

Implementation of the EU ecological flow policy in Italy with a focus on Sardinia

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ABSTRACT

River ecosystems are characterised by a naturally high level of hydrodynamic perturbations which create aquatic-terrestrial habitats indispensable for many species, as well as for the human beings' welfare. Environmental degradation and habitat loss caused by increasing anthropogenic pressures and global change affect freshwater aquatic ecosystems worldwide and have caused changes in water flow regimes and channels morphologies. These, in turn, decreased the natural flow capacity and reduced habitat availability, thus causing severe degradation of rivers' ecological integrity. The ecological flow (e-flow) is commonly intended as the quantity, timing, duration, frequency and quality of water flows required to sustain freshwater, estuarine and near shore ecosystems and the human livelihoods and well being. Maintaining the e-flow represents a potential tool for restoring and managing river ecosystems, to preserve the autochthonous living communities, along with environmental services and cultural/societal values. In the last decade, methods for the determination of the e-flow in European rivers moved from a simply hydrological approach towards establishing a linkage between the hydrological regime and the good ecological status (GES) of the water bodies, as identified by the European Water Framework Directive (WFD; 2000/60/EC). Each Member State is required to implement and integrate into the River Basin Management Plans (RBMP) a methodology for the determination of the e-flow, ensuring that rivers can achieve and maintain the GES. The competent river basin authorities have thus to ascertain whether national methodologies can be applied to different river typologies and basin environment characteristics. In this context, we narratively review the e-flow assessments in the heterogeneous Italian territory, in particular on a water scant region such as Sardinia, by analysing laws, guidelines and focusing on study cases conducted with micro and meso-scale hydraulic-habitat approaches. In the sight of a more ecological-based application of national e-flow policy, we suggest that meso-habitat methods provide a valuable tool to overcome several limitations of current e-flow implementation in the Italian territory. However, to face future challenges, such as climate change adaptation, we stress the need for further experimental studies to update water management plans with greater attention for nature conservation.

INTRODUCTION

The functioning of riverine ecosystems is the result of complex interactions among multiple abiotic and biotic components which, altogether, contribute to the establishment of specific and dynamic mosaics of aquatic and terrestrial habitats. The variability of flows in terms of magnitude, frequency, duration, timing and rate of change, controls river ecosystem functioning, by preserving their integrity and allowing the persistence of native species and natural habitats, as well as the development of the human society (Poff *et al.*, 1997; Bunn and Arthington, 2002; Acreman, 2016).

Nowadays, the increasing intensification of human activities is the primary factor of rivers natural flow regimes alteration (Peñas *et al.*, 2016; Horne *et al.*, 2017). As a consequence of a growing human population and associated economic development, many anthropogenic interventions have led to significant degradation of more than 60% of the world's rivers (Nilsson *et al.*, 2005). Global water withdrawals increase by about 10% every 10 years, with this rate being much higher in developing regions (Organisation for Economic Co-operation and Development, 2012). The exploitation of water resources for urban, agricultural and industrial purposes, together with changes in land use, transport and energy production negatively affects both the hydrology (reduced residual

water) and the morphology of rivers (longitudinal and lateral connectivity interruption) (Lake, 2007; Döll *et al.*, 2009). In parallel, climate change is also influencing rivers' flow regime (Barnett *et al.*, 2005; Blöschl *et al.*, 2017; Pletterbauer *et al.*, 2018). Indeed, the outflow of rivers is directly influenced by long-term changes in both precipitation and temperature trends (Dudgeon *et al.*, 2006). Variations in the amount of precipitations associated with global change can modify the hydrological cycles, which in turn, influence habitats availability for many aquatic organisms (Filipe *et al.*, 2013). Temperature variations affect the timing of the outflow and modify the chemical-physical features of the aquatic environment, ultimately altering ecological and biological processes (Pletterbauer *et al.*, 2018). Furthermore, climate change can cause a deep modification of human usages of rivers' water or directly interact with human pressures. For instance, in many regions of the world, due to the increasing water scarcity, a growing number of water management measures, such as impoundments, diversion weirs and dams, are being adopted, contributing significantly to lowering rivers' habitats quality (Postel, 1998; Magilligan *et al.*, 2005; Zhang *et al.*, 2015).

A well-established approach aimed to preserve freshwater ecosystems and river ecological status relies on the definition of a sustainable environmental flow

release from dams and other types of derivation (Acreman *et al.*, 2016). The environmental flow (e-flow) is commonly intended as the quantity, timing, duration, frequency and quality of water flows required to sustain freshwater, estuarine and near shore ecosystems and the human livelihoods and well being (Tharme, 2000). The concept of e-flow has been discussed for more than 40 years (Tharme, 2003; Acreman and Dunbar, 2004; King and Brown, 2006; Poff and Matthews, 2013; Acreman, 2016) and it is now worldwide recognized by several national and regional water protection policies, *e.g.* the European Water Framework Directive (European Commission, 2015), the South African National Water Act (Forslund *et al.*, 2009) and the Brisbane Declaration (Arthington *et al.*, 2018). Many countries have incorporated e-flow provisions as they have updated water policy and laws (Le Quesne *et al.*, 2010). Over the last few years, there has been a growing consensus about the need of science-based approaches and requirements for the assessment of e-flows in order to achieve successful management of freshwater ecosystems, conciliating natural habitats conservation with the supply of freshwater for human usage (Acreman and Dunbar, 2004). The achievement of such a trade-off can become more critical in the sights of modified hydrological conditions that will result as a consequence of current climate change (Tonkin *et al.*, 2019).

Tharme (2003) identified >200 methods to assess the water requirements of aquatic species and habitats, and support e-flows management practices to achieve both ecological and social targets (see also Acreman and Dunbar 2004). However, to date, there are still several limiting factors for the implementation of successful e-flow policy, due, mainly, to limitations in institutional capacity, scientific knowledge and monitoring resources. These have been summarized by Le Quesne *et al.*, (2010) in four crucial issues:

- i) the scarcity of knowledge about sites and species-specific e-flows requirements;
- ii) the lack of political decision and effort to recognizing a need to maintain sufficient water in rivers and wetland systems;
- iii) imperfect understanding of the practical issues and costs of implementation to achieve the e-flow regime;
- iv) the lack of a design and maintenance of robust monitoring systems to assess the ecological and other outcomes of environmental watering in an adaptive management framework.

In order to overcome these general issues, research and monitoring of e-flows' adjustments is often required (Richter, 2009; Zang *et al.*, 2012), as well as, the synthesizing of knowledge and experience gained from individual case studies (Arthington *et al.*, 2004; Poff *et al.*, 2010). In fact, regional and local approaches have a

fundamental role in the understanding e-flow methods limitations. They will be crucial for the implementation of an applicable methodology to define e-flows by River Basin Authorities. This is particularly needed in a context where heterogeneous climatic regions (*e.g.* Alpine, Mediterranean) occur and a homogeneous and more ecological-based methodology for the definition of the e-flow is requested. In this context, we review the status of e-flow implementation in Italy, with a focus on a region with high water scarcity such as Sardinia, by analyzing laws, guidelines and study cases conducted with hydraulic-habitat approaches, both at micro and meso-scale. The final aim of this review is to highlight current challenges and limitation that make difficult the application and adaptation of a common e-flows methodology and give cues for the selection of a suitable habitat simulation models that could be integrated to overcome these limits.

THE EUROPEAN GUIDANCE ON E-FLOWS

Nowadays, in Europe, the most significant pressures causing failure to achieve the Good Ecological Status (GES) are the hydro-morphological ones (affecting ca. 40 % of surface water bodies, with the highest proportion reported for rivers and transitional waters) (E.E.A. Report n. 7/2018). The largest proportion (26%) of water bodies is affected by physical alterations in the channel, bed, riparian zone, whereas up to 24% of the investigated water bodies are affected by the presence of structures, such as dams/barriers and locks, that alter the rivers' longitudinal continuity (E.E.A. Report n. 7/2018).

Since 2012, to implement e-flows management in the River Basin Management Plans the European Commission (EC) has asked the Member States (MSs) to focus on pressures affecting the hydrological status of water bodies (Schmidt and Benitez Sanz, 2012). However, the lack of harmonized methodologies and, consequently, of sufficient or sufficiently consistent data for the definition of e-flows' assessment by each MS has raised several operational and interpretation difficulties (Acreman and Ferguson, 2010). For this reason, in 2015, the EC released the e-flow Guidance Document (Ecological flows in the implementation of the Water Framework Directive; WFD CIS Guidance Document No. 31). In this document, the definition of e-flow is provided within the context of the Water Framework Directive (WFD) as "*a hydrological regime consistent with the achievement of the environmental objectives of the WFD in natural surface water bodies as mentioned in Article 4(1)*" and is interpreted as the "*amount of water required for the aquatic ecosystem to continue to thrive and provide the services we rely upon*". Once terminology has been clarified, concern has then arisen on how to

calculate e-flows in different environmental contexts. The document did not report a full protocol for the implementation of e-flows nor led to a uniform e-flow implementation strategy, instead encouraged MSs to share the knowledge obtained so far to evaluate site-specific e-flows implementation conditions (specific environmental values or ecosystem services) and to promote the e-flow definition in the WFD planning process, not considering it as a separate problem.

In the guidance document, the e-flow quantification methods are provided and classified in three major categories (Hydrological, Hydraulic-habitat and Holistic methodologies, Table 1), also according to cost-effectiveness, time-efficiency, complexity and focus (Dyson *et al.*, 2003; Tharme, 2003; Arthington *et al.*, 2004; Richter *et al.*, 2006; King *et al.*, 2008).

Hydrological methods are based on the analysis of the natural flow regimes derived from historical streamflow data (mean annual flows, monthly flows, high/low flows or more complex hydrological indices) that can be existing or simulated. These methods provide an overall baseline flow that aims to conserve the natural flow integrity of a stream and maintain native habitat and species. Hydrological methods are still the most widely used approaches (European Commission, 2015) and, often, are considered as initial analyses in the preliminary phases for supporting more complex methods. However, pure hydrology-based methodologies for e-flows assessment incompletely capture habitat dynamics and ecological responses of aquatic and riparian fauna. These methods fail to account for flow interactions with the channel morphology and its variation in space or modifications over time. Furthermore, in the absence or lack of streamflow gauging stations, hydrological modelling of

streamflow data series requires quite a lot of expertise, can be time-consuming and may produce significant uncertainties when predicting magnitude, frequency and timing of extreme events (low and high flows).

Hydraulic/Habitat simulation methods are more sophisticated approaches in which habitat availability for aquatic species and their vital stages are expressed as a combination of hydro-morphological features and their ecological preferences. Habitat modelling software such as TELEMAC (Galland, 1991), PHABSIM (USGS, 2001), RHYHABSIM (Jowett, 2010), CASiMiR (Schneider *et al.*, 2010) and RIVER 2D (Steffler and Blackburn, 2002) allow this type of accurate site and species characterisation at the micro-scale, while MesoHABSIM (Parasiewicz, 2001, 2007), MesoCASiMIR (Schneider *et al.*, 2001) and RHM (Maddock *et al.*, 2001) at the meso-scale. Hydraulic-habitat methods are often considered more accurate than hydrological ones since they complement them by incorporating flow-dependent and morphology-dependent ecological data, such as the occurrence of wetted areas and the connectivity between them, local hydrodynamic conditions of depth and flow velocity, sediment distribution and composition, and the presence of shelters and refuges for the fauna. However, they may require a considerable amount of fieldwork and expertise to collect the hydro morphological and biological data for model calibration.

Holistic methods are based on a global vision of the riverine ecosystem and encompass all major components or attributes of the river system. These methods require multidisciplinary inputs from different river scientists that integrate data, model predictions and expert knowledge (Tharme, 1996; Arthington, 1998; Tharme, 2000; King *et al.*, 2008). They consider both spatial and temporal

Table 1. List of e-flow approaches and methodologies in different countries and contexts.

Approach	Method	Source
Hydrological	Tennant (Montana)	Tennant (1976)
	Aquatic Base Flow	Caissie and El-Jabi (1995)
	Median Monthly Flow	Caissie and El-Jabi (1995)
	Range of Variability Approach	Ritcher <i>et al.</i> (1997)
	Sustainability Boundary Approach and Presumptive	Ritcher <i>et al.</i> (1997; 2011)
Hydraulic/Habitat simulation (modelling) methods	PHABSIM (Physical HABitat SIMulation)	Bovee (1982)
	MesoHABSIM	Parasiewicz (2001)
	EVHA (Evaluation de Habitat)	Ginot (1995)
	RSS (River System Simulator)	Alfredsen <i>et al.</i> (1995)
	CASIMIR (Computer Aided SIMulation of habitat in Regulated streams)	Jorde (2006)
	River 2D	Blackburn and Steffler (2003)
Holistic frameworks	MesoCASIMIR	Eisner <i>et al.</i> (2005)
	Generalized Habitat models (e.g. STATHAB)	Lamouroux and Jowett
	Building Block Method (BBM)	Tharme and King (1998)
	DRIFT (Downstream Response to Imposed Flow Transformation)	King <i>et al.</i> (2003)
	Benchmarking	Arthington (1998; <i>et al.</i> , 2006)
ELOHA	Poff <i>et al.</i> (2010)	

variations, allowing stakeholders and decision-makers to establish an acceptable risk as a balance among ecological goals, economic costs and scientific uncertainties. Two different main categories of holistic methods exist: bottom-up approaches, *i.e.* the Building Block Methodology (King and Louw, 1998), and top-down approaches, *i.e.* DRIFT (Downstream Response to Imposed Flow Transformation, King *et al.*, 2003) and ELOHA (Ecological Limits of Hydrological Alteration; Poff *et al.*, 2010), that define e-flows in terms of acceptable degrees of departure from the natural (or another reference state) flow regime and, therefore, require accurate quantification of ecological response to stress.

To integrate the methodologies described above and to define a stepwise approach, the European e-flows framework, following the global trends, indicates three study levels:

- i) a preliminary risk analysis to define water bodies at risk of not achieving the WFD objectives because of hydrological alteration;
- ii) the establishment of an extensive hydrological monitoring network able to provide a good data collection in different water release situations to improve the usage of hydrological/habitat approaches in advanced steps of the analysis;
- iii) once the results of the experimental analysis are elaborated, the determination of a water-body type-specific environmental flow assessment (EFA), together with an assessment of the gap between current and reference state (gap analysis), to guide specific measures.

E-FLOW ASSESSMENT IN ITALY

The Italian territory overlooks the Mediterranean Sea and is characterised by a complex geo-morphological structure, with 51% of the country dominated by high mountains chains (the Alps and the Apennines), 29% covered by hills, and 20% occupied by plains (Surian *et al.*, 2003). Such heterogeneous geo-morphological system interacts with the variability of the atmospheric circulation patterns making this Mediterranean region one of the most vulnerable to future climate change (Surian *et al.*, 2003; Giorgi, 2006). Recent studies have predicted an increase in mean temperature of around 1.5-2.0°C in all seasons until 2050 (Tomozeiu *et al.*, 2017), together with an expected slight decrease of the mean annual rainfalls, and an intensification of extreme rainfall events (Brunetti *et al.*, 2001; Giorgi and Lionello, 2008; Coppola and Giorgi, 2010; Lionello *et al.*, 2012). Additionally, scientific literature tends to agree that in spring and summer, change in the climate patterns is predicted to cause an increase in the frequency and intensity of droughts (Spinoni *et al.*, 2017).

In this context, water demand is continuously increasing to satisfy the growing socio-economic needs and justified the construction of a significant number of large reservoirs in the Italian territory, placing Italy in the fifth place among the European member states with the highest number of dams (542, ICOLD, 2007). Additionally, in the last century, most of the Italian rivers have experienced a considerable morphological change in terms of bed-level lowering (commonly of the order of 3–4 m), channel narrowing (in some cases up to 50%) and changes in channel pattern, due to sediment extraction, weirs and channelization (Surian *et al.*, 2003). Such increasing impacts caused by these hydro-morphologic pressures, coupled with the current climate change, have led to significant alteration of the hydrology of Italian rivers, with consequent spatial and temporal reduction of fluvial habitats, accompanied by a decline of the environmental status and biodiversity loss (Dudgeon *et al.*, 2006; Feyen *et al.*, 2009; Carlisle *et al.* 2010; Filipe *et al.*, 2013; Blöschl *et al.*, 2017; De Girolamo *et al.*, 2017; Horne *et al.*, 2017; Spinoni *et al.*, 2017).

In 1989, with the enactment of the Italian Law n.183, the hydrological regime relevance was recognized by the Italian Government, which established the first legal act, including the qualitative definition of the e-flow. The concept of e-flow was initially associated to the idea of a “minimum constant flow” to be guaranteed in riverbeds, to promote a balance between human needs and the natural requirements of the riverine ecosystem (Law 183/1989). The Ministerial Guidelines for the definition of the e-flow were issued only in 2004, and the subsequent Legislative Decree n.152/2006 introduced the concept of “Minimum Vital Flow” (hereafter MVF), as the instant outflow needed to be preserved in downstream water diversions in order to conserve the physical (morphological, hydrological and hydraulic), physical-chemical (water quality) and biological features of natural riverine ecosystems.

To date, the general formulas adopted among the Italian Districts by the River Basin Authorities, are based on simple hydrological formulas, mostly considering the percentage of mean annual or monthly flow, corrected through several coefficients taking into account different environmental aspects (Table 2). These formulas are the most exploited in Italy for their ease of application and cheapness. However, although this was the first step towards the implementation of a national rule to determinate the e-flow, three main problematic elements emerged: i) the absence of a univocal rule regarding the determination of the key hydrological parameters (*e.g.*, annual average flow, the average flow of a specified period, the average flow of specific months); ii) the presence of significant diversity among calculation

formulas resulting in territorial values of MVF notably heterogeneous, even within the same river basin district (when the rivers pass through different regions); iii) the

absence of an evident and robust correlation between the MVF values and the environmental status of the water bodies classified by the indices required by Legislative

Table 2. List of formulas adopted in different Italian regions for assessing the Minimal Vital Flow (MVF) in Basin Managements Plans (2015-2021).

Regions	Formula	Legend
Po	$MVF = k \times q_{meda} \times S \times M \times Z \times A \times T$	k: Experimental parameter determined for individual hydrographical areas
Piemonte		q_{meda} : specific annual average flow per unit of area of the basin (in l/s km ²)
Liguria		S: surface of the natural catchment area (Kmq)
Toscana		M: morphologic parameter
Valle d'Aosta		Z: greater (N, F, Q)
Emilia Romagna		N: coefficient of naturalness F: coefficient of fruition Q: parameter concerning the quality of river water A: parameter concerning the interaction between surface waters and groundwater R: monthly hydrological modulation (class) T: time flow modulation.
Marche	$MVF(\text{monthly}) = [(K0 - 2,24 \times 10^{-5} \times S)] \times Q_m \times (M \times Z \times A \times T)$	K0: 0,075 S: surface of the natural catchment area Qm: average annual natural flow regime in the considered section M: morphologic parameter Z: greater (N, F, Q) N: current naturalness F: fruition parameter Q: parameter concerning the quality of river water A: parameter concerning the interaction between surface waters and groundwater T: time flow modulation.
Provincia Autonoma di Trento	$MVF(\text{monthly}) = MVF \times SUP \times S \times P \times A \times G \times PE \times R$	SUP: absolute surface of the natural catchment area S: surface of the natural catchment area P: monthly precipitations A: average altitude of the catchment area PE: basin and riverbed permeability G: riverbed geomorphology
Veneto	$MVF = [(K_{biol}) + K_{nat}] \times 207 \times S0,8 \times q_{meda} \times 10^{-6}$	R: monthly hydrological modulation (class) K _{biol} : index of biological criticality K _{nat} : criticality naturalness Index S: surface of the natural catchment area (Km ²) q _{meda} : average annual flow (l/s Km ²)
Friuli Venezia Giulia	$QMVF = K \times T \times P \times M \times Q_{media}$	Q _{media} : average annual flow to the section concerned K: protection level T: timing coefficient P: coefficient of naturalness and tourism M: coefficient of seasonal modulation
Abruzzo	$MVF = Q \times K_{biol} = (K1 \times Q_{ruse} + K2 \times Q_{acqm} + K3 \times Q_{sorg}) \times (K_{itf} + K_{morf} + K_{i.B.E.} + K_{morf})$	Q _{ruse} : runoff flow Q _{acqm} : flow due to the emergence of minor aquifers Q _{sorg} : flow due to the emergence of significant groundwater bodies K1, K2, K3 are three coefficients that allow to weigh independently the contribution of each of the flow components defined above K _{itf} : coefficient fluvial functional K _{morf} : morphologic coefficient K _{itf} : ichthyofauna coefficient
Sicily	$MVF = 10\% (Q_{med})$	Q _{med} : average annual flow
Sardinia	$MVF = 10\% (Q_n)$ [In use] $MVF = Q_n(t, f) \times K$ [Under experimentation]	Q _n : natural flow Q _n (t, f): natural flow as a function of monthly mean rainfall K: coefficient related to hydro-morphological parameters

Decree 152/06. To overcome the above-highlighted issues, in 2017 the Italian Ministry of the Environment and Protection of the Territory and the Sea (MATTM) approved the Directorial Decree n. 30/STA (DD 30/STA hereafter), to update and provide homogeneous and scientifically advanced methodologies for the definition of the ecological outflow throughout the national territory, as requested by the European Commission (CIS Guidance Document n. 31/2015).

IMPLEMENTATION OF HYDRAULIC-HABITAT SIMULATION MODELS IN ITALY

Within the Italian territory, a variety of hydraulic-habitat approaches have been tested to enhance the hydrological based e-flow assessments. The meso-scale or meso-habitat models were used in different Italian regions for several species of fish. The geomorphic unit (or mesohabitat) generally ranges between about 1 m and 100 m (Hauer *et al.*, 2009; Parasiewicz *et al.*, 2013). This resolution allows the use of a wide range of environmental variables for the description of the fluvial habitat, obtaining a biological analysis of the life cycle of a single species or several communities, such a fish (Gosselin *et al.*, 2012; Wilkes *et al.*, 2015). The mesohabitat scale approach includes habitat suitability criteria to identify habitat characteristics in relation with different water regimes needed for the presence of particular species, for a particular biologically relevant periods of the year (*e.g.*, spawning), or for particular endangered or threatened species (Veza *et al.*, 2012). The MesoHABSIM model was used to describe habitat distribution and e-flow requirements needed to support local populations of the endangered White-clawed Crayfish (*Austropotamobius pallipes*) in Lombardy region and in the Gran Sasso and Laga National Park mountainous streams (Abruzzo region). With the use of a meso-habitat scale approach and time series analysis, detailed schemes of flow management were defined to represent habitat changes over time and to identify stress conditions for *A. pallipes*, created by the persistent limitations in habitat availability (Veza *et al.*, 2016). The habitat suitability model MesoHABSIM, based on the statistic models Random Forest and Logistic Regression, was also used to estimate habitat preferences for the bullhead fish (*Cottus gobio*) in Alpine streams (Veza *et al.*, 2014a). The distribution of bullhead fish in various habitat was also predicted with a MesoHABSIM model created with a deductive model, based on conditional habitat suitability criteria derived from expert knowledge and literature information (Adamczyk *et al.*, 2019). Furthermore, the meso-habitat suitability model was used to quantify habitat alteration and to define e-flow schemes in high gradient streams using biological and

hydro-morphological data from 40 study sites located within the mountainous areas of different regions, such as Aosta Valley, Piemonte and Liguria (Northwest Italy) (Veza *et al.*, 2014b). Moreover, the habitat meso-scale approach has been used to identify the optimal regime flow considering the limiting factors' approach and the assessment of basic ecological relationships. In a study conducted in the Serio River (Northern Italy), density-environmental variables relationships for three different life stages of the brown trout were investigated to select a range of flows able to preserve most of the physical habitat for all of the trout life stages. The results highlighted that the main factors limiting the trout densities were water velocity, substrate characteristics and availability of refugia from predation. This study also estimated the effect of varying discharge flows on macroinvertebrate biomass, and it was then used to identify an optimal flow maximizing either habitat and prey availability (Fornaroli *et al.*, 2013). In the Aosta Valley (North-Western Italy), the indices of river habitat integrity derived from the MesoHABSIM methodology were also used to demonstrate that the application of meso-scale habitat models allows the assessment of hydro-morphological spatio-temporal alterations of habitat's structure and that these models and indices can be adequately integrated into a multi-criteria analysis framework, supporting decision-making processes by the competent authorities (Vassoney *et al.*, 2019).

Another type of hydraulic-habitat methodologies for estimating the e-flow assessment relies on the micro-habitat approach. Such an approach is used when the scale of investigation zooms in at site-specific or species-specific level, for example, when the focus switch on the conservation of one or few targeted species. This approach requires the acquisition of precise knowledge and data on the relationships between specific flow conditions and the life cycle requirements of the targeted species. Such data are essential to create Habitat Suitability Curves (HSC) and apply microhabitat-hydrological approaches to estimate a suitable e-flows tailored at the site-specific scale. However, in the literature, Habitat Suitability Curves are available only for a few species, and the availability of experimental curves on the Italian national territory is still very limited (Vismara *et al.*, 2001). Another important limitation of the use of micro-habitat approaches is their dependence on hydraulic simulation models (1D or 2D), which are difficult to be used, or even inappropriate, in high gradient streams (Veza *et al.*, 2014), in intermittent streams (Acuña *et al.*, 2020), in lowland macrophyte-dominated rivers (Hearne *et al.*, 1994) and in rivers with winter ice (Alfredsen and Tesaker 2002). Experimental studies, using the micro-habitat approach, have been mostly carried out to correct

the suitability of flow regimes released by the Basin River Authorities' formulas for several target species. The micro-habitat methodology PHABSIM was used by the Marecchia-Conca Basin River Interregional Authority (Salmoiraghi and Morolli, 2007) to determine the value of the optimal flow needed to guarantee the functionality of the river system and the life of its organisms in several sections of the Marecchia River and its tributary Senatello (as a contribution to the Partial Basin Plan for the Hydrological Instability). This study provided evidence of the need to correct the e-flows previously established to ensure the optimal habitat availability for the trout (*Salmo trutta*), the barbel (*Barbus plebejus*), and the chub (*Leuciscus cephalus*) with those obtained from the application of the PHABSIM model. The micro-habitat approach, Instream Flow Incremental Methodology (IFIM, Bovee *et al.*, 1998) was applied in the Taro River (Northern Italy) to estimate the e-flow for three fish species (*Barbus plebejus*, *Chondrostoma genei* and *Leuciscus souffia*) and their vital stages (young, adults and reproductive stage). Once again, the results highlighted how the value of the e-flow, adopted so far for the Taro river, calculated according to the general formula proposed by the Basin Authority for the Po river, did not guarantee the preservation of any of the species analyzed in the study case. The same study also determined two different flow thresholds for each species: a "Critical" threshold that indicates the flow in which species can "survive", and an "Ecological flow" threshold in which species can spend their life in a habitat favorable to their needs (Chiussi *et al.*, 2009). Finally, microhabitat simulation using the PHABSIM software was used to estimate e-flow requirements for salmonids and brown trout in the Cordevole river basin. This study case demonstrated that a fixed water release of 600 L s^{-1} could be sufficient for the maintenance of good quality habitat for salmonids, whereas a water release of at least 350 L s^{-1} is sufficient for the maintenance of a good quality condition for brown trout's habitat (Schmidt and Benítez Sanz, 2012). More recently, other models have used alternative approaches based on a mix of expert opinions and fuzzy logic-based rules to describe the habitat use by target species and for the application of hydraulic-habitat models. A modified IFIM micro-habitat method, using a fuzzy logic-based model, was applied to the barbel (*Barbus plebejus*) and the chub (*Leuciscus cephalus*) habitat suitability response to hydrologic and water quality parameters variation in the Arno and Serchio rivers. This trial provided evidence that fuzzy logic-based estimates of the target species' response to critical environmental variations are more reliable than those obtained through the conventional IFIM approach (Marsili-Libelli *et al.*, 2013).

E-FLOW IMPLEMENTATION IN SARDINIA (ITALY)

Sardinia is the second largest island in the Mediterranean Sea. It is characterized by a typically Mediterranean climate with warm and moderately rainy winters and dry and hot summers. Sardinian rivers are characterized by a strong variability of the water outflow, due to seasonal hydrological oscillations (Gasith and Resh 1999; De Waele *et al.*, 2010), and they constitute the predominant water contribution to the island water resources since the contributions from snowmelt and groundwater are almost negligible. In the last decades, a drastic mean yearly runoff decrease (up to ca 40% over the 1975-2010 period when compared with the previous 50 years; Montaldo and Sirigu, 2017) has been registered for Sardinian basins. This caused relevant water scarcity issues and led to the construction of more than 50 dams, to store water in critical periods of the year. Winter precipitations will reduce in the near future because of expected changes in the North Atlantic Oscillation (NAO) index associated with climate change (Montaldo and Sirigu, 2017). This will likely determine a further decrease of water resources availability in Sardinia, which, in turn, will require an increase in the number of hydro-morphologic alterations to satisfy the water demand for agriculture and human uses. Additionally, this scenario will also be exacerbated because of unpredictable extreme rainfalls, to which Sardinia is being more and more vulnerable. For example, in years from 2004 to 2018, these events became particularly frequent (at least once per year) and often produced flash floods causing severe changes in channel morphology and sediment distribution, damage to private and public infrastructure, and even human deaths (Bodini *et al.*, 2010; De Waele *et al.*, 2010).

Given the present and future critical scenario in rivers' runoff and their predictable strong impacts on freshwater habitats, new strategies and designs in water resources planning and management are required. This need appears crucial, especially for the assessment of a sustainable e-flow regulation plan aimed at ensuring the maintenance of key (including endemic) habitats and species.

To date, the Sardinian Water Basin Management Plan simply requires the maintenance of a fixed MVF equal to the 10% of the natural flow regime (*i.e.*, the natural water flow, excluding any withdraw or artificial input). However, in 2018, following the DD 30/STA, the regional Ecological Flows Resolution n.8/2018. This directive sets out a methodological approach for the determination of the e-flow in order to ensure the maintenance, in watercourses, of the ecological flow to support the achievement of environmental objectives defined in accordance with Directive 2000/60/EC. This directive updated the formula to estimate e-flow as follows:

$$E_{flow} = Q_n(t, f) \times K$$

where $Q_n(t, f)$ is the water flow of the watercourse at its natural condition in the time t as a function of the monthly average rainfall f , and K is a coefficient calculated from the combined assessment of the current river ecological status, the analysis of the pressures affecting the river, and the hydro-morphological and biological parameters. According to the Directive n.8/2018, this new formula, and its hydro-morphological and biological parameters, has to be tested and validated with specific technical-scientific experimentation for the determination of site-specific e-flow values. Since none experimental application of hydraulic-habitat models have been tested in the Sardinian territory, this formula has been identified as the basis for a rapid, homogeneous district-scale e-flow implementation plan, coping with the large heterogeneity of eco-hydraulic conditions of the Sardinian rivers. In particular, the adoption in the formula of a rainfall-related coefficient, of patterns in flow regime at either intra- and inter-annual temporal scales and of correction coefficients considering hydro-morphological and biological targets is expected to allow the development of a more reliable and GES-oriented e-flow assessment, integrated into the WFD process.

CHALLENGES AND LIMITATIONS

E-flow science has evolved substantially in the last decades, with a growing number of experts involved to develop new approaches and methods to respond to the numerous challenges that the implementations of the e-flow policy triggers (Acreman, 2016). However, despite the increasing number of published e-flow related studies, approaches, models, methods, and experimental applications to numerous locations, remain a global lack of achievement of appropriate e-flow assessment policy, mainly due to the conflicts arising between the preservation of the riverine environment and the management and exploitation of water resource for human needs (Le Quesne *et al.*, 2010).

In Europe, considerable progress has been made on the application of the e-flow through the implementation of the Water Framework Directive (European Commission, 2015). The CIS Guidance Document No. 31 provided an important and useful tool for MSs to refine e-flow targets by developing new methods, spanning from relatively simple hydrologic to the highly sophisticated ones. However, significant challenges remain to achieve the ambitious objectives of the WFD, especially with regard to the e-flow assessment. Some of these challenges revolve around the integration of macro-scale considerations into regional and basin-scale integrated water management plans. In a context of changing society,

increasing population and changing climate, the water flow governance has to be adapted to the territorial specificities, in terms of regulatory and institutional frameworks, cultural practices, climatic, geographical and economic conditions.

In Italy, the e-flow matter has been faced in a more concrete way only in recent years. The introduction of the DD 30 / STA in 2018 imposed to all the District Authorities a substantial change in the water management policies, in terms of the amount of outflow released downstream dams and weirs and the release of new water withdrawal concessions. This process led to move from a merely water management oriented MVF concept to another one oriented primarily at preserving the river ecosystems and maintain them in a Good Environmental Status. A more detailed approach is needed, as suggested by the DD 30/STA, to update the already available methods with new ones. A spatial downscaling process of e-flow assessment will require new quantitative and qualitative approaches involving a multidisciplinary panel of experts (e.g., engineers, hydrologists, hydraulic modellers, ecologists and socio-economists) but also a large effort to test, by an accurate monitoring plan, the reliability and efficacy of the estimated e-flow values in the field. Ideally, the process should become so accurate and reliable to allow a feedback monitoring approach, by which corrections to the e-flow will be adopted pending the availability of early warning indicators of environmental change. This approach, by cascade, will allow the design and operability of management measures able to correct any gap from the expected GES. This process, again, will need an accurate implementation of e-flow values and monitoring of its efficacy at the different spatial scales, from the regional to the basin one. This will require a huge effort in ameliorating the knowledge of biological and ecological processes sustaining the GES at the different spatial scales, which will require more and more commitments to either basic or applied research.

This, in our view, will hold true especially for the case of Sardinia, where the management of water resources is heavily dependent on the socio-economic and climate contexts. In a territory that has been suffering for the past ten years one of the most critical water scarcity conditions, numerous technical and logistical challenges will presumably arise. For example, the necessity of providing the needed water for agriculture, industrial or human usages insight of critical periods will likely push the authorities to never allow the release of a proper e-flow. The need of different approaches to be adopted for very different rivers arises if we consider the plausible difficulties in establishing an e-flow value for intermittent or even ephemeral rivers (as the majority of those encountered in Sardinia) when compared with the

perennial ones (Theodoropoulos *et al.*, 2019). A critical issue for the application of e-flow, wherever defined and quantified, remains - peculiarly for the Sardinian territory - the limited infrastructural tools to manage waters' release from dams built in a time when e-flow was not considered at all and, therefore, which are not equipped, yet, with the technology able to operate in a reasonable time the needed water release in response to a change or decline in river ecosystem ecological integrity. Arguably, in the future, a scientifically grounded implementation of water management infrastructures embodying the e-flow concept will be needed in order to address also the potential societal implication of water management, especially where this will generate conflicts between economic and ecological sustainability targets.

In this context, hydraulic-habitat models can provide ecologically important data to calibrate hydrological methods and update e-flow release at different spatial and time scale within the Italian territory. In Italy, micro-habitat approaches have been used mostly to correct minimum vital flow adopted in the River Basin Management Plans. These methodologies tailored e-flow assessment at the site-specific scale, mostly downstream dams and hydropower stations, for only a few fish species and their vital stages. This approach can be useful when there is the necessity of focusing on one endangered species or when dealing with a specific e-flow release situation. Nevertheless, due to their dependence on hydrological models, they are unreliable for low flow and non-flow periods. These limitations make this approach not well suitable for the definition of a regional or basin-scale e-flow assessment, especially in a water-scarce region such as Sardinia. Differently, the application of meso-scale methodologies, in particular the MesoHABSIM method, results to be more suitable to the Italian territory as it can be adequately integrated into a multi-criteria analysis framework allowing the calculation of e-flow criteria from site-specific to the regional and basin-scale (Veza *et al.*, 2014; Parasiewicz *et al.*, 2019). Furthermore, using deductive models, based on conditional habitat suitability criteria derived from expert knowledge and literature-based information, MesoHABSIM model can provide general information about habitat suitability even with a small amount of field data. Another important benefit of this approach, especially in a heterogeneous territory such as Italy, is the applicability of this model to different hydro-morphological river types, allowing to describing complex habitat dynamics also in temporary rivers (Acuña *et al.*, 2019) or where characteristics of the riverbed do not allow the use of hydraulic simulation models (Vassoney *et al.*, 2019). In conclusion, we suggest that the meso-habitat approach result particularly appropriate for modelling and evaluating the integrity of

ivers' habitats within the Italian territory, with the aims of defining the regional and basin e-flow assessment. It could be also used in monitoring e-flow release from catchments and dams and rivers requalification projects, as well as evaluating the impact of hydro-morphological pressure over fish fauna of watercourses and conserving particular protected aquatic species.

It is also worth to notice that the MesoHABSIM method uses an open-source software, which is reliable and traceable, and it expresses a judgement, through the habitat integrity index, which is divided into five classes, as for other indicators required by the European legislation. For the Italian territory, the set of models available for the MesoHABSIM methodology includes 24 fish species (and relative vital stages), typical of the Italian hydrographic system (SimStream software, referred to in MLG ISPRA 154/2017). However, this method has been applied mostly on northern regions, in order to further developed and improved the integration of this method for e-flow assessment within the Italian territory, is essential to conduct further field studies at local and regional scale to calibrate and validate habitat suitability index in different contexts and for different species. In particular, in the Sardinian region, insight of the high climate change-driven flow alterations predicted for the future scenario, the best science-based information of species response to habitat limitation will be required. We suggest that MesoHABSIM method should be implemented together with the validation of the recently proposed formula to obtain a solid and reliable e-flow assessment methodology. Today, more than ever, human actions in river ecosystems have become one of the primary contributions to the decline of freshwater habitats and species (Postel and Richter, 2003). Worldwide, maintaining ecosystem functions and services at current levels in a warmer climate and under changing socio-economic conditions is a major challenge for water resources managers. Reducing pressures on water quality and maintenance of natural flow regimes are two of the main management actions that can help to ensure habitats conservation, at the same time favouring species resilience to flow alterations (Dudgeon *et al.*, 2006). Thus, we further conclude that the definition of handling and reliable e-flow assessment methods embedding the expected consequences of natural and anthropogenic disturbance with the need of nature conservation is to be considered a basic priority of any water management plan.

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