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Habitat modeling in high-gradient streams: the mesoscale approach and application

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Abstract. This study aimed to set out a new methodology for habitat modeling in high-gradient streams. The methodology is based on the mesoscale approach of the MesoHABSIM simulation system and can support the definition and assessment of environmental flow and habitat restoration measures. Data from 40 study sites located within the mountainous areas of the Valle d'Aosta, Piemonte and Liguria regions (Northwest Italy) were used in the analysis. To adapt MesoHABSIM to high-gradient streams, we first modified the data collection strategy to address the challenging conditions of surveys by using GIS and mobile mapping techniques. Secondly, we built habitat suitability models at a regional scale to enable their transferability among different streams with different morphologies. Thirdly, due to the absence of stream gauges in headwaters, we proposed a possible way to simulate flow time series and, therefore, generate habitat time series. The resulting method was evaluated in terms of time expenditure for field data collection and habitat-modeling potentials, and it represents a specific improvement of the MesoHABSIM system for habitat modeling in high-gradient streams, where other commonly used methodologies can be unsuitable. Through its application at several study sites, the proposed methodology adapted well to high-gradient streams and allowed the: (1) definition of fish habitat requirements for many streams simultaneously, (2) modeling of habitat variation over a range of discharges, and (3) determination of environmental standards for mountainous watercourses.

Key words: brown trout; environmental flows; GIS; high-gradient streams; hydropower; marble trout; mesohabitat; mesoscale; mountain streams; Salmo; *small dams.*

Introduction

Mountainous high-gradient streams are increasingly being exploited by water abstractions, diversions, and small hydroelectric dams (e.g., Horne et al. 2004, Anderson et al. 2006*a*, *b*, Zimmerman and Lester 2006, Marnezy 2008, CIPRA 2010, McLarney et al. 2010, GIM-UNDP 2011). Several studies have shown that many types of flow alteration (e.g., magnitude, frequency, and timing) modify the aquatic and riparian habitat and induce a variety of ecological responses (Poff and Zimmerman 2010).

High-gradient streams are generally low-order watercourses or headwaters and are defined as having from moderate to quick flow with some turbulent water (e.g., MNHESP 1999). The stream morphology is usually characterized by scoured channels on moderate to steep slopes with abrupt drops, and boulders, cobbles, gravel, and sand substrates. In addition to pools, glides, and riffles, which are common units in channels with low to moderate gradients, cascades, rapids, and step-pools are typical channel hydromorphologic units (HMUs) in these particular watercourses (Halwas and Church 2002).

Since high-gradient streams generally have small dimensions and are located in remote sites, they are characterized by low or no human impact and have high ecological value. Moreover, due to their limited discharges, they can be more susceptible even to small water withdrawals and management practices. However, information about the impacts of water abstractions is particularly scarce for these small streams, and more research is needed to investigate the effects of flow reduction on instream environments (Dewson 2007). Many of these high-gradient streams can support different fish species whose conservation status is of community (e.g., the European Habitats Directive 1992/42/EEC, for marble trout, *Salmo marmoratus*) and/or local interest (e.g., brown trout, *Salmo trutta fario*; Vezza et al. 2012*a*). Furthermore, mountainous high-gradient streams and headwaters are also an important source of inorganic and organic matter for the

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downstream reaches in the watersheds (Bryant et al. 2007).

It is, therefore, important for decision-making in water resources planning to address the environmental management of mountainous watercourses, including environmental flows assessment. The limited availability of reference hydrological data series in high-gradient streams or headwaters (Watson et al. 2009, Vezza et al. 2010) often prevents the definition of the sustainability boundaries around the natural flow regime (Richter et al. 2011) or the application of a priori eco-hydrological stream classification for the definition of environmental flow standards (Arthington et al. 2006, Poff et al. 2010). Modeling the channel hydro-morphology and its relations with stream biota is then needed to evaluate how much habitat is available for selected organisms under specific environmental conditions (Poff et al. 1997, Maddock 1999, Rosenfield and Hatfield 2006). However, an adequate and comprehensive methodology concerning habitat–hydraulic modeling in high-gradient streams has not yet been proposed in the scientific literature.

Most of the studies linking habitat characteristics and aquatic biota were carried out in moderate-gradient or alluvial valley streams (e.g., Crowder and Diplas 2000, Covington and Hubert 2003, Hauer et al. 2010). For example, the most widely advocated method (Acreman and Dunbar 2004) to appraise flows related to fish species is the physical habitat simulation system (PHABSIM; Bovee et al. 1998) and the instream flow incremental method (IFIM; Bovee 1982). However, PHABSIM has been proven to be adequate only for perennial low/moderate-gradient streams (e.g., using a one-dimensional hydraulic model; Gordon et al. 2004). Since the end of the 1990s, multidimensional hydraulic models (e.g., two- or three-dimensional; Crowder and Displas 2006, Shen and Diplas 2008) have been used to describe detailed channel hydraulics. These techniques generally need detailed bed topography, which can be provided by electronic total stations or terrestrial laser scanners (de Jalon and Gortazar 2006, Kozarek et al. 2010). However, mountainous headwater streams have spatially complex, hydro-morphologic habitats (Bryant et al. 2007), and a detailed survey may lead to extensive efforts for the field data collection (Halwas and Church 2002).

Although hydraulic variables are important in habitat assessment and maintenance, other factors such as cover, water temperature, chemical parameters, shore characteristics, and biological interactions (e.g., food competition and predation) may be of greater importance in limiting species biomass or abundance (Gordon et al. 2004). In order to cope with this issue, the use of multivariate habitat suitability models has recently increased (Ahmadi-Nedushan et al. 2006). In particular, multiple logistic regressions (e.g., Pearce and Ferrier 2000, Parasiewicz 2007*a*, Tirelli et al. 2009) currently represent an appropriate model to analyze the relationship between a binary response variable (e.g., presence/absence of fish or suitable/unsuitable habitat) and several explanatory environmental factors (Ahmadi-Nedushan et al. 2006).

The recently developed mesoscale habitat models (i.e., MesoHABSIM; Parasiewicz 2001, 2007*a*) show considerable potential in allowing rivers to be surveyed for longer stretches encompassing a larger range of habitat variables and enabling regional-scale assessment (e.g., Vezza et al. 2012*a*). The aim of this paper was to propose a new methodology for habitat modeling in high-gradient streams. In order to handle the present lack of tools to address these habitats, an adaptation of the MesoHABSIM is presented along with a description of the key methodological steps and examples of applications. Finally, to provide quantitative information for environmental management activities, we also evaluated the methodological efficiency in field data collection and habitat modeling.

Study Domain

The mountainous areas of the Valle d'Aosta, Piemonte, and Liguria regions in Northwest (NW) Italy, where mountains and hills cover 60% of the territory, were the study domain of this research (Fig. 1). Piemonte and Valle d'Aosta together represent 28% of the total length of the Alps mountain range and constitute the upper part of the Po River drainage basin, Italy's largest river. Liguria is the coastal region of NW Italy, characterized by a very steep and narrow continental shelf, among the Alps, Apennines, and Tyrrhenian Sea.

The climatic characteristics of this 34 000-km^2 area vary from the Apennine–Mediterranean climate in Liguria and southeastern hills of Piemonte, to the Alpine–Continental one in the NW Alps of Piemonte and Valle d'Aosta; in the first zone, watersheds are characterized by little snowpack storage, high evapotranspiration, and low flows occurring in summer, while in the second one, low flows occur in winter affected by freezing processes, presence of glaciers, and snow cover accumulation (Vezza et al. 2009). Within the mountainous areas, land cover varies from the rocky and forested areas of the Alps (elevation from 300 to 4800 m above sea level [a.s.l.]), to the small mountains and hillsides of the Apennines characterized by forests, crops and vineyards (elevation from 0 to 2000 m a.s.l.).

Five dominant morphology types are used in this paper to describe mountain streams (Fig. 2): cascade, cascade-pool, step-pool, riffle-step, and plane bed (Montgomery and Buffington 1997). The study sites considered in the analysis are stretches of 40 mountainous watercourses (Fig. 1) characterized by reach gradients varying from 2% to 22%. The average bed slope was calculated using the available information coming from surveys (see the following section) in order to determine the gradient of the entire surveyed stream reach. A stream gradient equal to 2%, i.e., the lower

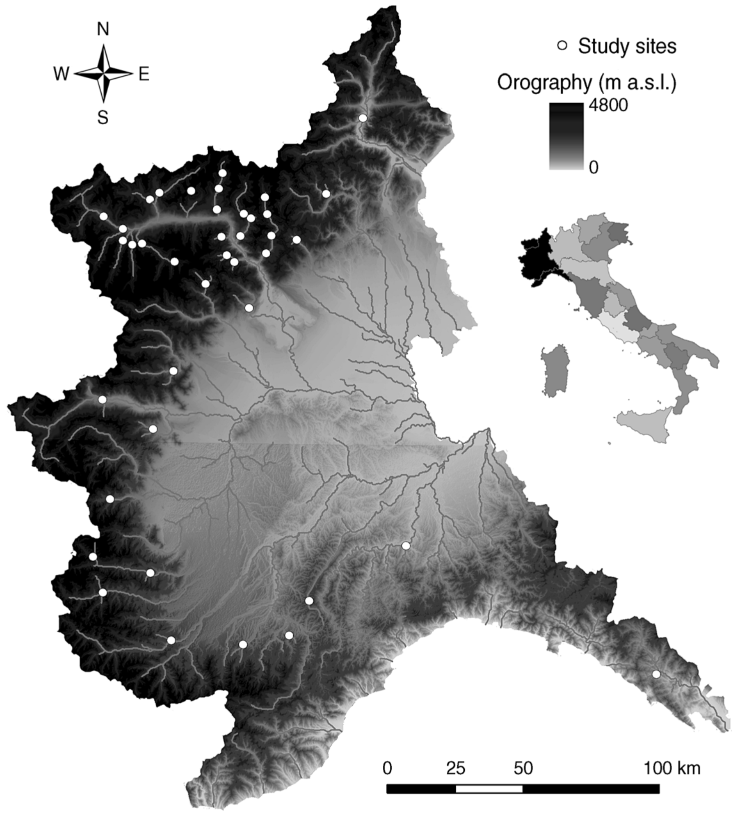

FIG. 1. The 40 study sites located in Northwest Italy, within the Alps and Apennines mountain ranges (m a.s.l., meters above sea level).

threshold of plane bed morphology (Montgomery and Buffington 1997), was considered the lower limit value for the analysis in order to test the methodology in both moderate as well as high-gradient reaches. Table 1 shows the main features of the selected streams, while Fig. 2 reports representative pictures of the five reference alluvial morphologies.

METHODOLOGICAL DESCRIPTION

The proposed methodology is an adaptation for high-gradient streams of the MesoHABSIM procedure reported in Parasiewicz (2007*a*, *b*), defining (1) the habitat description, (2) the biological model definition, and (3) the development of habitat rating curves and time series analysis. The flow chart presented in Fig. 3 outlines inputs and outputs of the model and the sequence of the main steps of the methodology.

Habitat description

The habitat description was based on two main processes: the representative site selection and the habitat survey. For the representative site selection, we used a project base map and a digital elevation model within a geographic information system (GIS) environment to identify the stream gradient, the areas of interest, the possible access locations (which represent a considerable limiting factor in mountainous headwater streams), and hence defining a preliminary field data collection schedule. However, the narrow and V-shaped valleys and the presence of high-density vegetation near the main channels often did not allow the use of aerial photography, and on-the-ground river observation was usually required. This reconnaissance survey involved hiking in the study area along the entire river length, estimating portions of the stream that are often delimitated by considerable change in stream gradient (knickpoints). Within homogeneous stream sections, the shortest representative reach, normally from hundreds of meters to kilometers, was then selected for detailed survey. This subsampling of representative river sections could be based on expert opinion up to sophisticated analysis using statistical approaches, e.g., cluster analysis to group the sections that were similar to each other (Parasiewicz et al. 2003), depending on the study objectives, costs, and logistic constraints.

The habitat survey described the changes in mesohabitat types over a selected range of discharges. Since reference to aerial photos (Parasiewicz 2007*a*) was often limited, we usually relied on the use of a rangefinder (e.g., Trupulse 360B, Laser Technology, Centennial, Colorado, USA), a photographic tripod, and a rugged field computer (e.g., Nomad TDS [tripod data system],

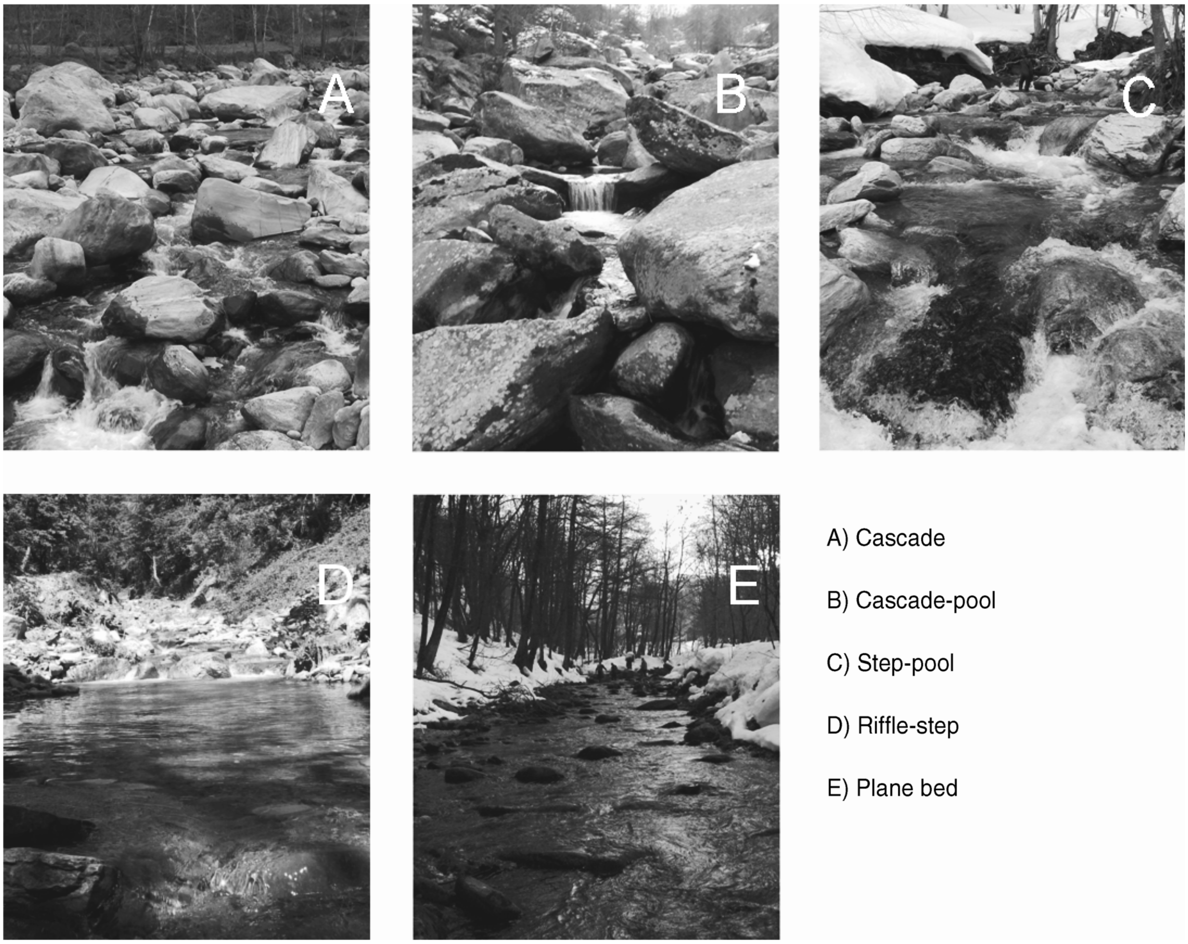

FIG. 2. Examples of the reference alluvial morphologies considered dominant within high-gradient stream reaches.

with global positioning system (GPS) positioning; Field Environmental Instruments, Sunnyvale, California, USA) to record the HMU characteristics. The GPS positioning was used to capture the starting point of the survey, defined from a nearby opening with good satellite coverage or from a clearly identifiable ground control point. Each HMU (e.g., pool, riffle, rapid) is a definable area that reflects the interplay between hydraulics and riverbed topography and can be inferred by visual observation of surface flow character and verified by water depth, flow velocity, and substratum types (Gosselin et al. 2010). Surveys were usually carried out by walking downstream, delineating the HMU polygons in a GIS environment and recording the mesohabitat-scale features (HMU area and type, cover, shores characteristics, mesohabitat longitudinal connectivity, gradient) and coming back upstream (toward the access point), collecting depth, velocity, and substrate information from each of the mapped mesohabitats.

An example of habitat descriptors collected during a habitat survey is reported in Table 2. Overall, both chemical (e.g., pH, dissolved oxygen, turbidity, and organic contaminants) and physical characteristics (e.g., HMU gradient, frequencies classes of depth, velocity, and substrate) were considered in the mesoscale habitat description due to their combined effects on habitat resources. Chemical variables generally do not change within the surveyed stream reach, but are important in defining habitat reference criteria for different streams. For each HMU, we collected from 7 to 30 mean water column velocity values (by using the flowmeter Marsh-McBirney Flo-Mate; Hach Company, Loveland, Colorado, USA), and carried out depth measurements and substrate estimates in order to cover the variability of instream flow conditions and to describe the HMU area. For detailed studies and within large non-wadeable pools, the ADCP SonTek RiverSurveyor (M9-ADP; San Diego, California, USA) was used to describe depth and velocity frequencies. Depending on the size of the stream, either the Marsh-McBirney Flo-Mate or the ADCP SonTek RiverSurveyor was also used to measure the discharge. Based on the fact that the habitat in rivers changes regularly with flow, three surveyed discharges were considered the minimum required to describe the hydromorphological characteristics. According to the MesoHABSIM simulation model (Parasiewicz 2007*a*,

TABLE 1. Main features of the selected study sites: centroid longitude (UTM X), centroid latitude (UTM Y), catchment area, morphology type, gradient, and elevation.

ID	Stream reach	UTM X	UTM Y	Catchment area (km^2)	Morphology type	Gradient (%)	Elevation (m)		
							Mean	Minimum	Maximum
1	Artanavaz	366559	5073558	131.99	step-pool	0.10	2145	1004	3716
2	Ayasse	394774	5053102	62.64	cascade-pool	0.11	2202	1146	3101
3	Belbo	425100	4925715	31.17	plane bed	0.02	680	568	869
4	Buthier	369985	5076077	213.36	cascade	0.06	2524	936	3918
5	Campiglia	386906	5042490	32.66	cascade	0.13	2154	1110	3287
6	Cavaglione	431421	5075644	13.03	cascade-pool	0.11	1435	620	2274
7	Chalamy	392759	5059853	32.00	cascade	0.09	2112	1089	3097
8	Crest	397494	5050583	12.22	cascade-pool	0.22	1857	929	2523
9	Dora Baltea	349328	5067411	447.02	riffle-step	0.05	2331	887	4672
10	Dora Rhemes	356483	5058443	124.01	cascade	0.07	2451	1084	3546
11	Dora Valgrisenche	356483	5062776	159.72	step-pool	0.11	2407	727	3562
12	Evancon1	401021	5068318	148.51	cascade	0.07	2443	1278	4174
13	Evancon2	399711	5060156	225.82	cascade	0.06	2234	662	4174
14	Graine	403641	5066706	14.85	cascade-pool	0.15	2056	1403	2693
15	Grandeyvia	363635	5057334	238.45	riffle-step	0.03	2510	1052	3830
16	Lurisia	400741	4909666	19.60	riffle-step	0.04	2745	652	1724
17	Lys1	408780	5074364	67.40	cascade	0.05	2516	1596	4487
18	Lys2	409687	5068217	107.85	riffle-step	0.04	2296	1364	4487
19	Lys3	411199	5060257	171.99	riffle-step	0.02	2143	962	4487
20	Lys4	409183	5053808	234.62	cascade	0.11	2114	635	4487
21	Malacqua	552887	4898751	29.50	plane bed	0.02	781	163	360
22	Marmore1	393161	5083231	59.44	cascadepool	0.07	2642	1641	3773
23	Marmore2	391851	5077518	115.47	cascadepool	0.05	2476	1158	3773
24	Marmore3	391146	5069930	203.38	cascadepool	0.09	2248	734	3788
25	Melle	366623	4936056	14.14	steppool	0.08	1315	752	1884
26	Pragnetta	420499	5058742	11.08	cascadepool	0.19	1681	888	2387
27	Ravine	444816	5103579	15.24	cascade	0.09	1177	232	2075
28	Ricchiaglio	375077	5010493	26.70	riffle-step	0.05	1240	938	2614
29	Rifreddo	417734	4913054	10.88	Plane bed	0.02	625	442	901
30	Saint Barthelemy	381674	5076736	42.20	cascade	0.17	2177	1237	3043
31	Savara	359909	5056931	137.00	cascade-pool	0.08	2577	1157	3938
32	Savenca	402946	5033543	33.35	cascade	0.04	1241	476	2566
33	Scaglione	348980	4999938	24.91	step-pool	0.12	1699	460	2846
34	Subiasco	351740	4963347	14.38	cascade	0.10	1669	722	2777
35	Taonere	367653	4989059	15.19	step-pool	0.09	1163	573	2058
36	Urthier	375527	5050684	48.80	cascade	0.04	2555	1615	3487
37	Vallanta	345430	4941936	24.05	cascadepool	0.18	2589	1492	3848
38	Valle Ritta	374230	4911278	16.29	riffle-step	0.04	1033	643	1780
39	Vallone Delva	349123	4928720	38.69	cascade	0.10	1944	1523	3033
40	Visone	460682	4945988	49.65	plane bed	0.02	414	135	695

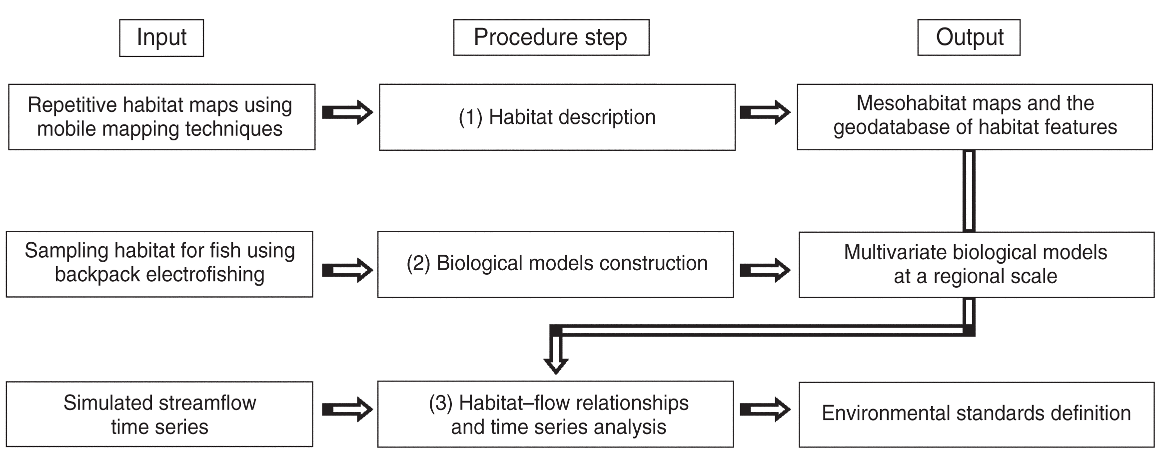

FIG. 3. Implementation steps of the proposed methodology for the definition of environmental standards in high-gradient streams, based on a modification of the MesoHABSIM simulation system (Parasiewicz 2007*a*).

TABLE 2. Habitat physicochemical attributes for describing hydromorphologic units (Parasiewicz 2007*a*, Vezza et al. 2012*a*).

Variable name	Units	Classes	Categories/description
Hydromorphologic units (HMUs)	yes/no	12	pool, plunge pool, glide, run, fast run, riffle, ruffle, step-pool, rapid, waterfall, backwater, side arm
HMU gradient	%	1	bottom mean slope of the HMU
HMU longitudinal connectivity	yes/no	1	habitat binary attribute describing mesohabitats longitudinal connectivity
Cover	yes/no	7	boulders, canopy shading, woody debris, overhanging vegetation, submerged vegetation, shallow margin, undercut bank
Substrate	percentage of random samples	12	pelal, psammal, akal, microlithal, mesolithal, macrolithal, megalithal, phytal, xylal, sapropel, detritus, debris
Water depth	percentage of random samples	9	classes in 15-cm increments (range 0–120 cm and above)
Flow velocity	percentage of random samples	9	classes in 15-cm/s increments (range 0–120 cm/s and above)
Froude number	(flow velocity)/(9.81 depth)$^{0.5}$	1	average over the HMU area
Flow velocity standard deviation (SD)	cm/s	1	SD over the HMU area
Water temperature	°C	1	water temperature at site level
Water pH		1	water pH at site level
Percentage of dissolved oxygen	%	1	value at site level
Turbidity	formazin attenuation unit	1	value at site level
Biological oxygen demand	mg/L	1	value at site level

Note: This list, used in the present study, can be adapted (e.g., additional parameters to be surveyed) according to study objectives.

Vezza et al. 2012*a*), the HMU survey was normally repeated from three to five times between the minimum low flows (e.g., defined using low flows regionalization formulas; Vezza et al. 2010) and the medium/high flows expected on that river (e.g., derived from flow duration curves; Piedmont Region 2007).

The lower flow threshold occurs during late autumn and early winter in Alpine streams and during summer in Apennine–Mediterranean ones (Vezza et al. 2010). In contrast, the upper flow threshold is usually controlled by the spring snowmelt processes in the Alps and by the spring/autumn rainy events in the Apennines. As a general rule, reference conditions for habitat surveying are indicated as the flow range in the key bioperiods for the considered fish community, e.g., rearing and growth stage or migration and spawning period (sensu Parasiewicz et al. 2008).

Biological models

The biological indicators proposed in the present research for high-gradient streams are based on the Target Fish Community approach (Bain and Meixler 2008), and can be particular species of fish, their life stages, guilds, or the entire fish community.

The fish community composition varies within the region of interest according to the catchment coordinates and elevation, also including reach gradient and morphology (Carta Ittica Regionale 2004, Comoglio et al. 2007). To determine the fish community composition, a list of the expected species was created considering different fish bioperiods, especially in rivers with high levels of seasonal migration (Parasiewicz et al. 2007). The list can be extrapolated from existing institutional databases (e.g., Carta Ittica Regionale 2004) and subsequently integrated through direct fish samplings.

The fish samplings were carried out to get precise data for the construction of biological models through the observation of the mesohabitat use by a selected organism during its diurnal routine. For model application purposes, and even for setting habitat restoration measures in regulated or channelized streams, biological models were built in these natural reference conditions in terms of natural flow regime and fish community composition (age-structured populations, only autochthonous species, absence of restocking and fisheries). Within pristine high-gradient streams characterized by little or no human impact, fish data were collected by sampling every HMU with backpack electrofishing and using the multiple-pass removal method (Kruse et al. 1998). Mesohabitats were separated using nets in order to assure the direct association between sampled areas and sampled fish species. Before being released within the same sampled HMU, each fish was measured in terms of mass and fork length, then classified into adult and juvenile life stages by means of length–age relationships and, in more detailed species studies, by using scales analysis (Vezza et al. 2012*a*).

The biological data were the basis for the calculation of probabilistic models aimed at establishing habitat suitability criteria with information coming from one or more rivers. As reported in Ahmadi-Nedushan et al. (2006), logistic regressions currently represent an appropriate method for the habitat evaluation process to identify the habitat attributes affecting species distribution. In the present work, the Akaike's information criteria (AIC; Sakamoto 1991), along with a multiple logistic regression model, were performed to select the habitat attributes influencing species presence or abundance at different life stages. The algorithm uses AIC and a stepwise forward procedure to determine which parameters should be included in the following regression formula:

$$R = e^{-z} \quad (1)$$

where e is natural-log base and $z = b_1x_1 + b_2x_2 + \ldots + b_nx_n + a$, where x_n are significant habitat attributes, b_n are regression coefficients, and a is a constant. Habitat suitability models were built using a fivefold cross-validation procedure in which 20% of the randomly selected data were separated and used for model validation. These data have the same proportion of suitable units as the whole data set. To increase model certainty, this procedure was repeated 20 times and, each time, a new set of randomly selected data was set aside for validation purposes. After 20 runs, the model generated a list of parameters selected in at least two runs and conducted one additional run using only these parameters as input attributes. The last step was the review of standard errors calculated for each recorded attribute and the removal of the attributes with errors greater than the regression coefficient derived from using standardized variables (Parasiewicz et al. 2012*a*).

Two binary habitat suitability models were created as follows: a suitable habitat model indicating the potential for fish presence (to distinguish between absence and presence of the fish) and an optimal habitat model for high abundance of fish (to distinguish between fish presence and abundance). The cutoff value for low and high abundance was determined as the inflection point of the envelope curve of the fish density histograms (Vezza et al. 2012*a*). The area under the receiver operating characteristic (ROC) curves and the model accuracy (in terms of correctly classified instances) provided the measures of the model's performance (Hosmer and Lemeshow 2000). The area under the ROC curve defines the discrimination capacity of the model over a range of threshold levels (Pearce and Ferrier 2000) by plotting the proportion of HMUs correctly predicted (sensitivity or true positive rate) vs. the units incorrectly predicted to be occupied (false positive rate). In the area under the ROC curve, a value of 0.7 indicates moderate discrimination power of the model to distinguish between absence/presence (or presence/abundance) of fish, while a value of 0.8 refers to acceptable discrimination, and one of 0.9 refers to outstanding discrimination (Hosmer and Lemeshow 2000).

The obtained habitat suitability criteria were applied to all HMUs mapped in the study area to calculate the probability (p) of presence and high abundance by using the following equation:

$$p = 1/(1 + e^z) \quad (2)$$

and it was used to classify habitat into suitability categories (not suitable, suitable, or optimal). The inflection point on the ROC curve was used to define the probability threshold to determine the best separation of suitable and not suitable (or suitable and optimal) units (Parasiewicz 2007*a*).

The reference habitat attributes considered in this study are presented in Table 2. Unfortunately, the literature-based information that could be used for the development of habitat suitability criteria is currently underdeveloped for the region of interest, and the available studies have low applicability in high-gradient streams, being mainly related to micro-scale suitability models, low-gradient reaches, and carried out only for water depth and flow velocity (Vismara et al. 2001). Thus, we relied on field data rather than literature for developing habitat suitability criteria for high-gradient streams.

Habitat rating curves and time series analysis

The digital mesohabitat maps built during the habitat surveys and the mesohabitat suitability criteria were the basis for the development of habitat–flow rating curves for each site. The area of HMUs with suitable (or optimal) habitats was summarized for every site by weighting suitable habitat area by 25% and the optimal habitat area by 75%, and it was plotted against the wetted area at the highest measured flow Parasiewicz (2007*a*). The habitat values were interpolated using a mathematical spline function for the target species and life stages to represent the habitat rating curve. Moreover, rating curves for generic fish were also calculated. The generic fish was considered as a hypothetical species that uses the same habitat as all the investigated species in the community for which the multiple-occupant areas are counted only one time. Therefore, the generic-fish habitat can be seen as the total physical habitat available for the considered fish community. Obviously, the available physical habitat area does not take into account any limitations caused by biotic interactions (such as predation, competition, and mutualism). Another option reported in (Parasiewicz 2007*a*) is to compute community habitat by weighting the habitat of each species by their expected proportion in the target fish community. However, the quantitative fish data, along with life history information in the fish community, were often unavailable for our study sites and, therefore, we considered the approach for generic fish to be the best available approximation.

In addition to reference fish community rating curves, the definition of the reference streamflow and habitat time series was the final element needed in the full determination of the environmental reference conditions, which could be analyzed using the uniform continuous under threshold (UCUT) methodology (Parasiewicz 2007*b*). Although the understanding of hydrological characteristics in headwater streams is critical for managing water resources in mountainous areas, we have to face the problem of a frequent lack of stream gauge data (e.g., Watson et al. 2009, Vezza et al. 2010). To address this issue, the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS; McEnroe 2010), along with the Snow-Band snowmelt computation of the Streamflow Synthesis and Reservoir Regulation (SSARR) model, were used in the present study to generate the flow time series for high-gradient streams (HEC 2001, Hu et al. 2006). The model with snowmelt capability (HEC; *available online*)[7] requires precipitation and air temperature as inputs, and estimates the snow water equivalent (SWE) and the impacts of snowmelt on the streamflow. The HEC-HMS model is characterized by a large number of parameters that are often not directly measurable. Therefore, these parameters must be estimated through model calibration in a neighboring similar catchment (i.e., the donor) where streamflow data series are available and by fitting the simulated outputs of the model to the observed outputs of the catchment. The choice of the donor catchment was based on the similarity approach (Parajka et al. 2005) in which the hydrological model parameters were transposed from a catchment that was most similar in terms of its physiographic attributes (mean elevation, drainage density, land use, and geology). The optimization method and the execution of trials were used to calibrate the model by finding the values for the model parameters that minimize each calibration criterion. The coefficient of efficiency (E) was then used to provide an indication of the degree of association between simulated and recorded flows (Chiew and McMahon 1993). The flow time series were generated for the ungauged stream using the calibrated model and the reference habitat time series produced.

The habitat time series was calculated as:

$$\mathrm{HA}(t) = \mathrm{PH}(Q(t)) \quad (3)$$

where PH is the physical habitat-vs.-stream flow function for a given life stage, species, or generic fish, $Q(t)$ is the streamflow at time t, and $\mathrm{HA}(t)$ is the habitat area for time t (Milhous et al. 1990). The obtained habitat time series was then statistically analyzed using the uniform continuous under thresholds (UCUTs; Parasiewicz 2007*b*) methodology to establish the habitat stressor thresholds (HST). This analysis was based on the assumption that habitat is a limiting factor, and events occurring rarely in nature create stress to aquatic fauna and shape the community. Identification of HST considers not only the magnitude of an impact, but can also provide a means of quantitatively comparing duration and frequency of events, as well as different flow management scenarios (Parasiewicz et al. 2012*b*, Vezza et al. 2013*a*). To evaluate environmental thresholds, it was therefore essential to consider not only the magnitude of an impact, but also its duration and frequency. The UCUT-curves are considered projected contours of a habitat surface area in the three-dimensional space of duration, frequency, and habitat area. They are defined for a given bioperiod and were used to evaluate the durations and frequency of continuous events with habitat lower than a specified threshold. Therefore, the sum length of all events of the same duration within bioperiods was computed as a ratio of a total duration of all bioperiods in the record and the proportions are plotted as a cumulative frequency. This procedure is repeated for the entire set of thresholds with constant increments (e.g., 2% increment of suitable habitat).

To identify HST, we analyzed the specific regions with a higher or lower concentration of the curves on the plot, and common and less common habitat events were based on the changes in area slope expressed by the shape of and distances between the curves. The procedure had two steps: (1) determination of habitat threshold levels by selecting curves on the graphs and (2) identification of critical durations by locating inflection points. Interpretation of these patterns was based on the following observations: (1) The horizontal distance between curves indicates the change in frequency of events associated with a habitat increase to the next level (e.g., the larger the distance between two curves at the same continuous duration, the larger the change in the frequency of the events), (2) steep curves represent low change in event frequency, and (3) inflection points reflect rapid change in frequency of continuous durations.

Typically, the UCUTs for very low habitat availability happen infrequently and are located in the bottom left corner. As habitat level continues to increase, this pattern of UCUTs rapidly changes and distance between the curves increases. We selected the highest curve in the rare-habitat group of curves as a rare-habitat level threshold. The critical level defines a more frequent event than rare, below which the habitat circumstances rapidly decrease. Therefore, the next higher UCUT line (the first that stands out) is identified as a critical level. The distance between the lines after exceeding the critical level are usually greater than in the previous group, but are still close to each other. The next outstanding curve, demarcating rapid change in frequency of events, was assumed to mark the stage at which more common habitat levels begin (no stress;

[7] http://www.hec.usace.army.mil/

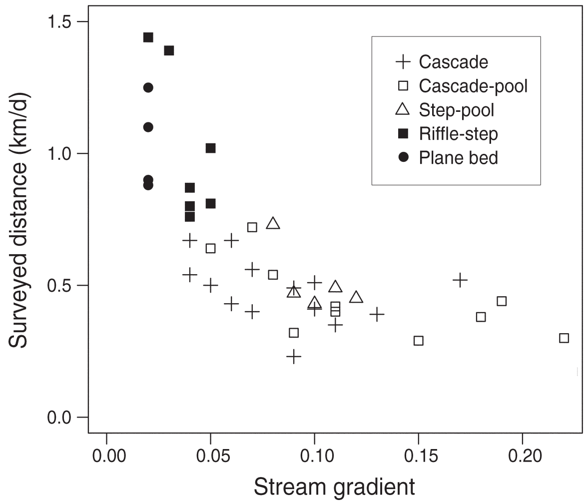

FIG. 4. Efficiency of mesoscale field data collection in high-gradient streams, expressed in terms of surveyed linear distance. Stream gradient has no unit and it is expressed as elevation change/horizontal distance.

Parasiewicz 2007*b*). The inflection points on the UCUTs demarcate change in frequency of habitat under-threshold durations. This observation helps to identify the longest periods that a habitat condition is allowed to continue under a specified threshold. The events exceeding these durations were subdivided into one of two categories: allowable or catastrophic. An allowable event is likely to occur every few years, but at the intra-annual scale, these long events are unusual, i.e., do not happen more than twice in a year. Catastrophic events occur on a decadal-scale, and we chose as catastrophic threshold the shortest of the longest durations.

The results of HST analysis were used to develop habitat augmentation strategies, i.e., short-term flow increases, aimed at reducing continuous duration of habitat under HST. Once the allowable duration of habitat under rare or critical habitat levels was exceeded, the strategy called for release of water that will increase the amount of habitat to critical or common level, respectively. This strategy was then summarized in operational rules that can be used for dam operations.

RESULTS

As a first step, the efficiency of the proposed methodology was evaluated in terms of field data collection, i.e., mesohabitat survey and description. Fig. 4 shows the expenditure of time for data collection in the selected streams, referring to an eight-hour working day of a team of two people. It is interesting to note how performance values decrease in line with stream gradient and are stratified referring to stream morphology and riverbed characteristics. A breakpoint was located at 7% gradient, beyond which the performance in terms of surveyed linear distance was around 0.4 km/day. For very high-gradient study sites, i.e., those with 22% gradient and rocky cascade-pool channel morphology, performance decreased to 0.25 km/day.

A database of ~500 records of HMUs observation, quantitatively sampled for fish, was collected since fall 2008 and is currently available for the study area. For the purpose of demonstration in this paper, we focused our attention on salmonids, i.e., marble trout (*Salmo marmoratus*) and brown trout (*Salmo trutta fario*), which are characteristic of the region of interest (see Vezza et al. 2012*a* for further mesohabitat suitability models). Table 3 shows the models for each fish species, related to adult and juvenile life stages. The autumn/winter model for marble trout is shown, which is related to its migration and spawning season, while for brown trout, the spring/summer model related to the rearing and growth bio-period is reported. Due to the limited number of observations of juvenile marble trout, the abundance model is not shown here. Overall, for the area under the ROC curve, values range from 0.81 (acceptable discrimination) to 0.90 (outstanding discrimination), while the accuracy of the models, in terms of correctly classified instances, varied from 61% to 72%.

In Fig. 5, several examples of habitat–flow rating curves are presented that define the habitat variation at the selected range of flows for different species, life stages, and the generic fish for each of the considered five morphological channel types separately. For catchments characterized by only one fish species, i.e., brown trout for Vallone d'Elva and Campiglia Streams and Taonere and Subiasco Creeks, the habitat curve for generic fish was not calculated.

An example of hydrological model calibration is shown in Fig. 6, using Grana Stream as the donor catchment. The model inputs (temperature, precipitation, streamflow time series) and outputs (simulated and residual flow time series) for the period August 2001–December 2010 are reported. The obtained residual flow, i.e., the difference between the observed and simulated time series, shows the inability of the model to capture the peak streamflow magnitude, while the coefficient of efficiency ($E = 0.64$) demonstrates a relatively good association between simulated and recorded flows (Parajka et al. 2005).

The calibrated hydrologic model was then used to generate the reference habitat time series for Valleritta Creek (ID 38 in Table 1) and to calculate the uniform continuous under threshold (UCUT) curves for the winter low-flow period (simulated period 1970–2010; Fig. 7). Each curve on the diagram represents the cumulative duration of events (between 2% and 30% of the channel area). The reduction in slope, as well as the increase of spacing between two curves, indicate an increase in the frequency of under-threshold events (Parasiewicz 2007*b*). Rare-catastrophic (8% of channel area), critical-persistent (10%), and common habitat (28%) thresholds were then selected, and their inflection points were used to demarcate associated persistent and catastrophic durations of events (Fig. 7).

TABLE 3. Marble trout (*Salmo marmoratus*) biological models for autumn/winter and brown trout (*Salmo trutta fario*) biological models for spring/summer.

Species, model, and parameter	Value
Marble trout: adult	
Presence model	
Estimated success (%)	66
Area under ROC curve	0.87
Probability cutoff	0.40
Constant	−0.868
HMU gradient (%)	−0.094
Depth 60–75 cm (%)	4.49
Velocity 30–45 cm/s (%)	4.39
Akal (gravel) (%)	14.11
Abundance model	
Estimated success (%)	62
Area under ROC curve	0.87
Probability cutoff	0.74
Constant	−2.36
No connectivity (yes/no)	20.49
Pool (yes/no)	20.23
Velocity 0–15 cm/s (%)	−4.58
Marble trout: juvenile	
Presence model	
Estimated success (%)	72
Area under ROC curve	0.77
Probability cutoff	0.34
Constant	−2.56
Ruffle (yes/no)	−16.95
Depth 15–30 cm (%)	−2.62
Velocity 0–15 cm/s (%)	1.94
Macrolithal, 20–40 cm (%)	1.68
Brown trout: adult	
Presence model	
Estimated success (%)	72
Area under ROC curve	0.84
Probability cutoff	0.45
Constant	−2.38
HMU gradient (%)	−0.124
Boulders (yes/no)	2.55
Canopy shading (yes/no)	0.68
Step-pool (yes/no)	1.91
Depth 30–45 cm (%)	−1.19
Megalithal, >40 cm (%)	2.16
Macrolithal, 20–40 cm (%)	3.59
Abundance model	
Estimated success (%)	62
Area under ROC curve	0.82
Probability cutoff	0.51
Constant	−24.24
Boulders (yes/no)	18.35
Step-pool (yes/no)	1.96
Depth 60–75 cm (%)	3.22
Velocity 15–30 cm/s (%)	−4.29
Water temperature (°C)	3.85
Brown trout: juvenile	
Presence model	
Estimated success (%)	68
Area under ROC curve	0.81
Probability cutoff	0.35
Constant	−6.27
HMU gradient (%)	−0.089
Boulders (yes/no)	2.23
Run (yes/no)	−1.21
Depth 30–45 cm (%)	2.22
Velocity 30–45 cm/s (%)	−2.77
Macrolithal, 20–40 cm (%)	5.27
Akal (gravel) (%)	4.30
Water temperature (°C)	1.35
Abundance model	
Estimated success (%)	67
Area under ROC curve	0.86
Probability cutoff	0.60
Constant	−8.20
HMU gradient (%)	0.29
Canopy shading (yes/no)	2.22
Plunge pool (yes/no)	7.83
Depth 75–90 cm (%)	−25.50
Mesolithal, 6–20 cm (%)	4.42
Water temperature (°C)	1.79

Notes: The habitat variable coefficients are multipliers of the significant habitat attribute values, and the model accuracy and the area under the receiver operating characteristic (ROC) curve were used to estimate the predictive power of the model. The probability cutoff for both presence and abundance models was derived from the ROC curves in order to classify habitats into suitability categories (Parasiewicz 2007*a*). Habitat physico-chemical attributes for describing hydromorphologic units (HMU; Parasiewicz 2007*a*, Vezza et al. 2012*a*). This list, used in the present study, can be adapted (e.g. additional parameters to be surveyed) according to the study objectives. Attributes with many categories (e.g., HMUs) are broken down into multiple variables in binary (yes/no or 1/0) format.

DISCUSSION

A recent European report (CIPRA 2010) has highlighted that, in addition to an already relevant number of existing hydropower plants and other water abstractions, several hundred applications for new small hydropower plants (SHP) are being presented across the whole Alpine area. The key conclusion of the report is that regional-based planning is considered necessary in order to make decisions about new SHP facilities to ensure that further development of hydropower is compatible with both environmental protection requirements and the targets set for renewable energy production. This European trend reflects the increasing worldwide significance of small-hydro (NREL 2001, Anderson et al. 2006*a*, McLarney et al. 2010, GIM-UNDP 2011) as a "new" renewable energy source (REN21 2010). Despite this increasing demand for further exploitation of water resources in mountainous high-gradient streams, an adequate methodology concerning habitat–hydraulic modeling for these particular watercourses is not yet available in the scientific literature.

To cope with the issues noted in the previous paragraph, we propose a new methodology for habitat–hydraulic modeling in high-gradient streams based on an adaptation of the MesoHABSIM simulation model reported in (Parasiewicz 2007*a*), which we have developed and tested in several streams of the Alps and Apennines in NW Italy. To adapt MesoHABSIM to high-gradient streams: (1) The data collection strategy was modified to address the challenging conditions of

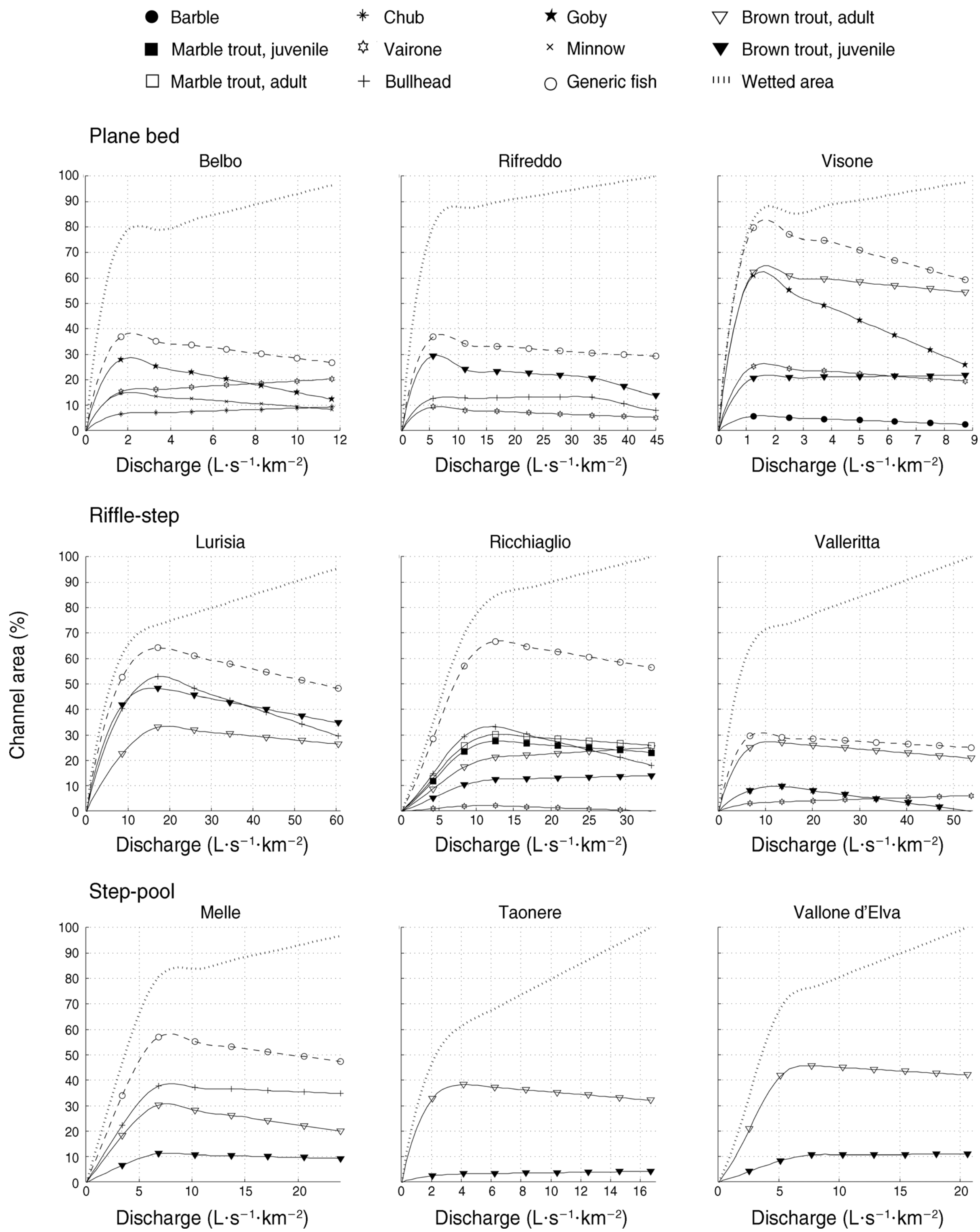

FIG. 5. Habitat–flow rating curves obtained for 15 of the 40 considered streams reporting the available habitat for fish in terms of percentage of channel area. The considered streams are also grouped using the five reference morphology types reported in Fig. 2. The biological indicators used for the definition of environmental standards can be particular species of fish (e.g., threatened species such as marble trout) or life stages. The curve for generic fish is also reported (Parasiewicz 2007*a*), showing the total available habitat area for the fish community within the considered stream reach.

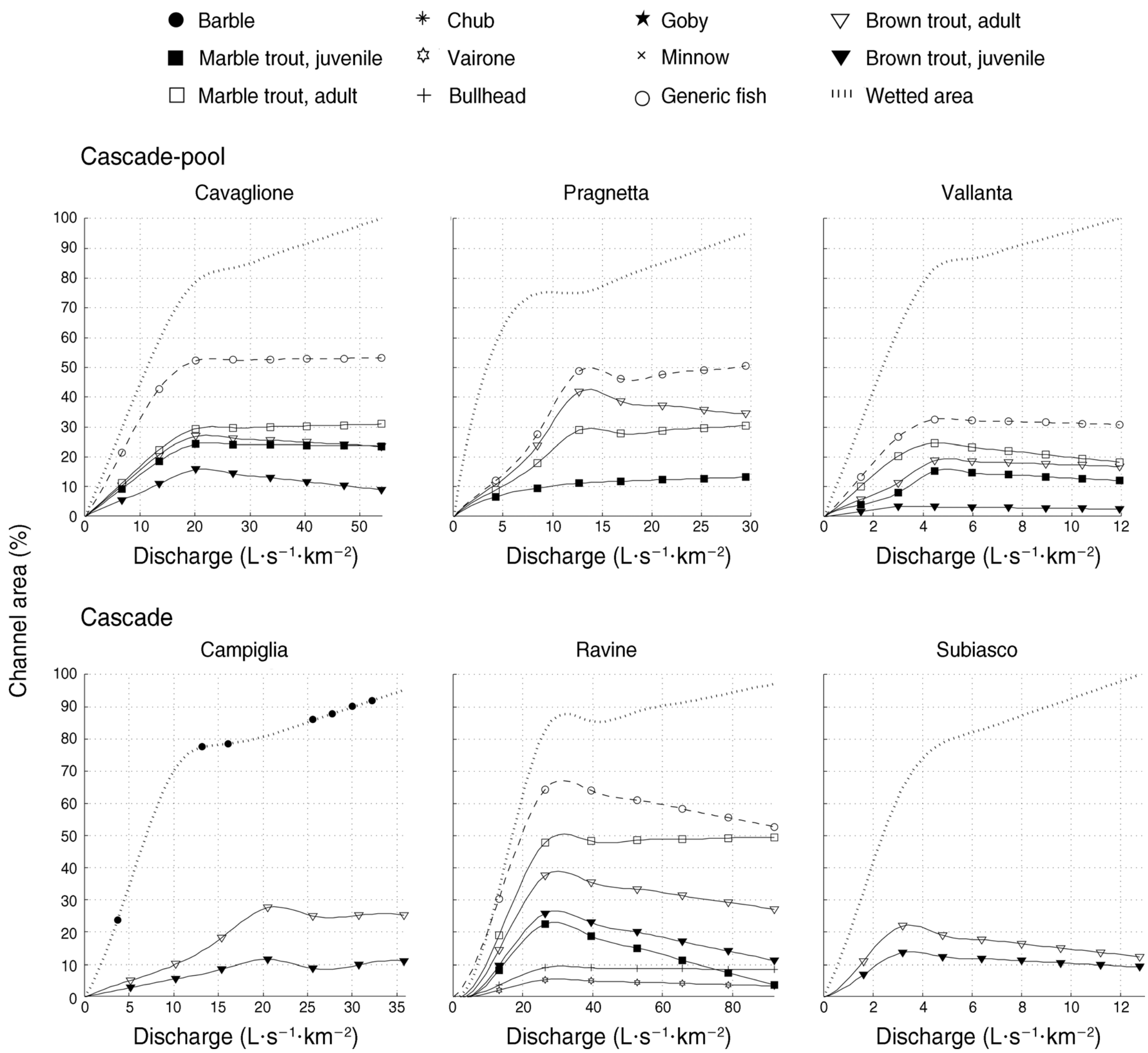

FIG. 5. Continued.

surveys, (2) the habitat suitability models were built at a regional scale to enable their transferability among different streams with different morphologies, and (3) due to the absence of stream gauges in headwaters, a possible way to simulate flow time series and, therefore, generate habitat time series was proposed. The resulting method was evaluated in terms of time expenditure for field data collection and habitat-modeling potentials and represents a specific improvement in the MesoHABSIM system that allows instream habitat modeling in high-gradient streams where other commonly used methodologies can be unsuitable.

The proposed data collection strategy included habitat description and fish sampling. For low-gradient streams, the MesoHABSIM method (Parasiewicz 2007*a*) refers to orthophotographs to delineate the spatial distribution of HMUs within stream sections. In high-gradient streams, due to the dense tree canopy and the narrow V-shaped valleys, the use of aerial images was often limited, and we relied on a rangefinder and a rugged field computer to record the hydro-morphological data. This mobile mapping technique was considered an appropriate solution for high-gradient streams. It is based on the use of light equipment, and it can be performed along streams when satellite coverage is marginal or nonexistent, or in zones characterized by hiking difficulties among rocks and/or by the presence of snow and ice. Compared to the performance values reported in Parasiewicz (2007*a*), in terms of surveyed linear distance, in steep streams, the performance with MesoHABSIM decreased in line with the stream gradient due to the increasing number of HMUs within stream reaches and to the challenging conditions of field work (Fig. 4). It is important to highlight that the increase in stream gradient reduces subjectivity in the definition of the mesohabitat type and extent, since it

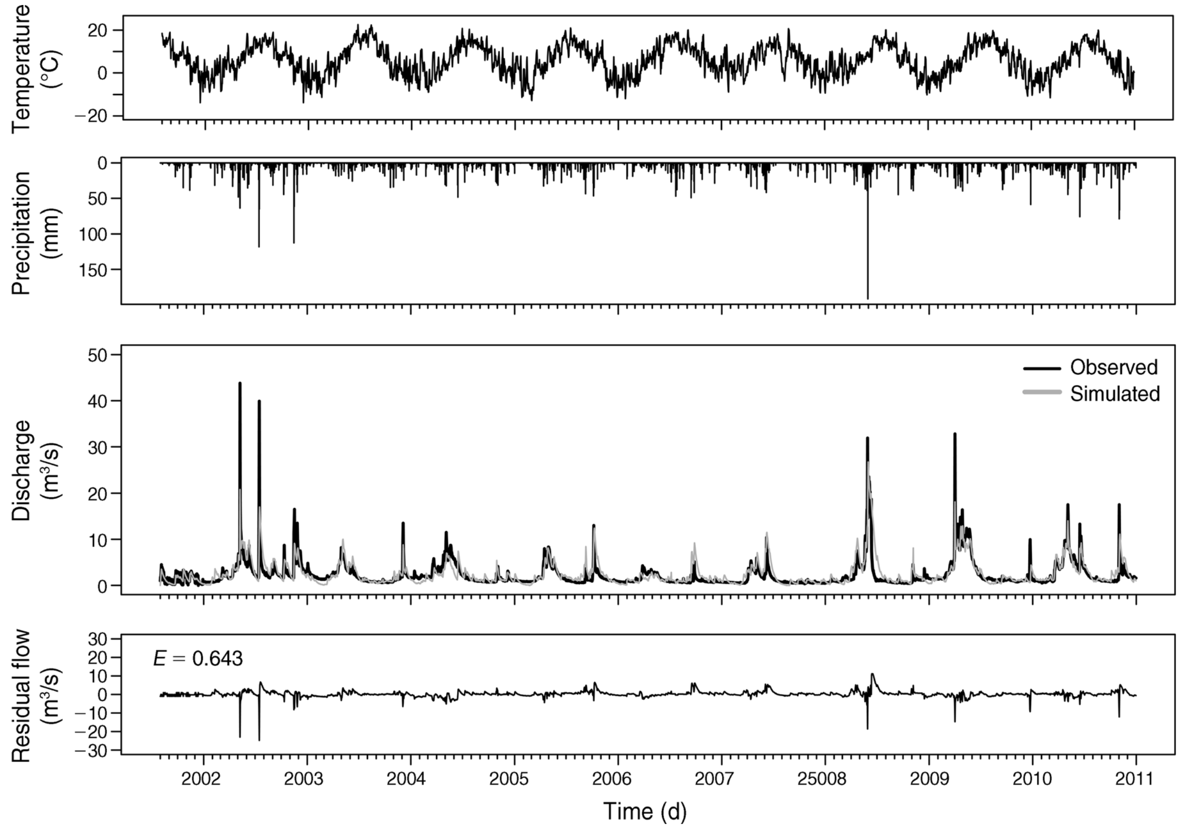

FIG. 6. The application of the HEC-HMS rainfall-runoff hydrologic model, along with the Streamflow Synthesis and Reservoir Regulation (SSARR) module for the calculation of snow water equivalent. The simulation was run between August 2001 and December 2010 for the Grana Stream (Piedmont, Italy). The peak streamflow magnitude was not captured by the model, while the residual flow and the coefficients of efficiency ($E = 0.64$) demonstrate a relatively good association between simulated and recorded flows.

allows mappers to define the start and end points of HMUs and the habitat type more precisely (Vezza et al. 2012*a*).

To describe the main channel, PHABSIM (Bovee et al. 1998) requires consecutive transect measurements, which are longitudinally extrapolated upstream and downstream to represent instream areas using distance weights. For steep streams, extrapolating hydraulic variables from one cross section to another unmeasured one may involve large errors, even when the two transects are located in the same channel unit (Reid et al. 2010). In contrast, the mesoscale approach reported here allows the representation of channel hydromorphology and habitat distribution, since it gives more emphasis to the longitudinal variations rather than to the cross-sectional variations (Rivas Casado et al. 2004). Furthermore, PHABSIM simulates flow characteristics at unmeasured discharges by using a one-dimensional hydraulic model. This flow simulation requires assumptions about flow and channel conditions, such as steady, gradually varied flow and absence of waterfalls and sudden changes, which are conditions that are commonly not satisfied in high-gradient streams.

The steepness of the riverbed, the complex morphology and the challenging conditions of surveys generally also prevent the application of other established hydraulic models (2D or 3D) for discharge simulation, which may require a considerable effort in the topographic surveys of the stream units and lead to overwhelming field work (Kozarek et al. 2010). As reported in Halwas and Church (2002), the use of high order surveying instruments (e.g., laser scanners or total stations) can be extremely fatiguing when there is onerous access to the study sites caused by thick canopy understory and difficult hiking conditions. Note that these hydro-dynamic models, which are implemented in different methodologies for habitat analyses (e.g., River2D [Steffler and Blackburn 2002] and CaSiMiR [Jorde 1997]) can describe complex channels and provide detailed hydraulic habitat metrics. However, they may have high overall cost and, despite the intensive data collection, involve slow data processing procedures and large computational efforts.

Since the mesoscale approach does not require hydraulic simulation, it adapts well to the mountainous watercourses, characterized by rock and boulder substrata and step-pool or cascade riverbeds. The use of

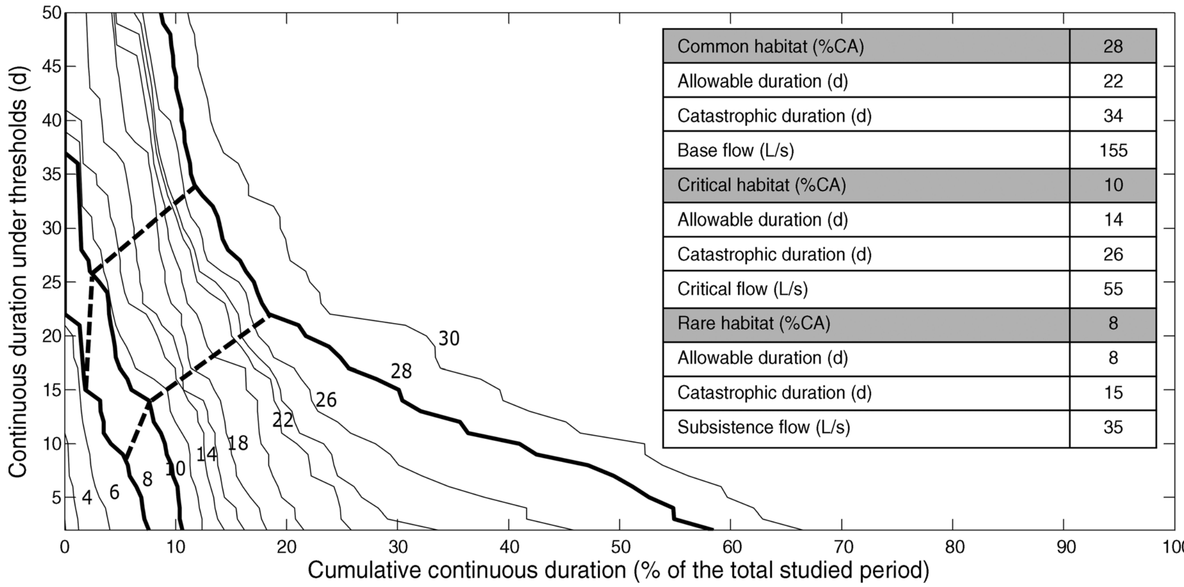

FIG. 7. The application of uniform continuous under threshold (UCUT) curves for Valleritta Creek to determine habitat stressor thresholds (HST). Events between 2% and 30% of channel area (%CA) suitable for fish were analyzed referring to winter low-flow periods (1 January–21 March between 1970 and 2010). Reduction in slope, as well as an increase of spacing between two curves, indicate an increase in the frequency of under-threshold events (Parasiewicz 2007*b*). Rare, critical, and common habitat thresholds (8%, 10%, and 28% of channel area, respectively, shown in the gray rows of the inset table) were selected and their inflection points were used to demarcate associated allowable and catastrophic durations of events (expressed in days).

repetitive mapping of stream reaches demonstrates a good performance in terms of surveyed linear distance and allows modeling of habitat variations over the range of measured discharges. The multiple mapping approach is, therefore, suggested for high-gradient streams, since it is based on a more effective data collection procedure. Note that during medium/high flow, the hydrodynamic conditions are characterized by tumbling and jet-and-wake flows around rocks, and the possibility of wading the stream channel can set the upper limit for surveys. The habitat–flow rating curves show how habitat availability generally decreases or remains constant after reaching a maximum habitat value. A flow increase after optimal conditions leads to an increase of turbulence and flow velocity and, therefore, to a reduction of shelters and suitability (e.g., Visone, Lurisia, Ravine Streams). This characteristic is particularly valid for plane bed, riffle-step, and cascade morphologies in which the high gradient and the stream dimensions often prevent the lateral expansion of wetted area at higher discharges. In contrast, the shape of the curves for step-pool and cascade-pool morphologies seems to capture the persistence in habitat availability for fish according to the increase of discharge (e.g., Vallone d'Elva, Cavaglione, Vallanta Streams). As pool size increases, habitat condition will also increase in stability when flow increases.

Due to the steepness of the river bed, the use of electrofishing grids or snorkeling surveys (mentioned in Parasiewicz 2007*a*) was limited in high-gradient streams. Collecting fish data in each HMU with backpack electrofishing can be considered an appropriate technique to quantitatively collect fish data at the mesoscale and to represent fish population densities in each sampling site. From a biological perspective, the mesoscale habitat models in high-gradient streams offer several interesting opportunities and show flexibility in modeling habitat for the fish community. This mesoscale approach can reveal larger spatial and temporal ecological patterns, since it involves a large range of habitat variables (Jewitt et al. 2001), e.g., consideration of river longitudinal connectivity and fish seasonal response to habitat characteristics (Table 3). The list of habitat characteristics, chosen for the biological models construction, can be easily adapted according to the study objectives (e.g., considering additional parameters to be surveyed). The mesohabitats description across the region of interest can be considered the appropriate scale resolution to capture the different ways in which these animals interact with the spatial arrangement of habitat characteristics. For model extrapolation and application purposes, we recommend construction of biological models using data from different streams with different morphologies and gradients. This regional-scale approach represents an improvement in transferability of habitat models among streams and has revealed potential for the definition of fish habitat requirements for many streams simultaneously. Moreover, to define the environmental standards at a regional scale, one can refer to the bottom-up approach proposed in Vezza et al. (2012*a*) to upscale the MesoHABSIM results for the entire region of interest.

In that study, homogeneous subregions were defined by grouping streams according to the environmental requirements of fish species.

The habitat suitability models showed acceptable performance values (Mouton et al. 2011) and, for the seasonal variation in fish habitat use, it is interesting to note how different habitat attributes affect fish presence or abundance considering the two different bio-periods (autumn/winter and spring/summer) and the two fish species (marble and brown trout). During autumn/winter, marble trout presence is related to HMUs, which are characterized by moderate depth and flow velocity, as well as by a gravel substrate suitable for egg deposition. Where the habitat is suitable, the abundance model seems to capture the marble trout migration behavior (e.g., Maddock et al. 2008) of accumulating below obstacles that prevent the upstream migration (i.e., chutes, waterfalls). In contrast, during summer, brown trout occurrence is related to step-pool mesohabitats with adequate cover in the form of boulders, submerged rocks (megalithal and macrolithal substrate), and canopy shading. These results agree with other studies (Fausch and White 1981, Fausch 1984, Hughes and Dill 1990) that show the preferences of feeding on drift and habitats with fast currents close to velocity shelters where fish can rest after feeding. Water temperature, which varies across the surveyed streams, also has a positive influence on the mesohabitat use of brown trout during spring/summer, and this is probably related to nutrition and metabolic rate. Among the chemical parameters, dissolved oxygen concentration and pH are not related to fish presence or abundance because of the high water quality conditions within the selected streams. It is important to note that habitat suitability models for marble trout, developed in Piemonte and Valle d'Aosta regions, were also applied and validated in Rabies Creek (Noce River basin, Trentino Alto Adige region), and the model accuracy in validation ranged from 64% to 76% (Vezza et al. 2013*a*).

Further developments in habitat suitability models can be made that also consider biological habitat descriptors, e.g., fish guild and macroinvertebrate community composition, due to their importance in limiting species presence or abundance (Gordon et al. 2004). This analysis can include the evaluation of intraspecific interactions and can be used to understand if fish habitat selection is mainly driven (or not) by instream physical characteristics (Vezza et al. 2012*b*). Furthermore, other discrimination techniques (e.g., random forest and artificial neural networks) can be used to model ecological binary response variables (i.e., absence/presence and presence/abundance of fish). As an example of this application, Vezza et al. (2013*b*) compared random forest and logistic regression models to predict habitat suitability for bullhead in NW Italy. Results indicate that both techniques constitute valuable tools to produce mesohabitat suitability models for fish, although random forest outperformed logistic regressions. The available hydro-ecological database at the regional scale, i.e., ~500 sampled mesohabitats georeferenced in a GIS environment, has important further potential for defining habitat suitability models. Small mountainous streams are often poorly documented, and the available regional database will provide a consistent set of field data to be used for flow management strategies by using the distributed hydrological and ecological information. The fish habitat requirements that were defined at environmental reference streams, i.e., watercourses with little or no human impact, can also be a site-specific target and the information base for environmental flows at existing or new water abstractions (Vezza et al. 2012*a*).

As reported in Milhous et al. (1990), the habitat time series analysis is a key component in the definition of environmental flows; it is important to represent how physical habitat changes through time and to identify stress conditions created by persistent limitation in habitat availability. The reference habitat time series requires a stream flow record of at least three decades and mountainous high-gradient streams and headwaters frequently lack this hydrological information. The HEC-HMS model is, therefore, proposed as a possible tool to simulate streamflow in such watercourses. Although the HEC-HMS model performance was not very high ($E = 0.64$), the result was acceptable (Parajka et al. 2005), and it can be considered an appropriate hydrologic modeling tool for achieving the goals set for high-gradient streams. In particular, the temporal occurrence of spring snowmelt-generated peaks and the impacts of snowmelt on streamflow seem to be well captured by the model (Fig. 5). However, high flood peaks are generally underestimated, but the performance in the simulation of low flows was good and was considered reliable for the analysis of habitat availability during dry periods.

The reference flow time series can be used to develop a reference habitat time series, which is investigated to define the UCUT curves and to establish natural habitat stressor thresholds (HSTs; e.g., Parasiewicz 2008). The UCUT curves and the HSTs represent a three-dimensional description of habitat distribution in the continuous duration/frequency space. These highly informative diagrams allow approximation of an envelope of typically occurring habitat events that are harmless to the fauna. Hence, the environmental flows should fall within this envelope. The method also captures stress conditions that are created by persistent limitation of habitat availability and those created by catastrophically low habitat quantity. Although the latter events occur in natural conditions, they are not common and, therefore, cause only limited harm to the aquatic communities, which are characterized by high resilience to environmental stress. Consequently, environmental flow management should avoid increasing the frequency of such disturbances.

With this information, detailed schemes of flow management that take into account specific operations can be developed for individual hydropower facilities. In general, we recommend that the environmental flows shall follow the natural seasonal pattern and fall within the identified criteria. Such approach maintains some portion of natural system dynamics and offers flexibility in implementation. The flow management schemes will be strongly dependent on the type of hydropower facility, inflow, and size of the stream. For example, for small hydropower plants without storage capacity, one possible scenario would be to release the flows that create critical habitat level. If the allowable duration of such flows is exceeded, the operation should be stopped for a few days to allow fauna recovery. This would only be possible if the natural inflow is higher than the one creating critical habitat level. Using Valleritta Creek as an example, a possible option would be to allow hydropower generation with environmental flow release in the bypass section of 55 L/s with two-day interruptions every two weeks. Once the inflow drops below this value, the operation would cease until there is an increase to 155 L/s for two consecutive days. This conservative scenario, which aims to avoid subsistence flow, is one of the available options. For the dams with considerable storage, the hydropower generation interruptions could be replaced with temporal increases of flow release. Hence, the facilities on larger rivers, where more water is available, could use more water for hydropower. This procedure offers more protection to the most vulnerable stream sections while maintaining the natural flow paradigm (Poff et al. 1997) and can be used for other types of flow alteration, e.g., in rivers affected by hydropeaking (Vezza et al. 2013*a*).

Establishing flow recommendations across multiple streams and for streams that may not have available flow data is important, and this methodology provides a tool where few are currently available. As such, it can be used for development of regional rules, as well as for defining more site-specific flow management criteria. However, in its current state, the approach presented here ignores limitations that could be caused by other factors, e.g., thermal stresses. The tool provided for the environmental management of high-gradient streams is critically needed to implement recent water laws, such as the European Water Framework Directive, and to cope with the present lack of available instruments. Specifically, it is possible to understand fish responses to stream flow alterations or habitat modifications to guide river rehabilitation projects and environmental flow design. In addition, specific negative impacts on the aquatic biota can be detected, allowing restoration strategies to be focused on especially threatened species.

Acknowledgments

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