Small catchments environmental flows assessment at regional scale: the case study of Piedmont Region (NW Italy)

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Abstract: In the context of water planning, this work defined a possible approach to quantify the environmental flow requirements at regional scale. Focusing on catchment smaller than 50 km^2, the problem was addressed through the meso-scale habitat models (MesoHABSIM) and a catchments classification technique (regression tree algorithm). Within Piedmont region in NW Italy, 25 reference streams were chosen for the definition of the environmental flows. According to MesoHABSIM, logistic regression model along with 55 habitat descriptors were used to build a multivariate habitat suitability criteria, identifying the habitat characteristics mostly used by a target fish. The biological models were applied to each stream reach and used to classified each mesohabitat to suitability categories. Changes in habitat area were predicted over a range of discharges by building the habitat-flow rating curve. To define the regional criteria for environmental flows, we split the study domain according to the regression tree classification criterion defining homogenous sub-regions distinct on both environmental flows and catchment/reach characteristics. This bottom-up approach employed a catchment grouping technique by using directly the environmental requirements of fish communities and demonstrated to have some potential for further applications in defining environmental flows at regional or national level.

Keywords: Meso-habitat, MesoHABSIM, environmental flows, regression tree

Introduction

The ability to estimate the environmental flow requirements is a fundamental issue for water resources management and river restoration, including the maintenance of water quantity and quality for wildlife conservation. The increasing interest in this topic is demonstrated by the numerous works that arise from research groups all over the world (e.g., Bovee, 1982; Jowett, 1997; Eisner et al., 2005; Parasiewicz, 2007; Shen and Diplas, 2008). This study faced the problem of environmental flows assessment at regional scale focusing on catchments smaller than 50 km^2, most of them located within mountainous areas of Apennines and Alps mountain range. The study area was Piedmont, a region located in NW Italy with an area of about 25,000 km^2.

The evaluation of the ecological discharge necessarily needs to relate instream flow to the total habitat area available for organisms (e.g., Poff et al., 1997; Lamouroux et al., 1998; Acreman and Dunbar, 2004). However small mountainous watercourses have an high variability of stream geometry and the association of fish species and biomass to a preference habitat area is far from obvious. Recently, meso-scale habitat models (i.e., MesoHABSIM, Parasiewicz, 2001) were developed integrating system-scale assessment of ecological integrity in flowing waters with quantitative information on physical habitat distribution.

To assess environmental flow requirements at regional scale, a bottom-up approach was used choosing within the study area 25 catchments not affected by water abstractions as reference in terms of their natural conditions of the flow regime and the target fish communities. For each stream we chose a representative reach and obtain fish data by sampling every single functional habitat within the site. We kept separated each meso-habitat by using nets to assure a direct association between the area and the captured fish. From this observation of habitat use by a selected organism, the suitability criteria were obtained for seven target fish species by using a multivariate relationship between habitat characteristics and fish presence or abundance. According to MesoHABSIM, we used a logistic regression model with the AIC selection criteria (Akaike's Information Criterion) to build a multivariate biological model, identifying the habitat characteristics mostly used by the target fish. Logistic regression equations were applied to each stream reaches and used to classified each mesohabitat to suitability categories. The percentage of channel area with suitable and optimal habitat for a species or life stage was summed to build the habitat-flow rating curve and the minimum ecological support (or minimum critical level) was determined by using the highest inflection point value.

Results of these meso-scale habitat analysis was finally evaluated in order to check to what extent they can be considered transferable to a larger scale, such as clusters of similar catchments or the entire regional study area. Using a bottom-up approach, the study area was split according to the regression tree classification criterion, defining homogenous sub-regions distinct on both environmental flows needs and catchment/reach characteristics (see Vezza (2010) PhD dissertation for details). Hereafter, the dataset used in this research is presented along with the application of the meso-scale habitat models to the 25 reference streams in NW Italy. Furthermore, the multivariate habitat suitability criteria developed for 7 different target species and life stages are reported. Finally, the catchment classification for the environmental flows assessment at regional scale is presented and discussed for future applications.

Data

Study Area

The study area was Piemonte (Piedmont), a region located in NW Italy. In this relatively small area (of about 25,000 km^2) the climate varies from the Apennine-Mediterranean one in the South-Eastern hills, to the Alpine-Continental one in the Northern Alps mountain range. In the Alpine areas, the most important drought period occur during winter when instream discharges are affected by freezing processes in soils and snow cover. Instead, in the Apennine-Mediterranean areas, low flows events occur during summer with a strong drought period and are mainly due to moderate aquifers recharge, low snowpack storage during winter and high evapotranspiration (Vezza et al., 2010).

Catchment choice

In Piedmont region 312 catchments smaller than 50 km^2 are taken into account in the context of regional-scale water planning. To build up a regional criteria to fulfill the environmental flow requirements we chose 25 catchments not affected by water abstractions or other human impacts in the upstream part, as reference in terms of their natural conditions of the flow regime and the target fish communities. Figure 1 shows the spatial distribution of the selected catchments which were chosen to cover differences in topography, geology, precipitation and natural flow regime.

Representative site

Within each selected streams, the representative site was defined in terms of (i) its proximity to the drainage basin outlet, (ii) the absence of human impacts in the upstream part of the watershed and (iii) the possibility to cover, with the survey, from 5 to 10% of the river length. According to MesoHABSIM the site was also considered habitat-persistent in terms of changes in spatial distribution of mesohabitats.

Target fish community

The target species were brown trout (*Salmo trutta fario*), bullhead (*Cottus gobio*), barbel (*Barbus barbus*), chub (*Leuciscus cephalus*), vairone (*Leuciscus souffia*), Italian freshwater goby (*Padogobius martensii*) and eurasian minnow (*Phoxinus phoxinus*). Belonging to this fish community, in this study about 6000 fishes were measured and identified in terms of species and life stage by means of scales analysis and referring to length/age relationships.

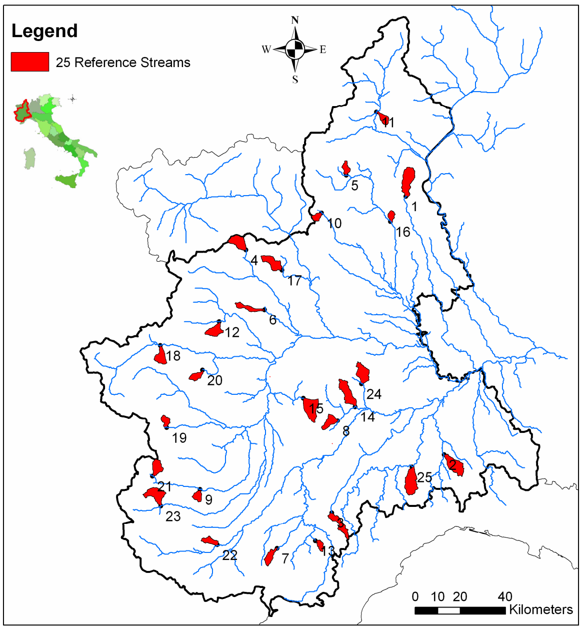


Figure 1. The application of a bottom-up procedure: the figure shows the 25 reference catchments chosen for the definition of environmental flows requirements at regional scale

Sampling habitat for fish

Fish data were obtained by sampling every single functional habitat within the site with backpack electrofishing. In order to assure the direct association between sampled areas and the captured fish species, each mesohabitat was kept separated by using nets. Due to the small dimensions of streams and in particular the hydromorphologic units sampled, we did not use electrofishing grid as suggested in Parasiewicz (2007). This because, in some cases, grids had almost the size of considered mesohabitats and we preferred to sample the whole area. Each fish was measured in terms of weight and length before release within the same sampled area. Within the representative sites of the 25 reference streams (our study domain), 240 mesohabitats were sampled.

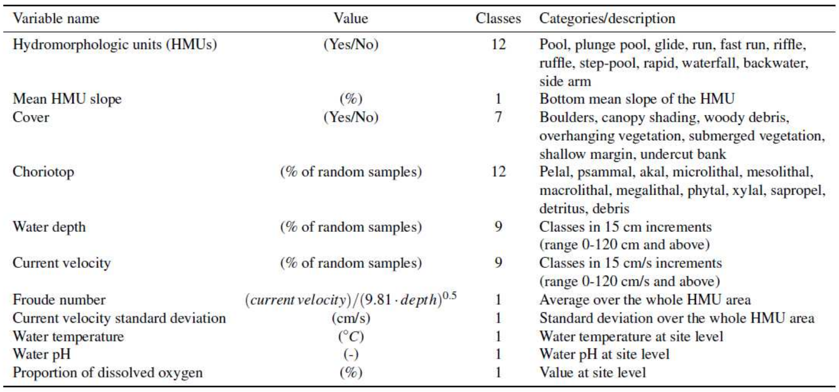
Mobile mapping techniques

Unlike in Parasiewicz (2007), due to the small dimensions of stream reaches and the high vegetation densisity, we did not draw directly on the PC the mesohabitats distribution by using the high-resolution aerial photographs. Repetitive detailed maps under multiple flows (normally three different flow conditions) were created by using a Rangefinder (TruPulse 360B), a Pocket PC (Nomad TDS), ArcPAD software and GPS positioning.

Habitat descriptors

Both chemical and physical factors are used to describe stream reaches conditions. For this study 55 habitat attributes are collected for each sampled area. Table I lists the 55 attributes used to describe mesohabitats. According to MesoHABSIM, physical attributes with many categories (e.g. HMU type and cover, see Table I) were broken down into multiple variables in binary (Yes/No) format. Measurements of depth, velocity and substrate are divided in frequency categories of 15 cm for depth and 15 cm/s for velocity, and all values above 120 cm and 120 cm/s are lumped together. In order to cover the entire HMU area by a good density of measured points, from 7 to 30 current velocity, depth measurements and choriotop estimates were collected for each HMU, depending on the size of the unit in order to cover the variability of instream flow conditions.

Table I: Habitat physical attributes for describing hydromorphologic units (HMUs)



Variable name	Value	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
Mean HMU slope	(%)	1	Bottom mean slope of the HMU
Cover	(Yes/No)	7	Boulders, canopy shading, woody debris, overhanging vegetation, submerged vegetation, shallow margin, undercut bank
Choriotop	(% of random samples)	12	Pelal, psammal, akal, microlithal, mesolithal, macrolithal, megalithal, phytal, xylal, sapropel, detritus, debris
Water depth	(% of random samples)	9	Classes in 15 cm increments (range 0-120 cm and above)
Current velocity	(% of random samples)	9	Classes in 15 cm/s increments (range 0-120 cm/s and above)
Froude number	$(current\,velocity)/(9.81 \cdot depth)^{0.5}$	1	Average over the whole HMU area
Current velocity standard deviation	(cm/s)	1	Standard deviation over the whole HMU area
Water temperature	($^{\circ}C$)	1	Water temperature at site level
Water pH	(-)	1	Water pH at site level
Proportion of dissolved oxygen	(%)	1	Value at site level

Methods

Biological models

An appropriate model to analyze the relationship between a binary response (present/absent or suitable/unsuitable) and several explanatory environmental factors describing the quality of the habitat is the logistic regression. The use of logistic regression to model the probability of fish presence and habitat requirements has recently increased (Pearce and Ferrier, 2000; Filipe et al., 2002; Parasiewicz, 2007; Tirelli et al., 2009). In this study (i) a cross-correlation analysis to exclude highly correlated parameters and (ii) logistic regressions were used to identify the habitat characteristics preferred by a target species. According to MesoHABSIM two different binary models were employed: the presence-absence model to distinguish between suitable and unsuitable habitats and the presence-abundance model to distinguish between suitable and optimal habitats. In particular, a logistic regression model with the AIC selection criteria (Akaike's Information Criterion) was performed to identify the habitat characteristics mostly used by a target species at different life stages, i.e. different models for juvenile and adult (Parasiewicz et al., 2008). For a target species, either for presence or abundance prediction, the probability thresholds (P_{pres} and P_{abun}) were defined by using the relative operating characteristic (ROC) curves (Pearce and Ferrier, 2000; Parasiewicz, 2007) and MaxKappa procedures (Freeman and Moisen, 2008). The habitats with a probability of presence greater than P_{pres} were classified as suitable, while the suitable habitats with a probability of abundance greater than the selected P_{abun} were deemed optimal (Parasiewicz, 2007). Moreover, the area under ROC curve (AUC), witch ranges from 0 to 1, provides a measure of the model's ability to discriminate between areas which experience the outcome of interest (e.g. presence of fish) and areas which do not. Within "R" statistical software, in this study scripts written and provided by Rushing Rivers Institute along with the PresenceAbsence library were used, yielding complete analysis of the model results.

Habitat-flow relationship

Using the probability thresholds as guidelines, digital maps of the sites were constructed at each measured flow condition showing areas of unsuitable, suitable and optimal habitat. Suitable and optimal habitat can be aggregated into one effective flow-habitat rating curve by weighting the optimal habitat with 0.75 and suitable with 0.25 (Parasiewicz, 2007). In this study the minimum flow requirement was defined at the inflection point of the curve, in order to prevent a rapid declining in terms of suitable area for lower instream discharges (Jowett, 1997).

Catchment classification

The regional criteria needed to fulfill ecological requirements was defined by splitting the study domain according to the regression tree classification criterion. The Classification and Regression Trees (CART) algorithm is a classification method which uses the data set to construct the so-called decision trees. For building decision trees, CART splits a learning sample (i.e. environmental flows needs and catchment characteristics) by using an algorithm known as binary recursive partitioning (Breiman et al., 1984). CART can easily handle both numerical and categorical variables, classification trees operate on categorical variables while regression trees operate on continuous variables.

Results

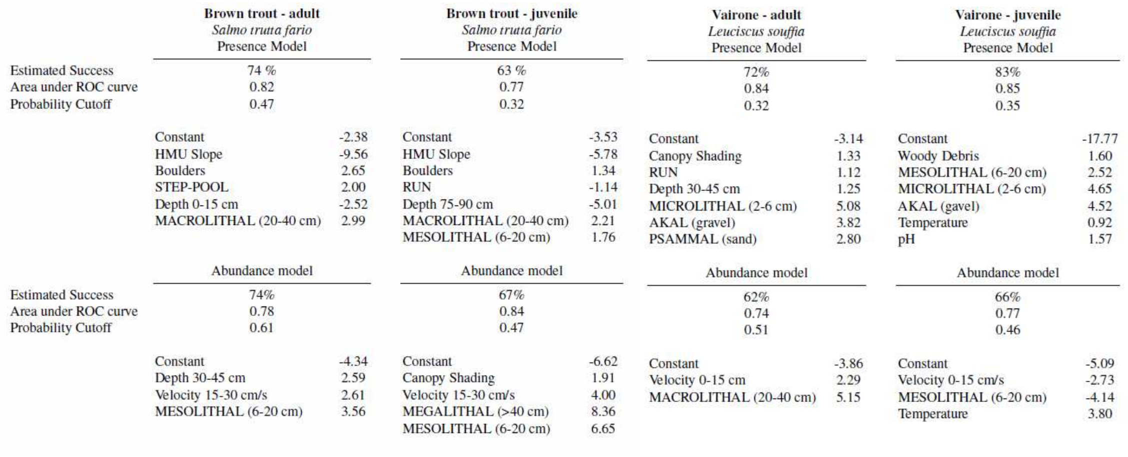
Biological models at regional scale

During the fishing surveys, a total of 240 mesohabitats were sampled and about 6000 fish belonging to the 7 target fish species were caught. Two binary biological models for every fish species and life stages were performed: the presence-absence and the presence-abundance models. Thresholds for abundant fish density were derived from the inflection point of the fish density histograms. As an example, the suitability criteria obtained for brown trout and vairone are shown in Table II. The most important variables for a target fish and the regression coefficients were selected using the AIC technique. Overall, the estimated success varies from 62% to 92%, while the area under ROC curve values ranges from 0.77 (acceptable discrimination) and 0.91 (outstanding discrimination). Water depth, current velocity, substrate, cover or hydromorphologic unit type demonstrated to be the most important variables for fish distribution. Furthermore, for brown trout the bottom slope of the HMU resulted to be indicative of fish presence.

Habitat-flow rating curves

Logistic regression equations were applied to each mapped mesohabitat and produced a habitat probability index (HPI, e.g. Guay et al., 2000) representing the probability of observing a species under the given habitat conditions. The habitat probability was used to classify each mesohabitat to suitability categories by comparing the probability of presence and abundance with the cutoff probability derived from ROC curve analysis. The percentage of channel area with suitable and optimal habitat for a species or life stage was summed for different discharge conditions and a linear interpolation between obtained values was used to build the habitat-flow rating curve. Using the highest inflection point of the curves, the recommended minimum flow value was defined for each streams.

Table II: Biological models at regional scale for brown trout and vairone (adult and juvenile life stages)



	Brown trout - adult		**Brown trout - juvenile**		**Vairone - adult**		**Vairone - juvenile**	
	Salmo trutta fario		*Salmo trutta fario*		*Leuciscus souffia*		*Leuciscus souffia*	
	Presence Model		Presence Model		Presence Model		Presence Model	
Estimated Success	74 %		63 %		72%		83%	
Area under ROC curve	0.82		0.77		0.84		0.85	
Probability Cutoff	0.47		0.32		0.32		0.35	
	Constant	-2.38	Constant	-3.53	Constant	-3.14	Constant	-17.77
	HMU Slope	-9.56	HMU Slope	-5.78	Canopy Shading	1.33	Woody Debris	1.60
	Boulders	2.65	Boulders	1.34	RUN	1.12	MESOLITHAL (6-20 cm)	2.52
	STEP-POOL	2.00	RUN	-1.14	Depth 30-45 cm	1.25	MICROLITHAL (2-6 cm)	4.65
	Depth 0-15 cm	-2.52	Depth 75-90 cm	-5.01	MICROLITHAL (2-6 cm)	5.08	AKAL (gavel)	4.52
	MACROLITHAL (20-40 cm)	2.99	MACROLITHAL (20-40 cm)	2.21	AKAL (gravel)	3.82	Temperature	0.92
			MESOLITHAL (6-20 cm)	1.76	PSAMMAL (sand)	2.80	pH	1.57
	Abundance model		Abundance model		Abundance model		Abundance model	
Estimated Success	74%		67%		62%		66%	
Area under ROC curve	0.78		0.84		0.74		0.77	
Probability Cutoff	0.61		0.47		0.51		0.46	
	Constant	-4.34	Constant	-6.62	Constant	-3.86	Constant	-5.09
	Depth 30-45 cm	2.59	Canopy Shading	1.91	Velocity 0-15 cm	2.29	Velocity 0-15 cm/s	-2.73
	Velocity 15-30 cm/s	2.61	Velocity 15-30 cm/s	4.00	MACROLITHAL (20-40 cm)	5.15	MESOLITHAL (6-20 cm)	-4.14
	MESOLITHAL (6-20 cm)	3.56	MEGALITHAL (>40 cm)	8.36			Temperature	3.80
			MESOLITHAL (6-20 cm)	6.65				

eFlows at regional scale - catchments classification

Sub-regions were delineated in terms of distinction on both environmental flows needs and catchment/reach characteristics by using the regression tree algorithm. This “bottom-up” methodology turned out to be useful in assessing the amount of water to conserve river ecosystems at regional scale, which, to our knowledge, has not yet been proposed in the existing scientific literature. The independent variables used to employed the regression tree algorithm are reported in Table III.

The resulting regression tree is shown in Figure 2a. Results indicate that the optimum size consists of four terminal nodes dividing the study domain into four sub-regions represented in Figure 2b. The resulting classification uses first latitude (UTM-YB), then longitude of catchment centroid (UTM-XB) and the maximum elevation (Hmax) for partitioning, creating four groups of catchments having similar minimum environmental flows requirements.

Table III: Catchment/reach characteristics included in the regression tree algorithm

Symbol	Units	Description	Min.	Mean	Max.
A	km^2	Catchment area	10.48	26.60	49.65
$HMAX$	m	Maximum elevation	315	1714	3848
$HMIN$	m	Minimum elevation	117	556	1523
$HMED$	m	Mean elevation	197	1024	2589
$HRANGE$	m	Range of altitude	130	1175	2386
S	%	Mean catchment slope	0.03	0.35	0.63
SR	%	Mean river slope	0.01	0.11	0.30
OX	%	Proportion of dissolved oxygen	0.68	1.02	1.18
$TMIN$	^oC	Minimum temperature of water	1.1	5.7	11.3
$TMAX$	^oC	Maximum temperature of water	6.2	14.7	21.2
$UTM-XB$	m	Centroid longitude	346750	405660	479570
$UTM-YB$	m	Centroid latitude	4906000	4987080	5100730
RL	km	Length of the main stream	1.6	3.5	6.0
LU	%	Urbanized areas within the catchment	0.00	0.03	0.12
LF	%	Forested areas within the catchment	0.11	0.50	0.91
LCG	%	Crop and Grasslands	0.03	0.27	0.81
LR	%	Wastelands (rocks)	0.00	0.21	0.86
LW	%	Wetlands	0.00	0.01	0.08
CP	mm	Mean annual precipitation	680	1114	1750
q_{355}	$ls^{-1}km^{-2}$	Discharge exceeded 97% of all days	0.91	5.63	10.91
q_{182}	$ls^{-1}km^{-2}$	Mean annual discharge	4.55	16.77	29.09

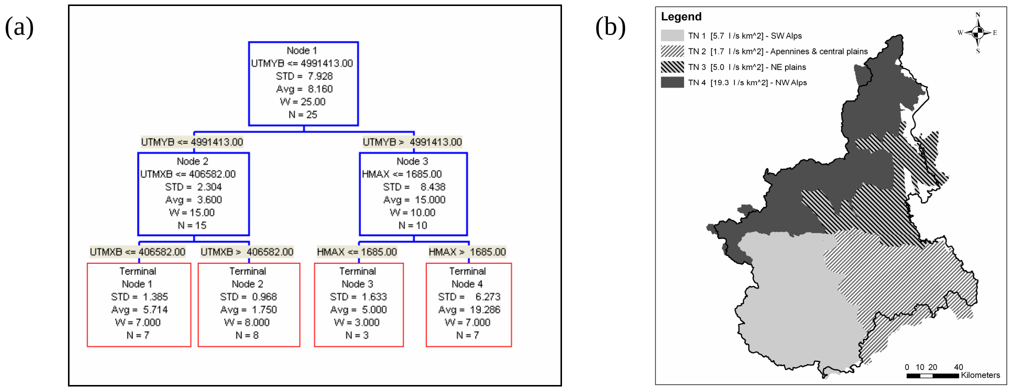


Figure 2: a) Regression Tree obtained using environmental flows need as target variable, while catchments characteristics as independent variables. Terminal nodes represent groups of catchments. Avg and STD represent respectively the mean and the standard deviation of the node. N indicates the number of streams within groups. The optimal number of terminal nodes was defined calculating the minimum value of cross-validated deviance of the tree (i.e. pruning algorithm); b) Sub-regions with similar minimum flows based on regression tree approach. Terminal nodes (TN_i) delineated four different areas.

Discussion

In this study a bottom-up methodology was used for the ecological discharge evaluation at regional scale. Meso-scale habitat models and in particular MesoHABSIM were used to provide habitat information in 25 streams of NW Italy. Compared to the micro-habitat approach, meso-scale habitat models change the data collection strategy and the analytical techniques in order to provide answers in applying models at lager spatial scales. The mesohabitat survey uses GIS and mobile mapping techniques to determine the spatial proportions of the mesohabitat units in selected sections. Not requiring detailed cross-sectional measurement, this kind of resolution is lower but it can provide larger coverage of surveyed rivers and enables understanding of fish behavior at larger spatial scale.

For each stream, the obtained biological model were applied and the habitat-flow rating curve was used to delineate the minimum flow requirements for the stream. According to the regression tree classification criterion, the study domain was split defining homogenous sub-regions distinct on both environmental flows and catchment/reach characteristics. Looking at the variables used for partitioning, catchments centroid coordinates are significant in terms of total annual precipitation and climate, which affect runoff and discharge magnitude. For example, in the South-Eastern Apennine-Mediterranean part of the study area (Terminal Node 2), strong drought periods occur during summer and are mainly due to dry climate, moderate snowpack storage and high evapotranspiration. In the Alpine mountain range (from South-Eastern to Northern Piedmont) instead, the mean annual runoff is higher (climate is wetter than in the Apennines) and varies according to precipitation (related to the latitude), interactions with aquifers and snowpack storage which is less effective for different elevations (Vezza et al., 2010). Indeed, CART used the maximum elevation H_{max} to split the Northern part of Piedmont to delineate a region characterized by small elevated catchments in North-Western Alps. In this region the available amount of water increases and is related to more rainfall and snowpack storage due to orographic effects.

Considering the proposed methodology, habitat-flow rating curves could also be employed to evaluate alternative flow management strategies. In particular, habitat rating curve methods can also in corporate flow regime requirements, in terms of both seasonal variation and flow fluctuations. Future applications and development of this bottom-up methodology could take into account flow fluctuations as an important component of the habitat of most naturally flowing streams. Furthermore, the fish community habitat requirements, being defined at reference streams (i.e. water courses with no human impacts), can also be a site specific target and the information base for environmental flows at existing dams or new water abstractions.

Conclusion

In the context of regional-scale water planning, this work attempted to define a possible approach to quantify the environmental flow requirements for catchments smaller than 50 km^2. The problem was addressed through the meso-scale habitat modeling approach (MesoHABSIM) and a catchments classification technique (regression tree algorithm). The contribution of the present work followed two directions, both representing very discussed issues in the assessment of environmental flows at large spatial scale such as clusters of similar catchments or at regional or national level. On the one hand, the availability at regional scale of habitat suitability criteria for fish communities is addressed by building multivariate biological models for 7 target species. On the other hand, the definition of minimum ecological support in terms of discharge is addressed by spitting the study domain in homogeneous sub-regions, employing the catchment grouping technique by using directly the environmental requirements of fish communities. This bottom-up approach demonstrated to have some potential for further applications in defining environmental flows at regional or national level.

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