Hydro-power production and fish habitat suitability: Assessing impact and effectiveness of ecological flows at regional scale

Hydro-Power Production and Fish Habitat Suitability: Assessing Impact and Effectiveness of Ecological Flows at Regional Scale

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Abstract

Anthropogenic activities along streams and rivers may be of major concern for fluvial ecosystems, e.g. abstraction and impoundment of surface water resources may profoundly alter natural streamflow regimes. An established approach aimed at preserving the behavior and distribution of fluvial species relies on the definition of ecological flows (e-flows) downstream of dams and diversion structures. E-flow prescriptions are usually set by basin authorities at regional scale, often without a proper assessment of their impact and effectiveness. On the contrary, we argue that e-flows should be identified on the basis of (i) regional and (ii) quantitative assessments. We focus on central Italy and evaluate the effects on habitat suitability of two near-threatened fish species (i.e. Barbel and Chub) and an existing hydropower network when shifting from the current time-invariant e-flow policy to a tighter and seasonally-varying soon-to-be-enforced one. Our example clearly shows that: (*a*) quantitative regional scale assessments are viable even when streamflow observations are entirely missing at study sites; (*b*) aprioristic e-flows policies may impose releases that exceed natural streamflows for significantly long time intervals (weeks, or months); (*c*) unduly tightening e-flow policies may heavily impact regional hydro-power productivity (15% and 42% losses on annual and seasonal basis, respectively), yet resulting in

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either marginal or negligible improvements of fluvial ecosystem.

Keywords: water resources management, hydro-electric production, e-flow, PHABSIM, Barbel, Chub

1. Introduction

Hydro-power is the worldwide leading renewable source for electricity production, with a capacity increase of more than 30% between 2007 and 2015 (WCE, 2016). Despite its economic relevance, several environmental concerns are associated with hydro-power production. Indeed, hydro-power plants are known to severely affect flows downstream of abstraction points over limited time periods (Person et al., 2014; Vigano et al., 2016). Under these conditions, the river natural flow regime (NFR), defined as the river signature in terms of flow magnitude, frequency, timing, duration and rate of change (Poff et al., 1997), is no longer guaranteed. NFR is a key driver of ecological and geomorphological processes (Bunn and Arthington, 2002; Allan and Castillo, 2007; Young et al., 2011; Ceola et al., 2014; Ceola and Pugliese, 2014), and thus, any flow disturbance may significantly affect and alter fluvial ecosystem dynamics (see e.g. Poff and Allan, 1995; Bradford et al., 2011; Ceola et al., 2013; Vanzo et al., 2016).

As recognized by several water protection policies, e.g. the European Water Framework Directive (EU, 2000), the water laws in Africa (1998) and China (2002), the Australian Environment Act (1999), ecological flows (e-flows) are commonly defined in order to sustain freshwater ecosystems and the river ecological status.

The concept of e-flows has existed for more than 40 years (Tharme, 2003; Acreman and Dunbar, 2004; Snelder et al., 2014) and it is widely applied throughout the globe, though presenting significant differences across site-specific applications. E-flows can be generally grouped under two main categories, based on the methodology they rely upon.

On one side, one may find the classical hydrologically-based methods (e.g. minimum flow, flow percentiles, see Tharme, 2003). This category embeds easily-applicable and simple approaches that can be employed across large areas, but do not focus on any ecological variable, being thus somehow in contrast with the definition of e-flows. Quite frequently, e-flows defined within this category are described by constant flows during the year, thus disregarding the inter-annual flow variability that controls species life stages (Stromberg et al., 2010).

On the other side, there are the so-called micro-scale and meso-scale physical habitat modeling methods, based on in-situ and experimental measurements to analyze optimal environmental conditions for target species. Several habitat suitability models are described in the scientific literature, see e.g. PHABSIM (Bovee, 1982), RHYHABSIM (Jowett, 2010), RIVER2D (Steffler and Blackburn, 2002), WHYSWESS (Yi et al., 2010) and CASiMIR (Munoz-Mas et al., 2012) at the micro-scale, and MesoHABSIM (Parasiewicz, 2001), MesoCASiMIR (Schneider et al., 2001) and RHM (Maddock et al., 2001) at the mesoscale. Among these PHABSIM and MesoHABSIM are probably the most widely used and representative ones.

While MesoHABSIM refers to specific hydromorphologic units (i.e. HMUs Bovee et al., 1998b; Parasiewicz, 2001) and performs a 2D analysis based on detailed input data, PHABSIM analyzes environmental conditions based on 1D hydraulic variables through the definition of habitat suitability curves within the Instream Flow Incremental Methodology (IFIM, Bovee et al., 1998a) framework. The ecological variables are key elements of this physical habitat approach, which considers specific target species and requires detailed and site-specific data. In case of limited data availability, expert knowledge is a common practice. The IFIM context allows PHABSIM to identify improvements in habitat state from different flow regimes, thus making predictions and supporting the negotiation of suitable water delivery scenarios (Booker and Dunbar, 2004).

According to recent e-flow prescriptions, all flow components, from base flow to flood regime, are to be included as operational targets for a sustainable water resources management (EU, 2000). In this respect, Flow Duration Curves (FDCs), a classical hydrological tool that embeds details on streamflow regime, which is widely used for flood control, water quality management and hydro-power purposes, represent a meaningful tool for analyzing several ecohydrological issues, such as e.g. the effects of e-flow scenarios on riverine habitat (Vogel and Fennessey, 1995).

The scientific literature collects a plethora of studies investigating the potential impacts of different flow releases downstream of hydro-power plants on energy production and riverine ecosystems (see e.g. Snelder et al., 2014; Person et al., 2014; Hirsch et al., 2014; Ayllon et al., 2014; Yin et al., 2014; Vigano et al., 2016; Yi et al., 2017), though only a few of them has employed FDCs, particularly at a regional scale (CAPRA et al., 1995; Ayllon et al., 2012; Pragana et al., 2017). In addition, quantitative assessments of e-flows impacts are considered to be unviable when the availability of hydrological data is limited (i.e. a frequent condition even for high-income countries). To overcome this issue, FDCs and Top-kriging are powerful hydrological tools that can be used to reconstruct streamflow regimes at ungauged sites (Pugliese et al., 2014; Farmer, 2016), thus enabling one to evaluate the hydro-power production and ecological status across large catchments and regions (see e.g. Popescu et al., 2012; Cuya et al., 2013).

In this study we quantitatively analyze the effects of alternative e-flow prescriptions on hydro-power production and fish habitat suitability for two Italian river basins by employing FDCs and Top-kriging techniques. In particular, we perform a regional-scale analysis by considering two different e-flow policies (i.e. current policy and a tighter future one, see Section 2.4) identified on the basis of empirical methods and set a-priori by the local Regional Authority without any former insight on possible effects on river biota. We demonstrate how to cope with a limited availability of streamflow data at locations of interest, thus supporting a quantitative assessment of the impacts and the effectiveness of e-flows at regional scale.

Our analysis focuses on Barbel (*Barbus barbus*) and Chub (*Leuciscus cephalus*) species, which are considered to be near-threatened in Italy (Zerunian, 2007) and require high protection level at regional scale. Barbel and Chub spawning occurs from April to June and their habitat requirements are well known (Rambaldi et al., 1997; Bicchi et al., 2006). While it is straightforward to anticipate a decrease in hydro-power production for higher e-flow releases (i.e. future prescriptions), ecological effects on the considered fish species cannot be easily predicted, nor were ever assessed for the study area by local authorities in charge of defining e-flow policies. To this aim, we employ different habitat suitability criteria to examine whether a loss or a gain in habitat suitability is associated with a modification in the e-flow releases (PTA, 2010). For assessing the ecological effect, we employ the classical PHABSIM approach and we elaborate an analytic approach based on FDCs and on a simpler hydraulic model, hereafter labeled as Habitat Suitability Duration Curve (HSDC), which can be easily applied across hydrologically and ecologically homogeneous large catchments and regions and particularly in any ungauged site.

2. Study Area: Data and e-flow Scenarios

The quantitative assessment of the effectiveness of two alternative e-flow scenarios and their impact on hydro-power production and fish habitat suitability is applied to hydro-power plants located within the Potenza and Chienti river basins, in the Marche administrative district in Central Italy (Figure 1 and Table 1).

2.1. River basins description

The Potenza and Chienti river basins, with a catchment area of 640 and 1070 km^2, respectively, flow northeasterly from the Apennines to the Adriatic Sea. The elevation ranges between 40 and 1400 m asl (above sea level) for Potenza, and 20 and 2000 m asl for Chienti. In these two catchments, agricultural areas (59%), forests and semi-natural areas (38%) share the majority of land covers, while human settlements and impervious areas are around 3% (EEA, 2007). Two major geological units dominate the study area from a hydro-geological perspective. The head-water catchments are dominated by fractured carbonate limestones, with frequently emerging subsurface water (see Figure 1), while the downstream area mainly presents sandstones and marble calcarenites. The study area shows a maritime streamflow regime (see Castellarin et al., 2004b,a), whose typical hydrologic year is characterized by a maximum monthly discharge during winter and minimum during summer. The climate of this area is conditioned by the close presence of both the Adriatic Sea and the Apennines, with average annual temperatures ranging from 8°C to 15°C. Mean Annual Precipitation (MAP) values evaluated at catchment scale are reported in Table 2 for the study stream gauges.

2.2. Hydro-Power Plants in the Study Area

We consider 14 hydro-power plants (see Table 1) operated by the energy multinational power company ENEL Group Ltd. and located within the Potenza and Chienti river basins (see Figure 1). In particular, as illustrated in Table 1, we consider three storage (DAM) and eleven run-of-the-river (ROR) hydro-power plants that share a common feature, i.e. power-houses are located downstream the corresponding dams or barrages and off-line relative to the river course. Hence, the water used for hydro-power production needs to be diverted and is returned to the river only downstream the abstraction point. As a consequence, the operation of the hydro-power plant alters the natural streamflow regime within the river stretch between the abstraction point and the power-plant outlet, which in several cases is a few kilometers long.

Several characteristics of the study dams/barrages and hydro-power plants illustrated in Table 1 are accessible from ENEL Group Ltd. technical reports and publications (ENEL, 1992; Galeati, 2013a,b). Observed data on the natural streamflow regime (NFR), instead, is sparse or completely missing for barraged and dammed river cross-sections considered in our study. We therefore estimate the natural streamflow regime at abstraction points by referring to the streamflow data described in Section 2.3 and by applying a geostatistical procedure that interpolates empirical flow-duration curves of daily streamflow (FDCs) along the stream-network (see Pugliese et al., 2014; Farmer, 2016).

Measurements of stream network hydraulic properties (i.e., river width w, water depth d, flow velocity v, and discharge Q) are available only for a subset (5 out of 14) of the considered hydro-power sites (see red filled symbols in Figure 1). These features are recorded downstream the hydro-power plants in correspondence of four distinct cross-sections within a nearly 100 m long river reach.

2.3. Hydrologic Data

Natural daily streamflow series are available for the study region at 17 stream gauges belonging to the former National Hydrographic Service of Italy (SIMN). Observed flow series span over the time period 1920-2000, with an observation period ranging from 5 to 40 years (average record length: 18 years). Table 2 reports drainage area and mean annual precipitation (MAP) of catchments upstream each stream gauge as well as some statistics of daily streamflow series (mean annual flow, MAF, minimum and maximum flows, 75%, 50% and 25% exceeded flow values). Empirical MAP values, relative to each of the 17 catchments, are estimated using data collected from a rather dense rain gauge network (i.e. 1 rain gauge per $\sim 50\text{km}^2$ on average) during the same time interval of daily streamflow records. Our daily streamflow dataset includes only complete years; missing daily streamflow records have been linearly interpolated for time intervals shorter than one week, while for longer time-intervals of missing observations we have discarded the entire year (see Castellarin et al., 2004a).

2.4. Regional River Regulation: e-flow Prescriptions

Two alternative e-flow scenarios prescribed by the Marche administrative district are considered in our study: the current time-invariant experimental e-flow release and the soon-to-be-enforced time-variant e-flow release based on Water Protection Plan prescriptions (PTA, 2010), hereafter labeled as PILOT and WPP, respectively. PILOT e-flows will be authorized until Dec. 31, 2019, while from Jan. 1, 2020 the Regional Authority is going to enforce WPP e-flows.

The PILOT e-flow release results from an experimental program agreed among the Regional administration and ENEL Group Ltd., which allowed a reduced e-flow release compared to WPP. This scenario refers to the most common practice in reservoir management, namely to consider a constant e-flow value across the whole year, regardless of the natural intra-annual flow variability. Activities aimed at monitoring the environmental effect of e-flows downstream of dams and barrages are still undergoing and at this stage data are not currently available.

The WPP e-flow release, by recalling the EU Water Framework Directive (EU, 2000), includes a temporal regulation of e-flows, thus reproducing natural streamflow regimes of river reaches downstream the abstraction points, which supposedly enhances ecosystem conservation. WPP e-flow releases (Q_{WPP} [m^3/s]) are computed from the following empirical expression:

$$Q_{WPP} = k \cdot MAF \cdot B \cdot E \cdot \max\{N, I_f\} \cdot G \cdot T, \qquad (1)$$

where k [-] is an empirical parameter ranging from 0.05 to 0.1; MAF [m^3/s] is the mean annual flow; B [-] is a parameter that takes into account the hydrogeologic features of the study area ($B = 2$ in upstream river reaches mainly consisting of fractured carbonate limestones, $B = 1$ in downstream areas presenting sandstones and marble calcarenites, see Section 2.1 and Figure 1); E [-] represents the river ecological status (ranging from 1 to 1.4 for very good or very poor conditions, respectively); N [-] represents the degree of wilderness of the area around the river reach (ranging from 1.3 for protected areas, i.e. natural parks, to 1 for urban and rural areas); I_f [-] represents the river functionality (ranging from 1 to 1.2 for very good to very poor river functionality, respectively); G [-] is geomorphologic parameter related to hydraulic and morphological characteristics of the river reach (ranging from 0.9 to 1.1); T [-] is the temporal factor identifying different flow seasons in a year. In this context, the term season refers to one of the four time intervals identified in the Water Protection Plan of the Marche administrative district, namely: November - January (total duration: 92 days, T=1.3), February - March (total duration: 59 days, T=1.5), April - June (total duration: 91 days, T=1.3), July - October (total duration: 123 days, T=1.0). Table 3 reports PILOT and WPP e-flow releases for the 5 hydro-power sites (see red filled symbols in Figure 1) for which both hydro-power production and habitat suitability are assessed.

2.5. Fish Species for Habitat Suitability Assessment

The study fish species, Barbel (*Barbus barbus*) and Chub (*Leuciscus cephalus*), belong to the *Cyprinidae* family and are typical in the study area. Three different life stages are examined, namely juvenile, spawning and adult. Given that the spawning season for both species is between April and June, we consider juvenile fish as those small fish, hatched from eggs spawned in the same year, whereas the adult stage represents individuals older than 1 year. By using the WPP e-flow seasonality described in Section 2.4, we associate each life stage with a specific e-flow season as follows: juvenile is associated with July-October, spawning with April-June, and adult with the whole year, from January to December.

3. Methods

3.1. Estimation of Natural Flow Regime at Hydro-Power Sites

In order to reconstruct the unknown natural inflows to the considered hydro-power sites, we employ observed streamflow data and apply a geostatistical technique. The procedure, which was originally proposed and applied by Pugliese et al. (2014) to the same study region, adapts the Topological-kriging (or Top-kriging, see Skøien et al., 2006), a block-kriging with variable support area coinciding with the catchment watershed (see Skoien et al., 2014), and enables the user to predict FDCs in ungauged basins by linearly weighting empirical curves constructed at available stream gauges. Kriging weights used in the linear weighting scheme take catchment size and nesting structure of the stream network into account. Using the Top-kriging adaptation by Pugliese et al. (2014), we predict long-term FDCs of daily streamflows at all 14 abstraction points of interest by interpolating empirical period-of-record (i.e. constructed on the basis of all available daily streamflow observations) FDCs. According to the regional river regulation illustrated in Section 2.4, minimum streamflow requirements have to be identified on a seasonal basis (the term season in this context coincides with one of the four time intervals specified in the regional regulation). Therefore, together with the long-term annual FDCs that describe the natural streamflow regime we also predict the long-term seasonal FDCs for the four periods of interest, as defined in the Water Protection Plan of our study area (PTA, 2010). The prediction of seasonal FDCs represents a novel application of the procedure developed by Pugliese et al. (2014). The validation is based on the same leave-one-out cross-validation scheme used in Pugliese et al. (2014) for assessing the accuracy of predicted long-term yearly FDCs. The results prove the suitability of the selected approach since the accuracy of predicted seasonal FDCs results to be comparable with the accuracy of predicted yearly curves and certainly acceptable for the scopes of the present analysis (i.e. overall Nash-Sutcliffe Efficiency computed for predicted log-flows in cross-validation varies between 0.91 and 0.94, and is equal to 0.96 for yearly curves, see also Pugliese et al., 2014).

3.2. Computation of Hydro-Power Production

The present section summarizes the different steps required by the computation of annual and seasonal hydro-power productions, distinguishing between run-of-the-river and storage power-plants (see Table 1). It is worth emphasizing here that our study neglects the interaction between power-plants located along the same stream (i.e. we do not consider the possible effects of streamflow regulation upstream the considered power-plant, that is we always adopt the NFR as inflow condition). This simplifying working hypothesis is correct when only run-of-the-river power plants exist upstream any given river dam/barrage, but is certainly associated with an approximation when artificial reservoirs with significant storage capacity exist upstream the location of interest. Nevertheless, the hypothesis seems viable in our study given the limited number of hydro-power plants located downstream the study dams (see Figure 1).

Concerning the eleven run-of-the-river hydro-power plants listed in Table 1, the assessment of hydro-power production under various constraints on e-flow release is straightforward when annual and seasonal FDCs relative to the NFR are available for the barraged river cross-sections (see e.g. Vogel and Fennessey, 1995). Therefore, seasonal FDCs of daily streamflow are predicted at all hydro-power plants via Top-kriging (see Section 3.1). Figure 2a provides a graphical example for Montefranco hydro-power plant (see

Table 1), which clearly shows that for roughly 10% of the season duration the e-flow value is higher than natural streamflows.

Concerning the three storage power plants (see Table 1), since they can store and manage inflow water volumes, the assessment of their hydro-electric productivity cannot be based solely on FDCs representative of the NFR, but it requires continuous, and possibly multi-annual, daily streamflow series and a conceptualization of reservoir management and functioning. Figure 2b,c illustrates reconstructed inflows, together with outflows relative to an arbitrarily selected year at Polverina dam (see Table 1). In particular, the figure reports the reconstructed daily inflows (blue line) and the seasonally variable e-flow releases (red line, WPP scenario), which are used as inputs, and the daily series of simulated outflows downstream the reservoir (black line).

The computation of yearly and seasonal hydro-power production for e-flow scenarios PILOT and WPP for run-of-the-river and storage power plants relies also on (*i*) hydro-power plant characteristics (e.g. minimum and maximum exploitable discharge, see Table 1) and (*ii*) seasonal e-flow values for the considered scenario (i.e. PILOT and WPP).

A detailed description of the computational steps for the evaluation of hydro-power production for any given site and season is reported in the Appendix.

3.3. Habitat Suitability Assessment

The potential impact of PILOT and WPP e-flow scenarios on Barbel (*Barbus barbus*) and Chub (*Leuciscus cephalus*) suitability to the physical habitat within the considered river basins is assessed by coupling the outflows from the hydro-power sites with habitat suitability criteria (HSC). HSC describe species habitat preferences, ranging from 0 (unsuitable) to 1 (most suitable), by accounting for the effects of hydro-morphological variables (i.e. water depth, HSC_d, flow velocity, HSC_v, and river substrate, HSC_s) on species distribution. Given that habitat suitability of target species changes during a lifetime, HSC are generally defined and associated with different life stages (see Section 2.5). The formulation of HSC should be generally based on field investigations, providing detailed ecological information of the target species from the study area. However, due to the difficulty of collecting sufficient data on species habitat, these data are not always available, as in the present study. When local information are missing, expert knowledge is a significant basis and multiple HSC, showing similar hydrological, morphological and ecological properties to those characterizing the study area, should be considered in order to test for consistency and account for the effects of different formulations. Here we consider two alternative HSC provided by Bicchi et al. (2006) and Rambaldi et al. (1997), both referring to the Central Apennines in Italy, and therefore suitable for our study area (see Figure S1). Habitat suitability values are then combined together by computing a composite habitat suitability (HS), as the product of $HSC_d \cdot HSC_v \cdot HSC_s$. It is worth highlighting here that, since the formulation proposed by Bicchi et al. (2006) neglects the effect of river substrate (i.e. by assuming a constant maximum preference regardless the substrate characteristics, HSC_s=1), for consistency we implement the same condition in the HSC from Rambaldi et al. (1997).

We employ two different methodologies to quantify a synthetic indicator of the habitat quality (i.e. Suitable Area Index, SAI [m^2/m]) associated with the different release scenarios illustrated in Section 2.4: (i) the classical PHABSIM procedure and (ii) an analytic method based on FDCs, hereafter labeled Habitat Suitability Duration Curve (HSDC). The habitat quality indicator SAI is then estimated for each hydro-power site (i.e. a total of 5 sites, see red filled symbols in Figure 1), each fish species (i.e. 2 species, Barbel and Chub), each life stage (i.e. 3 life-stages: juvenile; spawning; adult), each HSC (2, i.e. Rambaldi et al., 1997; Bicchi et al., 2006) and each flow regime (3, i.e. NFR, PILOT, WPP).

Due to the limited hydro-ecologic data availability, we adopt PHABSIM although more recent alternatives (see e.g. PHABSIM, RHYHABSIM, RIVER2D, WHYSWESS, CASiMIR, MesoHABSIM, MesoCASiMIR, RHM) are consolidated across the scientific literature. Furthermore, when analyzing e-flows at the micro-habitat level within an IFIM context (Bovee et al., 1998a), different flow scenarios and habitat suitability models are to be considered in order to assess the ecological effects and then negotiate e-flows to be prescribed. In our case study, given that e-flow scenarios prescribed by the Regional Authority were determined a-priori without performing any assessment of the effects on river biota, a sort of backward application of IFIM is performed (i.e. from prescribed e-flows, the current and the soon-to-be-enforced, to ecological and hydro-power production effects).

3.3.1. Estimation of Suitability Area Index from PHABSIM and HSDC

PHABSIM divides river cross-sections into several vertical elements, or grid cells, each one characterized by given flow velocity and water depth for a given streamflow value. More specifically, flow velocity and water depth are derived from 4 distinct cross-sections within a nearly 100 m long river reach in correspondence of each hydro-power site. Given that PHABSIM hydraulic modeling can be sometimes controversial (Shirvell, 1986; Ghanem et al., 1996; Dunbar et al., 1998), we calibrated the hydraulic model on the basis of concurrent observations of discharge and water level through HEC-RAS simulations (Brunner, 2016), which we then use as inputs to PHABSIM (see e.g. Nikghalb et al., 2016). The composite habitat suitability is computed for every grid cell and the Weighted Usable Area (WUA, i.e. the available habitat area for the target species within a river reach [m^2/m]) is then evaluated as a weighted sum of composite suitability and cell area for each flow scenario (NFR, PILOT and WPP). We estimate WUA values for a given set of discharges (i.e. streamflow values sampled from FDCs and associated with 16 durations within the range 0.005-0.995) and then combine these WUA values to quantify SAI as the integral of the WUA-duration curve:

$$SAI = \int_{D=0}^{D=1} WUA(D)dD \qquad (2)$$

where $WUA(D)$ is the Weighted Usable Area associated with a duration D, ranging from 0 to 1.

Concerning the HSDC approach, the composite habitat suitability HS is based on FDCs and on a simpler hydraulic procedure and it is evaluated for the entire river cross-section (i.e. without dividing the cross-section into computational grid cells). By following the procedure proposed by Vogel and Fennessey (1995), we combine the relation between HS and discharge (Figure 3b) with the predicted FDC (Figure 3a) and define the HSDC as the relationship between the composite habitat suitability and the duration or exceedence probability of the discharge value associated with that HS (Figure 3c). We then compute the Habitat Suitability Index (HSI) as the integral of the habitat suitability duration curve (shaded areas in Figure 3c):

$$HSI = \int_{D=0}^{D=1} HSDC(D)dD \qquad (3)$$

where D represents the duration associated with each composite habitat suitability value.

Finally, the Suitable Area Index (SAI) is defined by simply multiplying HSI and the wetted river width, w, from the equivalent rectangular cross-section. A detailed description of the 3-step procedure for the computation of HS as a function of discharge values is reported in the Appendix.

4. Results

4.1. Computation of Hydro-Power Production

Figure 4 shows through a box-plot representation the distribution of relative differences of hydro-power production for the set of 14 plants belonging to Potenza and Chienti river basins (i.e. run-of-the-river and storage power plants) for each reference period (i.e. the entire year and four sub-periods, namely Nov.-Jan.; Feb.-Mar., Apr.-Jun. and Jul.-Oct.). Each value is computed as the difference between the hydro-power production associated with PILOT (i.e. current) e-flow releases and with releases that are compliant with the regional water protection plan (WPP e-flow releases, soon-to-be-enforced), divided by the former.

All computations of hydro-power production refer to daily inflow series (storage hydro-power plants) or period-of-record yearly or seasonal FDCs (run-of-the-river hydro-power plants) reconstructed for a multiannual time span, roughly extending between 1920 and 2000. Hence, the resulting hydro-power production should be regarded as a long-term prediction of the hydro-power potential for any given study plant. Each prediction is necessarily associated with some degree of uncertainty, resulting from all simplifying assumptions adopted in our study. It is worth noting, though, that we are mainly interested in comparing different estimates of long-term hydro-power productivity rather than assessing their absolute values, which mitigates the impact of simplifying assumptions. One striking feature of Figure 4 is that values are all positive, meaning that the enforcement of WPP releases will result in losses of hydro-power production. This result was expected as the current prescriptions on e-flows are less stringent than WPP ones (see Table 3). Another feature of Figure 4 is the dependence of the reduction of hydro-power production on the considered time-period. Average relative differences (in %) are equal to 14.7, 13.7, 5.8, 10.2 and 42.8 for Year, Nov.-Jan., Feb.-Mar., Apr.-Jun. and Jul.-Oct. reference time-intervals, in this order.

Production losses are significant, or extremely significant, over the study area. More than 50% of the plants show a production loss larger than 10%

on an annual scale, or during the time period between November and January, which is one of the two wet seasons for the study catchments, the other spanning between March and early June. Losses become extremely important between July and October, with 50% of the plants showing losses larger than 44% and in excess of 58% in 25% of the cases. This result is associated with WPP e-flow prescriptions during the summer season (i.e. between July and October), which are particularly severe. During several weeks of the simulation time interval 1920-2000, WPP e-flows resulted to be larger than natural streamflows for the majority of study catchments. In particular, relative to PILOT e-flow releases and on the basis of the computations performed in our study, the enforcement of WPP releases is likely to increase the duration of plant-shutdown periods by 61 and 132 days per year on average for the Potenza and Chienti hydro-power plants, respectively (i.e. c.a. two and four months, respectively), which is an extremely significant amount of time.

The marked variability of production losses between different hydro-power plants (e.g. between 7 and 29%, or 20 and 82% for Year and Jul.-Oct., respectively) results from the extremely high variability of a few empirical parameters used by the expression adopted in the regional WPP for computing the e-flow. A noteworthy example is the parameter B, which is normally equal to 1 and is set to 2 for all basins that are entirely within with a specific geological unit that mainly consists of fractured carbonate limestones (see Section 2.1).

4.2. Habitat Suitability Assessment

Suitable Area Index (SAI) values computed for the 5 hydro-power sites are shown in Figures 5 and 6 for *Barbus barbus* and *Leuciscus cephalus*, respectively. In order to examine the regionalized (i.e. average) behavior of the study area, characterized by comparable hydro-geomorphic properties, we opted for grouping together the considered river cross-sections. The outcomes are presented in terms of mean ± standard deviation for the 2 alternative methodologies, namely PHABSIM and HSDC, and the 2 habitat suitability criteria (Bicchi et al., 2006; Rambaldi et al., 1997).

As expected, regionalized SAI values computed from the HSDC method are generally characterized by a higher variability compared to the PHABSIM ones. Indeed, while the application of PHABSIM generally results in at least some (a few) elementary cells of each river cross-section presenting suitable conditions for fish, the HSDC approach, which assumes an equivalent rectangular cross-section under uniform flow conditions, may bring forth either totally unsuitable or suitable states, thus showing a larger SAI range.

The application of the habitat suitability criteria proposed by Bicchi et al. (2006) shows a fairly good agreement between SAI values from PHABSIM and HSDC for both fish species (Figure 5a,b,c and 6a,b,c). For the adult life stage (Figure 5c and 6c), PHABSIM and HSDC methodologies consistently reveal a preference for the WPP e-flow scenario, whereas both PILOT and WPP e-flow scenarios present similar outcomes for juvenile (Figure 5a and 6a) and spawning (Figure 5b and 6b) life stages. The NFR always presents the lowest SAI values compared to PILOT and WPP e-flow scenarios. This result is likely to be associated with the large range of discharge values (i.e. from $10^{-1}\mathrm{m}^3/\mathrm{s}$ to $10^3\mathrm{m}^3/\mathrm{s}$), whose extreme conditions (i.e. floods and low-flows) are mostly unsuitable for fish. Indeed, habitat suitability is usually assessed for low-flows, thus entirely disregarding high or very high flow conditions (Booker and Dunbar, 2004). Furthermore, the HSDC approach reveals that juvenile (Figure 5a, 6a) and spawning (Figure 5b, 6b) life stages, which prefer low water depths and flow velocities, and thus lower discharges, may experience particularly small (and even negligible) SAI values under NFR. This condition intimately depends on the discharge values associated with the composite habitat suitability, which may lie outside the discharge range gathered from the FDC (see Figure 3). More specifically, when applying HSDC under NFR, negligible or even null composite suitability values can be associated with the majority of discharge values sampled from the FDC. As a consequence, SAI values may result in extremely low or even null figures.

Concerning the application of the habitat suitability criteria proposed by Rambaldi et al. (1997), a satisfactory match between PHABSIM and HSDC approaches on SAI values associated with the different flow regimes is evident only for the adult life stage of both fish species (Figure 5f, 6f). In this case, adult fish reveal an overall preference for NFR conditions, with the lowest values for the PILOT e-flow scenario. Conversely, juvenile (Figure 5d, 6d) and spawning (Figure 5e, 6e) life stages show rather contradictory outcomes with divergent SAI values. Evidently, the linkage among FDCs and the relationship between HS and discharge plays a key role.

Our analysis reveals that the two habitat suitability criteria employed in this study, both referring to Apennines rivers with comparable hydrologic regime and water resource availability, despite some differences in terms of absolute quantities, show a rather consistent trend when comparing the three flow regimes (i.e. NFR, PILOT and WPP) either with the PHABSIM or the HSDC methodology. In particular, given that (*i*) for juvenile and spawning life stages, the two e-flow releases present analogous impacts on habitat quality on the considered fish species (see Figure 5, 6), and (*ii*) the hydro-power production losses are significant within the associated sub-periods (see Figure 4), from a practical and operational perspective our analysis may suggest within the IFIM framework a review of the WPP e-flow releases, as prescribed by PTA (2010), possibly allowing smaller outflows during the aforementioned seasons.

Interestingly, the variability associated with different habitat suitability criteria is reasonably comparable with the overall variability between the proposed methodologies. The analytic HSDC approach, which is based on relatively few and simple hydraulic properties (see also Appendix), can thus constitute a valid alternative to the more complex and data-demanding PHABSIM approach for a fast and rapid identification of potential ecological impacts of different e-flow scenarios at the regional scale. This alternative approach can be successfully applied across hydrologically and ecologically homogeneous river networks, as our case study. Furthermore, to get more reliable results, multiple and possibly site-specific habitat suitability criteria should be considered in future studies.

5. Conclusions

In this paper we perform a quantitative analysis of the effects of alternative e-flow prescriptions at regional scale. In particular, we focus on hydro-power production and fish habitat suitability (Barbel and Chub fish species) across Chienti and Potenza river basins (Italy) referring to the current time-invariant regional e-flow prescription (PILOT) versus a new time-variant regional prescription (WPP), which will be enforced from Jan. 1, 2020. We employ natural and altered flow-duration curves (FDCs) to estimate both hydro-power production and an index of habitat quality (i.e. Suitable Area Index, SAI). The ecological effects are also assessed, for the sake of comparison, through the classical PHABSIM approach. The following conclusions are worth summarizing:

- An evident reduction of hydro-power production shifting from PILOT to WPP e-flow releases emerges without any significant uncertainty. At the annual time-scale, average relative differences are equal to 15%.

Higher losses (43% on average) characterize the July-October time interval.

- In addition, we find that WPP e-flows are frequently greater than the actual surface water availability at various cross-sections within the study river networks, thus causing a significant enhancement of shut-down periods for hydro-power plants located in the upstream part of the study area (i.e. fractured carbonate limestones).

- Given the prescription of a stricter e-flow scenario (i.e. WPP) by the Regional Authority, even though a significant hydro-power production loss is found, a clear outcome does not emerge from the habitat suitability assessment.

- From the ecological perspective, regardless of habitat suitability criteria and the methodology employed for assessing habitat conditions, increasing e-flow releases does not show a clear and consistent improvement of habitat status for Barbel and Chub. In order to get more accurate indications, future studies should preferably consider site-specific habitat suitability criteria or, alternatively, may benefit from adopting multiple (i.e more than one or two) criteria associated with rather homogeneous hydro-geomorphic environments and then refer the average behavior.

- When comparing NFR and e-flow scenarios for juvenile and spawning life stages, our results show a general preference for e-flows rather than natural streamflow conditions. This result was expected since these life stages tend to prefer low-flow conditions, whereas high- or very high-flows are indeed scarcely suitable for them. Outcomes are not as consistent when it comes to adult life stages. Different SAI values emerge due to the interrelation between FDCs and the composite habitat suitability criteria.

- The variability of our results associated with different habitat suitability criteria is comparable with the variability between PHABSIM and HSDC approaches. The HSDC approach proves indeed to be a valuable alternative method for rapidly assessing habitat suitability at the regional scale, when data availability (both hydrological and ecological) is limited and hydrologically and ecologically homogeneous river networks are considered.

Concluding, the proposed research is not intended to substitute site-specific and detailed studies, but rather to provide regional-scale guidance towards the identification of effective and sustainable e-flow policies for the conservation of fluvial ecosystems, when eco-hydrological data availability is limited and streamflow observations are entirely missing at the locations of interest.

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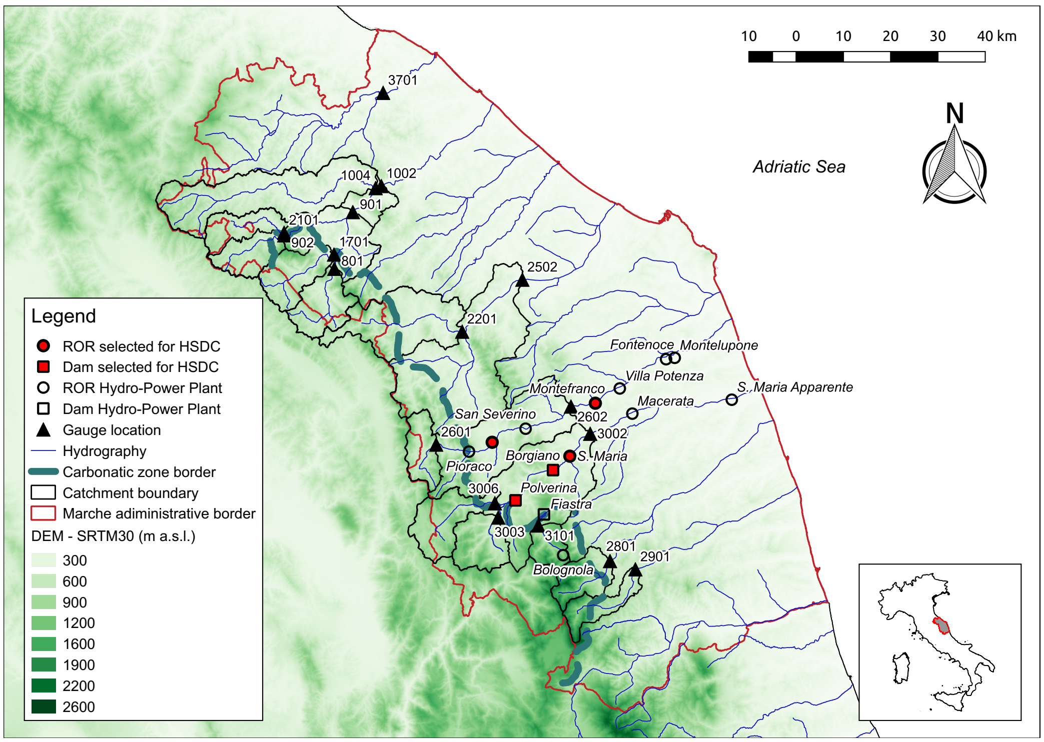

Figure 1: Study area: hydro-power plants considered for assessing hydro-power production (black circles for ROR and black squares for DAM) and fish habitat suitability (red filled symbols); 17 available stream gauges (black triangles) and corresponding upstream catchments (black solid lines) used for the discharge computation at ungauged sites (i.e. hydro-power plants); boundary of the carbonatic zone described in Section 2.1 (dashed thick grey line); Marche Region administrative border (red line).

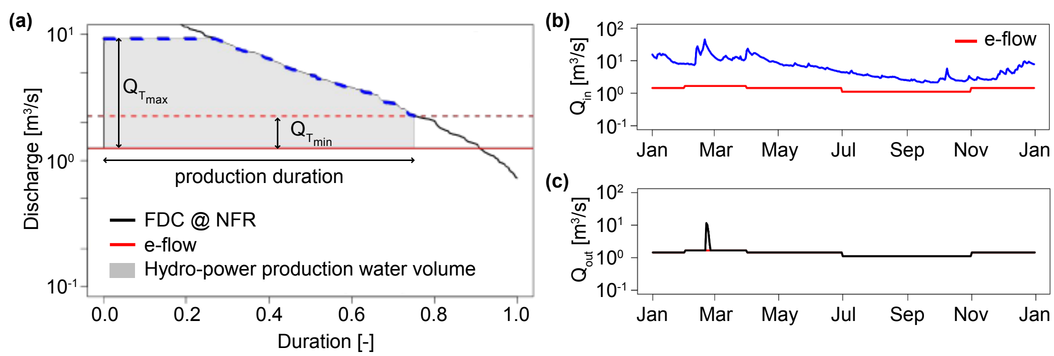

Figure 2: Schematic representation of seasonal hydro-power computation: (a) run-of-the-river power plants (ROR), example of seasonal FDC of daily streamflow estimated for Montefranco via Top-kriging (black solid line), seasonal e-flow (solid red line, current scenario, PILOT), summation of seasonal e-flow and turbine minimum discharge (dotted red line); indication of exploitable discharge (dashed blue line) and water volume (gray shaded area); (b) and (c) storage power plants (DAM), the example refers to Polverina and illustrates for an arbitrarily selected simulation year the reconstructed daily inflows (blue line), seasonal e-flow values (red line, future scenario, WPP), and simulated daily outflows (black line).

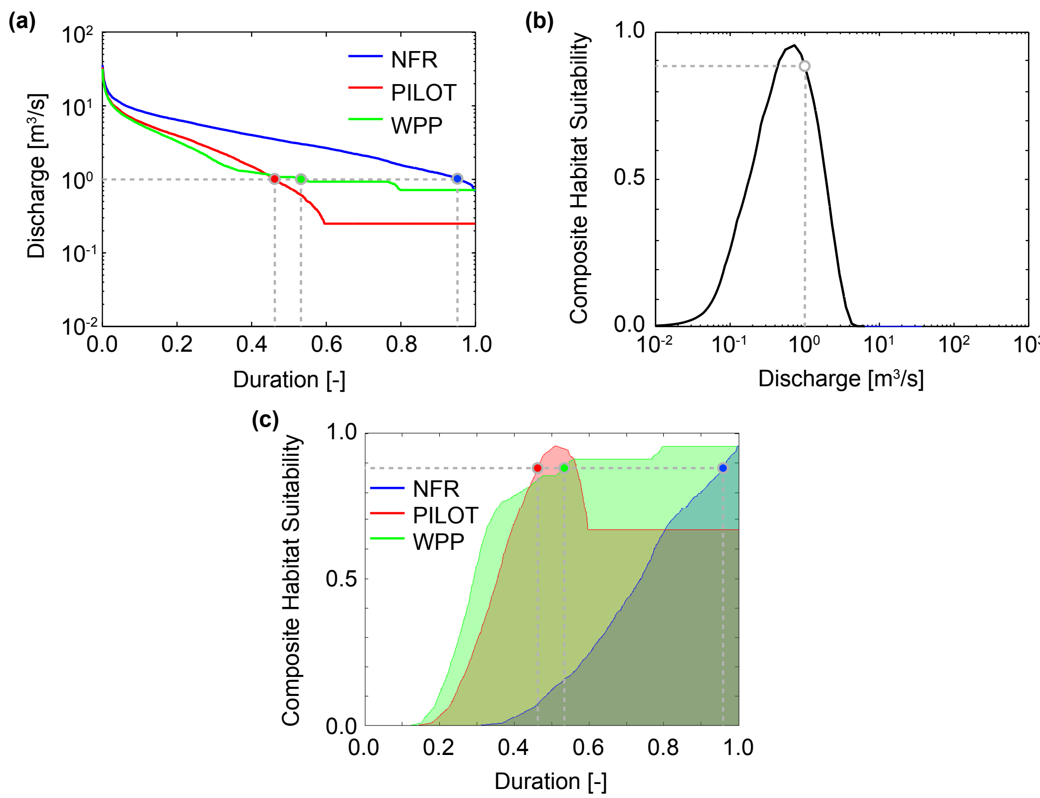

Figure 3: Schematic representation of Suitable Area Index (SAI) computation (example for Castelraimondo power plant): (a) annual flow-duration curves (FDCs) for natural flow regime (NFR, blue line), and current (PILOT, red line) and future (WPP, green line) e-flow policies; (b) composite habitat suitability for Barbel (*Barbus barbus*), adult life stage, derived from Bicchi et al. (2006); (c) habitat suitability duration curves (lines) and Suitable Area Index (shaded areas) associated with NFR (blue), and PILOT (red) and WPP (green) e-flow policies. Blue, red and green dots reported in the plots show the linkage between FDCs, composite habitat suitability and HSDC associated with Q = 1 m^3/s.

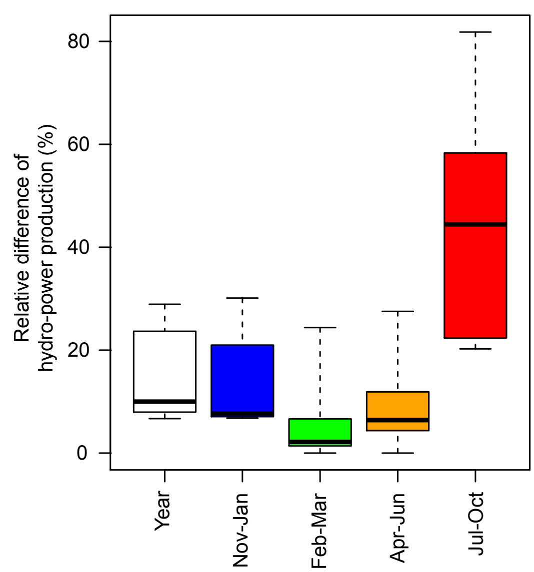

Figure 4: Relative differences (%) of hydro-power production for the set of 14 study plants: each value is computed as the difference between the hydro-power production associated with current (PILOT) and future (WPP) e-flow releases, divided by the former; the box-plots consider the entire year and four sub-periods (namely Nov.-Jan.; Feb.-Mar., Apr.-Jun. and Jul.-Oct.); each box-plot illustrates 25th, 50th (i.e. median, black thick line) and 75th percentiles, together with minimum and maximum values (whiskers).

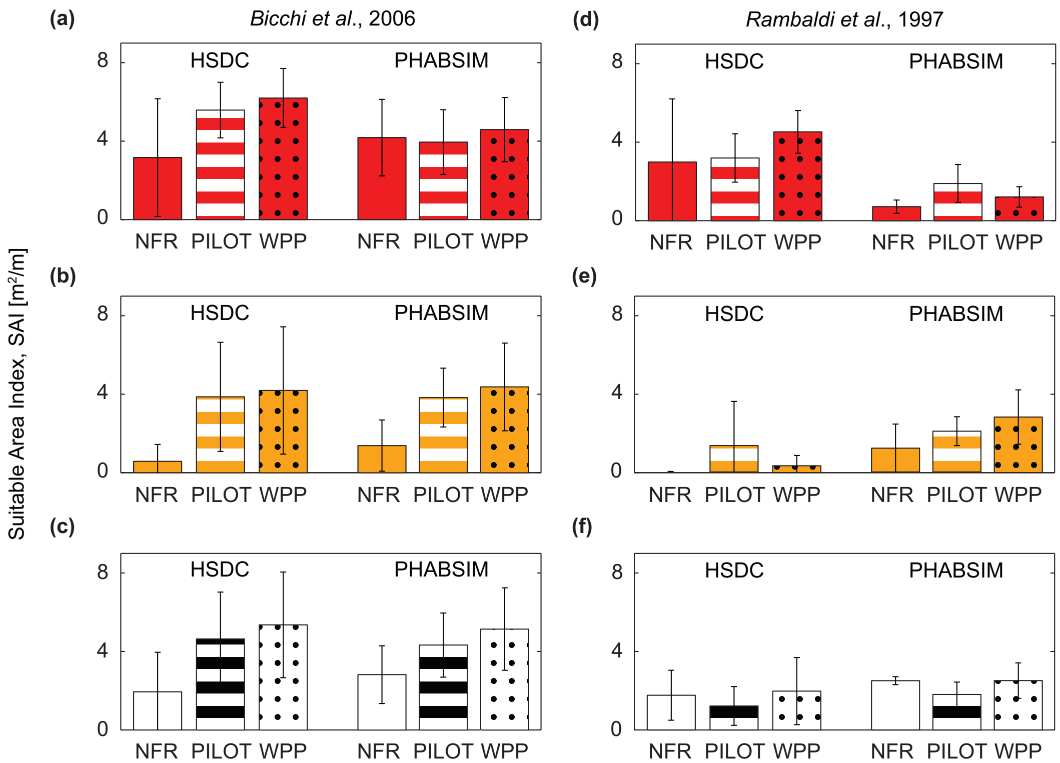

Figure 5: Suitable Area Index values (mean $\pm$ standard deviation) for *Barbus barbus* for the set of 5 study plants, whose river cross-section properties are available (see Figure 1): (a) and (d) juvenile (period: Jul.-Oct.); (b) and (e) spawning (period: Apr.-Jun.); (c) and (f) adult (period: entire year). Left and right columns refer to the habitat suitability criteria proposed by Bicchi et al. (2006) and Rambaldi et al. (1997), respectively. Filled, striped and dotted patterns represent NFR, PILOT and WPP scenarios, respectively. Bar colors refer to the seasonal representation in Figure 4.

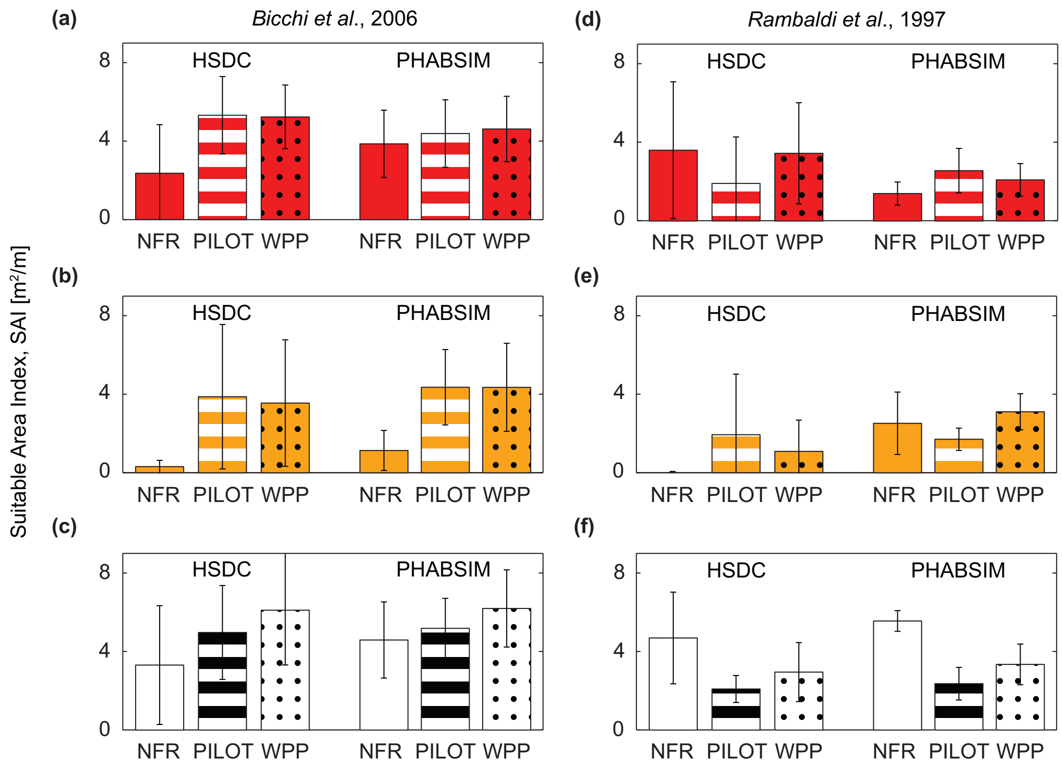

Figure 6: Suitable Area Index values (mean ± standard deviation) for *Leuciscus cephalus* for the set of 5 study plants, whose river cross-section properties are available (see Figure 1): (a) and (d) juvenile (period: Jul.-Oct.); (b) and (e) spawning (period: Apr.-Jun.); (c) and (f) adult (period: entire year). Left and right columns refer to the habitat suitability criteria proposed by Bicchi et al. (2006) and Rambaldi et al. (1997), respectively. Filled, striped and dotted patterns represent NFR, PILOT and WPP scenarios, respectively. Bar colors refer to the seasonal representation in Figure 4.

Table 1: Main characteristics for the 14 hydro-power plants considered in this study: river name (RN), hydro-power site name (HP), abstraction point location coordinates (Lat, Lon), drainage area (A), Mean Annual Flow (MAF), morpho-environmental parameter for WPP e-flow releases ($C = E \cdot max\{N, I_f\} \cdot G$), minimum and maximum turbine discharges ($Q_{T_{min}}$ and $Q_{T_{max}}$), plant typology (Run-of-the-River, ROR or storage, DAM), storage volume (V).

RN	HP	Lat, Lon (°N,°E)	A (km^2)	MAF (m^3/s)	C ($-$)	$Q_{T_{min}}$ (m^3/s)	$Q_{T_{max}}$ (m^3/s)	Typology	V (Mm^3)
Potenza	Pioraco	43.18, 12.99	170	3.71	1.30	1.0	6.0	ROR	-
Potenza	Castelraimondo	43.20, 13.05	204	4.32	1.00	0.6	2.5	ROR	-
Potenza	San Severino	43.22, 13.14	316	5.76	1.30	1.5	5.0	ROR	-
Potenza	Montefranco	43.27, 13.32	488	8.04	1.00	1.0	8.0	ROR	-
Potenza	Villa Potenza	43.30, 13.38	532	8.64	1.00	1.0	5.5	ROR	-
Potenza	Fontenoce	43.35, 13.50	643	10.15	1.00	1.5	6.6	ROR	-
Potenza	Montelupone	43.36, 13.52	648	10.24	1.00	1.0	6.5	ROR	-
Chienti	Bolognola	42.98, 13.23	11.3	0.31	1.30	0.2	0.8	ROR	-
Chienti	Fiastra	43.06, 13.18	80.0	1.99	1.30	1.0	10.8	DAM	18.025
Chienti	Polverina	43.09, 13.11	296.0	4.33	1.21	4.0	18.0	DAM	4.047
Chienti	Borgiano	43.14, 13.21	407.0	5.55	1.10	2.0	16.0	DAM	4.263
Chienti	S. Maria	43.17, 13.25	592.0	9.10	1.21	2.0	18.0	ROR	-
Chienti	Cittá di Macerata	43.25, 13.41	706.0	11.90	1.00	3.0	11.5	ROR	-
Chienti	S. Maria Apparente	43.28, 13.67	1074.0	16.78	1.00	1.5	4.3	ROR	-

Table 2: Key features for the 17 stream gauges considered in this study: streamgauge identifier, name and location (ID, Name, Lat, Lon, in this order), river name (RN), drainage area (A), Mean Annual Precipitation (MAP), years of record (Y), Mean Annual Flow (MAF), Minimum streamflow (Q_{min}), 75^{th}, 50^{th} and 25^{th} streamflow percentiles (Q_{75}, Q_{50}, Q_{25}), Maximum streamflow (Q_{max}).

ID	Name	Lat, Lon (°N,°E)	RN	A (km^2)	MAP (mm)	Y (-)	MAF (m^3/s)	Q_{min} (m^3/s)	Q_{75} (m^3/s)	Q_{50} (m^3/s)	Q_{25} (m^3/s)	Q_{max}
801	Foci	43.52, 12.64	Burano	123.7	1217.9	7	2.66	0.22	0.65	1.54	3.27	36.4
901	Acqualagna	43.63, 12.69	Candigliano	611.9	1160.1	22	13.4	0.06	2.63	6.86	16	229.3
902	Piobbico	43.59, 12.51	Candigliano	186.1	1163.1	8	4.05	0.03	0.48	1.72	4.64	44.6
1002	Barco di Bellaguardia	43.68, 12.76	Metauro	1040.3	1120	26	21.00	0.20	3.3	10.5	26	361
1004	Calmazzo	43.67, 12.75	Metauro	374.7	1131.1	10	6.36	0.04	0.89	2.86	8.64	93.9
1701	Cagli	43.55, 12.64	Bosso	125.7	1272.5	10	3.05	0.19	0.73	1.58	3.39	111.8
2101	Piobbico	43.59, 12.51	Biscuvio	64.9	1116.5	5	2.14	0.03	0.238	0.86	2.14	40.3
2201	San Vittore	43.40, 12.97	Sentino	262.7	918.1	12	6.3	0.23	1.29	3.42	8.2	127.7
2502	Moie	43.50, 13.13	Esino	795.3	1070.8	11	14.8	1.02	5.29	9.23	17.9	190
2601	Spindoli	43.19, 12.91	Potenza	87.9	1285.2	10	2.52	0.42	1.13	1.93	3.42	16.8
2602	Cannucciaro	43.26, 13.25	Potenza	423.1	1103.7	40	7.94	1.54	3.54	5.69	10	111
2801	Amandola	42.97, 13.35	Tenna	99.3	1145	39	2.82	0.56	1.46	2.32	3.43	42.7
2901	Comunanza	42.96, 13.42	Aso	83.2	946.9	21	2.94	0.77	1.77	2.51	3.42	39.1
3002	Tolentino	43.21, 13.30	Chienti	688.4	1297.5	5	13.7	2.00	4.93	9.81	19	109
3003	Pievetorina	43.06, 13.07	Chienti	115.3	981.0	29	2.16	0.34	0.78	1.66	2.8	20.1
3006	Pontegiove	43.08, 13.06	Chienti	140.9	1112.8	26	1.52	0.06	0.58	1.17	2.05	17.0
3101	Fiume	43.04, 13.17	Fiastrone	60.6	955.7	6	1.66	0.49	0.82	1.42	1.98	7.74

Table 3: Current (PILOT) and future (WPP) e-flow releases for the 5 hydro-power plants considered for both hydro-power production computation and habitat suitability assessment. WPP e-flow releases are reported on a seasonal basis, as defined by the Water Protection Plan of the Marche administrative district (see Section 2.4).

RN	HP	PILOT (m^3/s)	WPP Nov-Jan (m^3/s)	WPP Feb-Mar (m^3/s)	WPP Apr-Jun (m^3/s)	WPP Jul-Oct (m^3/s)
Potenza	Castelraimondo	0.250	0.932	1.076	0.932	0.717
Potenza	Montefranco	0.500	0.965	1.113	0.965	0.742
Chienti	Polverina	0.450	1.446	1.668	1.446	1.112
Chienti	Borgiano	0.550	1.314	1.516	1.314	1.011
Chienti	S. Maria	0.700	1.446	1.668	1.446	1.112

Appendix A. Detailed Computational Steps of Hydro-Power Production

Appendix A.1. Run-of-the-River Hydro-Power Plants

Concerning the eleven run-of-the-river hydro-power plants listed in Table 1, the computation of hydro-electric production for any given season consists of the following steps:

I the production duration (i.e. percentage of time of the season in which the turbine is working) is first identified by comparing the seasonal FDC (black line in Figure 2a) with a constant streamflow value equal to the sum of the seasonal e-flow for the considered scenario and the minimum turbine discharge (red dotted line in Figure 2a);

II the overall water volume that can be diverted and used for hydro-power production (identified by the gray shaded area in Figure 2a) is then computed by integrating the usable discharge (blue dashed line in Figure 2a) over the hydro-power duration identified at step I.;

III finally, the summation of four seasonal hydro-power productions (i.e. usable water volume) returns the yearly hydro-power production for the considered plant and e-flow scenario.

This procedure is repeated for all run-of-the-river power plants and both e-flow scenarios examined in the study.

Appendix A.2. Storage Hydro-Power Plants

As mentioned above, for the three storage power plants natural inflows are not available, therefore synthetic daily streamflow series are generated for these sites by adapting the methodology that was originally presented in Hughes and Smakhtin (1996) and briefly outlined here. A stream gauge is selected that is nearby to the target ungauged (i.e. dammed in our case) cross-section; for this stream gauge the observed daily streamflow series is continuous (no missing data) and sufficiently long (i.e. at least five years in this study) and the corresponding watershed is hydrologically similar to the target site. The observed daily streamflow series is converted into a duration series by referring to the empirical period-of-record FDC constructed from the observed streamflow series itself. The duration series is back-transformed into a daily streamflow series for the target ungauged site by using the long-term FDC predicted for this site through the geostatistical procedure proposed by (see Pugliese et al., 2014) and described in Section 3.1. The synthetic daily natural streamflow series is then used as input to a simplified algorithm that simulates the reservoir management through the following steps:

- I at any given day, the daily inflow volume is added to the volume stored during the previous time-step (which is initially set to zero);
- II the code checks the compliance between the stored volume and the e-flow prescriptions of the scenario (i.e. PILOT or WPP):
  - (a) if the stored volume is larger than or equal to the daily e-flow volume, the latter is subtracted to the stored volume and the computation continues to step III;
  - (b) the entire stored volume is released otherwise, and the calculation moves to the next day (step I) with an empty storage;
- III the stored volume is compared with the maximum, W_{max}, and minimum, W_{min}, daily volumes that can be exploited for hydro-power production (i.e. W_{max} is equal to the maximum turbine discharge over a duration of 24 hours, while W_{min} is equal to the minimum turbine discharge over a 1-hour duration):
  - (a) if the stored volume is larger than W_{max}, W_{max} is subtracted from the stored volume and the calculation goes to step IV;
  - (b) if the stored volume is between W_{min} and W_{max}, all stored volume is used and the computation moves to the next time day (i.e. step I) with an empty reservoir;
  - (c) if the stored volume is less than W_{min}, the stored volume is held in the reservoir and the calculation moves to step I;
- IV the stored volume which is left from step III-a is compared with the reservoir capacity:

(a) if the stored volume is larger than the reservoir capacity, the excess volume is released downstream, the stored volume is set to the reservoir capacity and the calculation moves to the next day (step I);
(b) otherwise, the stored volume becomes the initial volume and the computation starts from step I.

The algorithm described above does not aim at faithfully reproducing the real reservoir management and hydraulic behavior, but rather at performing a plausible simulation of reservoir operation at daily timescale, which maximizes hydro-power production while meeting the e-flow prescriptions for the considered scenario.

Our simplified numerical code is run for the multi-annual daily inflow time series relative to each one of the three considered storage plants and for all e-flow scenarios. The code returns as outputs the average seasonal and yearly usable water volumes.

Appendix B. Computational steps for the estimation of the composite habitat suitability following the HSDC approach

Concerning the HSDC approach, the composite habitat suitability is evaluated for the entire river cross-section (i.e. without dividing the cross-section into computational grid cells) through the following steps:

I An equivalent rectangular cross-section with average water depth and flow velocity, derived from river geometry data, is first defined. More specifically, for each of the 4 distinct cross-sections describing the river reach downstream any barrage or dam, we consider the water depth computed from HEC-RAS simulations and we then evaluate (i) the wetted area, (ii) the average flow velocity, as the ratio between discharge and wetted area, (iii) the wetted river width and (iv) the water depth associated with an equivalent rectangular cross-section, as the ratio between wetted area and river width.

II The relationships between geomorphic features and discharge ($v(Q)$, $d(Q)$) are then computed by applying at-a-station scaling laws developed by Leopold et al. (1964) for each of the 4 distinct cross-sections downstream each barrage or dam. The same 16 discharge values mentioned earlier (i.e. sampled from FDCs and associated with a duration ranging from 0.005 to 0.995) are then regressed against the corresponding average flow velocities and water depths (log-log regression). The regression coefficients computed for the 4 cross-sections are then averaged to identify at-a-station coefficients for the river branch downstream each barrage and dam.

III For each discharge value gathered from predicted FDCs, the composite habitat suitability HS is finally computed as $HSC_{d(Q)} \cdot HSC_{v(Q)}$.