RIVER RESEARCH AND APPLICATIONS
River Res. Applic. (2011)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/rra.1571

DEFINING MINIMUM ENVIRONMENTAL FLOWS AT REGIONAL SCALE: APPLICATION OF MESOSCALE HABITAT MODELS AND CATCHMENTS CLASSIFICATION

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ABSTRACT

In the context of water resources planning, this work defined a possible approach to quantify minimum environmental flows (e-flows) at a regional scale. Focusing on catchments smaller than 50 km^2, the problem was addressed through mesoscale habitat models and a catchment classification technique (regression tree algorithm). Within the Piedmont region in NW Italy, 25 reference streams were chosen on the basis of the natural condition of the flow regime and fish community. Mesohabitats were sampled for hydromorphic and fish parameters following the mesoscale habitat models approach. Logistic regression models, along with 55 habitat descriptors, were then used to build multivariate habitat suitability criteria, identifying the habitat characteristics mostly used by the target fish species. These models were applied to each stream reach and used to classify each mesohabitat into suitability categories. The reference minimum discharge for each stream was derived from habitat–flow rating curves. Finally, to define the regional criteria, the study domain was split according to the regression tree classification, defining homogenous sub-regions distinct on both e-flows and catchment/stream characteristics. This bottom–up approach used a catchment classification technique based on the environmental requirements of the fish communities and demonstrated potentials for further applications to defining e-flows at regional scales. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: mesohabitat; MesoHABSIM; environmental flows; regression trees; regional scale; GIS; *Salmo*; *Leuciscus*

Received 12 September 2010; Revised 15 June 2011; Accepted 28 June 2011

INTRODUCTION

The issue of developing environmental flow standards at regional scales is increasingly recognized at national and international levels (Petts, 1996; CAWMA, 2007; Poff *et al*., 2010). Currently, the Water Framework Directive (WFD–European Commission, 2000) is the main legislative reference in Europe for water-related issues and, although not using the term environmental flows explicitly, it requires the achievement of good ecological status in all water bodies. Acreman and Ferguson (2010) considered how the concept of environmental flows (e-flows) fits within the WFD, with some examples from its implementation in the UK. Within the WFD, it is accepted that ecologically appropriate hydrological regimes are necessary to meet the good ecological status, but nowadays the implementation of e-flows remains a major issue.

To integrate human and ecosystem water needs at large spatial scales, e-flow requirements have to be defined in a comprehensive manner for a cluster of similar rivers or an entire regional study area (Arthington *et al*., 2006). Worldwide, look-up tables and hydrological models at macroscales or catchment scales were one of the most commonly applied methods to define e-flows (see Acreman and Dunbar, 2004), using hydrologically defined indices for the environmental water management (such as percentages of the mean flow or exceedance percentiles from flow duration curves). Those methods, being based on fixed hydrological values, are cheap to apply and suitable for scoping studies but often characterized with little ecological validity. Acreman and Dunbar (2004) reviewed all the available methods for the e-flows assessment, considering, besides the look-up tables, also desktop analysis (Richter *et al*., 1997), functional analysis (King *et al*., 2000) and habitat hydraulic modelling (e.g. PHABSIM; Bovee *et al*., 1998), not identifying a method necessarily better than another but underlining that each may be suitable for different applications.

Considering habitat hydraulic modelling, notable scientific progress has been made over the last 20 years in developing methods linking habitat conditions and aquatic species needs (Jowett, 1989; Bovee *et al*., 1998; Eisner *et al*., 2005). The physical habitat models based on micro-scale level,

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such as physical habitat simulation (Bovee *et al*., 1998), are the most widely accepted techniques used to determine how streamflow alterations affect the habitat characteristics. However, the most common tools for habitat simulation are focused on small spatial scales and use univariate habitat suitability curves, taking into account habitat variables such as water depth, velocity and substrate separately (Parasiewicz and Walker, 2007). Furthermore, cross-sectional sampling (used within the data acquisition phase) has been criticized as being time-consuming (Parasiewicz, 2001) and for emphasizing cross-sectional variation over longitudinal variation (Rivas Casado *et al*., 2004).

On the other hand, mesoscale habitat models were recently developed, showing considerable potential for system-scale assessment, requiring less extrapolation to provide output at large spatial scales (see e.g. Parasiewicz *et al*., 2007a). Compared to the traditional micro-habitat evaluation, mesoscale habitat models change the methodological approach and the analytical procedures, allowing longer length of surveyed rivers, involving a larger range of habitat variables and enabling understanding of fish behaviour at larger spatial scales (see Parasiewicz and Walker, 2007, for a comparison between mesoscale habitat models (MesoHABSIM) and other micro-scale habitat models). Although sacrificing some detail, the mesoscale can reveal larger spatial and temporal ecological patterns representing whole-system properties (Jewitt *et al*., 2001). However, they require a river to be mapped at several discharges, not using established hydraulic models for discharge simulation and interpolating a functional relationship between habitat and discharge.

The main aim of the present work was the definition of a regional methodology for the minimum environmental flows assessment in Piedmont (NW Italy). It was focused on catchments smaller than 50 km^2, most of them located within the Apennines and Alps mountain ranges and characterized by a high ecological sensitivity to even small water withdrawals (see e.g. CIPRA, 2010). As a support for regional water planning and environmental flows assessment, innovative frameworks are currently proposed in the literature (see e.g. Poff *et al*., 2010) based on a top–down (or *a priori*) hydro-ecological stream classification. Snelder and Biggs (2002) defined the River Environmental Classification, which assumes that the catchment grouping is more useful if classes are defined according to the physical and/or hydrological characteristics of the watersheds. Anyhow, stream habitats in small mountainous streams are often poorly documented and the limited availability of distributed hydrological and ecological data (as in our study sites) prevented the application of such regional-scale frameworks.

In the context of regional water planning, and to handle the lack of hydro-ecological information within small watercourses, the goal of this research was to propose a bottom–up approach for defining the minimum environmental flow requirements at a regional scale, by directly up-scaling the environmental requirements of fish communities.

METHODS

The proposed methodology for minimum e-flows assessment at regional scales consisted of five consecutive steps:

- Reference catchment selection;
- Field data collection;
- Construction of regional biological models;
- Definition of habitat–flow relationships and minimum e-flows;
- Catchment classification based on fish community requirements.

The sequence of the main steps and the scale of the different approaches in the methodology are outlined in Figure I.

Reference catchments selection

Study area. The study area was the Piedmont region of NW Italy, where the Alps covers 43.3% of the regional territory (in total approximately 25 000 km^2), whereas the Apennine area (to the south) represents 30.3% and the central river Po plains, 26.4%. The Piedmont region is the upper part of river Po drainage basin, which is Italy's largest river. In terms of mean annual values, the specific contributions of the numerous streams vary from 2 to 51 l s^{-1} km^{-2}. Within the region, there are 3000 abstractions more from watercourses, of which more than 50% withdraw river water for hydroelectric purposes. In the Alpine area, the nival flow regime has low flows in winter, whereas in the Apennines areas, the Mediterranean flow regime is characterized by summer low flows (Vezza *et al*., 2009). Land use varies from the rocky and forested areas of Alps to the hillsides of Apennines characterized by crops and vineyards. The plains constitute the most populated zones, studded with urbanized areas, croplands and a mixture of farms and industrial complexes.

Reference catchments. The Water Protection Plan (Piedmont Region, 2007–PTA) identifies 312 catchments smaller than 50 km^2 within the regional territory. Excluding ephemeral streams, 25 watercourses were chosen as environmental reference streams (Table I), considering the following: (i) the natural conditions of the flow regime; (ii) the fish community composition; and (iii) the spatial distribution across the region (Figure II). The selection of reference streams for a target river system followed the virtual reference river concept (Parasiewicz *et al*., 2008), using the biological needs of desired fauna (e.g. the target fish community) in order to set the foundation of habitat assessment at broad scales.

DOI: 10.1002/rra

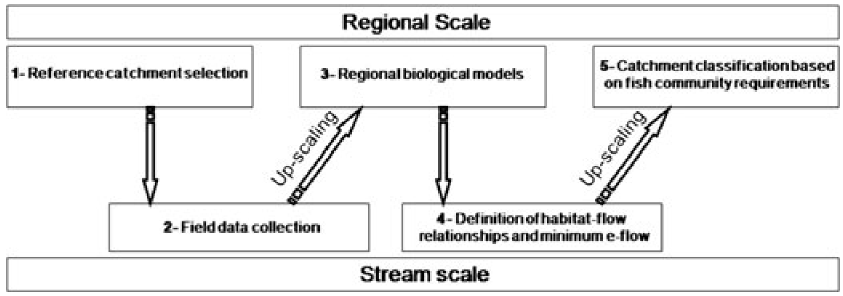

Figure 1. The consecutive steps of the proposed bottom–up methodology for the minimum e-flows assessment at regional scale.

Catchment/stream characteristics. To describe the selected watersheds, 21 physical characteristics were used (Table II). These attributes give synthetic information of the catchment area (*A*), elevation (*H*), physiographic slope (*S*), river length (*R*), centroid coordinates (*UTM*), percentage of dissolved oxygen (*O*), water temperature (*T*), land use (*L*), precipitation (*P*) and specific discharge (*q*). Some of the physical characteristics had to be adapted from the original data sources to make them applicable for the regional analysis. For instance, the original classification of the Coordination of Information on the Environment programme of the EU land cover map was condensed to five main land-use classes (*L*) and a number of topographical characteristics (*A*, *H*, *R* and *S*) were derived from a digital elevation model at a 50-m-grid resolution.

Because of the limited availability of stream gauges (only three gauges located in the Piedmont region within catchments smaller than 50 km^2, Vezza *et al*., 2010), it was not possible to provide a comprehensive hydrological description of the selected catchments. As an indicator of the low flow regime, the predicted low flow index q_{95} (i.e. the specific discharge that is exceeded 95% of the time) is reported in Table I (see Vezza *et al*., 2010, for the low flows regionalization in NW Italy). The mean annual precipitation

Table I. Main features of the reference streams in Piedmont: area (*A*), centroid longitude (UTM_{XB}), centroid latitude (UTM_{YB}), maximum elevation (H_{MAX}), minimum elevation (H_{MIN}), mean elevation (H_{MEAN}), mean slope (*S*) and mean annual precipitation (*P*)

ID	Stream name	A(km^2)	UTM_{XB}	UTM_{YB}	$H_{MAX}(m)$	H_{MIN}(m)	H_{MEAN}(m)	S(%)	P(mm)	q_{95}(l s^{-1} km^{-2})
1	Agogna	49.41	458672	5073423	1175	358	654	0.03	1700	2.64
2	Albedosa	43.06	479571	4946757	636	141	260	0.01	858	0.89
3	Belbo	31.17	428375	4920582	869	568	680	0.01	881	1.10
4	Campiglia	32.66	383442	5045920	3287	1110	2154	0.16	1037	15.88
5	Cavaglione	13.03	431267	5078843	2274	620	1435	0.20	1690	8.03
6	Fandaglia	19.90	387634	5017037	1295	271	527	0.06	1289	3.34
7	Lurisia	19.60	397472	4906004	1724	534	870	0.07	1308	5.12
8	Maggiore	22.88	423997	4966113	364	146	214	0.02	761	0.68
9	Melle	14.14	365456	4933179	1884	666	1315	0.22	796	1.35
10	Pragnetta	11.08	418310	5057077	2387	888	1681	0.28	1749	7.56
11	Ravine	15.24	448031	5100728	2075	232	1177	0.20	1558	13.13
12	Ricchiaglio	26.70	373003	5006599	2614	628	1240	0.12	1320	5.88
13	Rifreddo	10.88	419864	4911114	901	442	625	0.06	1179	0.91
14	Rilate	43.39	431802	4979036	315	117	197	0.01	680	0.65
15	Robeirano	49.19	415692	4972180	371	241	275	0.01	743	0.69
16	Roccia	10.48	451410	5057592	605	270	341	0.04	1388	1.12
17	Savenca	33.35	398621	5036845	2566	476	1241	0.15	1376	16.77
18	Scaglione	24.91	349094	4995031	2846	460	1699	0.16	846	7.01
19	Subiasco	14.38	351171	4966437	2777	722	1669	0.30	1065	6.09
20	Taonere	15.19	364742	4986475	2058	573	1163	0.19	1275	3.42
21	Vallanta	24.05	347366	4945921	3848	1492	2589	0.17	831	6.36
22	Valle Ritta	16.29	370917	4913057	1780	643	1033	0.10	1265	2.06
23	Vallone d'Elva	38.69	346751	4933837	3033	924	1944	0.15	846	12.04
24	Viazza	35.59	438658	4987795	472	138	222	0.02	704	3.85
25	Visone	49.65	460175	4939407	695	135	414	0.03	701	0.94

As characteristic low flows unit runoff, q_{95} (i.e. the specific discharge that is exceeded the 95% of the time) is reported (Vezza *et al*., 2010).

DOI: 10.1002/rra

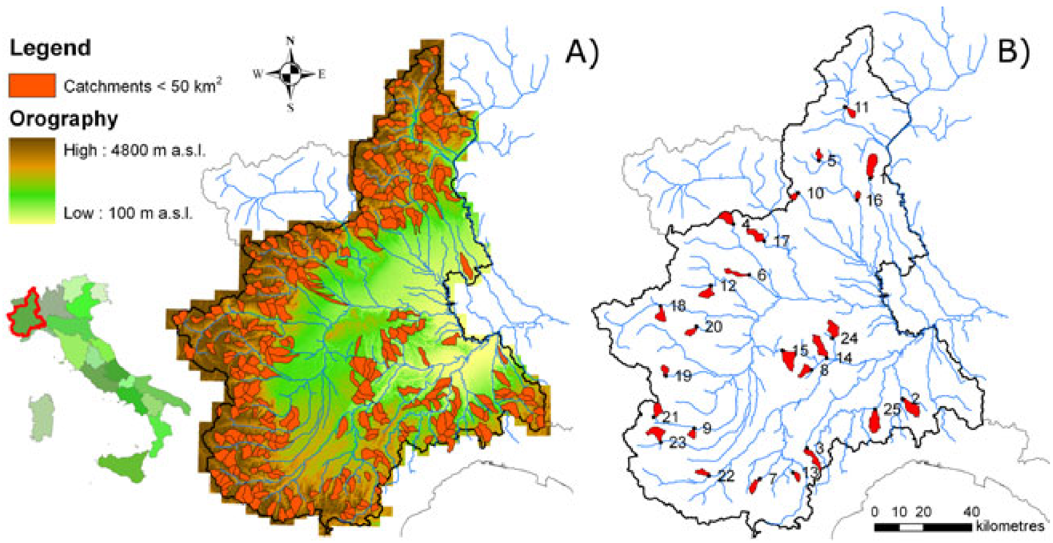

Figure 2. (A) The 312 catchments smaller than 50 km^2 defined by the regional Water Protection Plan (Piedmont Region, 2007); (B) reference catchments chosen for the definition of minimum environmental flows. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

Table II. Catchment/stream characteristics of the selected watersheds included in the minimum e-flows assessment

Symbol	Units	Description	Min.	Mean	Max.
A	km^2	Catchment area	10.48	26.60	49.65
H_{MAX}	m	Maximum elevation	315	1714	3848
H_{MIN}	m	Minimum elevation	117	556	1523
H_{MEAN}	m	Mean elevation	197	1024	2589
H_{RANGE}	m	Range of altitude	130	1175	2386
S	%	Mean catchment slope	0.03	0.35	0.63
S_R	%	Mean river slope	0.01	0.11	0.30
R_L	km	Length of the main stream	1.6	3.5	6.0
UTM_{XB}	m	Centroid longitude	346 750	405 660	479 570
UTM_{YB}	m	Centroid latitude	4 906 000	4 987 080	5 100 730
O	%	Proportion of dissolved oxygen	0.68	1.02	1.18
T_{MIN}	°C	Minimum water temperature (winter period)	1.1	5.7	11.3
T_{MAX}	°C	Maximum water temperature (summer period)	6.2	14.7	21.2
L_U	%	Urbanized areas within the catchment	0.00	0.03	0.12
L_F	%	Forested areas within the catchment	0.11	0.50	0.91
L_{CG}	%	Crop and grasslands	0.03	0.27	0.81
L_R	%	Wastelands (rocks)	0.00	0.21	0.86
L_W	%	Wetlands	0.00	0.01	0.08
P	mm	Mean annual precipitation	680	1114	1750
q_{95}	$l\ s^{-1}\ km^{-2}$	Specific discharge exceeded 95% of all days	0.91	5.63	10.91
q_{50}	$l\ s^{-1}\ km^{-2}$	Mean annual specific discharge	4.55	16.77	29.09

P and the mean annual discharge q_{50} were instead estimated by the regionalization models of the regional Water Protection Plan (Piedmont Region, 2007).

Field data collection

Representative site and habitat description. Within each stream, a representative site was defined in terms of the following: (i) its proximity to the drainage basin outlet; (ii) the absence of human impacts; and (iii) the possibility of surveying from 5% to 10% of the stream length in one day. According to the procedure reported in Parasiewicz (2001, 2007a), repetitive detailed maps were created for each site under multiple flows by using a rangefinder (TruPulse 360B, Laser Technology, Inc., Centennial, CO, USA), a pocket PC (Nomad TDS, Field Environmental Instruments, Inc., Sunnyvale, CA, USA), ARCPAD software (ESRI, Redlands, CA, USA) and GPS (US Department of Defense,

DOI: 10.1002/rra

Arlington County, VA, USA) positioning. Using an uploaded aerial photograph, the GPS positioning was used to capture the starting point of the survey. During each survey, we collected the offset points using the rangefinder (with a range accuracy of ±10–30 cm and an inclination accuracy of ±0.1–0.25°). This mobile mapping technique employed light equipment and could be performed in difficult environments (such as the headwater streams of Alps characterized by high gradient), allowing fast habitat surveys and sampling, especially when satellite coverage was marginal or nonexistent under dense tree canopy and within narrow V-shaped valleys.

Between three and four surveys were carried out on each representative reach at different flow conditions, including at least one low flow, one low-medium flow and one lower high flow (using as reference the regionalization formulae defined in Vezza *et al*., 2010, and in the Water Protection Plan, Piedmont Region, 2007). These covered the flow range of key fish bio-periods (*sensu* Parasiewicz, 2008a), such as rearing and growth or migration and spawning. Three surveyed discharges were considered the minimum required to describe the hydromorphological characteristics (Parasiewicz, 2001, 2007a, 2008a), based on the fact that the habitat in rivers changes regularly with discharge. In order to set minimum e-flows, the number of surveys at low flow conditions was the highest possible and, when the number of surveys was limited to three, two measurements were performed at the low end of the analysed range of flows and one at the high end.

During each mapping campaign, 55 habitat variables (Table III) were collected for each mesohabitat (or hydromorphologic unit–HMU), including both chemical and physical factors. In order to cover the spatial variability of instream flow conditions and to describe the HMU area, between 7 and 30 measurements were taken of mean water column velocity, water depth and substrate size. Seven measurements were empirically chosen as the smallest statistically relevant quantity (see Parasiewicz, 2007a). Physical attributes with many categories were broken down into multiple variables in binary (Yes/No) format and measurements of depth, velocity and substrate were divided into frequency categories (Table III).

Target fish community. The target fish species expected to be found in small streams were identified by using the fish zonation available from Piedmont Regional Government (Carta Ittica Regionale, 1992–2004). Brown trout (*Salmo trutta fario*), bullhead (*Cottus gobio*), barbel (*Barbus plebejus*), chub (*Leuciscus cephalus*), vairone (*Leuciscus souffia*), Italian freshwater goby (*Padogobius martensii*) and Eurasian minnow (*Phoxinus phoxinus*), whose conservation status is of European (Habitats Directive 1992/42/EEC) and/or local interest, were selected as a biological indicator to protect the entire aquatic community (see Bain and Meixler, 2008, for a target fish community definition).

Regional biological models

Fish surveys were carried out on each stream during each mesohabitat mapping campaign to get precise data for constructing the models, over a period of 18 months between autumn 2008 and winter 2010. Within each representative reach, fish data were obtained by sampling every HMU by backpack electrofishing. In order to insure the direct association between sampled areas and the captured fish species, each mesohabitat was isolated with nets. Each fish was classified into adult or juvenile life stage through scales analysis

Table III. Habitat physical and chemical attributes used for describing the hydromorphologic units (HMUs) (see Parasiewicz, 2007a, for details on the substrate and choriotop classification)

Variable name	Value	Classes	Categories/description
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)
Flow velocity	(% of random samples)	9	Classes in 15 cm s^{-1} increments (range 0–120 cm s^{-1} and above)
Froude number	(flow velocity)/(9.81 depth)$^{0.5}$	1	Average over the whole HMU area
Flow velocity standard deviation	(cm s^{-1})	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

DOI: 10.1002/rra

and length/age relationship (see e.g. for similar approaches, Schneider *et al*., 2000; Cheung *et al*., 2007) and its weight and fork length were measured before releasing the animal into the same sampled HMU.

Logistic regression was used to model the probability of the presence of fish and to obtain information about habitat requirements (following e.g. Pearce and Ferrier, 2000; Filipe *et al*., 2002; Tirelli *et al*., 2009). The logistic regression technique enabled us to analyse the relationship between a binary response variable (present/absent or suitable/unsuitable) and several explanatory environmental factors, which describe the quality of the habitat (Ahmadi-Nedushan *et al*., 2006). Following Parasiewicz (2007a), two different binary models were developed using the data collected during the fish sampling campaigns: an absence–presence model to distinguish between unsuitable and suitable habitats and a presence–abundance model to distinguish between suitable and optimal habitats. The cutoff value for low and high abundance was determined as the inflection point of the envelope curve of the fish density histograms (Parasiewicz and Walker, 2007).

AIC selection criteria (Akaike Information Criteria, Akaike, 1974) and a logistic regression model were used in order to identify the attributes of each mesohabitat that affected the fish species at different life stages. Finally, the area under the relative operating characteristic (ROC) curves, which ranges from 0 to 1, provided a measure of the model's ability to discriminate between HMUs that experienced the outcome of interest (e.g. presence of fish) and HMUs that did not (Hosmer and Lemeshow, 2000). Compared to other methods (e.g. standard linear regression), one disadvantage of logistic regression is that more data are needed for each target species in order to achieve stable and meaningful results (see Hosmer and Lemeshow, 2000, for details). Moreover, logistic regression models are affected systematically by the prevalence (i.e. the frequency of occurrence) of the target organism. However, the area under curve, measured from ROC plots, is independent of prevalence (Manel *et al*., 2001) and represents a useful measure of how well a model is parameterized and calibrated.

Habitat–flow relationships and minimum e-flows

The obtained regional biological models were applied to each stream and every mesohabitat was classified into suitability categories by using the probability thresholds derived from the ROC curves (Parasiewicz, 2007a). Digital maps of the sites were then drawn at each measured flow condition in order to distinguish areas of unsuitable, suitable and optimal habitat. For each fish species and life stage, suitable and optimal habitats were aggregated into one effective flow-habitat rating curve (obtained by a mathematical spline function defined piecewise by polynomials) by weighting the optimal habitat with 0.75 and the suitable habitat with 0.25. In accordance with Parasiewicz (2007a), the coefficients were defined in order to assure a higher contribution of the optimal habitats than the suitable ones. The rating curves were created using at least four points (the zero value and the three surveyed discharges) and it was conservatively assumed that there is no habitat for zero flow.

The minimum flow requirement was defined for each stream at the flow that corresponded with the highest inflection point found on the obtained habitat–flow rating curves. The inflection point was calculated where the slope of the curve was equal to unity (Gippel and Stewardson, 1998) and was considered as a point of diminishing return (Jowett, 1997).

Catchments classification

A catchments classification was used to upscale the obtained results to a regional scale. By using the classification and regression trees (CART) algorithm, catchments were grouped according to both environmental needs of their fish communities and catchment/stream characteristics. CART is a classification method that uses the data-set to construct the so-called decision trees. For building decision trees, CART splits a learning sample (i.e. the e-flows' needs and catchment/stream characteristics) by using an algorithm known as binary recursive partitioning (Breiman *et al*., 1984) and can easily handle both numerical and categorical variables. Classification trees operate on categorical variables, whereas regression trees operate on continuous variables. Groups of catchments are subsequently subdivided by the optimal binary condition (e.g. IF $H_{MAX} < 1685$ m THEN sub-group *x* ELSE sub-group *y*), which minimizes the sum of squared differences between the observed values and the group mean. The tree stops growing when each terminal node consists of one single observation. Because of the consequent overfitted classification, we used the CART tree optimization algorithm, which prunes back the tree and determines the optimal number of terminal nodes (Breiman *et al*., 1984).

An example of a CART application for the hierarchical classification at river-stretch scale is reported in Peredo-Parada *et al*. (2009), where the CART algorithm was applied for the Chilean River Environmental Classification, based on the main hydrologic controlling factors at different spatial scales. Table II shows the catchment/stream characteristics (as independent variables of the system) that were used in the CART algorithm (software: CART v6.0, Salford Systems, San Diego, CA, USA).

RESULTS

Figure II shows the spatial distribution of the 312 catchments identified by the regional Water Protection Plan (Piedmont Region, 2007) along with the 25 selected

DOI: 10.1002/rra

reference watersheds. The surveyed reach lengths varied between 80 and 350 m. During the surveys, a total of 240 HMUs (or mesohabitats) were sampled. About 4500 fish belonging to the seven target fish species were caught and classified in terms of life stages (adult and juvenile). Table IV shows the number of captured fish, the maximum and minimum values of fish densities and the abundance thresholds (expressed in individuals m^{-2}).

The habitat suitability models obtained for the seven target fish species are shown in Table V and outline how different variables relate to fish presence or abundance. Overall, the estimated success rate varied from 62% to 92%, whereas the area under ROC curve values ranged from 0.77 (acceptable discrimination) to 0.91 (outstanding discrimination, see Hosmer and Lemeshow, 2000). Water depth, mean column velocity, substrate, cover and hydromorphologic unit type were found to be the most important variables for fish distribution. It is interesting to note that, among chemical parameters, the proportion of dissolved oxygen did not affect the fish presence or abundance, probably due to the high quality of water within the selected streams. Also, the Froude number and the standard deviation of the flow velocity were not selected by the model as important variables for habitat suitability, but rather the different frequency classes of depth and flow velocity resulted as highly significant variables. Because of the limited number of observations of juvenile barbel and Eurasian minnow, it was not possible to compute the abundance models and the models for the juvenile life stage were only performed for brown trout and vairone.

In Figure III, one of the habitat–flow rating curves is presented, which defines the minimum e-flow requirement for the Lurisia stream (Table I, Stream ID 7) by using the three measured flow conditions (4.3, 18.2 and 69.2 $l\,s^{-1}\,km^{-2}$) and the highest inflection point among the curves. The minimum e-flow values obtained for the 25 reference streams, which ranged from 0.5 to 28 $l\,s^{-1}\,km^{-2}$, are reported in Table VI, along with the range of surveyed discharges, the predominant HMU types, the substrates and the target fish community. The Alpine catchments (from the south-western to the northern Alps) showed the highest values and the largest variability (from 3.5 to 28 $l\,s^{-1}\,km^{-2}$), whereas for the Apennine and plains areas (the south-eastern and central parts) lower environmental flow needs were identified (from 0.5 to 3.0 $l\,s^{-1}\,km^{-2}$).

The classification of catchments in four groups is shown in Figure IV: the optimum tree size consisted of four terminal nodes (TN_i) thus creating four groups of catchments. The resulting classification used first the latitude (UTM_{YB}), then the longitude (UTM_{XB}) of the catchment centroid and the maximum elevation (H_{MAX}) for partitioning and resulted in a division of the study domain into four homogeneous sub-regions (Figure IVB). The average minimum e-flows (grouped by CART and rounded to the nearest integer) varied among sub-regions from 2 $l\,s^{-1}\,km^{-2}$ in the south-eastern part of Piedmont (the Apennine–Mediterranean area with summer low flows), 5 $l\,s^{-1}\,km^{-2}$ in the south-western Alps (characterized by lower mountains and nivo-pluvial streamflow regimes), 6 $l\,s^{-1}\,km^{-2}$ within the north-western plains and 19 $l\,s^{-1}\,km^{-2}$ in the north-western Alps (high mountains with important snowpack storage and presence

Table IV. Number of captured fish (species, adult, juvenile), fish density extreme values and abundance cutoff (expressed in individuals m^{-2}) to distinguish between suitable and optimal habitats, for the seven target fish species

	Brown trout–total	Brown trout–adult	Brown trout–juvenile
Captured	1401	964	437
Max density	0.667	0.600	0.186
Min density	0.005	0.001	0.004
Abundance cutoff	0.100	0.100	0.050
	Vairone–total	Vairone–adult	Vairone–juvenile
Captured	2115	1663	452
Max density	4.463	3.488	1.750
Min density	0.003	0.003	0.009
Abundance cutoff	0.400	0.400	0.600
	Chub–total	Chub–adult	Chub–juvenile
Captured	158	138	20
Max density	1.421	1.368	0.143
Min density	0.005	0.005	0.004
Abundance cutoff	0.200	0.200	–
	Goby–total	Goby–adult	Goby–juvenile
Captured	265	231	34
Max density	0.557	0.557	0.083
Min density	0.011	0.011	0.010
Abundance cutoff	0.150	0.150	–
	Bullhead–total	Bullhead–adult	Bullhead–juvenile
Captured	166	145	21
Max density	0.176	0.167	0.012
Min density	0.003	0.003	0.002
Abundance cutoff	0.050	0.050	–
	Eurasian minnow–adult	Barbel–adult	Overall
Captured	132	88	4465
Max density	1.708	0.313	9.268
Min density	0.010	0.003	0.009
Abundance cutoff	0.200	0.100	–

DOI: 10.1002/rra

of glaciers). The values reported in Figure IVB represent the reference minimum discharge to be released from water abstractions in the different sub-regions.

DISCUSSION

This study proposed a possible approach to assess the minimum environmental flows at a regional scale, focusing on catchments smaller than 50 km^2. The applied methodology built clusters of catchments by up-scaling the environmental needs of the target fish communities. This bottom–up approach, which has not yet been proposed in the literature, substantially differs from the top–down classification presented in Snelder and Biggs (2002) and Poff *et al.* (2010) and demonstrated to have some potentials for the general definition of e-flows at regional scales.

Table V. Biological models at regional scale for the selected fish and life stages (i.e. absence/presence and presence/abundance models) defined by means of the AIC selection criteria and logistic regressions

	Brown trout–adult		Brown trout–juvenile		Bullhead–adult	
	Salmo trutta fario		*Salmo trutta fario*		*Cottus gobio*	
	Presence model		Presence model		Presence model	
Estimated success (%)	74		63		83	
Area under ROC curve	0.82		0.77		0.90	
Probability cutoff	0.47		0.32		0.46	
	Constant	−2.38	Constant	−3.53	Constant	−7.06
	HMU slope	−9.56	HMU slope	−5.78	Run	1.58
	Boulders	2.65	Boulders	1.34	Depth 15–30 cm	−1.84
	Step-pool	2.00	Run	−1.14	Velocity 0–15 cm s^{-1}	−2.24
	Depth 0–15 cm	−2.52	Depth 75–90 cm	−5.01	Macrolithal (20–40 cm)	7.99
	Macrolithal (20–40 cm)	2.99	Macrolithal (20–40 cm)	2.21	Mesolithal (6–20 cm)	10.00
			Mesolithal (6–20 cm)	1.76		
	Abundance model		Abundance model		Abundance model	
Estimated success (%)	74		67		68	
Area under ROC curve	0.78		0.84		0.91	
Probability cutoff	0.61		0.47		0.54	
	Constant	−4.34	Constant	−6.62	Constant	−4.21
	Depth 30–45 cm	2.59	Canopy shading	1.91	HMU slope	7.17
	Velocity 15–30 cm s^{-1}	2.61	Velocity 15–30 cm s^{-1}	4.00	Ruffle	−3.22
	Mesolithal (6–20 cm)	3.56	Megalithal (>40 cm)	8.36	Depth 15–30 cm	5.62
			Mesolithal (6–20 cm)	6.65	Velocity 0–15 cm s^{-1}	−6.32
	Vairone–adult		Vairone–juvenile		Barbel–adult	
	Leuciscus souffia		*Leuciscus souffia*		*Barbus plebejus*	
	Presence model		Presence model		Presence model	
Estimated success (%)	72		83		87	
Area under ROC curve	0.84		0.85		0.86	
Probability cutoff	0.32		0.35		0.48	
	Constant	−3.14	Constant	−17.77	Constant	−3.71
	Canopy shading	1.33	Woody debris	1.60	Rapid	1.72
	Run	1.12	Mesolithal (6–20 cm)	2.52	Depth 45–60 cm	4.11
	Depth 30–45 cm	1.25	Microlithal (2–6 cm)	4.65	Macrolithal (20–40 cm)	−5.38
	Microlithal (2–6 cm)	5.08	Akal (gravel)	4.52	Microlithal (2–6 cm)	7.13
	Akal (gravel)	3.82	Temperature	0.92		
	Psammal (sand)	2.80	pH	1.57		
	Abundance model		Abundance model			
Estimated success (%)	62		66			
Area under ROC curve	0.74		0.77			
Probability cutoff	0.51		0.46			
	Constant	−3.86	Constant	−5.09		
	Velocity 0–15 cm	2.29	Velocity 0–15 cm s^{-1}	−2.73		
	Macrolithal (20–40 cm)	5.15	Mesolithal (6–20 cm)	−4.14		
			Temperature	3.80		

(*Continues*)

DOI: 10.1002/rra

Table V. (Continued)

	Chub–adult *Leuciscus cephalus*		Italian freshwater goby–adult *Padogobius martensii*		Eurasian minnow–adult *Phoxinus phoxinus*	
	Presence model		Presence model		Presence model	
Estimated success (%)	92		84		91	
Area under ROC curve	0.91		0.88		0.90	
Probability cutoff	0.29		0.39		0.50	
	Constant	−4.61	Constant	−4.93	Constant	−6.59
	Woody debris	1.68	Riffle	1.46	Canopy shading	2.50
	Depth 45–60 cm	3.03	Depth 15–30 cm	2.37	Woody debris	2.27
	Microlithal (2–6 cm)	5.50	Velocity 0–15 cm s^{-1}	1.73	Ruffle	1.50
	Psammal (sand)	10.11	Microlithal (2–6 cm)	7.02	Run	2.12
	Pelal (silt and clay)	3.82	Psammal (sand)	9.70	Velocity 0–15 cm s^{-1}	2.16
					Pelal (silt and clay)	3.58
	Abundance model		Abundance model			
Estimated success (%)	83		63			
Area under ROC curve	0.94		0.90			
Probability cutoff	0.42		0.52			
	Constant	−5.39	Constant	2.85		
	Riffle	2.30	Depth 30–45 cm	−5.84		
	Psammal (sand)	7.82	Velocity 15–30 cm s^{-1}	−5.72		
			Microlithal (2–6 cm)	−6.97		

The estimated success and the area under the relative operating characteristic (ROC) curve were used to estimate the predictive power of the model (Hosmer and Lemeshow, 2000). The probability cutoff for both the presence and abundance models was derived from the ROC curves in order to classify habitats into suitability categories (Parasiewicz, 2007a), whereas the habitat variable coefficients are multipliers of the significant habitat attribute values, constituting the multivariate habitat suitability model. A positive regression coefficient means that the variable increases the probability of the outcome (presence or abundance of the fish), whereas a negative regression coefficient means that the variable decreases that probability.
HMU, hydromorphologic unit; ROC, relative operating characteristic.

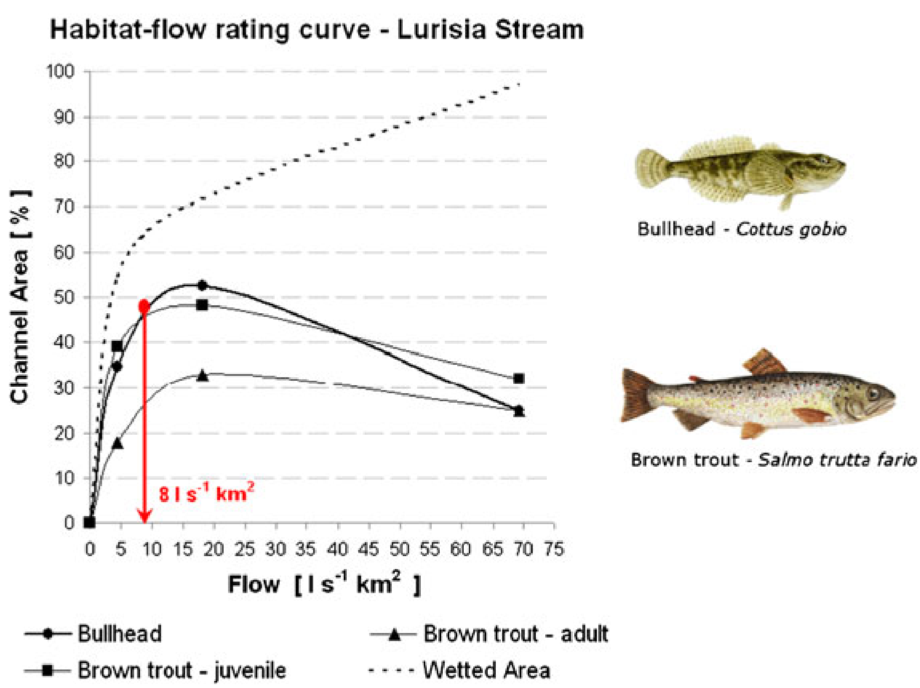

Figure 3. The habitat–flow rating curves for the Lurisia stream, Piedmont, Italy [Table I, Stream ID 7] obtained by a mathematical spline function defined piecewise by polynomials. Measured discharges were 4.3, 18.2 and 69.21 s^{-1} km^{-2}. The fish community was locally represented by bullhead and brown trout (adult and juvenile life stages) and the highest value among the inflection points of the curves sets the minimum e-flow requirement (81 s^{-1} km^{-2}). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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Table VI. Range of surveyed discharges and minimum e-flow requirements expressed in $l\ s^{-1}\ km^{-2}$ for the 25 reference streams; along with the proportion of suitable habitat area (%), predominant hydromorphologic unit (HMU) types, substrate diameter (cm) and target fish community (TFC)

ID	Stream name	Range	Min e-flows	Suitable area	HMUs	Substrate	TFC
1	Agogna	7.2–31.2	9.0	18	Pool, riffle	2–20	Barble, chub, vairone, minnow, bullhead, trout
2	Albedosa	0.1–5.3	0.5	63	Run, riffle	0.2–2	Vairone, goby
3	Belbo	2.3–13.3	1.0	36	Pool, riffle	2–40	Chub, vairone, goby, minnow
4	Campiglia	25.9–41.0	19.0	21	Rapid, step-pool, plunge pool	20–>40	Trout
5	Cavaglione	15.5–53.8	18.0	16	Rapid, step-pool, plunge pool	6–>40	Trout
6	Fandaglia	2.9–9.7	3.5	50	Run, riffle	2–20	Barble, chub, vairone, goby, minnow
7	Lurisia	4.3–69.2	8.0	47	Rapid, riffle	6–40	Bullhead, trout
8	Maggiore	3.8–9.1	1.0	16	Run, riffle	0.2–20	Chub, vairone, minnow
9	Melle	5.6–27.5	6.0	37	Rapid, step-pool	6–>40	Bullhead, trout
10	Pragnetta	13.7–28.2	13.0	28	Rapid, step-pool, plunge pool	20–>40	Trout
11	Ravine	33.3–94.0	28.0	32	Rapid, step-pool	6–>40	Vairone, bullhead, trout
12	Ricchiaglio	10.5–23.5	10.0	35	Rapid, step-pool	6–>40	Bullhead, trout
13	Rifreddo	10.4–32.0	3.5	15	Rapid, riffle	2–20	Bullhead, vairone
14	Rilate	0.7–5.3	1.0	24	Run, riffle	0.2–6	Chub, vairone, minnow
15	Robeirano	4.5–10.1	4.0	26	Run, riffle	0.2–2	Chub, vairone, minnow
16	Roccia	3.9–7.6	5.0	18	Run, riffle	0.2–20	Chub, vairone, goby, minnow
17	Savenca	24.8–36.4	20.5	25	Rapid, step-pool	6–>40	Bullhead, trout
18	Scaglione	24.6–30.3	22.0	22	Rapid, step-pool, plunge pool	6–>40	Trout
19	Subiasco	3.5–10.2	3.0	21	Rapid, step-pool	6–40	Trout
20	Taonere	2.1–16.7	2.5	30	Rapid, step-pool, plunge pool	6–>40	Bullhead, trout
21	Vallanta	3.9–10.5	4.0	14	Rapid, step-pool, plunge pool	20–>40	Trout
22	Valle Ritta	10.3–53.3	8.5	22	Rapid, step-pool	6–40	Trout
23	Vallone d'Elva	7.4–15.4	6.5	46	Rapid, step-pool, plunge pool	20–>40	Trout
24	Viazza	2.7–15.1	3.0	73	Run, Riffle	0.2–20	Chub, vairone, goby, minnow
25	Visone	0.9–10.0	1.0	25	Pool, riffle	2–40	Barble, chub, vairone, goby

The obtained picture (reported in Figure IV) showed some interesting hydro-ecological features. Catchment centroid coordinates (UTM_{XB} and UTM_{YB}), used for sub-regions definition, are significant in terms of total annual precipitation and climate, which affect runoff and the magnitude of discharge (e.g. dry climate, moderate snowpack storage and high evapotranspiration for the Apennines area–TN2). Moreover, the maximum elevation (H_{MAX}) delineated a region (the north-western Alps–TN4) characterized by higher water availability as a result of higher rainfall, snowpack storage and the presence of glaciers. The identified four sub-regions also have a biological meaning in terms of fish distribution and zonation. The Apennines area (TN2) is characterized by a fish community dominated by cyprinids in which trout is almost absent. In the south-western Alps (TN1) and north-eastern plains (TN3), salmonids are dominant and rheophiliccyprinids are rare and located at low elevations. Finally, in the north-western Alps (TN4), only trout is present mainly due to natural limiting factors (high elevation, steep streams, low water temperature).

In order to handle the present lack of information for the watercourses belonging to watersheds smaller than 50 km^2, a regional hydro-ecological database was created, which allowed the definition of a relationship between streamflow and the available habitat for the fish community. Considerable effort was therefore needed to collect field data (consisting of 18 months and 25 sampled streams) as a starting point for an empirically based flow management system. In the context of regional water planning, the obtained e-flow values represent the minimum amount of water that must remain in the river in order to preserve the fish fauna. However, regulated discharges set constantly at the minimum flow would produce substantial demographic changes in the fish community and cause problems mainly for adult fish through the loss of quality and availability of the habitat

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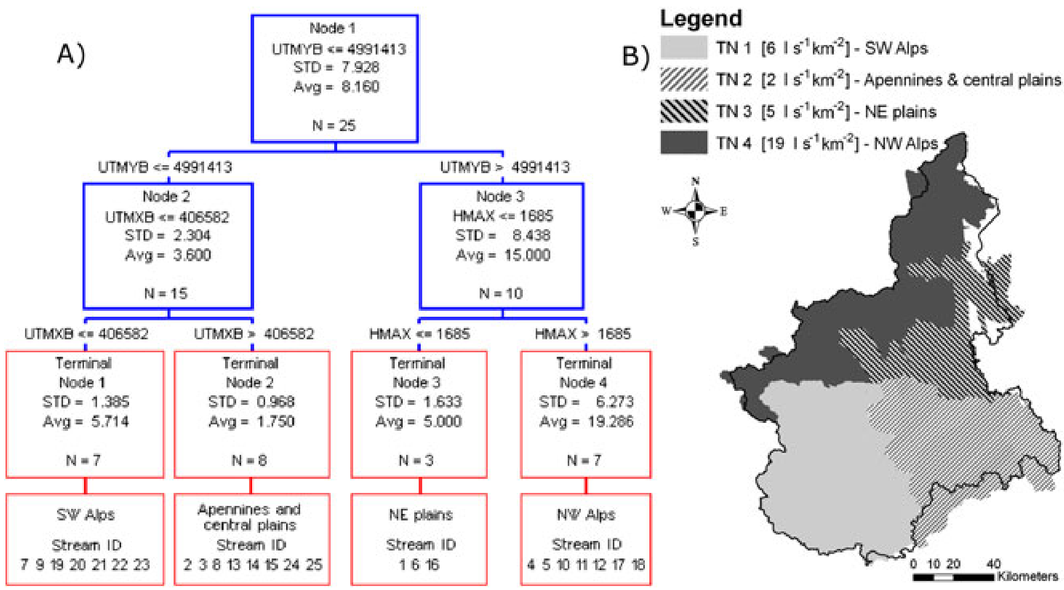

Figure 4. (A) Regression tree obtained using the minimum environmental flow values as target variable and catchment/stream characteristics as independent variables. UTM_{XB} and UTM_{YB} represent the catchment centroid coordinates, whereas H_{MAX} is the maximum elevation. The terminal nodes of the tree (TN_i) represent groups of catchments. The standard deviation (STD, expressed in $\mathrm{l\,s^{-1}\,km^{-2}}$), the average value of minimum e-flows (*Avg*, expressed in $\mathrm{l\,s^{-1}\,km^{-2}}$) and the number of streams (*N*) are reported for each group of catchments. The optimal number of terminal nodes is defined calculating the minimum value of the cross-validated deviance of the tree (i.e. pruning algorithm, Breiman *et al*., 1984). Finally, the lower row of boxes outlines the identified four sub-regions and the related stream ID for each group of catchments. (B) Map of the four sub-regions defined by the regression tree, useful to allocate catchments for future e-flow studies. The minimum e-flow values are also reported, rounded to the nearest integer. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

(Ovidio *et al*., 2008). The full determination of environmental flows in terms of discharge fluctuations (quantity, timing, duration and frequency) related to seasonality and bio-periods of water-related ecosystems (e.g. Parasiewicz, 2007b) is scheduled as a further development of the methodology. The developed habitat–flow rating curves could be used to incorporate these flow regime requirements, which are an important component of the habitat of most naturally flowing streams. Furthermore, although habitat time series analysis using uniform continuous under threshold methodology is one of the strengths of the MesoHABSIM approach (Parasiewicz, 2007b; Parasiewicz, 2008b), the lack of adequate hydrological data for the investigated small streams prevented the application of this technique in this project.

Eisner *et al*. (2005) showed how mesoscale habitat models face the issue of subjectivity (i.e. two observers could map the same mesohabitat and produce a different description). It is important to note that, within the considered watercourses, the high gradient and the small size of mesohabitats allowed an easier and unique identification of the HMU features. On the other hand, the challenging conditions of the surveys (i.e. Alpine headwater streams with the presence of large rocks and snow and ice in the main channel) and the high variability of the channel geometry lowered the accuracy in drawing precise contours of the mesohabitats by means of the rangefinder (see e.g. CIFGS–Clackamas Instream Flow/Geomorphology Subgroup, 2003) and consequently the digital map polygons needed to be checked for errors before merging them into the GIS database.

A spline curve fit function was used to interpolate the habitat values over the range of selected discharges (see Parasiewicz, 2007a, for details). This is a limitation of the MesoHABSIM approach, which is not based on the use of established hydraulic models to simulate water depth and flow velocity for unmeasured discharge conditions. On the other hand, this procedure assures that only flows, for which the habitat suitability criteria are valid, were modelled (e.g. preventing the application of suitability criteria at high flows or flood events). Interestingly, because the mesoscale habitat models do not require hydraulic simulation, they adapted particularly well to the high-gradient streams (i.e. characterized by a high degree of flow complexity owing to the presence of boulders, waterfalls, step-pool cascades) and were able to model the hydrodynamic conditions over the analysed range of discharges.

For the final step of assessing the minimum ecological support for the riverine ecosystems, we examined the scatter plot of the minimum e-flows versus the predicted specific discharge q_{95} (Figure V). This allowed an evaluation of the magnitude of the defined minimum e-flows in terms of percentage of q_{95}, detecting the existence of outliers. The

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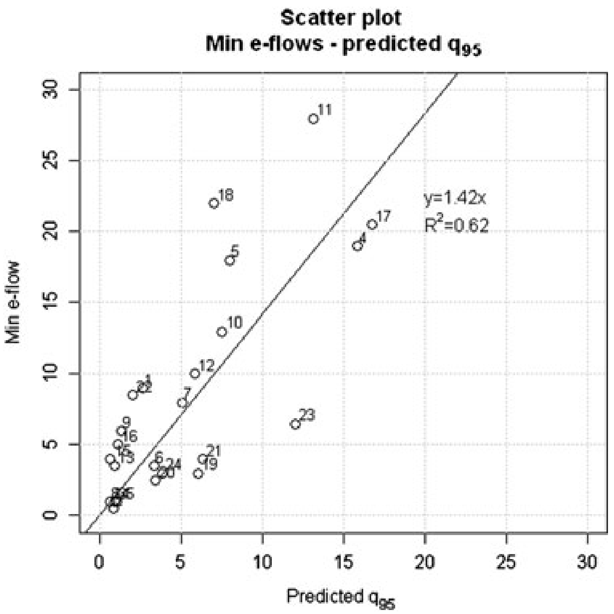

Figure 5. Scatter plot of minimum e-flows and q_{95} predicted by the regional regression models defined in Vezza *et al.* (2010). Values are expressed in l s^{-1} km^{-2}.

minimum e-flow values defined in the present study can be referred, on average, to 1.42 times q_{95}, with a coefficient of determination equal to 62%. However, it is important to state that the reliability of the regional hydrological models for low flow assessment, defined in Vezza *et al.* (2010), was quite low within small watersheds because of the limited availability of stream gauges located in small headwater catchments. Although the reliability of the predicted q_{95} is not high, one can state that the obtained minimum e-flows are however validated by this result in terms of their magnitude, being representative of the natural low flow regime of the selected catchments.

To further test the above procedure, we plotted the habitat data from all sites within the obtained groups of catchments in one diagram and analysed the interpolated trend lines. The habitat values of the fish species with the highest flow requirements (normalized to the maximum habitat value) are reported in Figure VI for all measured flows. Because of their similar minimum e-flow values, TN1 and TN3 groups of catchments were combined onto one graph. Overall, one can observe how the magnitude of the values obtained using the inflection points of the polynomial curves ($y'=1$, i.e. slope equal to unity, Gippel and Stewardson, 1998) could validate the results derived from the regression tree classification, with a deviation ranging from 14% to 29%. Although the R^2 values of the trend lines are relatively low, it is possible to observe how the maxima form a group in relatively close proximity to the average values defined by the regression tree. For regional level studies, this should be considered highly informative.

It is important to emphasize that the model results presented here are not intended to substitute site-specific and detailed studies (e.g. for new HEPs, renewal of water licence, etc., the e-flow values shall be locally verified) but rather to provide regional-scale guidance and to conservatively estimate the basic range of minimum flows within homogeneous sub-regions. Where the variance of the e-flow requirements is higher (i.e. TN4) or in protected natural areas, an environmental safety factor from 1.2 to 2 could be applied in order to establish a more conservative criterion. Moreover, within river sections where the high

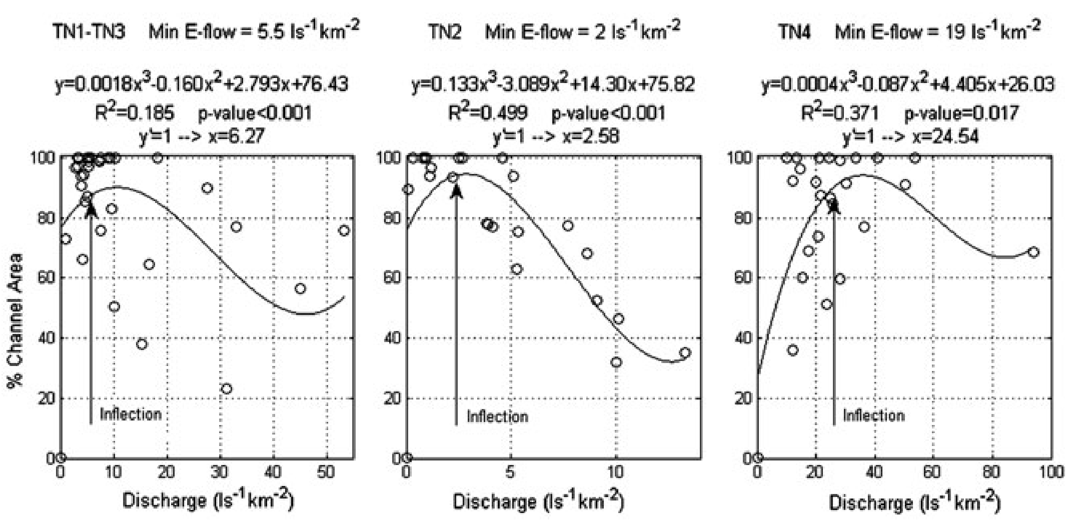

Figure 6. Polynomial rating curves for the obtained groups of catchments. Using the normalized habitat values of the fish species with highest flow requirements, the curves defined at the inflection point ($y'=1$, i.e. slope equal to unity) a minimum e-flow value that slightly differed (from 14% to 29%) from the values obtained by the regression tree classification. In the figure, TN1 and TN3 groups of catchments were combined into one graph because of their similar minimum e-flow values.

DOI: 10.1002/rra

riverbed infiltration rate prevents sufficient habitat availability during low flow periods (in particular for adult fish species, see e.g. Ovidio *et al*., 2008) a multiplicative factor can also be locally defined to safeguard the aquatic community. Furthermore, the regional biological models did not capture the seasonal variability of chemical variables (i.e. water temperature, pH and proportion of dissolved oxygen), which did not seem to be important habitat characteristics. In order to cope with this drawback, shifts in the fish community structure over time should also be investigated (e.g. modelling fish response to habitat seasonal changes) by using the present regional database and carrying out further field work and data collection. This further step will contribute to improve the described methodology, allowing the validation of biological models within the regional territory.

The proposed bottom–up approach demonstrated to be reliable in terms of cost-effectiveness, particularly for the regionalization purposes of minimum e-flows and it represents an innovative methodology to derive a general conservative rule to preserve riverine ecosystems. Further improvements, such as model validation and seasonality analyses, are planned for the near future to address potential shortcomings and provide a more comprehensive methodology.

ACKNOWLEDGEMENTS

This research has been funded by the Regione Piemonte, C61 Project–CIPE 2004. Moreover, the authors wish to acknowledge Ferdinando Benatelli, Sabino Cannone, Filippo Rossi, Gianfranco Bertolotto and all of those who contributed during the development of the research. Lastly, we are very grateful to the anonymous reviewers for the valuable comments on the manuscript.

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DOI: 10.1002/rra