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MESO-SCALE HABITAT MODELLING IN ALPINE HIGH GRADIENT STREAMS

PAOLO VEZZA
Department of Land, Environment and Geo-Engineering (DITAG)
Politecnico di Torino
24, C.so Duca degli Abruzzi 10129 Torino, Italy

PIOTR PARASIEWICZ
Rushing Rivers Institute
592, Main Street 01002, Amherst, Massachusetts, USA

MICHELE SPAIRANI
Eaulogie s.r.l.,
Via Federico Chabod, 11100, Aosta, Italy

CLAUDIO COMOGLIO
Department of Land, Environment and Geo-Engineering (DITAG)
Politecnico di Torino

Alpine high gradient streams are small watercourses or headwaters and experience a continuously increasing exploitation by water abstractions and small hydroelectric dams. 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 regulated flow conditions. High gradient streams are defined as from moderate to quick flowing streams with turbulent water, with a morphology usually characterized by channels on moderate to steep slopes with abrupt drops, rocks, boulders, cobbles and gravel substrates. Based on the meso-scale approach of the MesoHABSIM simulation system, the aim of this study is to propose a possible methodology for habitat modeling in such watercourses in order to support the environmental flows assessment and the definition of habitat restoration measures. For high gradient streams, a comprehensive and adequate instrument is not currently available in the scientific literature and through the application of the proposed methodology in several study sites we evaluate its efficiency in field data collection and habitat modeling. Valle d'Aosta and Piemonte regions in North-Western Italy constitute the study area for this research and together represent the 28% of the total length of the Alps mountain range. Among the mountainous watercourses, 35 study sites are considered in the analysis, characterized by reach gradients varying from 2% to 22%. Meso-scale combines hydromorphological-units (e.g. pools, rapids, cascades), with multivariate biological models, considers both fish community and single target fish species in the analysis and represents a good resolution in describing the high gradient stream habitats. Moreover the meso-scale approach can include the longitudinal continuity and interaction of hydro-morphological units, which is important for the key fish bioperiods, such as migration and spawning. On-going research and possible future developments are discussed, providing examples for water resources management and regulation activities. Overall, the proposed methodology demonstrates some interesting potentials for future applications in the Alpine context in order to define environmental standards for high gradient streams.

1 INTRODUCTION

Mountainous high gradient streams are increasingly being exploited by water abstractions, diversions and small hydroelectric dams (Cipra [1], Marnezy [2]]). Several case studies and experts 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 (see Poff *et al.* [3] for a review of ecological responses to flow alteration).

High gradient streams are generally small watercourses or headwaters and are defined as having from moderate to quick flow with some turbulent water (Montgomery *et al.* [4]).

The stream morphology is usually characterized by scoured channel 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 hydro-morphologic units (HMUs) in these particular watercourses (Halwas *et al.* [5]).

Since high gradient streams generally have small dimensions and are characterized by low or no human impact, they are more susceptible to management practices as they have a high ecological sensitivity even to small water withdrawals. Furthermore, 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, e.g. marble trout, *Salmo trutta marmoratus*) and/or local interest (e.g. brown trout, *Salmo trutta fario*, Vezza *et al.* [6]). Among other characteristics, mountainous high gradient streams and headwaters are also an important source of inorganic and organic matter for the downstream reaches in the watersheds (Bryant *et al.* [7]).

For water resources planning it is therefore important to address the environmental management of mountainous watercourses, including the environmental flows assessment. However, an adequate and comprehensive methodology concerning habitat-hydraulic modeling in high gradient streams has not yet been proposed in the scientific literature. It is interesting to note that most of the studies linking habitat characteristics and aquatic biota are carried out in moderate-gradient or alluvial valley streams (Gordon *et al.* [8]). For example, the most widely advocated method (Acreman *et al.* [9]) to appraise flows related to fish species is the physical habitat simulation system (i.e., PHABSIM, Bovee *et al.* [10]) and the instream flow incremental method (i.e., IFIM, Bovee [11]). However, PHABSIM has been demonstrated to be adequate only for perennial low/moderate gradient streams (e.g. using a 1-D hydraulic model, Gordon *et al.* [8]). Since the end of the 1990s, detailed channel hydraulics are described with multi-dimensional hydraulic models (e.g., 2-D or 3-D, , Shen *et al.* [12]). These techniques generally need detailed bed topography which can be provided by electronic total stations or terrestrial laser scanners (Kozarek *et al.* [13]). However, mountainous headwater streams have spatially complex hydro-morphologic habitats (Bryant *et al.* [7]) and a detailed survey may lead to extensive efforts in field data collection (e.g., Halwas *et al.* [5]).

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.* [8]). In order to cope with this issue, the use of multivariate habitat suitability models has recently increased (Ahmadi-Nedushan *et al.* [14]). In particular, logistic regressions (e.g., Pearce *et al.* [15], Parasiewicz [16]) 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.

The recently developed meso-scale habitat models (MesoHABSIM, Parasiewicz [16]) show considerable potential in encompassing a larger range of habitat variables, allowing rivers to be surveyed for longer stretches and enabling regional-scale assessment (see, Vezza *et al.* [6]). In order to handle the present lack of instruments, the aim of the paper is to propose a possible methodology for habitat modelling in high gradient streams. 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 evaluate the methodological efficiency in field data collection and habitat modelling.

2 METHODS

2.1 Study area

The study domain are the mountainous areas of Valle d'Aosta and Piemonte regions located in North-Western Italy, where mountains cover 45% of the territory. Piemonte and Valle d'Aosta together represent the 28% of the total length of Alps mountain range, constituting the upper part of the Po river drainage basin (Italy's largest river). In this mountainous area, low flows occur in winter and are affected by freezing processes, presence of glaciers and snow cover accumulation. Moreover, elevation ranges from 300 to 4800 m a.s.l. and land cover is mainly represented by rocks and forested areas (Vezza *et al.* [17]).

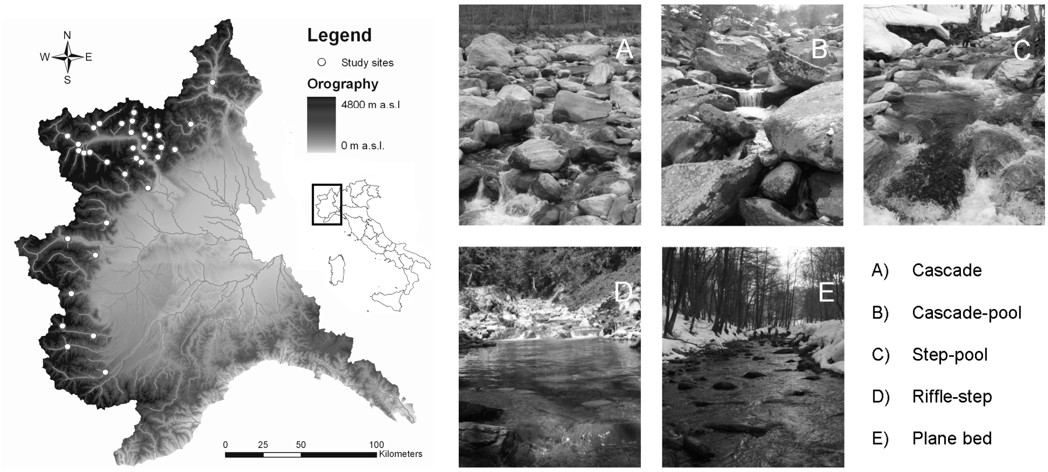

Figure 1. The left hand side of the figure depicts the 35 study sites located within the Alps mountain range (NW Italy). The right hand side reports the 5 reference morphologies for high gradient streams (Montgomery *et al.* [4])

The study sites considered in the analysis are stretches of 35 mountainous watercourses (Figure 1) characterized by reach gradients varying from 2% to 22%. Stream gradient equal to 2% is considered the lower limit value for the analysis to test the methodology also in moderate gradient reaches (the lower threshold of plane bed morphology, Montgomery *et al.* [4]). According to Montgomery *et al.* [4], five dominant morphology types are used to describe mountain streams, namely: cascade, cascade-pool, step-pool, riffle-step and plane bed.

2.2 Methodological description

The proposed methodology is an adaptation for high gradient streams of the MesoHABSIM procedure reported in Parasiewicz [16] and Parasiewicz [18], defining (i) the habitat description, (ii) the biological model definition and (iii) the development of habitat rating curves and time series analysis.

Habitat description. The habitat survey, carried out in representative sites, describes the changes in mesohabitat types over a selected range of discharges. Since reference to aerial photos (Parasiewicz [16]) is often limited, we usually rely on the use of a rangefinder (e.g., Trupulse 360B) and a rugged field computer (e.g., Nomad TDS) to record the mesohabitats characteristics. Surveys are usually carried out walking downstream, delineating the HMU polygons and recording the mesohabitat-scale features (HMU type, cover, longitudinal connectivity, gradient, etc.) and coming back upstream (towards the access point), collecting depth, velocity and substrate information from each of the mapped mesohabitats. An example of habitat descriptors is reported in Table 1.

Table 1. Habitat physical attributes for describing hydromorphologic units (see, Vezza *et al.* [6], for details).

Variable name	Value	Classes	Categories and description
Hydro-morphologic units – HMUs	(Yes/No)	12	Pool, plunge pool, glide, run, fast run, riffle, ruffle, step-pool, rapid, waterfall, backwater,side arm
HMU Gradient	(%)	1	Mean gradient of the HMU
HMU Longitudinal Connectivity	(Yes/No)	1	Habitat binary attribute describing mesohabitats longitudinal connectivity
Cover sources	(Yes/No)	7	Boulders, canopy shading, woody debris, overhanging vegetation, submerged vegetation, shallow margins, undercut bank
Substrate	(% of samples)	12	Pelal, psammal, akal, microlithal, mesolithal, macrolithal, megalithal, phytal, xylal, sapropel, detritus, debris
Water depth	(% of samples)	9	Classes in 15 cm increments (range 0-120 cm and above)
Flow velocity	(% of samples)	9	Classes in 15 cm/s increments (range 0-120 cm and above)
Current velocity standard deviation	(cm/s)	1	Standard deviation over the whole HMU area
Water temperature	(° C)	1	Water temperature at site level
Water pH	-	1	Water pH at site level
Proportion of dissolved oxygen	(%)	1	Value at site level
Turbidity	(FAU)	1	Value at site level

Overall, both chemical and physical characteristics are considered due to their combined effect on habitat resources (Table 1, see, Vezza *et al.* [6], for details). Based on the fact that the habitat in rivers changes regularly with flow (little or no backwater effects), three surveyed discharges are considered the minimum required to describe the hydromorphological characteristics (Vezza *et al.* [6]). According to the MesoHABSIM simulation model, the survey is normally repeated from 3 to 5 times between the minimum low flows (Vezza *et al.* [17]) and the medium/high flows expected on that river (Piedmont Region [19]). As a general rule, reference conditions for habitat surveying are referred to the flow range in the key bioperiods for the considered fish community (e.g. rearing and growth stage or migration and spawning period).

Biological model. The biological indicators proposed in the present research for high gradient streams are based on the Target Fish Community approach (Bain *et al.* [20]), and can be particular species of fish, their life stages, guilds or the entire community. The fish community composition varies within the region of interest according to the catchment morphology and elevation (e.g., Carta Ittica Regionale [21]) and a list of the expected species is created, also considering different fish bioperiods. For the purpose of demonstration, in this paper we focus our attention on Salmonids (i.e. marble trout and brown trout, adult life stages), which are characteristic of the region of interest (see, Vezza *et al.* [6] for further mesohabitat suitability models).

The fish samplings are carried out to get precise data for biological models construction, observing the mesohabitat use by a selected organism during its diurnal routine. Within pristine high gradient streams, fish data are collected by sampling every HMU (isolated by nets) with backpack electrofishing. Before release within the same sampled HMU, each fish is measured in terms of weight and fork length and then classified into adult and juvenile life stage (details in, Vezza *et al.* [6]). These data are the basis for the calculation of multivariate probabilistic models in order to establish habitat suitability criteria with data from one or more rivers simultaneously. In the present work, the AIC selection criteria (Sakamoto [22]) along with logistic regressions, is performed to identify the habitat attributes influencing species distribution. The area under the Relative Operating Characteristic (ROC, Pearce *et al.* [15]) curves and the relative estimated success provide the measure of the model's performance (Hosmer *et al.* [23]). Lastly, the probability thresholds derived from the ROC curves is used to classified mesohabitats into suitability categories (Parasiewicz [16]).

Habitat-flow rating curves and time series analysis. The digital mesohabitat maps built during the habitat surveys and the multivariate suitability criteria are the basis for the development of habitat-flow rating curves. The area of HMUs with suitable (or optimal) habitats is summarized for every site and plotted against the wetted area at the highest measured flow; the habitat values are interpolated for the target species and life stages. Note that rating curves for generic fish or the entire fish community can be also calculated (details in, Parasiewicz [16]).

In addition to rating curves, the definition of the reference streamflow and habitat time series is the final element needed for the full determination of environmental standards, which can be defined by using the Uniform Continuous Under Threshold (UCUT) methodology (see, Parasiewicz [18]). Although the understanding of hydrological characteristics in headwaters streams is critical for managing water resources in mountainous areas, we have to face the problem of a frequent lack of stream gauge data (see Vezza *et al.* [17]). To address this issue, the HEC-HMS hydrological model (e.g., HEC [24]) is used in the present study to generate the flow time series for high gradient streams. The model, with snowmelt capability, requires the parameters calibration in a similar catchment (Parajka *et al.* [25]) where streamflow data series are available and needs precipitation and air temperature as inputs. After the calibration process, the reference flow time series are generated for the ungauged stream and the reference habitat time series are produced.

The obtained habitat time series is statistically analyzed to establish the Habitat Stressor Thresholds (i.e., HST, see Parasiewicz [18] for details). Intra-annual rules (e.g. for winter low flow period) specify the magnitude of extreme habitat that should always be exceeded, as well as the magnitude and the duration of uncommonly low or long events which can occur in an average year. Parasiewicz [18] defines three particular duration types for habitat conditions under thresholds: common habitat (natural condition), critical habitat (equivalent to a press stressor occurring every 2 or 3 years) and rare habitat (pulse stressor at ten-yearly scale) events. The results of HST analysis can be used to develop habitat augmentation strategies (i.e. short-term flow increases) to reduce continuous duration of habitat under HST.

3 RESULTS

As a first step, we have evaluated the efficiency of the proposed methodology in terms of field data collection (i.e. mesohabitat survey and description). The expenditure of time for data collection in the selected streams, referring to an 8-hour working day of a team of 2 persons, decreases in line with stream gradient and is stratified referring to stream morphology and riverbed characteristics (Figure 2).

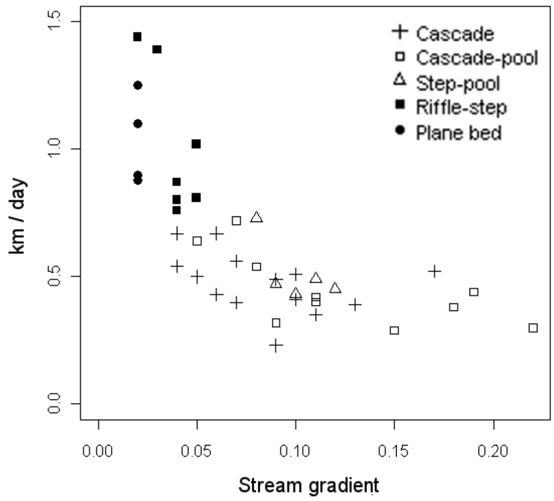

Figura 2: Efficiency of meso-scale field data collection in high gradient streams, expressed in terms of surveyed linear distance [km/day].

A database of about 500 records of HMUs observation, quantitatively sampled for fish, has been collected since Fall 2008 and is currently available for the study area. Table 2 shows the habitat models related to adult marble trout (autumn/winter model, which relates to its migration and spawning season) and adult brown trout (spring/summer model, referred to the rearing and growth bioperiod). The area under ROC curve values ranges from 0.81 (acceptable discrimination) to 0.90 (outstanding discrimination, see, Hosmer *et al.* [23]), while the estimated success rate varied from 62% to 72%.

Table 2: Marble and brown trout (adult life stage) habitat models, for autumn/winter and spring/summer respectively. The habitat variable coefficients are multipliers of the significant habitat attribute values. The estimated success and the area under ROC curve estimate the predictive power of the model. The probability cutoff is derived from the ROC curves to classify habitats into suitability categories (Parasiewicz [16]).

Marble trout - adult Autumn/Winter 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	20.49
POOL	20.23
Velocity 0-15 cm/s	-4.58

Brown trout – adult Spring/Summer Presence Model	
Estimated Success	72 %
Area under ROC curve	0.84
Probability Cutoff	0.45
Constant	-2.38
HMU Gradient	-0.124
Boulders	2.55
Canopy Shading	0.68
STEP-POOL	1.91
Depth 30-45 cm	-1.19
MEGALITHAL (>40 cm)	2.16
MACROLITHAL (20-40 cm)	3.59
Water Temperature (°C)	1.35
Abundance model	
Estimated Success	62%
Area under ROC curve	0.82
Probability Cutoff	0.51
Constant	-24.24
Boulders	18.35
STEP-POOL	1.96
Depth 60-75 cm	3.22
Velocity 15-30 cm/s	-4.29

Habitat-flow rating curves (not showed) define the habitat variation at the selected range of flows for single species, life stage or the entire fish community and are used, along with the reference flow time series (predicted by the HEC-HMS model), to generate the reference habitat time series. The statistical analysis of the habitat time series is then carried out to produce the Uniform Continuous Under Threshold (UCUT) curves (e.g., for winter low flows, see Figure 3). Each curve on the diagram represents the cumulative duration of habitat under threshold 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 [18]). Rare (8% of channel area), critical (10%) and common habitat (28%) thresholds are then selected and their inflection points are used to demarcate associated persistent and catastrophic durations of events (Figure 3).

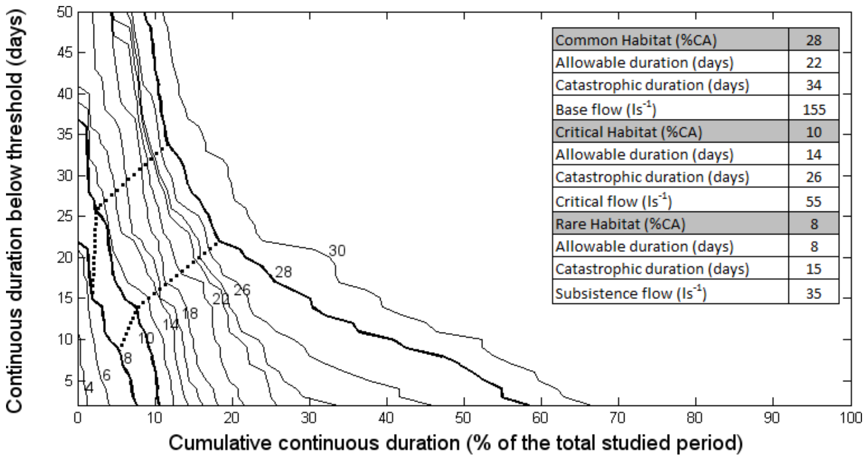

Figure 3. The application of Uniform Continuous Under Threshold (UCUT) curves for Valleritta creek (Piedmont, Italy) to determine Habitat Stressor Thresholds (HST). Events between 2% and 30% of channel area (% CA) suitable for fish are analyzed referring to winter low flows period (simulated period: 1 January - 21 March between 1970 and 2010). Reduction in slope as well as increase of spacing between two curves indicate increase in the frequency of under-threshold events Parasiewicz [18]. Rare, critical and common habitat thresholds (8%, 10% and 28% respectively) are selected and their inflection points are used to demarcate associated allowable and catastrophic durations of events (expressed in days). For more details on construction and interpretation of UCUT curves see Parasiewicz [18].

4 DISCUSSION AND CONTINUING DEVELOPMENT

A recent European report (Cipra [1]) 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. This European trend reflects the increasing worldwide significance of small-hydro (NREL [26], Marnezy [2]) as a “new” renewable energy source (see also, REN21 [27]). 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 above mentioned issues, we propose a possible methodology for habitat-hydraulic modeling in high gradient streams based on an adaptation of the MesoHABSIM simulation model reported in (Parasiewicz [16], Parasiewicz [18]), which we have developed and tested in 35 streams of the Alps in NW Italy. The proposed methodology is useful to set standards for environmental flows and for the definition of habitat enhancement measures and was evaluated in terms of time expenditure for field data collection and habitat modeling potentials. The use of the meso-scale approach shows three main advantages. Firstly, the data collection can be easily carried out in harsh environments using GIS and mobile mapping techniques. Secondly, measo-scale resolution involves a large range of habitat variables and enables the habitat evaluation both for single species and community levels. Thirdly, the MesoHABSIM adapts well to the high gradient watercourses since they do not require hydraulic simulations to model the habitat variations with flow.

Compared to the performance values reported in Parasiewicz [16], i.e. 2 km/day with MesoHABSIM, in steep streams the performance in terms of surveyed linear distance decreases in line with stream gradient (see Figure 2) basically due to the increasing number of HMUs within stream reaches and the challenging conditions of field work.

The proposed mobile mapping technique is based on the use of light equipment and can be performed along streams in zones often characterized by hiking difficulties among rocks and presence of snow and ice; when satellite coverage is marginal or nonexistent due to dense tree canopy and narrow V-shaped valleys (Vezza *et al.* [6]). Since the technique does not require detailed consecutive transect measurements to describe the main channel (e.g., PHABSIM, Bovee *et al.* [10]), the meso-scale approach performed very well for channel hydro-morphology description, since it gives more emphasis to the longitudinal variation rather than to the cross-sectional variation.

From a biological point of view the application of meso-scale habitat models in high gradient streams offers survey efficiency and flexibility in modeling fish community behavior, since it involves a large range of habitat variables (see Table 1). In particular, habitat seasonal analysis represents an important result of this meso-scale methodology and the application of the procedure to other water-related organisms can be seen as a potential model extension. For adult fish, 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 eggs deposition. Where the habitat is suitable, the abundance model seems to capture the marble trout migration behavior of accumulating below obstacles (i.e. chutes, waterfalls, etc.) which prevent the upstream migration. In contrast, during the 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. This is in accordance to several literature studies (e.g., Fausch *et al.* [28]) which show the preferences of feeding on drift and habitats with fast currents close to velocity shelters where fish can rest after feeding. Water temperature, varying across the surveyed streams, also has a positive influence on the mesohabitats use for brown trout during the spring/summer, and this is probably related to nutrition and metabolism speed for growth. Further developments on habitat suitability models, already planned for the near future, will also consider biological habitat descriptors (e.g. macroinvertebrates community composition and biotic interactions). Moreover, other multivariate discrimination techniques (e.g. Random Forest, Artificial Neural Network, GAMs) will be used to model ecological binary response variables (i.e. absence/presence and presence/abundance of fish).

Since the meso-scale does not require hydraulic simulation, it adapts well to the mountainous watercourses, characterized by high gradient, presence of rocks, boulders and coarse substrate. Indeed, the stream morphology and the challenging conditions of surveys generally prevent the application of established hydraulic models for discharge simulation, which would require a considerable effort in topographic surveying leading to a overloading of the field work (Kozarek *et al.* [13]). The multiple mapping approach of MesoHABSIM is therefore suggested as a possible way to model the variation of habitat characteristics associated with changing flows since it is based on a more effective data collection procedure (Vezza *et al.* [6]).

As a final step reported in Parasiewicz [18], the obtained reference habitat-flow rating curve and a reference flow time series can be used to develop a reference habitat time series, which can be investigated to define the UCUT curves and to establish natural habitat stressor thresholds (HSTs). 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 approximating an envelope of typically occurring habitat events that are harmless to the fauna. Hence the environmental flows should fall within this envelope. With this information, detailed schemes of flow management that take into account specific operations can be developed for individual hydropower facilities. 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 few days to allow fauna recovery. This would be only possible if the natural inflow is higher than critical. Using Valleritta creek as an example (Figure 3) a possible option would be to allow hydropower generation with environmental flow release in bypass section of 55 l/s with two-days-long interruptions every two weeks. Once the inflow drops under this value the operation would be ceased until the increase to 155 l/s for two consecutive days. This conservative scenario, which aims to avoid subsistence flow, is one of the available options.

The proposed methodology provides different possible tools for regulated river management and habitat restoration measures in high gradient streams, which are critically needed to implement recent water laws such as the European Water Framework Directive and to cope with the present lack of available instruments. Further improvements and potential shortcomings in habitat models, such as Random Forest use (Breiman [29]), along with biological habitat descriptors, will be investigated, as a continuing development of the methodology.

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