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Hydropeaking impact assessment for Iberian cyprinids and leuciscids: An adaptation of the hydropeaking tool method

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Abstract

Hydropeaking negatively affects fish assemblages, but knowledge gaps still constrain our ability to rank and mitigate the impacts of different hydropower operation regimes at particular power plants. This is especially relevant for species and rivers for which the effects of hydropeaking are less investigated, such as the Iberian Cypriniformes and Mediterranean rivers. Recognizing the potential of the hydropeaking tool method (HT) developed for salmonids to systematically assess hydropeaking impacts, we adapted it for Iberian Cypriniformes. The general tool framework developed for the salmonids was kept for the Cypriniformes, with the combined use of factors describing the hydromorphological effects and factors related with fish vulnerability to assess hydropeaking impact. Effect and vulnerability factors were developed for Iberian cyprinids and leuciscids establishing preliminary thresholds for each indicator with three different levels of hydropeaking impact on the targeted taxa. The proposed factors and thresholds were critically reviewed and ranked by experts on Iberian Cypriniformes ecology and Mediterranean rivers functioning. Overall, the timing and distribution of peaking events were ranked higher by the experts in the effect factors, whereas the population size of barbel and smaller native Cypriniformes, as well as the degree of limitations in recruitment, were ranked higher in the vulnerability factors. Although there was some divergence in the expert opinions, a final set of effect and vulnerability factors was established, that retained most of the ones proposed for the salmonids, but included new ones, particularly for vulnerability. The present study provided a comprehensive, straightforward, and systematic assessment tool for evaluating hydropeaking impacts on Iberian Cypriniformes.

KEYWORDS
expert judgment, freshwater fish, hydropower, Iberia, impact assessment, vulnerability

1 | INTRODUCTION

Recent growth in energy demand has escalated human reliance on hydropower, stimulating an increase in the construction of hydropower plants worldwide (Couto & Olden, 2018). Commonly, hydroelectric power plants operate in response to short-term, sub-daily changes of the electricity market, undergo rapid variations of turbine discharge, entailing quickly fluctuating water levels downstream (Moog, 1993). This operation regime often known as hydropeaking, causes numerous adverse effects on river ecosystems, particularly fish assemblages (Schmutz et al., 2015; Young, Cech, & Thompson, 2011).

Overall, hydropeaking can profoundly affect river hydromorphology, with cascading direct and indirect impacts on aquatic habitat and biota (Hauer, Holzapfel, Leitner, & Graf, 2017; Hauer, Unfer, Holzapfel, Haimann, & Habersack, 2014; Holzapfel, Leitner, Habersack, Graf, & Hauer, 2017; Vanzo, Zolezzi, & Siviglia, 2016). Research has focused on characterizing and quantifying such complex impacts, which include fish stranding and drift, obstruction to fish migration patterns, changes in food webs, degradation of habitat quality, impairment of flood intolerant river bank vegetation and macrophytes, sharp fluctuations in river temperature, and modifications of natural rates of sediment transport (Aksamit, Carolli, Vanzo, Weber, & Schmid, 2021; Costa, Fuentes-Pérez, Boavida, Tuhtan, & Pinheiro, 2019; Greimel et al., 2018; Moreira et al., 2019).

Although many rivers can naturally experience rapid flow changes, namely during floods, the hydrographs of peaking rivers are unique, leading to harsh environment of frequent and unpredictable disturbances for freshwater organisms, with no natural analog (García, Jorde, Habit, Caamaño, & Parra, 2011; Greimel et al., 2018; Moreira et al., 2019). The hydrograph of peaking rivers can be characterized by parameters that change over space and time, such as magnitude, rate of change, frequency, duration, and timing (Harby & Noack, 2013). Each of these parameters may be correlated with ecological consequences and therefore may be used to scale the impacts of hydropeaking.

The response of salmonids to hydropeaking has been studied for some years, as most studies have been conducted in regions where this family dominates (e.g., Boavida, Harby, Clarke, & Heggenes, 2017; Burman et al., 2021; Hauer et al., 2017; Hayes et al., 2019; Puffer et al., 2014; Rocaspana, Aparicio, Palau-Ibars, Guillem, & Alcaraz, 2019; Scruton et al., 2008; Valentin, Lauters, Sabaton, Breil, & Souchon, 1996). Salmonids can be affected by peaking flows, whereby the most common responses include stranding, downstream displacement, and dewatering of spawning grounds, which have been related to up- and down-ramping rates (Saltveit, Halleraker, Arnekleiv, & Harby, 2001), peak flow magnitude (Auer, Zeiringer, Führer, Tonolla, & Schmutz, 2017), and baseflow duration (Casas-Mulet, Alfredsen, Brabrand, & Saltveit, 2016). In contrast, information is much scarcer regarding other fish taxa (Alexandre, Almeida, Neves, Costa, & Quintella, 2015; Boavida et al., 2020; Boavida, Santos, Ferreira, & Pinheiro, 2015; Capra et al., 2017; Oliveira, Alexandre, Quintella, & Almeida, 2020), making it difficult to appraise peaking impacts of existing and new hydropower plants in non-salmonid rivers.

The Iberian freshwater fish fauna is characterized by the presence of native Cypriniformes (cyprinids and leuciscids) that, except for headwater streams and lowland rivers, dominate riverine fish assemblages (Maceda-Veiga, 2013). Moreover, the high level of endemicity coexists with the high vulnerability of many fragmented rivers subjected to hydropeaking (Terêncio, Pacheco, Fernandes, & Cortes, 2021). Therefore, information gaps about hydropeaking impacts on Cypriniformes should be critical in the Iberian Peninsula.

Given this scenario, the ability to estimate a priori hydropeaking impacts in the Iberian Peninsula would be particularly useful to screen candidate hydropower plants or candidate river stretches to be flow regulated for further investigations and for the implementation of appropriate mitigation measures.

Bakken et al. (2021) developed the hydropeaking tool (HT), a systematic approach to assess the impacts of hydropeaking on salmonid fish. The approach divides the impact from hydropeaking into two components: (direct) effects and vulnerability. The effect component characterizes the possible ecological impacts of peaking from how hydromorphological conditions change, given the hydropower system and river morphology. The vulnerability component characterizes how vulnerable the system is to further influence from peaking.

Although the ecology of Cypriniformes is distinct from salmonid´s, this study aims to adapt the HT developed for salmonids in Scandinavia for some of the native taxa most commonly found at peaking rivers in Iberia. The targeted taxa included the cyprinids *Luciobarbus bocagei* and *Pseudochondrostoma duriense*, and the leuciscids *Squalius* spp. and *Achondrostoma* spp. The adaptation builds on the experience gathered so far on the impacts of hydropeaking in Iberia (Alexandre et al., 2015; Boavida et al., 2015; Boavida, Ambrósio, et al., 2020; Costa et al., 2019; Oliveira et al., 2020) and on expert knowledge from Portuguese and Spanish experts.

2 | MATERIAL AND METHODS

The effect factors of the HT for salmonids consider the rate of flow change (water level change ratio), the dewatered area (change in water-covered area when the flow is reduced from Q_{max} to Q_{min}), the magnitude of flow changes (Q_{max}/Q_{min}), and the frequency, timing, and distribution of peaking operations. For salmonids, the following vulnerability factors are considered in the HT: population size (number of adult females), degree of limitations in recruitment (amount and distribution of spawning grounds), low flow periods as bottleneck for fish stock size, habitat degradation, low temperature impacts, pollution and other external factors, and the percentage of impacted river length compared to the total length. These effect and vulnerability factors are assessed for each hydropower plant (HPP) and are classified in semi-quantitative classes according to criteria developed from the literature, non-published research or by expert opinion. The HT produces an overall assessment of hydropeaking impact at a particular site (from very high to small) by combining the scores for the effect and vulnerability factors (Figure 1). The reference situation to assess

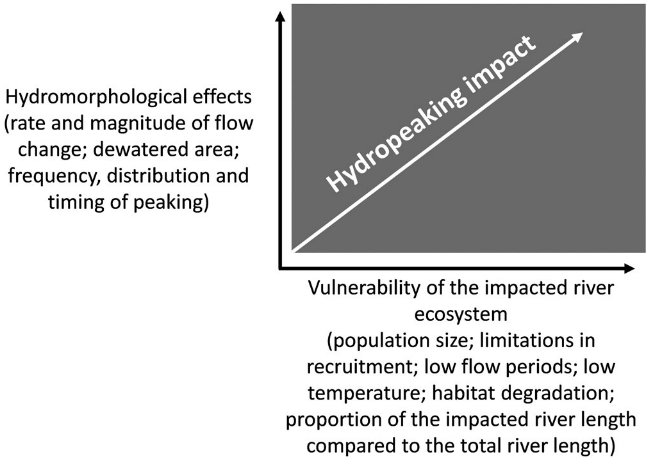

FIGURE 1 General framework of the hidropeaking tool method (HT) developed for salmonids in Scandinavia

the effect and vulnerability factors is a hydropower regulated river without peaking (Bakken et al., 2021).

The general framework of the HT developed for salmonids was kept for the Iberian cyprinids and leuciscids targeted (Bakken et al., 2021). The Iberian barbel (*L. bocagei*) is the largest native species present in many Northern Iberian rivers, reaching up to 1,000 m in total length (e.g., Godinho, Ferreira, & Cortes, 1997). The Northern straight-mouth nase (*P. duriense*), *Squalius* spp. and *Achondrostoma* spp. are smaller and frequently co-occur with the barbel (Santos et al., 2011).

As an initial step, a set of effect and vulnerability hydropeaking related factors were developed for Iberian Cypriniformes based upon the available, published, and unpublished information (see Tables 1 and 2 in the supplementary material). Upon that information, preliminary thresholds separating different effect and vulnerability classes were established for each factor to account for different levels of impact of hydropeaking on the targeted taxa.

All the effect factors proposed for the salmonids were retained for the Iberian Cypriniformes, except the magnitude of flow changes, because Q_{max}/Q_{min} would invariably return larger values than for Scandinavian HPP since flow is near zero or zero during the low flow period in many rivers in Mediterranean climate regions. Due to the limitations in available information, only three classes were established for each indicator. Other differences with respect to the salmonid studies (Bakken et al., 2021) included the consideration of distinct critical periods as well as different thresholds to classify some indicators given the specificity of the Iberian climate. Given the more generalist autoecology of the Iberian Cypriniformes, the thresholds proposed were generally less stringent than the ones proposed for the salmonids.

As expected, more differences were noticeable between the salmonids and the Cypriniformes vulnerability factors. In contrast to salmonids, two taxa groups were initially established, considering the larger Iberian barbel in one group, and the remaining Cypriniformes in another.

Instead of using the number of females as an indicator of the population size, the use of capture-per-unit-of-effort (CPUE; number of specimens collected in Spring with single-pass electrofishing/100 m^2) was proposed as an indicator of abundance for the species or group of species considered. Initial threshold criteria to separate vulnerability classes were obtained as percentiles of the CPUE for barbel and the other Cypriniformes occurring in several Portuguese Central and northern river reaches, including both natural and impacted sites.

The proportion of juvenile native Cypriniformes specimens based on total length, as a measure of recruitment limitations, was used instead of the amount and distribution of spawning grounds considered for salmonids. Although growth for a particular species varies among different rivers and reaches, the general use of the following size thresholds to identify juvenile specimens were proposed (total length, in mm): *L. bocagei* (120 mm); *P. duriense* and *S. carolitertii* (80 mm); *S. alburnoides* and *Achondrostoma* spp. (45 mm). The proposed values are a compromise between the maturity lengths for males and females (e.g., Doadrio, 2001). Habitat degradation was also included and assessed similarly to salmonids, as the change in magnitude and frequency of natural flood events.

Low flow periods as bottleneck for salmonid fish stock size were not considered due to the tolerance of most Iberian Cypriniformes to low flow conditions (e.g., Pires, Pires, Collares-Pereira, & Magalhães, 2010). The influence of reduced water temperature was also not included as a vulnerability factor because low temperatures are not common in Iberian latitudes. In contrast, a measure of habitat heterogeneity was also included (i.e., Habitat Quality Assessment index—HQA; Raven, Fox, Everard, Holmes, & Dawson, 1997), because fish populations should be more vulnerable to hydropeaking at homogeneous river reaches. Finally, the proportion of impacted river length compared to the total length was also used for Cypriniformes as for the salmonids.

The proposed factors and thresholds were sent to eight experts on Iberian Cypriniformes ecology and Mediterranean rivers functioning to be critically reviewed. More specifically, a questionnaire was prepared and sent electronically to each expert to be filled with several answers placed for each factor (e.g., Do you think this indicator should be divided into down and up-ramping? When do you think Iberian Cypriniformes would be less susceptible to stranding? See Questionnaire in the supplementary material [Data S1]). Further, the experts were asked to rank the effect and vulnerability parameters by importance regarding the impact of hydropeaking in Iberian Cypriniformes (from 5, very important, to 1, less important). The completed questionnaires were sent by the experts to the corresponding author.

A final set of effect and vulnerability factors and respective thresholds were developed for Iberian Cypriniformes by including the expert opinions in the initial proposal. The joint assessment of the effect and vulnerability factors was defined by adapting the combined assessment made for salmonids (Bakken et al., 2021).

3 | RESULTS

3.1 | Experts opinion

The degree of agreement in the expert opinions concerning the relevance of each factor was evaluated with the standard deviation of the average rank value (Table 1). Overall, the timing (E5) and distribution (E4) of peaking events were ranked higher among the effect factors, whereas the population size of barbel (V1a) and smaller native Cypriniformes (V1b), as well as the degree of limitations in recruitment (V2), were ranked higher in the vulnerability factors.

All the experts agreed with the inclusion of the rate of change (E1) in the effect factors due to its influence on fish and invertebrate stranding and dewatering, but only a part (62.5%) agreed with the possibility of considering separately up- and down-ramping, as they are sequent phases of hydropeaking. The inclusion of the dewatered area (E2), which intends to evaluate the potential for fish stranding and the dewatering of spawning grounds, was also agreed by all experts, but higher thresholds were suggested, as in rivers with Mediterranean flow the frequent dewatering of the river bed occurs during naturally decreasing flow conditions, either while approaching the summer or during the progression of drought years (Gasith & Resh, 1999).

Most of the experts (87.5%) agreed with the inclusion of hydropeaking frequency (E3). However, when asked if the peaking frequency should only be considered in the Summer low flow period, the experts suggested the inclusion of other stressful periods, including the spawning period and drought years, which are increasingly more common in the Iberia Peninsula (Cid et al., 2017). Most experts also agreed with considering the distribution (E4, 87.5%) and timing (E5, 100%) of hydropeaking events. Overall, hydropeaking should be more detrimental when occurring irregularly throughout the year and particularly during vulnerable ecological periods (Greimel et al., 2018), although there was a debate about when the vulnerable periods do occur for the targeted taxa.

Concerning the vulnerability factors, all the experts agreed with the inclusion of population size (V1) in the vulnerability factors, as lower density fish populations should be more vulnerable to the effects of hydropeaking. However, several suggestions were made, including the division of the smaller Iberian Cypriniformes in two groups, separating the cyprinid *P. duriense* (usually the second largest cyprinid in Iberian fish assemblages, reaching up to 500 mm) from the leuciscids *Squalius* spp., and the exclusion of *Achondrostoma* spp., due to their tolerance to hydropeaking and other anthropogenic impacts (Oliveira et al., 2012). Moreover, it was proposed to enlarge the database from where the CPUE were derived and to establish thresholds for specific river types in the future. The consideration of the degree of limitation in recruitment (V2) as a vulnerability factor was deemed adequate by most experts (87.5%), because the effects of hydropeaking could be particularly stressful for juvenile fishes, given their smaller size, reduced swimming ability, and preferential use of shallow marginal habitats (Martínez-Capel, García de Jalón, Werenitzky, Baeza, & Rodilla-Alamá, 2009), where hydropeaking effects such as dewatering or stranding are more likely to occur than in the middle of the river channel (Casas-Mulet, Alfredsen, Boissy, Sundt, & Rüther, 2015). Likewise, the addition of a measure of habitat heterogeneity (V3) as a vulnerability factor was considered adequate, because habitat heterogeneity could be an important buffer for the impacts of hydropeaking, namely by providing safe velocity refuges during up-ramping (Kalogianni et al., 2020). The inclusion of an additional approach to assess habitat heterogeneity (V3) (the Spanish protocol for the hydromorphological characterization of rivers, HYMO, Gobierno de España, 2019) was also suggested.

Floods are important mechanisms shaping the ecology of Iberian fluvial ecosystems, being crucial to maintain natural ecological balances (Gasith & Resh, 1999). Moreover, floods could be important to trigger spawning migrations of potamodromous Iberian cyprinids, such as the barbel and nase (García-Vega et al., 2021) and are often important to keep exotic invasive species in low numbers, as they are less fit to respond to such events (Fornaroli, Muñoz-Mas, & Martinéz-Capel, 2020). Therefore, the change in magnitude and frequency of natural flood events result in habitat degradation, and its inclusion as a vulnerability factor (V4) was sanctioned by most experts (87.5%). The thresholds proposed were also deemed adequate.

Finally, there was a large debate between the experts about the inclusion of the percentage of impacted river length (V5) and how it should be measured. Moreover, some noticed that the position of the HPP is also important to assess its impacts irrespective of the proportion of river affected by hydropeaking.

3.2 | Final set of effect and vulnerability parameters/indicators and impact assessment

The final set of effect and vulnerability factors proposed for Iberian Cypriniformes are depicted in Tables 2 and 3.

All the effect and vulnerability factors were considered equally important considering the expert judgment, and the values assigned to each one (from High, value 3, to Low, value 1) were added. The

TABLE 1 Average (±SD) of the ranks (from 5, very important, to 1, less important) given by each expert to the effects and vulnerability factors considered for hydropeaking impact assessment on non-salmonid rivers

Effect factors	Average rank (±SD)	Vulnerability factors	Average rank (±SD)
E1: Rate of change	2.9 ± 1.4	V1a: Effective population size of native barbel	3.6 ± 1.2
E2: Dewatered area	3.0 ± 1.4	V1b: Effective population size of small native fish	3.8 ± 1.5
E3: Frequency	2.9 ± 1.9	V2: Degree of limitations in recruitment	3.8 ± 1.1
E4: Distribution	3.4 ± 1.3	V3: Habitat heterogeneity	2.6 ± 1.4
E5: Timing	3.7 ± 1.7	V4: Habitat degradation	2.9 ± 1.1
		V5: Percentage of impacted river length	3.0 ± 1.4

TABLE 2 Final effect factors, indicators and criteria for characterization of Iberian non-salmonid rivers affected by hydropeaking

		Criteria for characterization		
Effect factors	**Indicator**	**Very large (value 3)**	**Moderate (value 2)**	**Small (value 1)**
E1: Rate of change	Water level change ratio (cm/h)	>15	5–15	<5
E2: Dewatered area	Change in water-covered area when flow is reduced from Q_{max} to Q_{min} (%)	>40	10–40	<10
E3: Frequency	Annual frequency (proportion/number of days per year with peaking)	>75% (>273 days)	25–75% (91–273 days)	<25% (<91 days)
E4: Distribution		Irregular during spring (spawning period)	Irregular	Regular throughout the year
E5: Timing	Flow reductions in critical periods	During the potamodromous migration, spawning and larvae period	During the winter	During the low flow period

total scores for the effect and vulnerability factors were then divided into three classes (Tables 4 and 5). For the factor V1a, V1b, and V1c a single value correspondent to the average of the species/species group naturally occurring in the river reach should be considered. In the end, the HT generates an overall assessment of hydropeaking impact, by combining the effects of hydropeaking with the vulnerability of the river system (Table 6).

4 | DISCUSSION

The effect factors used by Bakken et al. (2021) encompassed the majority of the hydromorphological alterations of hydropeaking described to influence fish (e.g., Greimel et al., 2016, 2018; Hayes et al., 2019). Despite the different hydrographs between Scandinavian and Iberian rivers, most of the effect factors included in the initial HT were kept for Iberian rivers. This likely reflects the similarities of hydropeaking regardless of river location, in what it relates to inflow variations over space and time in relation to sub-daily hydropower production. Notwithstanding, detailed analysis of sub-daily flow fluctuations have found different hydropeaking regimes (Greimel et al., 2016).

Overall, the final set of effect factors for Iberian cyprinids and leuciscids was similar after the expert inputs, but some class thresholds were changed, namely for the dewatered area and the hydropeaking frequency. The distribution of hydropeaking events was also changed, with the highest impact linked to events occurring irregularly during Spring instead of irregular events occurring during all year. Spring was selected as a particularly vulnerable period as all Iberian Cypriniformes spawn largely during this season (e.g., Rodriguez-Ruiz & Granado-Lorencio, 1992; Santos, Rivaes, Boavida, & Branco, 2018). In addition, regular hydropeaking events were considered less impacting, as individual fish appears to memorize spatial and temporal environmental changes and to adopt a "least constraining" habitat (Alexandre et al., 2015; Capra et al., 2017; Costa, Boavida, Almeida, Cooke, & Pinheiro, 2018; Halleraker et al., 2003; Oliveira et al., 2020).

The timing of hydropeaking was also changed after the expert's input, with the highest impact related not only to the spawning and larvae development periods but also the potamodromous pre-spawning migration performed by barbel and nase in Iberian rivers. The impact was considered reduced when occurring during the Winter, and moderate if happening during the Summer low flow period, when juveniles are already well developed. Contrasting with the effect factors, vulnerability factors for the Cypriniformes showed more differences with the ones proposed for the salmonids. These differences reflected the distinct ecology of the two fish orders. Two taxonomical groups were initially selected, but based on expert's opinions the niche breadth of the smaller Cypriniformes justified the separation in two groups, one including the nase, and the other including the leuciscids, that is, the chubs *Squalius* spp.

Instead of using the number of females as a measure of effective population size, as considered in the salmonids HT, CPUE was used as an indicator of the global population size of Cypriniformes, as this type of data are available for several river reaches from standard electrofishing procedures (INAG, 2008). The abundance thresholds developed in this study were supported on available CPUE data for native Cypriniformes in river reaches, but the indicator can be adapted to other databases on fish abundance, and can be also derived for specific river types. This possibility was considered an interesting line of future enhancement for the method by all experts.

As in other applications of expert knowledge (Drescher et al., 2013; Radinger, Kail, & Wolter, 2017), there was some divergence in the expert opinions. Nevertheless, at least one of the experts found each of the proposed factors, except hydropeaking frequency and habitat heterogeneity, to be very important. Considering the differences of opinion, the values of each factor were not weighted differently.

In the HT for salmonids, the rate of change (E1) is multiplied with the dewatered area (E2) factors. This is because the rate of change is not considered important if it does not lead to a significant reduction in dewatered area when water levels sink, and vice versa. This is due

TABLE 3 Final vulnerability factors, indicators and criteria for characterization of Iberian non-salmonid rivers affected by hydropeaking

		Criteria for characterization		
Vulnerability factor	**Indicator**	**High (value 3)**	**Moderate (value 2)**	**Low (value 1)**
V1a: Effective population size of native barbel (*Luciobarbus bocagei*)	Abundance: Capture-per-unit-of-effort (CPUE—number of specimens collected in spring with single-pass electrofishing/100 m^2)	<1.5[a]	1.5–6.0[b]	>6.0
V1b: Effective population size of straight mouth nase (P*seudochondrostoma* spp.)	Abundance: Capture-per-unit-of-effort (CPUE—number of specimens collected in spring with single-pass electrofishing/100 m^2)	<2.0[c]	2.0–6.2[d]	>6.2
V1c: Effective population size of sensitive smaller native Cypriniformes (*Squalius alburnoides*, *Squalius carolitertii* and other *Squalius* spp.)	Abundance: Capture-per-unit-of-effort (number of specimens collected in spring with single-pass electrofishing/100 m^2)	<1.5[e]	1.5–8.3[f]	>8.3
V2: Degree of limitations in recruitment	Proportion of juvenile native cyprinid specimens in spring samples (based on specimens' length)	<30%	30–50%	50–70%
V3: Habitat heterogeneity	River habitat survey (in Portugal) or the Spanish protocol for hydromorphological (HYMO) characterization of rivers (in Spain)	HQA or HYMO indicator compatible with bad ecological status	HQA or HYMO indicator compatible with moderate or mediocre status	HQA or HYMO indicator compatible with high or good status
V4: Habitat degradation	Change in magnitude and frequency of natural flood events	No floods	Some floods compared to the natural situation	Most of the natural floods (>50%) still occur

[a]30% percentile of the CPUE for barbel occurring in 202 central and northern river reaches.
[b]60% percentile of the CPUE for barbel occurring in 202 central and northern river reaches.
[c]30% percentile of the CPUE for nase occurring in 256 central and northern river reaches.
[d]60% percentile of the CPUE for nase occurring in 256 central and northern river reaches.
[e]30% percentile of the CPUE of small sized Iberian Cypriniformes (including *Squalius alburnoides* and *Squalius caroliterti*) occurring in 272 central and northern river reaches.
[f]60% percentile of the CPUE of small sized Iberian Cypriniformes (including *Squalius alburnoides* and *Squalius carolitertii*) occurring in 272 central and northern river reaches.

TABLE 4 Combined impact and score of different effect classes for characterization of Iberian non-salmonid rivers affected by hydropeaking

Combined impact	Score
Large	12–15
Moderate	8–11
Small	4–7

TABLE 5 Combined impact and score of different vulnerability classes for characterization of Iberian non-salmonid rivers affected by hydropeaking

Combined impact	Score
High	11–12
Moderate	8–10
Low	4–7

to the risk of stranding, which is considered a major challenge for salmonids (e.g., Hauer et al., 2014; Hayes et al., 2021; Nagrodski, Raby, Hasler, Taylor, & Cooke, 2012). In the system proposed for Iberian Cypriniformes, the effect factors are all additive, as other impacts like disturbing movements, changing habitats, access to feeding, and spawning were considered equally important. Besides, dewatered

TABLE 6 Assessment matrix combining hydropeaking effects and vulnerability for overall impact assessment

		Hydropeaking effects		
		Large (12–15)	Moderate (8–11)	Small (4–7)
Vulnerability	High (11–12)	Red	Red	Yellow
	Moderate(8–10)	Red	Yellow	Green
	Low (4–7)	Yellow	Green	Green

Note: The colors denote the impact classes (large, moderate and small impacts are denoted, respectively, by red, yellow and green.

areas in Mediterranean-streams are typically large due to peak magnitude (Boavida, Caetano, & Pinheiro, 2020).

The HT incorporates relevant factors for the preliminary assessment of hydropeaking impacts at particular hydropower plants, but other factors have been showed to influence hydropeaking effects. For example, a recent study evaluated the response of *Thymallus thymallus* to multiple stressors in hydropeaking rivers (Hayes et al., 2021), showing that factors such as connectivity were highly relevant in predicting fish population status in hydropeaking impacted rivers. The original HT and the initial factors proposed in the Iberian HT included the length of the river impacted by peaking, which could account for reductions in connectivity. Notwithstanding, the impacted river length was not included in the final Iberian HT given the debate among the experts and the difficulties of assessing the impacted river length without detailed studies that would undermine the objective of the HT, that is, to quickly assess a priori impacts of particular HPP.

The present study gathered valuable information regarding hydropeaking impact on Iberian Cypriniformes in the form of a straightforward to use tool for operators, engineers, and biologists to assess the level of impact of HPP considering the vulnerability of the downstream river reach, and therefore, could contribute to the sustainable development of hydropower energy. HPP with higher potential hydropeaking impacts can then be subjected to more detailed investigations and, if necessary, the implementation of mitigation measures.

Some of the most common native taxa in Northern Iberian rivers were targeted, but other species could be included in future versions of the HT. These could include other Cypriniformes and, in some river segments, amphidromous species, such as the sea lamprey (*Petromyzon marinus*), the allis shad (*Alosa alosa*), and the European ell (*Anguilla anguilla*).

Although more investigations are needed to refine the HT, thus decreasing the inclusion of expert-based judgment, the tool can be applied readily. In addition, complementary expert judgment has been used with success in ecology (e.g., Langhans, Gessner, Hermoso, & Wolter, 2016). Difficulties may arise during the application of the HT due to the lack of available information, including hydrological data with the needed short time span and fish sampling data for the river reaches under evaluation. Notwithstanding, modeling approaches can be used to derive the hydrological data from power production information, whereas for the fish assemblages, information could be obtained from the systematic fish sampling conducted by Water Authorities to assess Ecological Status according to the Water Framework Directive.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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