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Technologies for the study of hydropeaking impacts on fish populations: Applications, advantages, outcomes, and future developments

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Abstract

Dam construction and streamflow regulation are increasing throughout the world, with impacts in impounded aquatic ecosystems. Hydropower dams, some of them causing a phenomenon called "hydropeaking" during their operation, are known for having a variety of impacts on downstream aquatic biota, particularly fish, and respective habitat. This can result in significant changes, from the community (e.g., fish assemblage structure) to the individual level (e.g., physiological and behavioural adjustments). Researchers and managers involved in the assessment of hydropeaking impacts must be resourceful and use methods that allow their precise evaluation, from large to fine-scale habitat and biological responses. In the last decades, technological advances allowed for the development of techniques and instrumentations that are increasingly being used in hydropeaking impact and mitigation assessments. This paper aims to provide a review, to researchers and managers interested in this field, of some of the most innovative methods and techniques, involving technology, that are available to study hydropeaking effects on downstream ecosystem, particularly from a fish perspective. We discuss the fundamentals behind such techniques, their advantages, and disadvantages, while also providing practical examples of their application and of the type of results that can be obtained. We finish by discussing some of the shortcomings of these methods and how related technology can evolve to solve current limitations.

KEYWORDS
biotelemetry, habitat mapping, hydropower dams, intermittent respirometry, swim tunnels and flumes, technological advances

1 | INTRODUCTION

Dam construction, and resultant loss of connectivity and regulation of flow regimes, are considered some of the most significant and persistent threats to the ecological sustainability of rivers and their floodplains (Arthington, 2012; Bunn & Arthington, 2002; Nilsson, Reidy, Dynesius, & Revenga, 2005). They are responsible for direct and indirect impacts on the structure and composition of aquatic communities', and for changing the distribution and availability of riverine habitats (Bunn & Arthington, 2002; Poff & Allan, 1995; Richter, Baumgartner, Wigington, & Braun, 1998). Some dams working for hydroelectric production, more specifically hydropeaking dams, operate differently from other riverine infrastructures by discharging water intermittently. Although reducing large-scale temporal variability between typical high and low flow periods, the operation of these dams contributes to increase the daily variability of flow and habitat conditions on downstream affected reaches. Large flow fluctuations that would be expected seasonally, happen daily or hourly (De Vocht & Baras, 2005) and with different magnitudes (Robertson, Pennell, Scruton, Robertson, & Brown, 2004), a phenomenon known as "hydropeaking." Riverine biota have adapted to the magnitude, frequency, and predictability of natural flow regimes, including seasonal floods (Capra et al., 2017; De Vocht & Baras, 2005). However, the occurrence of these broad range, short-term flow fluctuations, makes habitat downstream of these dams highly unstable and unpredictable (Robertson et al., 2004).

In the last decades, there has been a strong impulse to build more dams or to increase the capacity of existing ones, particularly for hydropower production. This is because hydroelectricity is seen as a green and renewable energy source that produces lower amounts of greenhouse gases compared with hydrocarbon fuelled power generation (Couto & Olden, 2018; Jones, 2014). Hydropeaking operations are also able to rapidly meet electricity demands during high consumption periods (Scruton et al., 2005). However, if the demand for renewable energy sources, such as hydropower production, is increasing worldwide, the proper assessment of its effects on downstream riverine habitat and biota should be further deepened. It is of high importance that current and future research would be able to accompany these fast developments and give more precise details about hydropeaking effects on downstream riverine biota.

Several different methods and technologies (e.g., electric fishing, biotelemetry, swim tunnels, and flumes; Boavida et al., 2020; Murchie et al., 2008) are currently being used to study the biological and ecological impacts of hydropeaking on freshwater fish populations and habitats. However, most of the available literature fails to provide readers with a broad knowledge on the diversity and novelty of available monitoring tools. Some studies are based on the use of one or more complementary technological approaches for assessing fine-scale hydropeaking impacts on freshwater ecosystems (e.g., Oliveira, Alexandre, Quintella, & Almeida, 2020; Rato, Alexandre, Almeida, Costa, & Quintella, 2021; Taylor et al., 2014). However, the increasing request for shorter manuscripts in specialised journals forces authors to be succinct when describing applied methods and usually there is no space for discussing their fundamentals, advantages, or disadvantages. Several papers describe in detail technologies that can be used to study fish responses to environmental conditions. However, they are focused in only one technique, not specifically focused on the assessment of dam and flow regulation impacts (e.g., Cooke, Thorstad, & Hinch, 2004; Mochnacz et al., 2017) or they were published before the development of more recent technological monitoring tools (Murchie et al., 2008).

Dam operation and hydropeaking impacts on downstream freshwater habitat and fish populations, independently of the methods used to assess them, are already widely described in the literature, particularly the ones that deal with broader scales, such as assemblage composition and abundance, or large-scale movements (e.g., Gibeau et al., 2017; Murchie et al., 2008; Poff & Zimmerman, 2010). Therefore, we will not address, in detail, such impacts in this revision. The specific objective of this paper is, thus, to review the technologies currently available and being applied in studies addressing hydropeaking impacts on freshwater fish. This paper aims to be an updated and fundamental resource for researchers, dam managers, and entities responsible for the management and conservation of regulated river systems. It will be a particularly useful tool to increase the quality and precision of planned experimental research or monitoring programs dedicated to the impacts of dams, hydroelectric power production, and related short-term flow discharges variability on downstream fish populations and respective habitat.

2 | THE USE OF TECHNOLOGY TO STUDY HYDROPEAKING

The revision presented in this paper reflects an extensive literature review on the existing methods involving technology that are commonly used to monitor habitat changes and freshwater fish responses to regulated streamflow and, more specifically, hydropeaking operations. This was undertaken by scrutinising peer-reviewed articles and some grey literature selected in accordance with the authors expert opinion on the relevance to the field of hydropeaking-related studies. This expert opinion was, however, guided by some principles that can be replicated in future similar studies: (a) we tried to avoid the inclusion of older references, that were already included in past revisions about this theme, while mostly focusing on more recent works; (b) we guided the paper, and respective literature reviewed for it, to describe the principles behind these technologies, address their advantages and disadvantages, and provide examples of their application and of the results that can be obtained when using them; and (c) we included references on suggestions about how researchers can take advantage, in the future, of the rapid technological development to enhance the quality of their studies about this theme. The conducted review, based on the previously described guidelines, resulted in the presentation and discussion of four major types of technological tool to monitor hydropeaking impacts: biotelemetry, swim tunnels and flumes, intermittent respirometry, and aquatic and aerial unmanned vehicles.

2.1 | Biotelemetry

Biotelemetry is a technique that allows gathering biological information using electronic tags that are implanted on target animal species. Advantages of biotelemetry include the ability to assess differences among individual behaviours and to work across different spatial and temporal scales (Cooke, Hinch, LuCaS, & Lutcavage, 2012). Because telemetry is typically conducted in field settings, it provides better environmental insight than is possible in laboratory conditions and data that can be collected continuously under varying environmental conditions (Cooke et al., 2012). Adaptive responses of organisms usually are related with environmental perturbations. Those constraints cause populations to respond to a periodic disturbance by developing an adaptation with suitable time-constraints. In response to a constraint, change in behaviour is the first temporal response of mobile individual organisms, followed by physiological changes (Slobodkin & Rapoport, 1974). Biotelemetry is a particularly adequate monitoring technique to study the behaviour and ecophysiology of individual fish in a wide range of aquatic environments (Cooke et al., 2013) and by extension their associated short and middle term biological responses to hydropeaking events.

Organisms that are better adapted to unstable environments are those that can move to ensure survival and exploitation of available habitats under changing conditions (Scruton et al., 2003). Fish movements, distribution, home range, habitat use, and swimming activity are behavioural metrics that can be assessed in river reaches subjected or not to hydropeaking by a variety of biotelemetry techniques such as radio, acoustic, passive integrated transponder (PIT) tag, and physiological sensors (Figure 1; Table 1) in different types of aquatic environments.

Radio-telemetry uses the transmission of radio signals produced by an active tag to locate fish in aquatic environments. A radio telemetry system is made up of three parts: a radio transmitter, a radio

FIGURE 1 Biotelemetry techniques used to study fish movements in rivers: (a) manual tracking with radio telemetry receiver and hand held Yaggi antennae (photo by Carlos Alexandre); (b) passive tracking with acoustic telemetry receiver (photo by Bernardo Quintella); (c) manual tracking with a portable passive integrated transponder (PIT) antenna (photo by University of Liège-LDPH); (d) instream submersible stationary PIT antenna (photo by University of Liège-LDPH); (e) surgical implantation of an electromyogram (EMG) radio transmitter on an Iberian barbel *Luciobarbus bocagei* (photo by Carlos Alexandre); (f) detail of the gold electrodes of the EMG transmitter that will be secured on the red axial musculature to detect swimming activity (photo by Carlos Alexandre) [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Summary of biotelemetry techniques applied to study the impact of hydropeaking on fish

Biotelemetry technique	River/stretch	Advantages	Disadvantages	References
Radio	Small to middle size; depth <5 m	• Easy to conduct manual tracking—Possibility to obtain fine scale behaviour with high spatial resolution • High detection ranges—Depending on the transmitter (signal power and battery type/ size) and river conditions (i.e., depth) is frequently above 1 km in distance	• Expensive tags (unit ∼250€) leading to low sample sizes • Difficult to install an array of autonomous receivers to automatically track individuals—relatively low spatial definition on locations • Manual tracking is demanding in terms of human resources in the field • Not adequate to be applied in rivers with depths >5 m due to limitations in the propagation of the radio signal in water	Bunt et al. (1999); Almeida et al. (2002); Scruton et al. (2003); Berland et al. (2004); Scruton et al. (2005); Taylor et al. (2014); Alexandre et al. (2016); Boavida et al. (2017); Rocaspana et al. (2019); Oliveira et al. (2020)
Acoustic	Middle to large size; depth >2 m	• Possible to conduct a 3D high resolution location of individuals tagged with transmitters with depth sensors—The area covered depends on the number of acoustic receivers available (on average 3 acoustic receivers are needed to cover 2–3 acres of riverbed to continuously track the position of tagged individuals) • Medium detection range—depending on the transmitter (signal power and battery type/size) and river conditions (i.e., depth and presence of turbulent flows) is frequently bellow 500 m distance	• Expensive tags (unit ∼300€) leading to low sample sizes • Expensive fixed receivers (unit ∼2000€) • Not adequate to rivers with depths <2 m and with riffle habitats due to limitations on the propagation of the ultrasonic signal in turbulent flows	Capra et al. (2017)
PIT	Small rivers; depth <1 m	• Possible to tag very small fish • PIT tags are inexpensive (∼3€/tag) when compared to transmitters—Possibility to use large sample sizes • High longevity—PIT tags are energized by external antennae via an electromagnetic signal. Since no batteries are need the study can be conducted with the same individuals during long periods of time	• Manual tracking time consuming—Only possible to monitor a very small areas • Very low detection ranges—Generally less than 20 cm but they can go up to 60 cm depending on the PIT tag and antenna • Fish behaviour can be disturbed during manual tracking since it involves the use of a submersible handheld antenna with the operator wading the river on the downstream-upstream direction • Instream antennas for autonomous tracking are expensive and since the detection ranges are restricted (typically ∼20 cm) the probability of not detecting an individual is not negligible	Boavida et al. (2020); Bartoň, Brabec, et al. (2021)

(Continues)

TABLE 1 (Continued)

Biotelemetry technique	River/stretch	Advantages	Disadvantages	References
Physiological electromyogram (EMG) sensor (radio)	Small to middle size; depth <5 m	• The only technique that manages to obtain physiological data on the tagged individual concerning the muscle activity and possibly the energy expenditure (swim flume calibration procedures relating swim speed and EMG signal) • the same advantages mentioned in radiotelemetry	• Very expensive tags (∼600 €/tag) leading to low sample sizes • Intrusive method for tagging and implanting the electrodes on the red axial musculature to record the electromyogram signals—only large fish can be tagged (>1 kg) • the same disadvantages mentioned in radiotelemetry	Taylor et al. (2012); Rato et al. (2021)

antenna and a radio receiver. This technique is adapted to be used in small and middle-sized rivers with water depth up to 7 m. Manual and/or fixed radiotelemetry was the most frequently telemetry technique used, often with a limited number of fish individually tracked to allow more qualitative analysis of fish fine scale responses at spatial and temporal levels. Manual radio-telemetry provides quick, accurate, and on time locations, even if the location of the fish is labour intensive as it implies the presence of field workers to locate the fish. Passive automatic stations can be used and allow the automatic location of fish, but with a loss of spatial precision. Many studies about hydropeaking impacts targeted salmonids such as the brown trout *Salmo trutta* L. (e.g., Bunt, Cooke, Katopodis, & Mckinley, 1999; Rocaspana, Aparicio, Palau-Ibars, Guillem, & Alcaraz, 2019), the Atlantic salmon *Salmo salar* L. (Berland et al., 2004; Boavida, Harby, Clarke, & Heggenes, 2017; Scruton et al., 2003, 2005), the brook trout *Salvelinus fontinalis* Mitchill, 1814 (Scruton et al., 2005) and the bull trout *Salvelinus confluentus* Suckley, 1859 (Taylor et al., 2014). The results are divergent on what concerns the behavioural responses of fish to hydropeaking events, with some species demonstrating a higher propensity to move during hydropeaking conditions while others express the opposite behaviour. More recently, studies conducted in Europe targeted cyprinid fish such as the Iberian barbel *Luciobarbus bocagei* Steindachner, 1864. Radio tagged Iberian barbel inhabiting a hydropeaking river, exhibit larger and more continuous home ranges, in opposition to the smaller and patchy areas (summer refuges) used by fish inhabiting the non-regulated river (Alexandre et al., 2016). However, for the same species, differing results were obtained by Oliveira et al. (2020) using a before-after flow regulation impact sampling design, pointing out that there was no regulation impact on the movement patterns of the tracked Iberian barbel. On another study with a different species, the fast increases of flow associated with hydropeaking events can trigger the upstream directional movement of sea lamprey *Petromyzon marinus* L. (Almeida, Quintella, & Dias, 2002).

Radio-frequency identification (RFID) telemetry (or commonly called PIT-telemetry) uses electromagnetic fields to automatically identify and track tags inserted to fish. Although triggered by the energy from an electromagnetic interrogation pulse from an antenna connected to an RFID reader device, the tag transmits digital data, usually an identifying inventory number, back to the reader. As the tag is passive, the detection distance is limited to less than 1 m. PIT-telemetry has the advantage of lower cost, unlimited lifespan, and small size of the tag, but manual location of the fish is more fastidious due to the limited detection range and the installation of fixed antennas is hardly conceivable to study hydropeaking impact. However, this technology was successfully used to compare the spatial distribution of fish during or without hydropeaking events in cyprinids species (Boavida et al., 2020). They demonstrated that, overall, differences in the use of habitat were observed between different flow conditions, and among the two studied Iberian cyprinids: the nase *Pseudochondrostoma duriense* Coelho, 1985, and the chub *Squalius carolitertii* Doadrio, 1988. Bartoň et al. (2021) used passive PIT antennas to study asp (*Leuciscus aspius* L.) and observed that hydropeaking resulted in the change of spawning behaviour and likely caused interruption of spawning or shifting spawning outside the optimal area for egg development. During hydropeaking conditions, with the quick and abrupt change of flow water level and velocity, several conditions (e.g., restrict detection distance of the PIT tag, security conditions to operate a manual tracking) may hinder the application of this technique, particularly on medium-large size rivers. But, on small streams and with enough instream or pass-by antennas, it can be the adequate technique to monitor small fish species/juvenile's microhabitat use and behaviour when facing distinct flow conditions.

Acoustic telemetry uses active tags that are small sound-emitting devices allowing the detection and/or remote tracking of organisms in large and deep aquatic ecosystems. In riverine environments studies using acoustic telemetry can be conducted in lakes, large rivers, and estuaries. Aquatic environments with acoustic turbulence are not suited to acoustic telemetry monitoring because turbulence affects the propagation of the ultrasonic sound. This technology allows to obtain locational data of tagged fish. Depending on tag and receiver array configurations, by receiving simple presence/absence data, 2D positional data, or even 3D fish tracks in real-time with sub-meter resolution.

Studies in such deep and large environments focusing on hydropeaking impacts are particularly scarce due to logistical difficulties in obtaining the necessary information. Acoustic manual tracking is poorly adapted due to the difficulty to have quick positions by boat and the associated synchronism with the temporal changes in flow and was not used yet. Capra et al. (2017) deployed modern fixed high-resolution acoustic telemetry techniques to survey rheophilic cyprinids, catfishes, and chubs in the Rhone River, signalling their position every 3 s over a 3-month period in association with the modelling of hydraulic and temperature habitat conditions. This study suggested that fish appear to memorise spatial and temporal environmental changes and adopt a "least constraining" habitat selection. Thus, to avoid fast flowing midstream habitats, fish generally live along the banks in areas where the dewatering risk is high.

Changes in space and time use are among the first symptoms observed in the presence of a stressor (Scherer, 1992). The use of ElectroMyoGram telemetry is adapted to study the impact of hydropeaking on fish swimming activity and related energy expenditure. Electromyograms are bioelectric voltage changes that are proportional to the degree and duration of muscle tension (Sullivan, Hoefener, & Bolie, 1963). Thus, electromyograms (EMGs) recorded from electrodes implanted into myotomes of the red oxidative muscles can be used as quantitative indicators of swimming activity (Cooke et al., 2004). Using this technology, Taylor, Cook, Hasler, Schmidt, and Cooke (2012) showed for whitefish (*Prosopium williamsoni* Girard, 1856) that hourly mean discharge had a significant positive effect on swimming muscle activity, but fluctuating flows were no more energetically costly than stable flows. The same technique was used to assess the behaviour of the Iberian barbel, indicating that the increase in flow magnitude associated with daily hydropeaking operations decreased their activity and was associated with a refuge-seeking behaviour (Rato et al., 2021).

Based on this review, it would be important in the future to extend the hydropeaking research in large environments and to study a more diverse set of species since up to now only salmonids and a restricted number of other species have been studied with biotelemetry. Other types of biotelemetry techniques that can record physiological and very fine-scale behavioural/activity data, such as 3D accelerometer transmitter or archival tag (e.g., Almeida et al., 2013; Pereira et al., 2021), are yet to be applied to better understand the effect of hydropeaking on downstream fish populations. Three-axis acceleration sensor acoustic transmitters (AccelTag) programmed to identify specific acceleration patterns associated with particular behaviours (e.g., rapid change in direction and body movement associated with stressful flow conditions) could be used to obtain fine scale behaviour during distinct hydrological conditions. The initial investment in the calibration process (i.e., develop a mathematical algorithm to identify behavioural signatures with 3D accelerometer data) is time consuming but the outcome is a transmitter capable of recording data remotely with a level of detail not yet found in any other technology used to study fish behavioural ecology (Almeida et al., 2013). This device combines the features of archival tags (records acceleration in all three directions measuring and logging the processed data) and acoustic transmitters (send the relevant information on a pre-defined sampling rate). Therefore, this tag can autonomously identify and record specific signatures (i.e., behaviour patterns) of different movements transmitting the data autonomously and periodically to an acoustic biotelemetry receiver (Pereira et al., 2021).

2.2 | Swim tunnels and flumes

The effects of hydropeaking on fish communities can be assessed either in natural or in controlled conditions. Fish responses that are measured in rivers mirror the effects of the natural environment. However, there are numerous environmental factors other than flow that also affect those responses and increase the difficulty to isolate flow variability and interpret its effect. Those factors include the presence of habitat features (e.g., vegetation, substrate and woody debris), interactions with other species, or individual variability. Research conducted in artificial channels (i.e., flumes) has gained relevance in recent years to control for the effect of those confounding factors and attribute a biological response to specific changes in flow (Harby & Noack, 2013; Young, Cech, & Thompson, 2011). This research includes the use of two main types of flumes, outdoor (e.g., Auer, Zeiringer, Fuhrer, Tonolla, & Schmutz, 2017) and indoor (e.g., Costa, Ferreira, Pinheiro, & Boavida, 2019; Costa, Fuentes-Pérez, Boavida, Tuhtan, & Pinheiro, 2019). Outdoor flumes offer semi-natural habitat conditions, supporting the transferability of the results to natural conditions. At indoor flumes, it is possible to isolate external factors that add bias to the results, replicate experimental conditions and closely monitor fish behaviour. Flumes can differ in size, configuration, and location (Table 2), but, in both types, it is possible to manipulate the flow components described by Poff et al. (1997), namely magnitude, frequency, duration or rate of change, and simulate hydropeaking. Multiple fish responses, ranging from sub-organism level to whole-animal performance, have been examined in diverse flume-types, differing in size, configuration, and location (Table 2). Sub-organismal responses follow a neuroendocrine pathway, which aims to restore the homeostatic state after perceiving any external stimulus (i.e., stressor) that threatens it (Pankhurst, 2011). Negative effects occur when the organism is no longer capable of maintaining or recovering the homeostatic state, with consequences on key life-cycle events, such as reproduction, growth, and survival (Pankhurst, 2011). Simulated rapid flow fluctuations at outdoor and indoor flumes induced transient cortisol, glucose, and lactate adjustments in fish (Costa et al., 2018; Costa, Ferreira, et al., 2019; Costa, Fuentes-Pérez, et al., 2019; Flodmark et al., 2002). As glucose and lactate increments are respectively associated with primary responses to stress and anaerobic swimming (Pankhurst, 2011) it is expected that stress responses in hydropeaking conditions will be higher than those in base-flow conditions. Although the direction and range of these responses are difficult to determine (Costa, Lennox, Katopodis, & Cooke, 2017), they may represent reliable surrogates of a stress response to flow variability. Moreover, they can be further linked to a specific flow disturbance and be used to predict the effect of a potential mitigation measure. Whole-animal performance and movement behaviour shifts are the most studied responses in flume-based hydropeaking studies (Table 2). Different studies reported high swimming effort manifested by increased drifting rates (Auer et al., 2017), diversified preference patterns towards alternative substrates (Chun et al., 2011), refuge configurations (Costa, Ferreira, et al., 2019; Costa, Fuentes-Pérez, et al., 2019; Flodmark et al., 2002; Moreira

TABLE 2 Examples of experimental flume research, detailing flume types and impacts/mitigation measures studied

Flume type	Flume dimensions length × width × height (m)	Impacts/mitigation measure	Target species	Reference
Impacts				
Artificial indoor stream channel	21 × 3.8 m	Stress responses	Brown trout (*Salmo trutta*)	Flodmark et al. (2002)
Outdoor streams housed within circular tanks	2.2 × 21 m	Behaviour and growth	Brown trout (*Salmo trutta*)	Flodmark, Forseth, L'Abée-Lund, and Vøllestad (2006)
Nature-like experimental flume	40 × 6 m	Stranding, fish displacement	European grayling (*Thymallus thymallus*)	Auer et al. (2017)
Lateral-displacement flume	2.00 × 1.18 × 0.59 m (testing arena)	Stranding	Rainbow Trout (*Oncorhyncus mykiss* Walbaum, 1792), hardhead (*Mylopharodon conocephalus* Baird & Girard, 1854), Sacramento sucker (*Catostomus occidentalis* Ayres, 1854)	Cocherell et al. (2012)
Modified Brett-type tunnel	1.20 × 0.08 × 0.08 m	Eggs displacement	Asp (*Leuciscus aspius*)	Bartoň et al. (2021)
Mitigation measure				
Indoor artificial fiberglass flume	6.00 × 0.37 × 0.30 m	Cover structures	Brown trout (*Salmo trutta*)	Vehanen, Bjerket, Heggenes, Huusko, and Mäki-Petäys (2000)
Artificial stream	19.2 × 3.8 m	Operational measures	Brown trout (*Salmo trutta*)	Halleraker et al. (2003)
Artificial flume	1.80 × 0.5 × 0.5 m	Lateral refuge	Barbel (*Barbus barbus* L.)	Vilizzi and Copp (2005)
Experimental glass flume	16.5 × 0.6 m	Substrate heterogeneity	Juvenile hardhead (*Mylopharodon conocephalus*), rainbow trout (*Oncorhyncus mykiss*), Sacramento sucker (*Catostomus occidentalis*)	Chun et al. (2011)
Indoor channel	12.0 × 1.2 m	Lateral refuges (pool)	Brown trout (*Salmo trutta*)	Ribi, Boillat, Peter, and Schleiss (2014)
Indoor artificial flume	6.50 × 0.70 m (usable area)	Lateral flow-refuges	Iberian barbel (*Luciobarbus bocagei*)	Costa, Boavida, Almeida, Cooke, and Pinheiro (2018)
Indoor artificial flume	6.50 × 0.70 m (usable area)	Lateral flow-refuges	Iberian barbel (*Luciobarbus bocagei*)	Costa, Ferreira, et al. (2019)
Indoor artificial flume	6.50 × 0.70 m (usable area)	Instream structures	Iberian barbel (*Luciobarbus bocagei*)	Costa, Fuentes-Pérez, et al. (2019)
Indoor artificial flume	6.50 × 0.70 m (usable area)	Wood and acrylic L-structure	Iberian barbel (*Luciobarbus bocagei*)	Moreira, Costa, Valbuena-Castro, Pinheiro, & Boavida (2020)
Indoor artificial flume	5.27 × 0.7 m (usable area)	Vegetation	Iberian barbel (*Luciobarbus bocagei*), Iberian nase (*Pseudochondrostoma polylepis* Steindachner, 1864)	Baladrón, Costa, Bejarano, Pinheiro, and Boavida (2021)

et al., 2020; Ribi et al., 2014; Vehanen, Jurvelius, & Lahti, 2005; Vilizzi & Copp, 2005) and vegetation patches (Baladrón et al., 2021), and decreased stranding risk after slower ramping rates (Halleraker et al., 2003). However, other studies have not observed a clear effect of simulated hydropeaking (e.g., Flodmark et al., 2006). Although flume-based research evidenced that rapid flow fluctuations affect whole-animal performance, some findings can also be inconclusive.

The negative effects of hydropeaking on fish are widely recognized (Gibeau et al., 2017; Poff & Zimmerman, 2010; Young et al., 2011). In recent years, increasing research effort has been directed to finding mitigation solutions to hydropeaking consequences based on flume studies (Table 2). However, most of these studies were designed to offer flow refuge for salmonids based on changes in the swimming activity (Ribi et al., 2014; Vehanen et al., 2000), or the

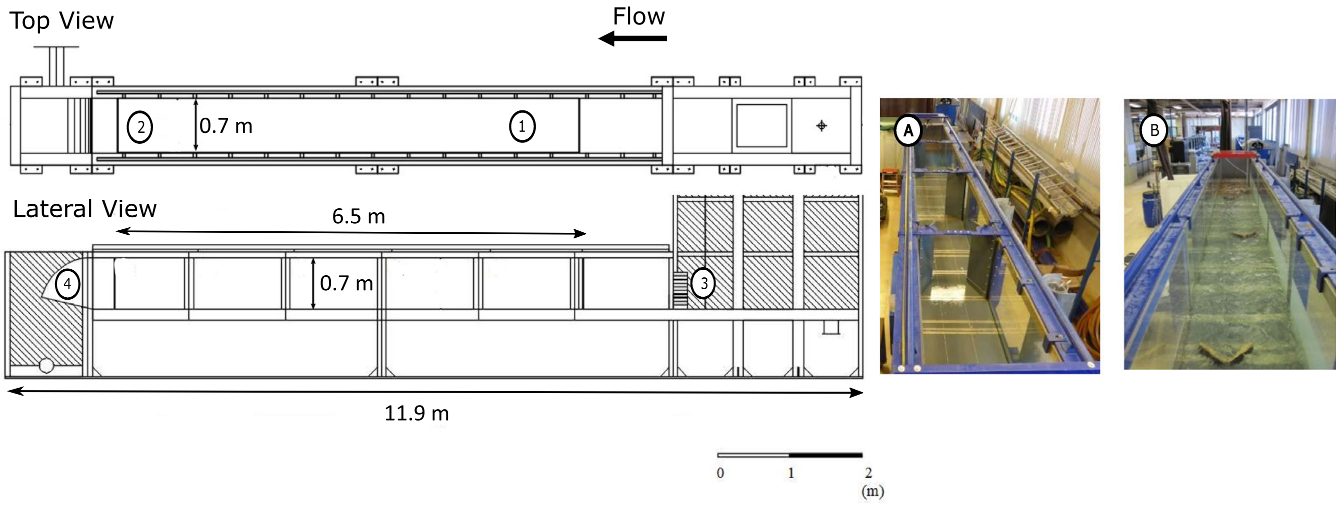

FIGURE 2 Top and lateral views of the flume located at the Laboratory of Hydraulics at Instituto Superior Técnico, University of Lisbon, with examples of the tested flow-refuges: (a) alternating deflectors, (b) v-shaped structures. 1—Flume false bottom where flow-refuges can be installed; 2—Downstream perforated panel. Fish can use the area between the down- and upstream perforated panels (i.e., 6.5 m); 3—Upstream plane gate; 4—Downstream flap gate. 3 and 4 control, respectively, the discharge and the water level (both photos by Isabel Boavida) [Color figure can be viewed at wileyonlinelibrary.com]

interaction with conspecifics in flume conditions (Sloman, Gilmour, Taylor, & Metcalfe, 2000; Sloman, Taylor, Metcalfe, & Gilmour, 2001). Specifically referring to habitat enhancement solutions in hydropeaking systems, substrate heterogeneity (Chun et al., 2011), T-shaped structures (Vehanen et al., 2000), and lateral refuges were suggested as potential flow-refuges for brown trout (Ribi et al., 2014) and young grayling (Valentin, Sempeski, Souchon, & Gaudin, 1994; Table 2). In recent years, the effects of hydropeaking and the design of flow-refuges as mitigation measures for Iberian cyprinids have been also examined at an indoor flume (Figure 2). Studies where instream structures (Costa, Fuentes-Pérez, et al., 2019), lateral deflectors (Costa et al., 2018; Costa, Ferreira, et al., 2019), cover structures (Moreira et al., 2020), and artificial vegetation patches (Baladrón et al., 2021) were tested, concluded that fish behaviour changed according to the hydrodynamic conditions created by the flow event and the presence of structures. Iberian barbel took advantage of the hydraulic conditions created by lateral structures, particularly alternating deflectors under moderate peaks (Costa et al., 2018), and wood L-structures that conferred both overhead cover and flow refuge (Moreira et al., 2020). The complementary analysis of physiological and movement behaviour responses, along with a detailed characterization of the hydraulic conditions are crucial to identify the most suitable flow event-structure configurations for fish. We expect that improving habitat would be beneficial to fish (Branco, Boavida, Santos, Pinheiro, & Ferreira, 2013). However, before implementing habitat enhancement measures it is essential to investigate the existing river habitat conditions and the advantages of adding heterogeneity to mitigate hydropeaking consequences (Costa, Fuentes-Pérez, et al., 2019).

In flumes, classical and novel flow sensing technologies provide distinct but complementary information on the hydraulic conditions and on how fish may perceive them. Costa et al. (2018) used acoustic Doppler velocimetry (ADV) measurements and hydraulic models to relate the hydraulic variables with fish responses. Consequently, it was possible to identify a flow threshold that represented the resting state for the Iberian barbel, as well as the velocity magnitudes that allowed fish to use the flume without any swimming effort (Costa et al., 2018). Still, the velocity maps were not sufficient to explain the diversity of biological responses. With the use of a biomimetic technology, the Lateral Line Probe (LLP) (Tuhtan, Fuentes-Perez, Toming, & Kruusmaa, 2017), which is based on the principles of the fish sensory system, other hydrodynamic conditions were determined as triggers of movement patterns by Iberian barbel (Costa, Fuentes-Pérez, et al., 2019). This study concluded that rather than just velocity, it was the combination of local scale hydrodynamic features that determined the fish movement patterns. On one hand, the hydraulic characterization given by hydraulic models was relevant to explain flow-refuge use and swimming activity patterns. On the other hand, the LLP may represent a potential tool to assess the distributed sensing capacity of fish. ADV and LLP technologies provide sound results regarding the characterisation of the hydraulic conditions in flume studies. Feasibility, cost, and post-processing are aspects to consider regarding the choice of a flow sensing technology. Yet, to assess the potential of habitat enhancement measures, it is important to consider the flow changes and their impact on fish responses. Thus, ADV provides an accurate assessment of the hydraulic conditions, while LLP illustrates fluid-body interactions, which provides a better assessment of the hydrodynamic field that fish would perceive.

Although experiments in flumes are an important research approach to understand the effects of rapid flow fluctuations on fish, it is still challenging to infer that the same responses will occur in natural conditions (i.e., downstream of a hydropower plant). Moreover, in flumes it is challenging to simulate rapid flow fluctuations of the same order of magnitude and rate of change as in some regulated rivers or to reproduce natural conditions of substrate, hyporheic flow, and sediment dynamics (Harby & Noack, 2013). Nonetheless, the behaviour patterns reported in flume-based research have been observed in studies conducted in rivers (Krimmer, Paul, Hontela, & Rasmussen, 2011; Taylor et al., 2012), in nature-like channels (Auer et al., 2017), and in artificial streams (Flodmark et al., 2002). Ideally, complementary studies in the field should be conducted to assess the ecological consequences of those patterns, and, particularly, in the context of hydropeaking.

2.3 | Intermittent respirometry

Besides the more well-known impacts at the meso-habitat, community, and population level (e.g., Gibeau et al., 2017; Poff & Zimmerman, 2010), there is also a set of downstream short-term environmental alterations caused by dam operation and hydropower production. This includes changes in water temperature (Naiman, Latterell, Pettit, & Olden, 2008; Olden & Naiman, 2010), current velocity, dissolved oxygen, turbidity (e.g., Bruno, Siviglia, Carolli, & Maiolini, 2013; Toffolon, Siviglia, & Zolezzi, 2010), which can cause significant responses from fish at a more basal physiological level, namely in their active metabolism such as during swimming exercise (Alexandre & Palstra, 2017; Halleraker et al., 2003; Saltveit, Halleraker, Arnekleiv, & Harby, 2001). However, conventional field monitoring methods are, in most cases, insufficient to correctly study and evaluate the real magnitude and temporal persistence of these fine scale impacts on affected fish specimens. This is mostly due to their lack of adequate detail in analysing specific physiological responses (i.e., oxygen consumption) and inability to control or isolate different environmental components, which usually prevents conducting repeatable experiments and provide reliable and robust results (Murchie et al., 2008; Svendsen, Bushnell, & Steffensen, 2016). Therefore, we need to find solutions that can provide adequate detail, reducing these shortcomings while suitably assess such impacts.

Intermittent Flow Respirometry (IFR) is an experimental protocol for measuring oxygen consumption in fish, which combines short measurement periods in a recirculating, but closed, respirometer, punctuated by clean water flush periods. These flush periods are long enough to ensure that the water in the respirometer has been thoroughly exchanged to eliminate potential hypoxia, hypercapnia, and nitrogenous waste buildup in the chamber (Steffensen, 1989; Svendsen, Bushnell, & Steffensen, 2016). IFR was not always the first option to measure oxygen consumption by fish, as other techniques were previously used with this objective, such as closed (e.g., Ege & Krogh, 1914; Scholander, Haugaard, & Irving, 1943) or flow-through (open) respirometry (Niimi, 1978). However, with time and the appearance of more modern techniques, both methods tended to be avoided due to problems associated with progressive hypoxia and accumulation of nitrogenous wastes to which fish, inevitably, are subjected (closed respirometry). These two methods also comprise issues of equilibration time, caused by the exponential washout effect of water in the respirometer (open respirometry) (Eriksen, 2002; Steffensen, 1989; Svendsen, Bushnell, Christensen, & Steffensen, 2016). IFR allows the evaluation of oxygen consumption by fish at a high frequency and for long durations (which is essential to assess fish response and eventual recovery), and it is now commonly used for this purpose. IFR combines elements of both former methods and reduces problems associated with either of them. IFR includes short oxygen measurement periods in a recirculating, but closed, swimming chamber or respirometer, intermediated by clean water flush periods. Flush periods should be long enough to ensure that the water in the respirometer has been sufficiently exchanged to eliminate potential hypoxia and nitrogenous wastes that tend to accumulate in the chamber and prevent reliable estimations of fish metabolism related with oxygen consumption (Steffensen, 1989; Svendsen, Bushnell, & Steffensen, 2016). Although this method is currently the best approach for measuring oxygen consumption in swimming fish, it has the disadvantage of requiring more equipment and a more complex experimental setup than the prior two methods (Svendsen, Bushnell, & Steffensen, 2016). However, IFR is probably the easiest, more reliable, and less stressful method of accurately determining oxygen consumption in aquatic organisms. It can be considered as a valid method to monitor fish responses to sudden downstream abiotic variations caused by hydropeaking operations, by quantifying swimming metabolism and related oxygen consumption variability when facing different and highly variable environmental conditions (Alexandre & Palstra, 2017; Svendsen, Bushnell, Christensen, & Steffensen, 2016; Svendsen, Bushnell, & Steffensen, 2016). Measuring active metabolic rates through IFR (reviewed by Steffensen, 1989) and assessing the oxygen consumption of fish swimming at different speeds, requires a Blazka-type or Brett-type swim flume (Blazka, Volf, & Cepela, 1960; Brett, 1964) with high fish: flume volume ratio to efficiently assess the decrease in oxygen content over short time periods. Typical read out is a collection of "sawtooth waves" representing periods with the valves closed and then open when flushing, and where the decline of the slope indicates the decline in oxygen concentration and, indirectly, the metabolic rate. Generally, individual fish are subjected to IFR trials, but also (small) groups can be tested, allowing to also assess the effect of schooling on oxygen consumption (Burgerhout et al., 2013). Relations between swimming speeds and oxygen consumption can be determined in swimming trials where fish swim during a prolonged period (up to 200 min) per speed, and then oxygen consumption for each one of these periods is assessed. The relation between swimming speed and oxygen consumption is generally described by an exponential function at the lower speeds, accomplished aerobically by red (slow) skeletal muscle performance, until recruitment of the anaerobically functioning white (fast) skeletal muscle at the higher speeds when the relation starts to flatten, and the oxygen debt is increasing (Goldspink, 1977). Oxygen consumption can be expressed per unit of time (e.g., mg O_2 per kg fish per minute) or unit of distance (e.g., mg O_2 per kg fish per meter) where the latter is also referred to as Cost of Transport (CoT). The optimal swimming speed (*U*opt) represents the speed where CoT is lowest and the energetic efficiency highest. *U*opt is hypothesized to reflect the speed for optimal growth during swim training of athletic fish (Davison & Herbert, 2013; Palstra et al., 2015) or migration speeds of long-distance swimmers (Palstra, van Ginneken, & van den Thillart, 2008). At swimming speeds lower than *U*opt, individual variations in oxygen consumption can be high as a substantial amount of energy is spent on (aggressive) behaviour, towards *U*opt the variations become significantly smaller and most energy is spent on fuelling and building muscle (Palstra et al., 2010; Palstra, Mendez, Dirks, & Schaaf, 2019). Critical swimming performance and the high individual variations in oxygen consumption are often repeatable and heritable (Mengistu et al., 2021). Significant ecological impacts, such as by hydropeaking, on (active) metabolic rates would therefore require high throughput measurements (e.g., Drown, DeLiberto, Crawford, & Oleksiak, 2020).

IFR was consistently used in recent years to successfully assess the effect of natural long-term or circadian environmental fluctuations (e.g., temperature) in the swimming performance and metabolism of distinct fish species (e.g., Beauregard, Enders, & Boisclair, 2013; Chabot, McKenzie, & Craig, 2016; Enders & Boisclair, 2016). However, until now, the number of studies using this method to evaluate the effects of the sudden and more accentuated environmental fluctuations that are usually observed in hydropeaking scenarios are scarce. Although, IFR has a great potential to perform detailed analyses of fish physiological fine-scale responses to this anthropogenic stressor. In 2017, Alexandre & Palstra conducted what is perhaps the first study to use IFR to directly evaluate fish response, in terms of swimming metabolism, when facing short-term temperature variations like the ones observed for a Portuguese case study of hydropeaking operations (Alexandre & Palstra, 2017). Testing experimental (temperature variation of approximately 4°C in 1 hr) versus control (no temperature variation) approaches, this study revealed that Atlantic salmon smolts show a strong metabolic response to sudden temperature variation, significantly reducing the oxygen consumption rate up to a seven-fold change. However, fish quickly returned to initial swimming costs shortly after reestablishment of temperature values, indicating a non-persistent impact of these dam-induced thermal changes. The study by Alexandre and Palstra (2017) is a good example of how IFR can be used to quantify the variations in oxygen consumption associated with accentuated environmental variability caused by hydropeaking operations. At the same it also allows us to evaluate the persistence of the studied impact, through the analysis of the time taken by tested fish to resume initial metabolic parameters.

Existing studies that use IFR to assess fish swimming metabolism in varying environments are mostly focused on the thermal variation component, as previously described in this section. However, there are other environmental factors (e.g., dissolved oxygen, turbidity, and current velocity) that may also influence oxygen consumption rates of individual migratory fish and that can be severely and suddenly altered when hydropower dams operate (e.g., Bruno et al., 2013; Nagrodski, Raby, Hasler, Taylor, & Cooke, 2012; Toffolon et al., 2010). Future studies should evaluate the individual and joint effects of these factors on the swimming economy of fish. Species-specific effects of hydropeaking at the fine-scale metabolic level should also be considered, due to the large biological and ecological variability existent in the ichthyofauna occurring in world regions facing increased hydroelectric exploitation (e.g., Europe and Australia; Arthington, 2012).

2.4 | Aquatic and aerial vehicles for river system characterization

The study of hydropeaking impacts at the habitat and ecological levels related to riverine fish populations implies conducting field work to characterise and map the physical environment of the river. A detailed understanding of the fluvial hydrosystems (Figure 3) will allow, for example, to quantify and characterise flow velocity fields and better describe the relation between hydrographical attributes and fish behaviour. Relevant attributes include the characterization of morphology, types and distribution of vegetation, margins, and hydraulic flow conditions (e.g., riverbed roughness, cross-section and longitudinal profiles, flow depths, and discharge fluctuations). Some of these attributes can be very complex to describe, and good quality data of the characteristics of river environments are needed, for example, for running and validating hydraulic and hydrologic models that describe interactions with fish mobility. In addition, suitable data would increase our understanding of the local impacts on the fluvial hydrosystem caused by hydropeaking.

Important developments in sensors and electronic devices can be used to monitor hydraulic variables and bathymetric surveys (e.g., cameras, sonar/acoustic imaging, ADCP—acoustic Doppler current profile, multiparametric sondes, fluorometers, Lidar technology, infrared thermography, or multispectral cameras). Field data collection and mapping can be supported by aerial UAS—Unmanned Aerial Systems (e.g., aircrafts or aerial fixed wings or multirotor aerial drones; Castendyk, Voorhis, & Kucera, 2020; Koparan, Koc, Privette, & Sawyer, 2018, Lally, O'Connor, Jensen, & Graham, 2019) and aquatic drones (e.g., Bibuli et al., 2014; de Lima, Boogaard, & de Graaf-van Dinther, 2020; Dunbabin & Marques, 2012), including ASV—Autonomous Surface Vehicles or UUV—Unmanned Underwater Vehicles. There are already examples of amphibious drones (e.g., Alzu'bi, Mansour, & Rawashdeh, 2018; Esakki et al., 2018), such as aerial drones that can land on the water and move as an ASV or that can dive and move underwater, UAS and aquatic drones allow characterizing the environmental changes caused by hydropeaking on fish habitat, collecting data on the explanatory environmental variables of the observed hydropeaking impacts on fish populations. In particular, because of their versatility regarding the adaptation of surveys to local conditions and study requirements, UUV, ASV, and UAS are overviewed below in more detail.

UUV can be operated remotely (ROV) or autonomous (AUV) and are used to perform a wide variety of tasks in underwater environments (e.g., inspections, repair and maintenance tasks, environmental surveys). These systems are usually tethered (when remote controlled) and equipped with different sensors and systems for navigation, or underwater positioning. ROV's are categorised according to their shape and size, which makes them suitable for different diving depth ranges, flow conditions, or able to carry varying payloads (e.g., water quality sensors or velocity measurement devices). Despite being commonly used in maritime environments, the costs associated with this type of systems have decreased drastically over the last few years,

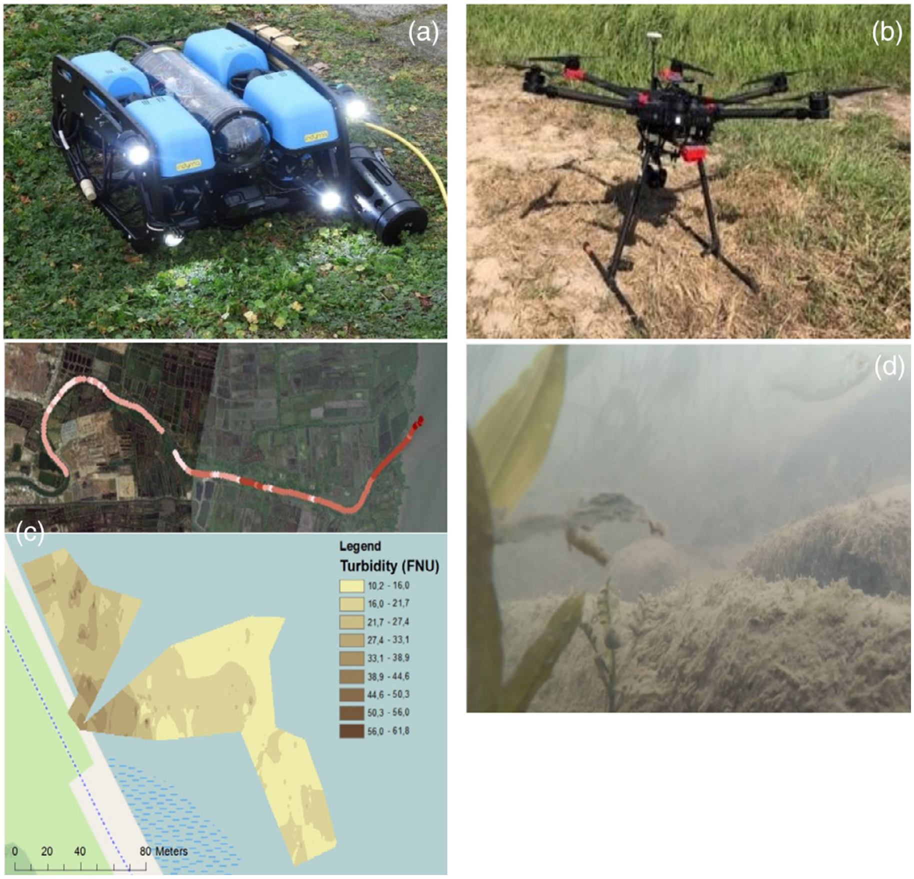

FIGURE 3 Examples of different unmanned vehicles/systems and results from data collection campaigns: (a) unmanned underwater vehicles equipped with cameras and water quality sensors; (b) unmanned aerial system, including multirotor drone equipped with sensors; (c) water quality mapping using aquatic drones equipped with sensors: electrical conductivity (top) and turbidity (bottom) in different sections of rivers (datasets obtained during a climate café workshop); (d) snapshot of underwater environment (fish, sediments and vegetation) captured with an aquatic drone at the river Maas, in The Netherlands (all photos by Rui Lima) [Color figure can be viewed at wileyonlinelibrary.com]

including Doppler velocity log systems, sonar, or acoustic modems. These technologies allow operating in difficult environments and conditions such as strong currents or lack of visibility, enabling new applications such as monitoring in rivers or in lakes (Capocci et al., 2017; de Lima et al., 2020; Norgren, Ludvigsen, Ingebretsen, & Hovstein, 2016).

The use of autonomous aquatic surface vessels for the collection of data and mapping is also gaining significance (e.g., Caccia et al., 2007; Demetillo & Taboada, 2019; Ødegård, Sørensen, Hansen, & Ludvigsen, 2016; Wibowo, Destarianto, Riskiawan, Agustianto, & Kautsar, 2018). Using vehicles that are smaller than manned boats allow reaching shallow or narrow parts of the water bodies and collecting data more efficiently. Autonomous navigation of these systems is possible by using GPS networks, as well as distance sensors or Lidar scanners to support obstacle avoidance algorithms. The main operation challenges include aspects such as the interaction with other boat traffic, or clogged propellers in the presence of aquatic vegetation. A wide variety of payloads (e.g., sensor, or system for sample collection) is possible with this solution.

UAS are used to perform aerial scans (i.e., by collecting different types of remote sensing imagery from the air; Manfreda et al., 2018), collect water samples for subsequent analysis (Agarwal & Singh, 2019) or collect in-situ data using sensors (e.g., Koparan et al., 2018). UAS allows us to measure (surface) flow velocity, monitor algal blooms, monitor migrating fish, or map water bodies and vegetation characteristics and condition (e.g., Flynn & Chapra, 2014; Manfreda et al., 2018; Shkurti et al., 2012). The range of options available both for non-professional and professional aerial drones have expanded considerably over the last few years, allowing for longer missions, with easier deployment, operation, and use of autonomous features that allow for systematic and precise sampling. In addition, different camera systems and imaging options (RGB, thermal infrared, multispectral, hyperspectral) are now available, which allow to calculate different indicators (e.g., vegetation indices, water mass area, river surface velocity, and turbulence metrics) and, for example, the effect of riparian cover on river temperatures. Optical sensors coupled with image velocimetry techniques are becoming popular for river monitoring applications (e.g., Perks et al., 2020; Pizarro, Dal Sasso, Perks, & Manfreda, 2020). UAS enable multi-temporal assessment and significantly improve hydro-morphodynamic modelling and calibration. Overall, the use of UAS is increasing, namely due to their affordable cost, flexibility, and ease of use, alongside advances in image processing tools and applied scientific approaches and methodologies. There are, however, some factors limiting their use, such as limited autonomy, adverse weather conditions (e.g., strong wind), flight regulations, and restrictions (e.g., in the proximity of airports and private properties) (see for example, Tmušić et al., 2020).

The understanding of hydropeaking impacts on fish populations can only be evaluated thoroughly if the physical environment is well perceived. The lack of detailed data of adequate temporal and spatial resolutions, and spanning specific river stretches and periods of interest hampers the full characterization of fish habitats. Such insight can presently be obtained by integrating data collected using different complementary innovative technologies, some of which are gaining popularity as powerful environmental monitoring tools. For example, aquatic and aerial drones are evolving rapidly, being equipped with new sensors that continue to open new avenues in research and operational purposes, because of the improved quality and diversity of the data collected, and competitive cost.

3 | FUTURE DEVELOPMENTS AND APPLICATIONS

Throughout this paper, we showed how different technologies can be used as monitoring methods to further detail and improve the evaluation of hydropeaking impacts on downstream freshwater ecosystems. We also showed how the application of such techniques in specific case studies was able to identify a diverse set of hydropeaking-related impacts in affected rivers, including their biological and habitat components. However, there are still shortcomings related with the application of such techniques and there is opportunity and need for technological and scientific progress before monitoring methods can encompass the full scale of potential biological and environmental variability associated with flow regulation impact assessments.

Biotelemetry technology, for example, has the great advantage of allowing for in-situ, real-time, and fine-scale monitoring of fish response to habitat changes related with hydropeaking operations. However, besides PIT-tags, most of the described tagging techniques have limitations related with the size of the fish that can be tagged and with the duration of the study (Cooke et al., 2013; Jepsen, Koed, Thorstad, & Baras, 2002; Jepsen, Thorstad, Havn, & Lucas, 2015). These are specifically related with battery lifetime, which is the main factor influencing tag size, limiting biotelemetry studies to large fish species or, when studying smaller fish, shorter studies. Biotelemetry should take advantage of later developments on micro and nanotechnology that allows the creation of very small electronic components with high performances that could be added to fish tags to make them smaller but highly durable. This would allow for movement-behaviour studies in the field to combine smaller species or younger life stages, prolonged study periods, and neglectable potentiasl effects on fish natural behaviour related with tag implantation (Cooke et al., 2013; Jepsen et al., 2015).

Laboratory studies involving swim tunnels, flumes or respirometry techniques, allow to study range-wide inter and intraspecific variation in fine scale individual behaviour and physiology (Alexandre & Palstra, 2017; Baladrón et al., 2021; Boavida et al., 2021; Costa, Fuentes-Pérez, et al., 2019). Working in these controlled conditions allows one to control all the factors affecting subsequent results obtained with these technologies and to clearly extract the data of interest for the respective objective (Farrel, 2008). However, it is from this strength that comes one of its main shortcomings: their strictly laboratory approach, as well as the lack of a multiple stressor evaluation (e.g., the joint impact of flow, temperature, and turbidity changes), reduce their applicability for real hydropeaking scenarios. Moreover, methods to analyse individual behaviour and physiology of fishes from remote areas or those that, due to their low tolerance to manipulations, cannot be brought back to the laboratory are lacking. Therefore, technological advances in this field should include the development of lighter and reliable swim tunnels, flume and respirometry systems, which would improve our capacity to conduct similar studies but directly in the field, without having to take fish from their natural environment (Mochnacz et al., 2017).

Advances in habitat mapping and characterization will be strongly dependent on the quality of the gathered data, namely the description of the physical environment. The progress observed in the use of unmanned aerial systems and aquatic vehicles will enhance the collection of good quality data that will contribute to the increasing understanding of processes and phenomena involved and, consequently, the modelling capacity. These habitat mapping technologies can be complemented with other available cutting-edge tools, currently playing an important role in environmental monitoring, such as satellite imagery (Cazenave, 2019; Vignudelli et al., 2019), smartphone apps (Higham & Plater, 2021), acoustic-based river stage recording, among other approaches.

The fast development of technology can contribute to enhance the future availability of more practical, precise, and reliable methods to study the relationship between aquatic biota and its environment, which is particularly valuable in rivers affected by hydropeaking. As demonstrated here, the application of modern technology to environmental science is of uttermost importance to improve our ability to predict how fish species will respond to changes in their environment. This knowledge is critical for informing related management, mitigation, and conservation strategies, while the increasing use of these modern and more precise technologies can provide a significant contribution towards a more sustainable use of hydropower.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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