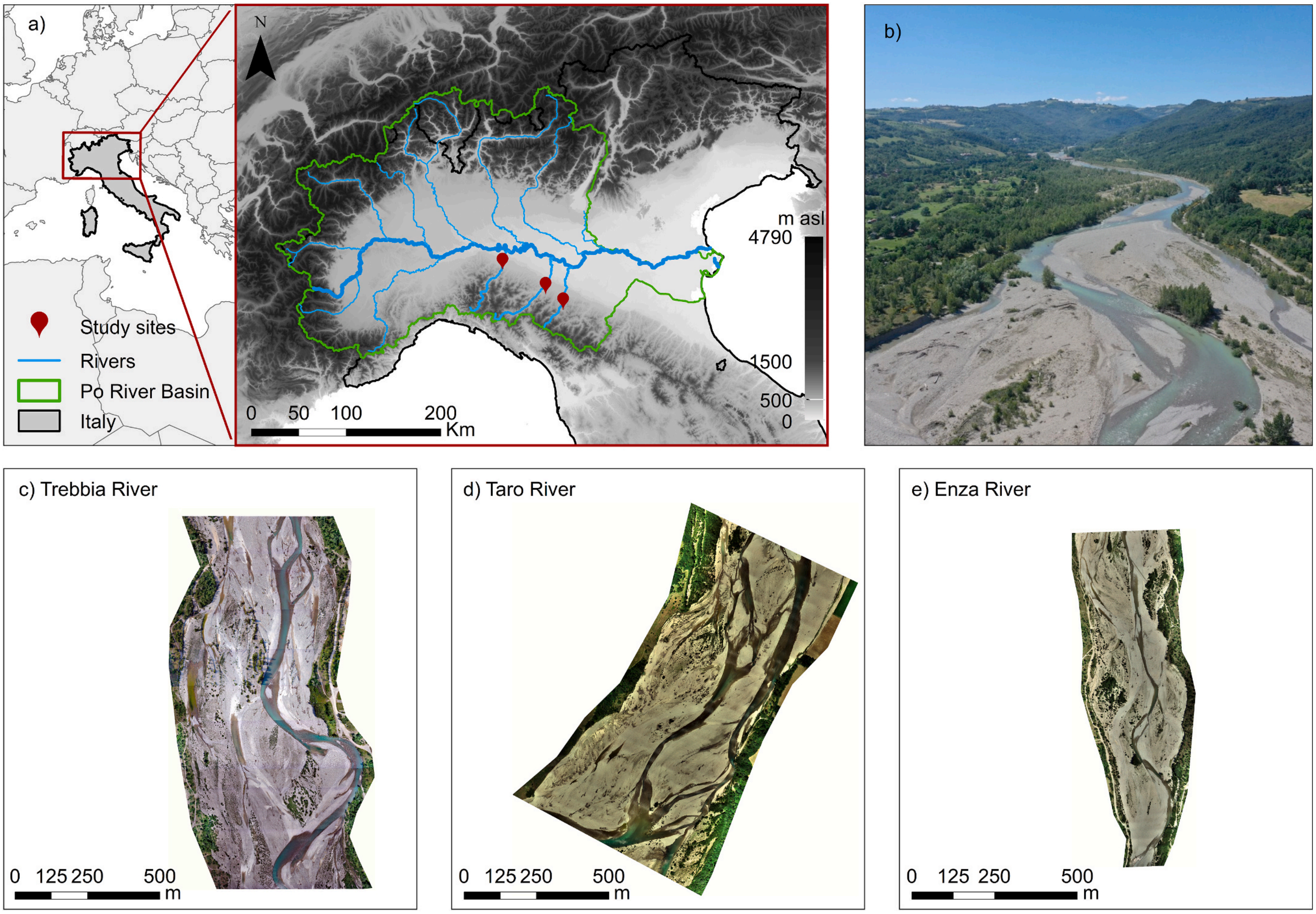

Fig. 1. a) Study sites location in Northern Italy within the Po River Basin, b) aerial photo of the Enza River near Ciano d'Enza, and high-resolution orthomosaic of the surveyed area of: c) Trebbia, d) Taro, and e) Enza rivers.

means of a RiverSurveyor M9 (Sontek, San Diego, CA, USA), made up of a HydroSurveyor Acoustic Doppler Current Profiler (ADCP). The acquisition system was completed with a double frequency antenna GNSS (Global Navigation Satellite System), assembled on a floating platform. The vessel was moved along the river by following a path from side to side to better describe the channel morphology. Together with the bathymetric data acquisition, a design of the mesohabitat mosaic was carried out, according to Belletti et al. (2017). In the Trebbia River, we performed a granulometric analysis on dry lateral bars and isles following the *Pebble count* method (Wolman, 1954), in order to define the grain size distribution. Within the identified mesohabitats, the substrate classification was carried out following a stratified random technique according to what suggested for the MesoHABSIM model application (Parasiewicz, 2007; Vezza et al., 2017).

Macroinvertebrates were collected, simultaneously to the hydro-morphological description, with a Surber net (0.05 m^2 frame area, 500 μm mesh size). The replicates were distributed in the river reach to capture the spatial extension and relative proportions of the different geomorphic units (pool, riffles, isolated ponds, etc.). In addition, within each mesohabitat, the location and the number of replicates were defined to proportionally represent the hydraulic units (i.e., spatially distinct patches of relatively homogeneous surface flow and substrate characteristics, Belletti et al., 2017). Following this procedure, in each mesohabitat, a different number of replicates, ranging from 1 (very small mesohabitats) to 11 (large mesohabitats), were collected, ensuring that the macroinvertebrate sampling was representative of the hierarchical structure of river geomorphic features (*sensu*, Belletti et al., 2017).

Organisms were identified at the stereomicroscope at the lowest practical taxonomic level (usually family and genus) according to Tachet et al. (2010). Flow preferences were retrieved from the affinity to the current velocity traits of the macroinvertebrate assemblage, and the Flow-T index was calculated, according to Laini et al. (2022), for each replicate. Lastly, for each mesohabitat, the average value among replicates was used to estimate the Flow-T index at the mesohabitat scale.

2.2.2. *Hydrodynamic modeling and mesohabitat characterization*

Optical photogrammetry, combined with bathymetry acquisition, may have sufficient precision in shallow clear waters to describe the riverbed elevation, and it is also a valuable approach to address the issues related to shallow zones bathymetric measurements (Dietrich, 2017; Kasvi et al., 2019). Following the approach reported in Kasvi et al. (2019), a bathymetric linear model was calibrated for each river, by comparing the riverbed elevation, obtained from the structure-from-motion DTM, and the real riverbed elevation provided by the bathymetric data. The obtained linear models were then used to reduce the error in water depth >0.2 m, since in very shallow water the elevation error was negligible. The corrected DTMs were employed in the HEC-RAS software (US Army Corps of Engineers, Hydrologic Engineering Center, Davis, California - version 5.0.7) to develop 2D hydrodynamic models. Such models were developed for each reach considering an unsteady state and fixed bottom conditions. A mesh size of 1 m was considered suitable for our applications and the Manning coefficient (n = 0.035 $m^{1/3}s^{-1}$ in Enza River, n = 0.036 $m^{1/3}s^{-1}$ in Taro River, and n = 0.036 $m^{1/3}s^{-1}$ in Trebbia River) was locally calibrated

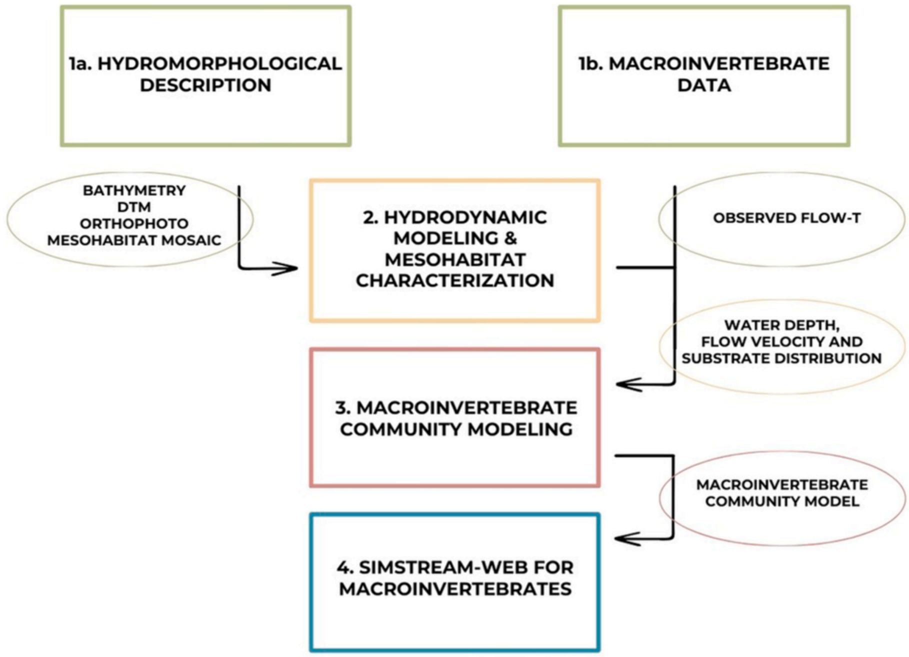

Fig. 2. Flowchart of the successive steps (1–4) of the entire process made of: 1a) and 1 b) hydromorphological description and macroinvertebrate data collection (see paragraph 2.2.1), 2) hydrodynamic modeling and mesohabitat characterization (see paragraph 2.2.2), 3) macroinvertebrate community modeling (see paragraph 2.2.3), 4) implementation of the macroinvertebrate module in SimStream-Web (see paragraph 2.2.4).

using discharge and sediment granulometry data collected during the surveys. The upstream boundary condition was set as a constant flow hydrograph, while the downstream boundary condition was set as normal depth, with a bed slope value corresponding to the considered section. For each river reach, five different discharge scenarios were simulated: one corresponding to the flow condition measured during the surveys, and 4 other discharge conditions, with a probability of exceedance ranging from 30% to 90% (Q_{30} and Q_{90}, respectively), estimated using a daily flow record of 15 years (2003–2018). Water depth and flow velocity distribution at the mesohabitat scale for the different discharge scenarios were extracted from the resulting raster maps. In this way, each mesohabitat was characterized in terms of flow velocity, water depth, substrate composition, and hydraulic connectivity with the main channel. The distribution of the simulated variables was organized in classes of relative frequency, ranging with steps of 15 cm (depth) and 15 cm/s (velocity) as suggested by Vezza et al. (2017). The classification of the riverbed substrate composition was based on what suggested by the MesoHABSIM methodology (Vezza et al., 2017); the observed classes of substrate were: *megalithal (>40 cm), macrolithal (20–40 cm), mesolithal (6–20 cm), microlithal (2–6 cm), akal (gravel), psammal (sand), pelal (silt, clay)*. The longitudinal connectivity of each mesohabitat to the main channel was set as a categorical binary (No/Yes) variable.

2.2.3. Macroinvertebrate community modeling

Random Forest (RF, Breiman, 2001) is considered a robust and efficient machine learning technique, largely used in ecological applications (Cutler et al., 2007; Evans and Cushman, 2009; Franklin and Miller, 2010; Murphy et al., 2010). RF can easily determine the variable importance ranking and capture the non-linear relationships between target variables and habitat descriptors.

In the current application, the RF technique was employed to build a multivariable habitat model to assess the response of the macroinvertebrate community to the mesohabitat descriptors. Therefore, the training dataset was composed of the habitat descriptors, whereas the responsive variable was represented by the Flow-T index computed for each mesohabitat. A regression model was employed, to relate the continuous target variable to the input training mesohabitat descriptors. The model was developed in R environment (R Development Core Team) using the package 'randomForest' version 4.6–14 (Liaw et al., 2002). RF is based on a combination of a large set of decision trees, trained by selecting random bootstrap samples of the original dataset and a random set of predictive independent variables. Each sample contains approximately two-thirds of the elements of the original dataset. The elements not included in the training dataset are referred to as out-of-bag data (OOB, i.e. the validation dataset) for each bootstrap sample. After growing the forest, the global accuracy in cross-validation (R^2_{CV}) and the error rates (E_{OOB}) were computed using the OOB data. To ensure the stabilization of the OOB error, the total number of trees in the forest was set to 5000 replicates. The best parsimonious model was outlined by selecting the most significant input variables. To assess the ranking of importance of the habitat predictors within the model we employed the *importance* function of the randomForest package. Specifically, the importance is expressed in terms of Mean Decrease in Accuracy (MDA, Liaw et al., 2002), indicating the accuracy that the model would lose by excluding each variable. In this case, the variables characterized by positive MDA values were selected. Additionally, a correlation matrix was built to avoid the usage of two or more correlated variables and collinearity effects on the performance of the model (Vezza et al., 2014). Lastly, the Partial Dependence Plots (PDPs) were used to visualize the RF (Breiman, 2001) results, and interpret their ecological meaning (Cutler et al., 2007). PDPs allowed to analyse the partial relationships between the Flow-T index and the selected habitat predictors.

Besides the cross-validation (OOB procedure), the model was validated with a test dataset collected on Trebbia, Taro, and Enza rivers (2020 field campaign). To evaluate the prediction power of the model, the same package randomForest (Liaw et al., 2002) was employed, by providing predictors and responses as a test data frame.

2.2.4. SimStream-web for macroinvertebrates

The RF model was integrated into the SimStream-Web platform, a web service used in Italy and abroad to perform habitat assessment and the application of the MesoHABSIM methodology. SimStream-Web is provided by the Italian Institute for Environmental Protection and

Research, ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale, Rome) and it is available at the url: https://mesohabsim.isprambiente.it/. It allows to obtain, for perennial and temporary rivers, i) the habitat availability for fish species (and life stages) of interest and (ii) the Habitat Integrity Index (IH, Vezza et al., 2017). The Homepage of SimStream-Web (Fig. 6a) shows two possible sessions: "Calculate session" and "Download session". The former allows the user to insert the hydromorphological information required to evaluate the river habitats for fish and macroinvertebrates, whereas the latter allows downloading the results. During the data input, SimStream-Web also performs data validation, aimed at verifying the hydromorphological data consistency, and at providing logs to the user. In the "Calculate session", the user is asked to insert the hydromorphological data of the surveys (Fig. 6b) and to select the community and the species models to be applied (Fig. 6c). Navigating to the "Download session" the user can download the outputs provided by the SimStream-Web in a compressed folder. SimStream-Web accepts the hydromorphological information, collected at the mesohabitat scale, as inputs (e.g., shapefiles and text files, .dbf, .prj, .shp, shx, and.txt formats), and the web service generates i) geo-referenced habitat maps, ii) habitat-flow rating curves (the relationships between habitat availability and the flow rate), and iii) habitat time series to calculate the IH Index.

In this work, the SimStream-Web service was modified and adapted by our research group to apply the Flow-T index at the mesohabitat scale, taking as input the mesohabitat descriptors of a river reach. The Flow-T index model will be available among the selectable models, in the macroinvertebrate model list. The selection of the Flow-T model in SimStream-Web provides the possibility to perform 2 different analyses and obtain 2 main outcomes: i) the Flow-T maps and ii) the Flow-T rating curve (the relationship between the Flow-T index and the flow rate). The first allows to visualize the Flow-T index associated with the mesohabitats in a GIS map in shapefile format. The latter indicates how the index varies with flow and how the wetted area increases, with an increase of the flow rate. The input data required by the service are: i) the date, ii) the daily discharge value expressed in m^3/s during that date, iii) the mosaic of mesohabitats inserted as a shapefile, iv) a tab-delimited text (.txt) containing water depth, flow velocity and substrate values collected or simulated for each mesohabitat.

To build the Flow-T rating curve, the weighted mean value of the Flow-T index, corresponding to each discharge condition ($FlowT_{Mean,Q}$) has been calculated as reported in the following equation:

$$FlowT_{Mean,Q} = \sum_{i=1}^{N} \frac{A_{mesohabitat_{i,Q}}}{A_{WET_{max}}} \times FlowT_{mesohabitat_{i,Q}}$$

where, the $FlowT_{mesohabitat_{i,Q}}$ is the sum of the Flow-T values obtained for each mesohabitat weighted on the ratio between the area of each mesohabitat ($A_{mesohabitat_{i,Q}}$, expressed in m^2) and the maximum submerged area of the reach ($A_{WET_{max}}$, expressed in m^2), corresponding to the maximum considered discharge condition.

3. Results

3.1. System description and field data

A total of 360 macroinvertebrate samples, 180 for the training dataset and 180 for the test dataset (60 for each of the 3 river) were collected. Overall, 317 mesohabitats divided into 5 categories (*glide*, *riffle*, *pool*, *backwater*, *isolated pond*) were described following the MesoHABSIM approach. In addition, 4 high-resolution orthophotos and 4 DTMs were produced using the 2019 and 2020 field campaigns. Using the ADCP, it was possible to collect a total number of measurement points ranging from 1350 (Trebbia River, 2020 field campaign) to 20,200 (Trebbia River, 2019 field campaign). The measured velocity was generally higher in the mesohabitats *riffle* and *glide*, as expected. The depth distribution varied among the different types of mesohabitat. Due to the reduced discharge conditions, in the Enza and Trebbia rivers (2020 field campaign) depth and velocity were generally lower than in Taro and Trebbia rivers (2019 field campaign). The substrate description obtained from the orthophotos allowed to determine the predominant substrate type in more than 9600 points overall in the 4 river reaches. The most frequently occurring substrates were *mesolithal* (6–20 cm diameter, 55%) and *microlithal* (2–6 cm diameter, 26%).

Concerning the macroinvertebrates, the largest number of samples was collected in the mesohabitat *riffle* (117), followed by the mesohabitat *glide* (111), *isolated pond* (64), *pool* (35), and *backwater* (33, Fig. 3). A total amount of 49,760 organisms belonging to 67 different families were identified. *Diptera* was the most abundant taxonomic group (27,630 individuals), followed by *Ephemeroptera* (11,598 individuals) and *Oligochaeta* (2847 individuals). The most abundant family was *Chironomidae* (22,299 individuals), followed by *Baetidae* (7174 individuals), *Simuliidae* (4374 individuals), and *Naididae* (2691 individuals, Fig. 3).

3.2. Hydrodynamic simulation and mesohabitat descriptors

The synergic combination of photogrammetry, bathymetry, and GPS field data collection lead to obtaining quite accurate bathymetric models, thus quite precise DTMs, and to defining and classifying the mesohabitats in the different river reaches (R2 coefficient ranging from 0.89 to 0.96 for the 4 linear bathymetric models). Globally, the highest number of mesohabitats (96) was found in the Trebbia River (2020 campaign), whereas the minimum number (51) was identified in the Enza River. The prevalent type of mesohabitat was *riffle* (96), followed by *glide* (90), *isolated pond* (54), *pool* (48), and *backwater* (26).

The hydrodynamic simulations were performed on the base of the DTMs of the 4 river reaches with a mesh size of 1 m. The flow velocity and water depth distribution were formatted in raster maps with a ground resolution of 10 cm. The manning coefficient was calculated from the Chezy equation, and its values for each river reach were: 0.035 $m^{1/3}s^{-1}$ (Enza River), 0.036 $m^{1/3}s^{-1}$ (Taro River), and 0.036 $m^{1/3}s^{-1}$ (Trebbia River). The distributions of water depth and flow velocity obtained from the hydrodynamic simulations were validated using the dataset collected on the field using the ADCP as ground truth. For Enza, Taro, and Trebbia rivers, the determination coefficient of the 2D hydrodynamic models ranged from 0.85 to 0.96, whereas the RMSE ranged from 0.05 m to 0.08 m for the 2019 and 2020 field campaigns. Based on the obtained information from the hydrodynamic modeling, orthophotos and field data collection, the mesohabitat mosaic for each discharge and each river was organized in a GIS platform, reporting the spatial information of i) water depth, ii) flow velocity, and iii) substrate composition at the mesohabitat scale (Fig. 4).

3.3. Macroinvertebrate community model

Table 2 shows the selected mesohabitat descriptors composing the RF macroinvertebrate community model, listed in order of importance (Fig. 5b). The model is represented in Fig. 5a where the PDPs coming from the RF algorithm, are shown. CONNECTIVITY is the only categorical variable, whereas all the others are continuous, with non-linear relationships. The trends are different: descending monotone (i.e. PELAL), ascending monotone (i.e. MICROLITHAL), step function (i.e. CV75_90, CV45_60, CV60_75, CV90_105, CV120, CV15, D60_75) or bell-shaped function (i.e. CV15_30, D15_30). Two classes of substrates (i.e. PELAL and MICROLITHAL) were the most important habitat descriptors in predicting the macroinvertebrate response to flow velocity (Fig. 5a and b), having opposite trends. PELAL (silt and clay) had a negative influence on the Flow-T prediction, whereas MICROLITHAL (2–6 cm) had a positive effect. Moderate to high velocities classes (CV45_60, CV60_75, CV75_90, CV90_105, and CV120) showed a general positive influence on the Flow-T index values. CV45_60, CV60_75, and CV75_90 showed a peak of around 10% frequency and then a slight decrease,

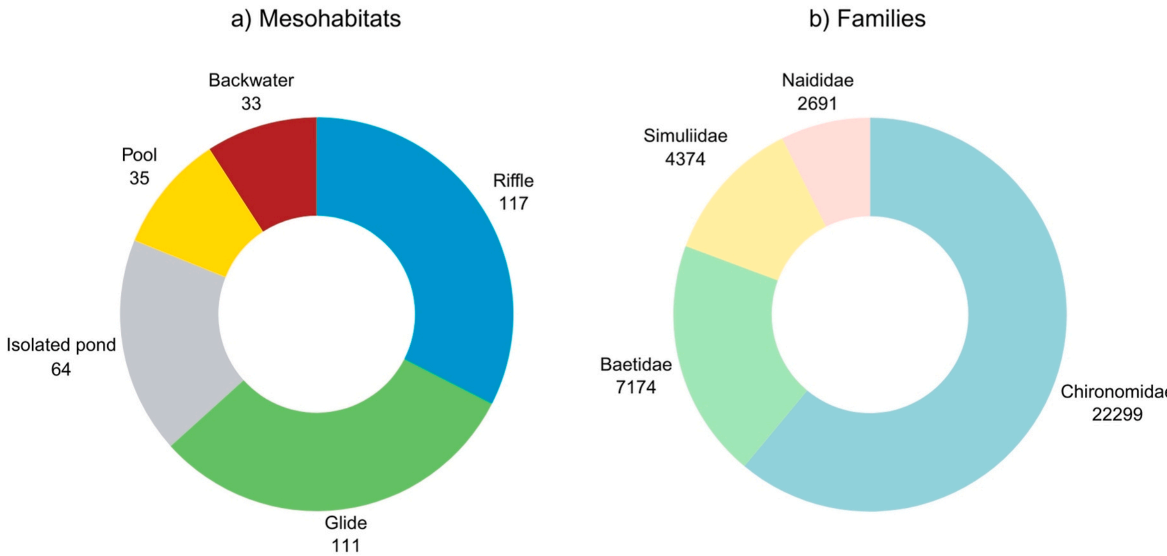

Fig. 3. Pie charts illustrate a) the distribution of sampled mesohabitats by type and b) the predominant families of macroinvertebrates across the three rivers.

whereas CV90_105 and CV120 were characterized by an increasing monotone trend. Conversely, the influence of the low flow velocity classes CV15, ranging from 0 to 15 cm/s, and CV15_30, ranging from 15 to 30 cm/s was much lower and negative (the two velocity classes were identified as less significant with a clear drop of the MDA, see Fig. 5b). The presence of the categorical variable CONNECTIVITY resulted in an increased predicted Flow-T index value. It follows that the mesohabitats not connected to the main channel (e.g. *isolated ponds*) will be marked by lower Flow-T index values. Two classes of water depth were selected by the model as less important in the prediction. The water depth class ranging from 60 to 75 cm (D60-75) had a negative effect on the prediction of the Flow-T index, whereas the class ranging from 15 to 30 cm (D15-30) presents a bell-shaped behavior with a maximum of around 20% occurrence. Note that, on the vertical axes of the PDPs, the range of predicted values of the Flow-T index was limited between 0.39 and 0.45, but this represents the obtained Flow-T curve after averaging the effects of all other variables in the model, beside the one considered in the PDP. The predictive powers in calibration (Fig. 5c) and in validation (Fig. 5d) were: $R^2_{CV} = 0.71$ and $R^2_{test} = 0.63$, $RMSE_{CV} = 0.073$ and $RMSE_{test} = 0.060$, Pearson correlation coefficient $\rho_{CV} = 0.844$ and $\rho_{test} = 0.800$. The same figure also highlights how the model described the linkages between the macroinvertebrate community assemblage and the physical habitat descriptors. This remarkable finding can be appreciated in the pattern of points in Fig. 5c and d, arranged in clusters stratified by types of mesohabitat. Specifically, the data of the mesohabitats characterized by low flow velocity (i.e. *Backwaters* and *Isolated Ponds*) and, therefore, by the occurrence of lentic taxa, are grouped in the low Flow-T area of the scatter plots. On the contrary, *Glides* and *Riffles* are grouped in the higher Flow-T area of the scatter plots, being characterized by higher flow velocity and lotic taxa.

3.4. *SimStream-web for macroinvertebrates*

In the SimStream-Web service is now possible to select as an ecological target the macroinvertebrate community, to apply the Flow-T biological model. Specifically, the application of the macroinvertebrate community model provides the following results: i) Hydromorphological unit data, ii) Biological model results, and iii) Flow-T rating curve. A user manual is available in the "Resources" area, on the SimStream-Web homepage.

Fig. 7 shows an example of the application of the Flow-T biological model through the SimStream-Web service. The application was performed on the Enza River, considering 5 different discharge scenarios. The results of the analysis consisted of the Flow-T maps (Fig. 7a and b) and the Flow-T rating curve (Fig. 7c). Two different Flow-T maps are reported considering the minimum (0.33 m^3/s, Q_{30}) and the maximum (5 m^3/s, Q_{90}) simulated discharge scenarios. The wetted area and Flow-T rating curve indicate the evolution of wetted area and Flow-T index at different discharge conditions. Fig. 7a and b shows how an increase in discharge from 0.33 m^3/s to 5 m^3/s causes the activation of two secondary channels where some isolated ponds became connected to the main channel and, therefore, the Flow-T index increased.

4. Discussion

The present research contributes to developing a mesohabitat model focused on the trait-based Flow-T index (Laini et al., 2022), able to track the effects of hydromorphological changes on the whole macroinvertebrate community. We led the foundation for broadening the range of ecological targets used by the MesoHABSIM methodology and we implemented a specific module for macroinvertebrates in the SimStream-Web service. The biological model has a satisfactory prediction power of the Flow-T index and shows good accuracy and reliability. It is important to state that the model was calibrated and validated during summer low flow conditions in summer; thus, further analyses and validation will be needed to ensure the applicability during other periods of the year, or during high flows. The presented approach can be applied through the SimStream-Web service to assess the spatial distribution of the community and to quantify its ecological response to morphological variation or flow alteration at both mesohabitat and reach scale.

4.1. *Macroinvertebrate community model*

The present research gave insight into mesohabitat modeling for the whole macroinvertebrate community. For the first time in species distribution modeling, a mesohabitat model was developed to assess the ecological response of the whole macroinvertebrate community to physical habitat changes, in particular to the flow velocity. These results are in line with literature that supports the key role of velocity in determining the macroinvertebrate response to physical habitat conditions (Statzner et al., 1988). It is important to note that the Tachet database of macroinvertebrate traits, employed to develop the Flow-T index (Laini et al., 2022), and the hydromorphological field dataset used to predict the same index, are based on different spatial scales. This ensures using distinct and independent datasets for the original

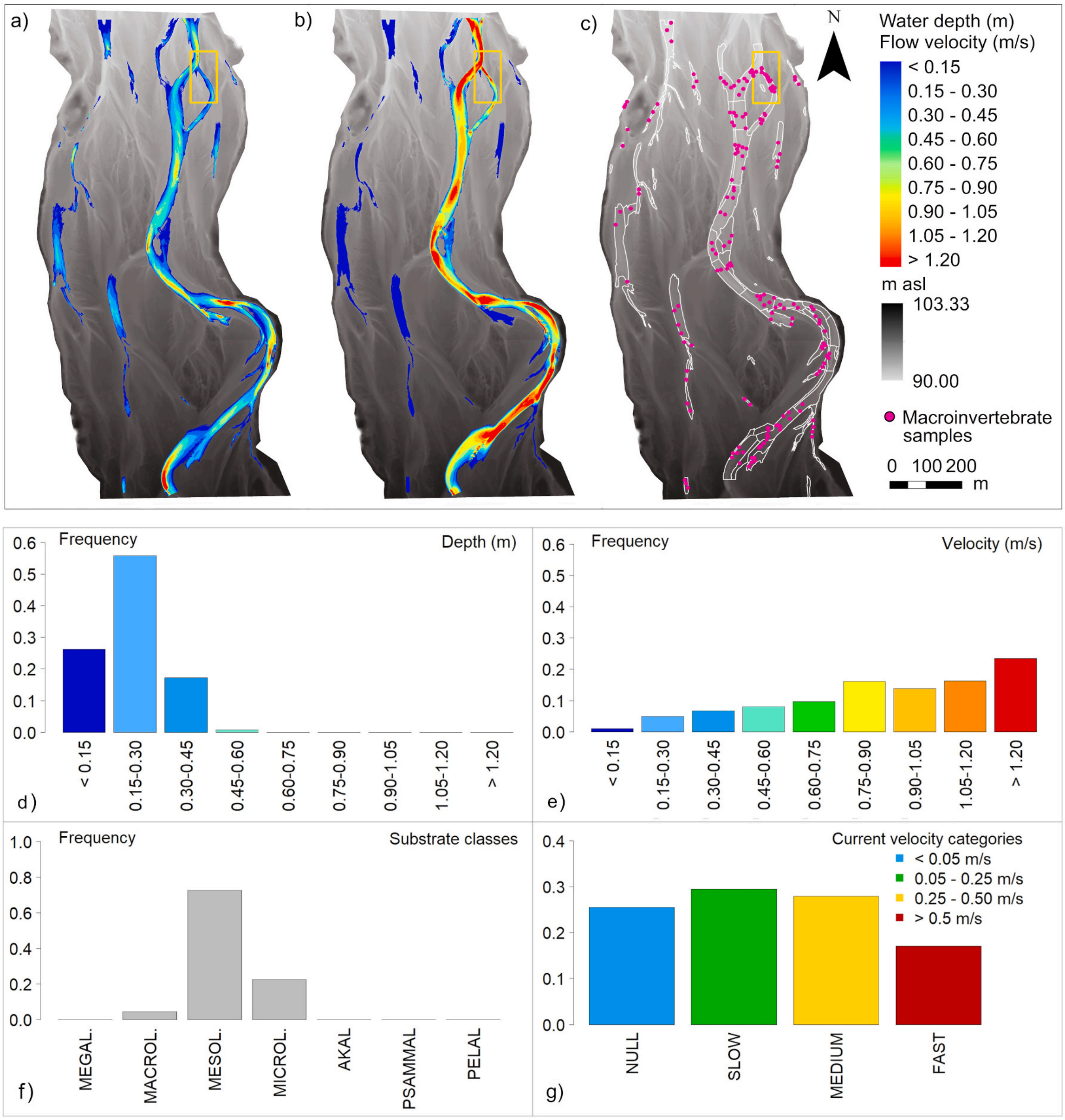

Fig. 4. Top: Digital Terrain Model of the Trebbia River (2019) associated with the distribution of a) water depth and b) flow velocity raster resulting from the 2D hydrodynamic simulation, c) location of macroinvertebrates sampling points. Bottom: detailed description of a mesohabitat riffle: d) water depth, e) flow velocity, f) substrate composition frequency, and g) degree of affinity of the taxa present in the mesohabitat to current velocity categories.

Table 2
Independent variables selected as part of the parsimonious RF model of the Flow-T metric. The variables are ranked in order of importance.

Independent variables	
PELAL	Substrate (<0.06 cm, clay)
MICROLITHAL	Substrate (2–6 cm, coarse gravel)
CV75_90	Class of current velocity (75–90 cm/s)
CV45_60	Class of current velocity (45–60 cm/s)
CV60_75	Class of current velocity (60–75 cm/s)
CV90_105	Class of current velocity (90–105 cm/s)
CV120	Class of current velocity (>120 cm/s)
CV15_30	Class of current velocity (15–30 cm/s)
CV15	Class of current velocity (<15 cm/s)
CONNECTIVITY	Hydraulic longitudinal c.
D60_75	Class of water depth (60–75 cm)
D15_30	Class of water depth (15–30 cm)

development of the Flow-T index and the community model at the mesohabitat scale, avoiding collinearity and circularity issues (Dormann et al., 2013). The mesohabitat spatial scale was shown to be appropriate for modeling the spatial distribution of the community Burgazzi et al. (2021). Some other authors obtained similar results, although using different mesohabitat classifications compared to the one used in our study (Belletti et al., 2017). More in detail, Gray and Harding (2009) assessed the community variability among main channels, side braids, spring creeks, spring sources, and ponds, whereas Karaus et al. (2013) evaluated the total diversity of Ephemeroptera, Plecoptera, and Tricoptera (EPT) among lateral aquatic habitats (i.e., tributaries, backwaters, and ponds). Moreover, the interaction between the geomorphological structure and the macroinvertebrate community assemblage was also demonstrated by other studies (Pastuchová et al., 2008; Starr et al., 2014). Furthermore, the mesohabitat scale allows the grouping of distinct combinations of hydraulic conditions (i.e. flow velocity, water depth, and substrates), in which macroinvertebrates may persist (Jowett, 2003).

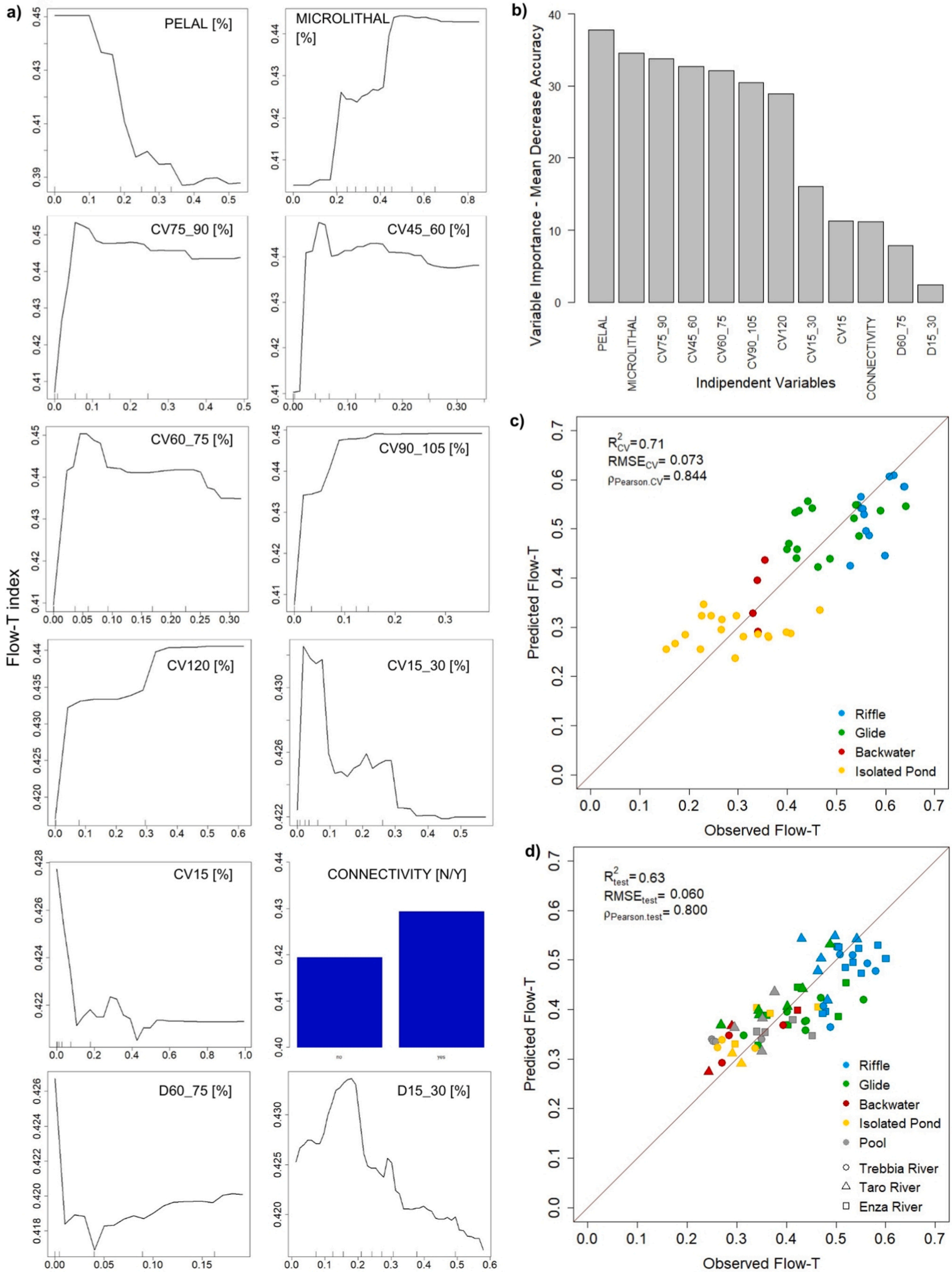

Fig. 5. a) RF Flow-T Partial Dependence Plots of the most important mesohabitat attributes, b) variable importance ranking, c) scatter-plot of observed vs predicted Flow-T (calibration), and d) scatter-plot of observed vs predicted Flow-T (validation).

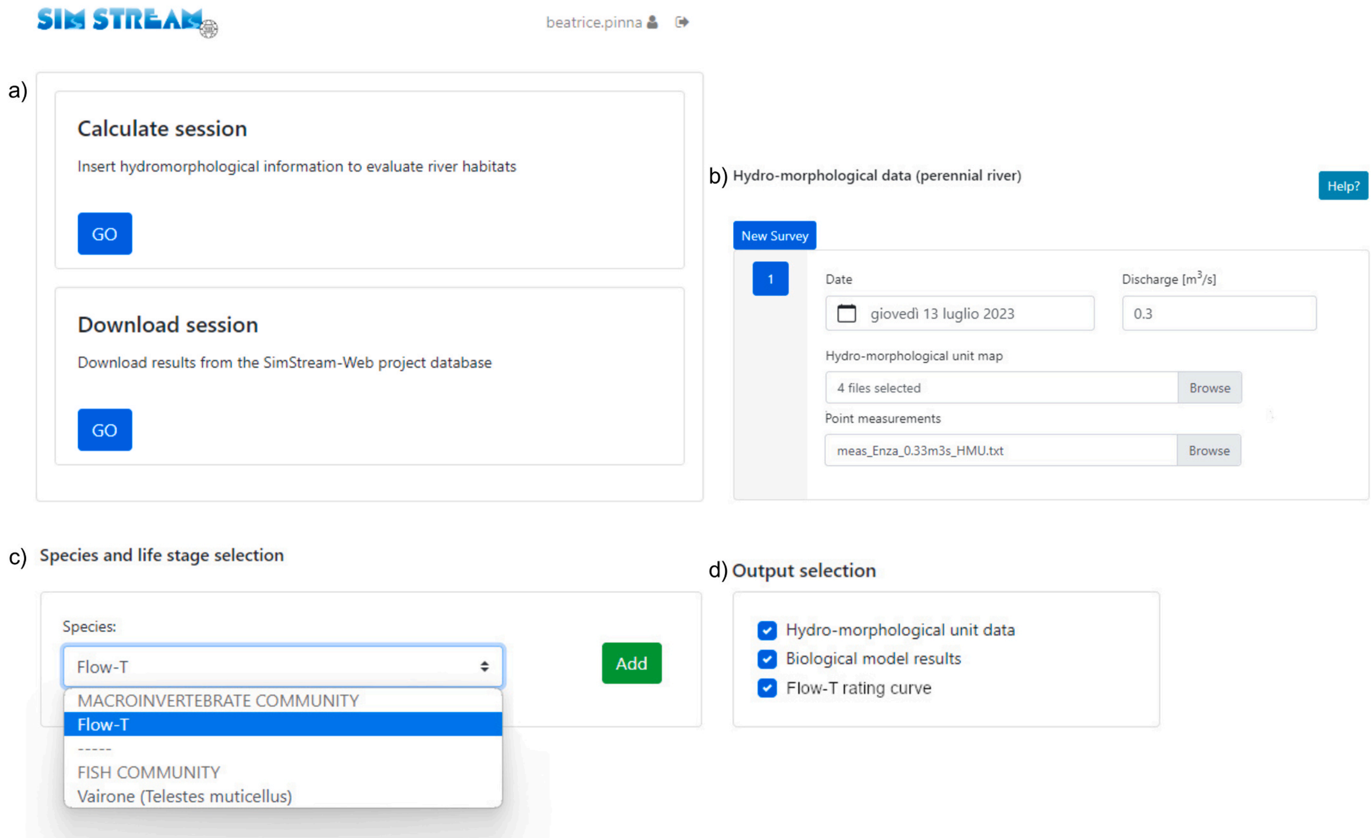

Fig. 6. SimStream-Web service: a) Homepage with sessions for data upload and results download, b) form for hydromorphological data upload, c) species selection with the possibility to choose the Flow-T index model, and d) selection of output to be provided by the service.

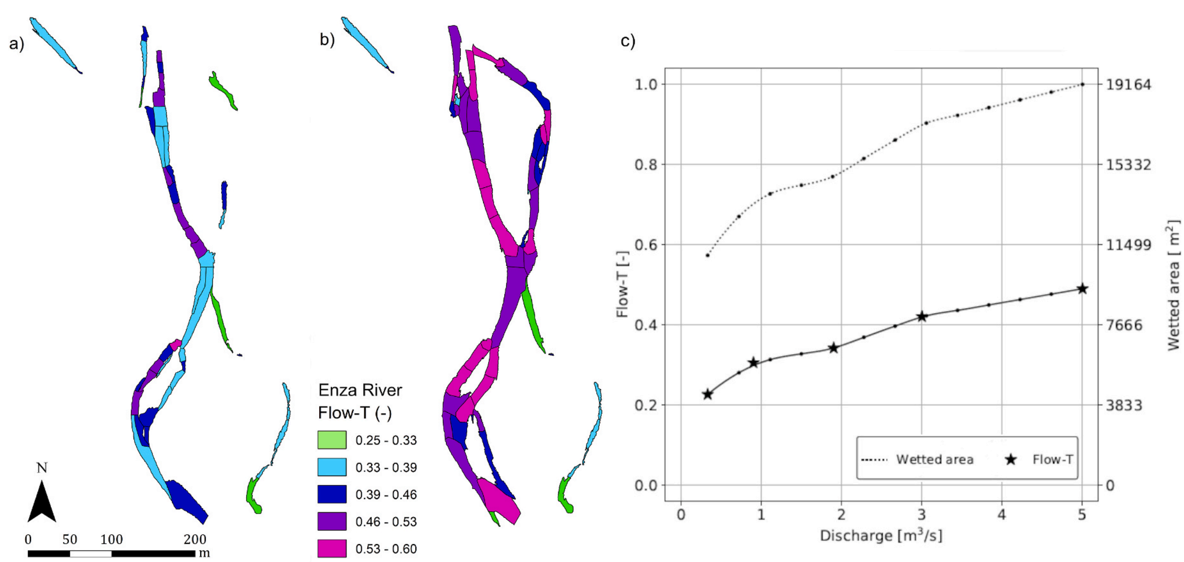

Fig. 7. Flow-T maps at: a) minimum (0.33 m3/s) and b) maximum (5 m3/s) discharge conditions, and c) Flow-T and wetted area rating curves.

Our results showed that two types of substrates (PELAL and MICROLITHAL), the most important habitat descriptors, had the opposite effect in predicting the Flow-T and this can be explained by the linkage between the sediment composition and the flow field that characterizes each mesohabitat. Indeed, the occurrence of fine sediment such as PELAL can be attributed to low flow velocity, and this substrate was characterized by the presence of lentic taxa (e.g., *Dytiscidae*, *Hydrophilidae*, most *Odonata*). On the contrary, the presence of coarser substrates such as MICROLITHAL can be related to flow velocity and to the presence of lotic taxa (e.g., filter feeders). The positive effect of moderate and high velocity (from 45 cm/s to >120 cm/s) on the Flow-T index values demonstrated that the model can capture changes in the community assemblage, depending on the flow conditions. The higher the occurrence of moderate and high velocity classes, the higher the Flow-T index, indicating a larger presence of lotic taxa adapted to persist in lotic ecosystems (Statzner and Holm, 1989). The trend showed by low velocity classes CV15 and CV15_30 highlighted that the occurrence of these classes (greater than 10%) produces a decrease in the response of the community to the flow velocity, due to an assemblage characterized by lentic taxa.

Regarding the role of the CONNECTIVITY variable, this finding is in line with former studies (Bonada et al., 2006; Gallardo et al., 2008; Leigh et al., 2009), demonstrating the effect of loss of connectivity on the macroinvertebrate assemblage with a decreasing trend in richness and abundance along the gradient riffle – connected pool – isolated pool. Furthermore, the recent study of Harrison et al. (2023) conducted in the Mississippi River, shows how the reduced or less frequent connectivity of secondary channels to the main channel, has a strong effect on both richness and structure of the macroinvertebrate community. Specifically, during periods of reduced connectivity, the community structure is mainly characterized by the presence of lentic or generalist taxa, consistent with the findings of our study.

Generally, the range of variability of the target decreased with the decreasing importance of the variables in the model. For example, the less important descriptor D15_30 predicts Flow-T index values ranging from 0.415 to 0.435. The reduced range of the target variable represented in the PDPs can be explained by the fact that the plots show the average of all the possible curves generated by the trees of the forest. The predicted values of the Flow-T index in the three rivers ranged from 0.2 to 0.6 (Fig. 5d).

Our model, which we validated with a robust dataset, can describe the relationship between the macroinvertebrate assemblages and the physical habitat descriptors, as shown by the good separation of the mesohabitats in the observed vs predicted Flow-T scatter plots. This result is aligned with the findings of Laini et al. (2022) regarding the association between the Flow-T index and the mesohabitat types, and those of Burgazzi et al. (2021) about the effects of mesohabitats on the community assemblage. Moreover, this result is representative of the relationship between the macroinvertebrate community composition and the physical hydraulic variables, as supported by literature (Dunbar et al., 2010; Petts, 1984; Wood and Armitage, 2004). In detail, the influence of flow conditions on the macroinvertebrate community is highlighted by Mérigoux & Dolédec (2004), although, according to these authors, shear stress and Froud number, directly related to flow velocity, were selected as the most important hydraulic parameters, among a set of five. However, the results obtained from the study of Mérigoux & Dolédec (2004), show that Froude number and shear stress were the most important parameters, whereas substrate type and bed roughness were less important. In the present study, two classes of substrate types were selected as the most important variables. This dissimilarity could be related to several aspects, including i) the difference in seasons investigated by Mérigoux & Dolédec (2004) (i.e., spring and autumn), and in the present study (i.e., summer), ii) the difference in spatial scales used by the authors (i.e., sample-unit), and in the present study (i.e., mesohabitat), iii) the different statistical approaches to assess the community response.

It is of great interest to notice that the set of variables selected by our study is composed of different types of habitat descriptors, which have an important role in describing the macroinvertebrate spatial distribution, as demonstrated also by Brooks et al. (2005). Additionally, some of those habitat descriptors act as a proxy for other ecological characteristics. For example, flow velocity and hydraulic connectivity can be considered as a proxy for the presence of food for macroinvertebrates or their ability to feed. However, other important physical characteristics, such as the hydraulic conductivity in the hyporheic zone, the temperature, or the presence of the substrate detritus, are not included in the model calibration. We did not take them into account because of the intrinsic morphological characteristics of the case study: a supporting thermal flight performed on the Trebbia River did not show high variability of the water temperature among the mesohabitats. The same behavior was observed also for the hydraulic conductivity, which is strictly related to the temperature distribution (Lapham, 1989; Su et al., 2004). Furthermore, the detritus substrate was not present in the studied reaches, even though it represents an important variable. In fact, as demonstrated by the review of Wissinger et al. (2021), the presence of organic matter, such as dead leaves or wood, would provide benefits to macroinvertebrates, being used as habitat or as food source.

As further developments of these findings, a recently started study, conducted by our research group, will perform a broader validation of the Flow-T biological model, in several rivers with different morphologies within the Po River Basin. A deeper investigation of the relevant physical variables will be performed and, if necessary, the model improved. Future model applications are however recommended below the threshold of incipient motion for sediments. Indeed, as demonstrated by Gibbins et al. (2004), bedload sediment transport may trigger macroinvertebrate drift and may strongly change the macroinvertebrate distribution in mesohabitats.

4.2. *SimStream-web for Flow-T index applications*

As supported by previous works (Parasiewicz, et al., 2013; Vezza et al., 2014, 2016), we used a mesohabitat approach to develop the above-described macroinvertebrate community model. The mesohabitat allowed to build a biological model with a wide variety of mesohabitat descriptors, evaluating the community composition at a large scale (Parasiewicz et al., 2013). Burgazzi et al. (2021) and Laini et al. (2022) demonstrated that the mesohabitat is effective in capturing the ecological functionality and describing the spatial distribution of the whole macroinvertebrate community. The usage of the mesohabitat spatial scale enabled a broadening of the range of the ecological targets used by the MesoHABSIM methodology (Parasiewicz, 2001). Our findings contribute to investigating the effects of flow variation and river morphological characteristics on the macroinvertebrate community assemblage. Being the macroinvertebrates one of the most important bioindicators (Buss et al., 2015) sensitive to flow regime alteration, these findings are important to fill a gap in their habitat modeling. The SimStream-Web platform (https://mesohabsim.isprambiente.it/app/home/) allows the application of the community model by selecting it among the other available models. In contrast to the other fish species-specific models, the Flow-T model considers the whole community of macroinvertebrates. This result allows the integration of other available methods focused on single species (Parasiewicz et al., 2008, 2012; Vezza et al., 2016) or to a smaller spatial scale (Li et al., 2009; Mérigoux et al., 2009; Shearer et al., 2015).

The Flow-T maps (as exemplified by Fig. 7a) represent an effective tool to understand how the macroinvertebrate communities respond over time to the changing discharge conditions. In most of the mesohabitats, an increase in discharge resulted in an overall increased Flow-T index, except for *isolated ponds* and *backwaters*. The Flow-T index responds to the increase in flow due to its effects on connectivity (i.e., connection of isolated pools to the main channel). The same response of the community to flow changes can be observed in the Flow-T rating curve at the spatial scale of the river reach. Indeed, the general increasing trend of the Flow-T index with the flow is perfectly in line with the aforementioned result. It is of great interest to notice that the Flow-T rating curve quite clearly traces the non-monotone evolution of the wetted area, intrinsically related to the peculiar morphology of the multithread system. The flexes of the curves are related to the activation of new secondary channels after an increase in flow conditions. These results meet literature and former studies (Doretto et al., 2019; Wood et al., 2000), which highlight the sensitivity of the macroinvertebrate community assemblage to the alteration of the flow regime, and to the occurrence of high and low flows.

As well as the Habitat-Flow rating curves allow to obtain habitat time series (Milhous et al., 1990) for fish species, similarly, the Flow-T rating curve represents the key element to generating Flow-T time series, analog of habitat time series. The habitat time series represents a crucial instrument to assess deviation in habitat availability (or macroinvertebrate response to flow velocity) between reference and altered discharge conditions. The effects of loss of habitat related to increased duration and frequency of flow events below minimum thresholds have been demonstrated (Parasiewicz et al., 2013; Vezza et al., 2015). Assessing the deviation of the Flow-T time series, between altered and reference flow conditions, could lead to the definition of a new Habitat Integrity Index (Vezza et al., 2017; WMO - World Meteorological Organization, 2019) for the macroinvertebrate community habitat. It would be also relevant to include in a multicriteria approach framework the two Habitat Integrity Indices, one for fish fauna and one for macroinvertebrates, performing an ecologically integrated approach to assess habitat availability for current and future scenarios (Gore et al., 2001; Vassoney et al., 2021). As reported by Vassoney et al. (2019, 2021), the multicriteria analysis (MCA) has been frequently applied in Italy to support decision-making problems concerning water resource management and environmental flow assessment. MCA is a kind of decision support system useful to improve the definition, understanding, and evaluation of different alternatives of water use, supporting the identification of a solution for the complex problems and conflicts involved in regional water resource planning.

5. Conclusion and further developments

This work lays the foundation of a gap-filling in habitat modeling, developing a biological model for the whole macroinvertebrate community. The RF model is focused on the Flow-T index (Laini et al., 2022) and achieved good accuracy and prediction power, in calibration and validation processes. Literature and former studies support the usage of the mesohabitat as spatial scale to describe the assemblage of the community according to hydromorphological conditions of the river and to evaluate the environmental needs of the target. The results were revealed to be effective in broadening the MesoHABSIM methodology to a different ecological target. The outcomes of the application of the model through the SimStream-Web tool highlight the ecological response of the community to the hydraulic conditions. The SimStream-Web tool disclosed interesting potentials in the spatio-temporal assessment of the macroinvertebrate community habitat.

Despite the limited number of studied watercourses and the need for further research in different morphological and seasonal contexts, the implemented approach has proved robust and has potential for applications. The findings may have relevance for an ecologically integrated forecasting methodology applicable for environmental flows design based on different ecological targets (fish and macroinvertebrates), in perennial and non-perennial rivers.

CRediT authorship contribution statement

Beatrice Pinna: Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Alex Laini:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Giovanni Negro:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Gemma Burgazzi:** Writing – review & editing, Investigation, Data curation, Conceptualization. **Pierluigi Viaroli:** Supervision, Project administration, Funding acquisition, Conceptualization. **Paolo Vezza:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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