

Review

Assessing the Impacts of Hydropeaking on River Benthic Macroinvertebrates: A State-of-the-Art Methodological Overview

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Abstract: As the global demand for renewable electricity grows, hydropower development of river basins increases across the world. Hydropeaking, i.e., streamflow alteration consisting of daily or subdaily rapid and marked discharge fluctuations, can affect river reaches below hydropower units. Environmental effects of hydropeaking include geomorphological alterations and possible modifications of the freshwater biota. Among affected instream communities, benthic macroinvertebrates are receiving increasing attention and the related scientific research has experienced significant progress in the last decade. In this context, this paper aims to summarize state-of-the-art methods for the assessment of hydropeaking impacts on benthic macroinvertebrate communities. The present review could support the proper design of monitoring plans aimed at assessing the ecological impacts of hydropeaking and the effects of possible mitigation strategies.

Keywords: hydropeaking; benthic macroinvertebrates; biomonitoring; regulated rivers; hydropower; ecological impact assessment; mitigation measures



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1. Introduction

Hydropower (HP) is the main source of renewable electricity, currently providing about 16% of the global demand of electrical energy [1]. Compared to other renewable sources (i.e., wind, solar), HP can efficiently meet electricity demand, allowing for strong variations in the production, even at the subdaily scale (i.e., peak HP). Basically, the modulation of power generation is achieved by storing water in reservoirs during periods of low electricity demand, generally resulting in low flows in the river reach below the tailrace channel, and to activate power generation during peaks of energy demand, thus rapidly increasing water release and, in case, downstream streamflow [2]. When changes in discharge, water level and ramping rates occur on a daily or subdaily scale and are more intense, rapid and frequent if compared to baseload energy production, the operational regime is named “hydropeaking” [2]. Among hydrological modifications caused by HP, hydropeaking induces the greatest impairment of the flow regime, with unfavorable ecological outcomes that cannot be overviewed when aiming at considering HP among sustainable energy sources.

Hydrological modifications induced by hydropeaking HP plants can be characterized in terms of amplitude, frequency and rate of change of flow fluctuations [3,4]. If compared to naturally occurring flow fluctuations (i.e., due to ice- and snow-melt or rainfall events) or to other types of hydrological alterations, variations in water velocity and the wetted channel area induced by hydropeaking are generally larger and faster [2]. As a consequence, natural adaptations of instream organisms to environmental variability, including species already adapted to hydrological alteration induced by baseload energy generation [5–7], are often insufficient for survival, with species requiring a narrow range of water velocities being particularly disadvantaged [2].

The effects of hydropeaking were indeed reported for many biological communities, and linked to hydraulic conditions during unsteady (i.e., up-ramping and down-ramping phases) and steady flow (i.e., base and peak flow conditions). In particular, downstream movement of fish occurs during the up-ramping phase [8]. While large adult fish may actively move downstream or avoid displacement, even if with significant stress due to energy consumption, juveniles and little-bodied species are especially affected, also due to their poorer swimming capacity [3]. These organisms, which generally inhabit shallow habitats with low flow velocities, are also the most heavily exposed during the down-ramping phase. Indeed, exposure to dry conditions in drawdown areas was highlighted by Casas-Mulet et al. [9] as the main cause for the mortality of Atlantic salmon (*Salmo salar* L.) alevins. Stranding, inducing fish mortality and egg-desiccation due to complete dewatering, and lethal to sublethal stress on individuals that remain trapped into temporary pools with unfavorable physical conditions (e.g., lack of oxygen and extremely low or high temperature) and overexposed to predation are documented in the literature [10]. However, unexpected results, such as high survival of Atlantic salmon eggs, have been found in dewatered areas where groundwater supply ensured the influx of oxygen-rich subsurface water [11].

Hydropeaking effects on vegetation include periphyton biomass reduction [12] and reduced establishment and growth of riparian vegetation, with the exception of few flood-tolerant species [13].

Regarding benthic macroinvertebrates, reported effects mostly concern the passive drifting during the up-ramping, with varying intensity according to differences in morphological and behavioral adaptations between taxa [14–16]. In addition, the rapidly changing water level and wetted channel area can induce acute egg-mortality and thus limited recruitment, particularly for taxa laying eggs near the shoreline [17] or requiring particular egg-laying substrates, such as partly emergent rocks [18]. Finally, streambed modifications due to altered entrainment and transport of sediments [19] as well as thermopeaking (i.e., abrupt variations in water temperature linked to the release of hypolimnetic water from reservoirs during hydropeaking [20]) can add further stress to the macroinvertebrate communities.

Among biological indicators, benthic macroinvertebrates are the most frequently used to detect river alterations, including hydropeaking impact. In fact, benthic macroinvertebrate communities have fundamental ecological functions in lotic ecosystems, including a prominent role in the organic matter cycling [21], and as primary prey for many fish species and terrestrial animals [22]. Studies on other biological components of the rivers, as autochthonous or allochthonous primary producers, are scarce, even if they could support the proper assessment of the impact on the whole trophic web.

In this paper, we summarize state-of-the-art methods for the assessment of hydropeaking impacts focusing on benthic macroinvertebrate communities. As the global demand for renewable energy increases, HP is experiencing a global development, posing the urgent need of improving the ecological sustainability of HP facilities, both the already existing and the new ones [23]. The availability of sound methods to efficiently monitor if related management solutions and mitigating measures ensure sustainable conditions for the freshwater biota is thus fundamental to achieving the ecological integrity of rivers [24].

2. Materials and Methods

For the scientific literature selection, we conducted a search on the Scopus database [25], considering papers including the terms “hydropeaking”, “hydro peaking”, “hydropeak” or “hydro peak”, combined with “macroinvertebrate” or “invertebrate” within the title, abstract or keywords. This allowed us to detect 45 peer-reviewed papers. Among these, we selected 24 papers, based on their content, i.e., providing specific information about methods for the assessment of hydropeaking effects on macroinvertebrates. To this selection, we added two further studies found by a snowball research approach, so that the basis for our review was composed of 26 papers.

Although we accounted for the basic knowledge that studies in flume experiments (e.g., [26]) provide on the relation between hydropeaking power generation and the status of macroinvertebrate communities, we decided not to include them in our selection, focusing only on the methods used in studies that reported on actual monitoring of the instream effects on benthic fauna downstream of HP plants.

3. Results

Among the 26 selected papers, 16 report on studies conducted in European water-courses, specifically in the Alpine and Pyrenean areas, and in Norway, while eight papers refer to United States and Canada and only two are from South America (Table 1). Although a few peer reviewed English-language studies might have been missed by our search approach, this geographical distribution is consistent with that of literature including other aspects of hydropeaking [4,13]. It is worth noting that most countries with the highest HP global capacity (China and Brazil [1]) and the highest number of HP dams planned or under construction (Asia, South America, Africa and East Europe [18]) are under-represented in the scientific literature, both considering our specific topic and in general [23].

Table 1. List of papers regarding monitoring of the effects of hydropeaking on benthic macroinvertebrates, subdivided by country and method.

Area	Country	Scientific Papers	Direct/Indirect Method
Europe	Austria	Holzapfel et al., 2017 [27]	Indirect
		Leitner et al., 2017 [28]	Indirect
		Moog, 1993 [29]	Direct
		Parasiewicz et al., 1998 [30]	Direct
	France	Hauer et al., 2017 [31]	Direct
		Céréghino et al., 2002 [32]	Direct
		Lagarigue et al., 2002 [33]	Direct
		Lauters et al., 1996 [34]	Direct
	Italy	Valentin et al., 1995 [35]	Direct
		Bruno et al., 2010 [14]	Direct
	Norway	Vanzo et al., 2016 [36]	Indirect
		Kjærstad et al., 2018 [37]	Direct
	Switzerland	Schneider et al., 2017 [38]	Indirect
		Aksamit et al., 2021 [39]	Direct
Bruder et al., 2016 [24]		Indirect	
Tonolla et al., 2017 [40]		Indirect	
Hauer et al., 2017 [31]		Direct	
North-America	Canada	Armanini et al., 2014 [41]	Direct
		Jones, 2013 [42]	Direct
		Mihalicz et al., 2019 [43]	Direct
		Pearce et al., 2019 [44]	Direct
	USA	Timusk et al., 2016 [15]	Direct
		Kennedy et al., 2014 [45]	Direct
		Miller and Judson, 2014 [46]	Direct
South-America	Brazil	Ruhi et al., 2018 [47]	Direct
		Castro et al., 2013 [48]	Direct
	Chile	Elgueta et al., 2021 [49]	Direct

Our selection of papers can be divided into two groups (separately commented in the following paragraphs), based on their approach for studying the effects of hydropeaking on benthic macroinvertebrates. Specifically, we defined (i) direct methods, which are those based on the direct study of macroinvertebrate communities affected by a hydropeaking HP plant; (ii) indirect methods, which are those based on the measure of physical variables affected by a hydropeaking HP plant, which can be linked to expected responses by the macroinvertebrate community. A total of 20 papers belonged to the first group and six to the second one (Table 1). The main aims and results of the selected papers are summarized in Table 2.

Table 2. Main aim and result of the selected studies, with particular reference to benthic macroinvertebrates. Ref = reference, Hpk = hydropeaking, HPP = hydropower plant, D = downstream site, U = upstream site and R = reference site, i.e., a site in an unimpacted river different from the river where downstream sites are located.

Ref	Main Aim	Main Result
<i>Direct methods</i>		
[14]	Assessing the macroinvertebrate response to a Hpk wave, accounting for the distance from the HPP and differences among taxa.	Most drift within the first 15 min of Hpk; 9-fold increase at the D site closest to the HPP, slightly attenuated with increasing distance; different timeframes in the response between taxa, possibly associated to habitat preferences.
[15]	Examining the drifting response to experimental subhourly changes in flow associated with a HPP, compared to the natural patterns of drift.	Average drift densities comparable between R and D sites, but less stable in D; multiple drift responses at the family level: consequently, the greatest taxonomic resolution required.
[29]	Quantitatively describing the effects of intermittent power generation, surveying Hpk-induced faunal damages and proposing mitigation measures.	Compared to the U site, biomass reduction of 75–95% within the first few km and of 40–60% within the following 20–40 km at D sites; structural or operational mitigation measures required to reduce ecological damage.
[30]	Evaluating the effects of two peaking flow options: single release (premitigation) and dual-flow release (postmitigation).	Biomass recovery from 15% to 60% of predicted values after mitigation measures (increased base flows and reduced peak flows).
[31]	Investigating the effects of peak flow in a longitudinal river profile downstream of the HPP and comparing the mitigating effects of artificial vs. natural sheltering habitats.	Abundance and biomass directly linked to substrate variability in self-formed sheltering habitats. These habitats should be targeted over the first 5 km downstream of the turbine outlet due to the higher stranding risk in this area.
[32]	Studying longitudinal changes in invertebrate composition and abundance downstream from the outlet of an HPP.	The low abundance of several species below the HPP outlet reflected the impact of both Hpk and zonation.
[33]	Determining the influence of intermittent Hpk on drift abundance, focusing on the differences between U and D site.	Drift density higher at D than at U site; no clear diel pattern at D; the larger the difference between natural and peak flows, the higher the catastrophic drift.
[34]	Determining the impact of Hpk on the aquatic environment, including benthic and drifting invertebrate populations.	Drift more abundant at the D than at the U site; significant drift peaks during Hpk; seasonal differences (the highest differences after the low-water period).
[35]	Investigating the effects of peaking flow regulation on the river trophic functioning, focusing on the role of the base flow between peaks.	Less diversified and more specialized communities at D sites; morphological unit specificity reduced in hydropeaking regime compared to base flow.
[37]	Investigating the effects of frequency and magnitude of Hpk regimes on the invertebrate community composition and changes along lateral gradients.	Different composition and lower density in the ramping zone, especially after Hpk.
[39]	Assessing the response to progressively decreasing recovery times between experimental Hpk events in pool and riffle habitats.	Habitat specific reactions to Hpk (more drift in pool than in riffle); drift abundance not correlated with recovery time, but cumulative effects for some taxa.
[41]	Investigating the ecological effects of altering a peaking HP scheme, by applying the Canadian Ecological Flow Index (CEFI).	Suitability of the CEFI index for detection of benthos response to changes in ramping rates.
[42]	Examining diversity patterns in different rivers, longitudinally within rivers and laterally from the shore to deeper waters by considering natural R rivers and a U–D study design.	Higher taxa densities in the permanently wetted zone than in the varial zone; few differences in diversity measures between D and R sites due to metric or reference site inadequacy.
[43]	Assessing the potential effects of a daily Hpk dam on downstream communities and the potential for seasonal variation in effects.	Lower ratios of sensitive to tolerant taxa at D than U sites; highest effect in spring.
[44]	Assessing the effects on the food web of changing ramping rates using carbon and nitrogen stable isotope analyses and both the BACI design and an examination of temporal trends.	No effect of changing ramping rates on food web metrics; need for considering large spatial and temporal scales.

Table 2. Cont.

Ref	Main Aim	Main Result
[45]	Developing a framework for modelling invertebrate drift to describe the functional relations between invertebrate drift and two primary controls: ramping of regulated flows and benthic densities.	Drift concentrations controlled by Hpk (within-day variation) and benthic densities (weeks to months).
[46]	Quantifying how drift and benthic assemblages respond to non-bed-mobilizing Hpk operations at both hourly and monthly time scales.	Mean daily drift biomass significantly higher during double-peaking; biomass peak during the rising limb of the hydrograph.
[47]	Assessing the influence of a novel flow regime for improved HP flow management on the long-term functional dynamics of an invertebrate metacommunity through time-series techniques.	Simplification of the functional structure by filtering out taxa with non-adaptive traits and by spatially synchronizing their dynamics.
[48]	Investigating the degree to which flow fluctuations alter daily and seasonal invertebrate drift patterns in a tropical river.	Daily and seasonal (wet vs. dry) drift patterns influenced by dam operations.
[49]	Unpacking the interplay of geomorphology and hydrology as drivers of assemblage structure in a river network subjected to Hpk.	Significant reduction of abundances in two functional process zones and at all ecological organization levels (except for scrapers).
<i>Indirect methods</i>		
[24]	To provide a conceptual framework combining Hpk impact analysis, evaluation of mitigation measures and monitoring of mitigation success.	Effects of mitigation measures on a set of indicators (which covers all hydrological phases of Hpk and the most important affected abiotic and biotic processes) can be predicted quantitatively.
[27]	Implementing a predictive habitat model to evaluate effects of flow fluctuations on potential epibenthic feeding grounds by revealing patterns of overlapping between fish and macroinvertebrate habitats.	Feeding from the benthos for juvenile and subadult brown trout is inhibited during peak flow and is therefore restricted to base flow periods; potential benthic feeding areas occurring at base flow increase with the level of river morphological heterogeneity.
[28]	Evaluating the national standard of invertebrate sampling in terms of Hpk and deriving functional relationships between the abiotic environment and habitat use of selected macroinvertebrate species.	The standard protocol was not capable to reflect the impact of pulse release; habitats of stagnophilic taxa are minimized in channelized stretches affected by Hpk.
[36]	Quantitatively exploring ecologically relevant hydraulic interactions between different Hpk scenarios and different channel morphologies, through the use of 2D hydraulic modelling.	Compared to alternate bars, braided reaches are more resilient to Hpk, offering the highest habitat diversity and very limited base-to-peak variation of drift.
[38]	Applying a fuzzy logic model for the investigation of macrobenthic habitats under Hpk conditions.	The amount of persistently high-quality habitat is closely related to the size and range of fluctuations in hydraulic conditions occurring during Hpk.
[40]	Examining possible methods for the evaluation of Hpk impacts; predicting ecological benefits of possible measures to mitigate these impacts; defining a viable procedure to select the most appropriate mitigation measure.	Most appropriate mitigation measure identified through representative hydrographs and quantitative or qualitative prediction of 12 biotic and abiotic indicators.

3.1. Direct Methods

In this section, we will briefly summarize the main elements that should be accounted for when planning a monitoring of river macroinvertebrates and relative solutions adopted in the literature regarding hydropeaking impacts.

Flow regime exerts a large variety of influences on riverine communities and ecosystem processes [50]; as a consequence, when attempting at quantifying biotic responses to altered flow patterns, the definition of the adequate spatial and temporal study frame becomes crucial [51], as well as the characterization of the HP scheme and hydropeaking regime (Table 3).

Table 3. Main characteristics of the study contexts of the selected papers. Ref = reference, HPP = hydropower plant, R = reservoir, ROR = run of the river, Q_m (m^3/s) = mean annual flow, Q_{base} (m^3/s) = minimum discharge, Q_{peak} (m^3/s) = peak discharge, UR = up-ramping phase, DR = down-ramping phase, ΔQ_U ($m^3/s \cdot min^{-1}$) = up-ramping rate, ΔQ_D ($m^3/s \cdot min^{-1}$) = down-ramping rate, n.a. = not available.

Ref	River	HPP Type	Q_m	Q_{base}	Q_{peak}	Q_{peak}/Q_{base}	Hydropeaking Characteristics
[27]	Alpine Rhine	R	119	27	185	7.0	n.a.
	Inn	R	156	38	129	3.4	n.a.
	Enns	R	40–45	15	52	3.4	n.a.
[28]	Ziller	R	43	8.9	118	13.3	n.a.
			29	4.0	90	22.8	
[30]	Drau	R	n.a.	27	110	4.1	DR = 1–120 min
	Inn	R	n.a.	33	86	2.6	n.a.
				29	84	2.9	
[32,33]	Alpine Rhine	ROR	n.a.	20	120	6.0	n.a.
	Oriège	R	1 (low flow)	1 (low flow)	11 (low flow)	11.0 (low flow)	UR + DR = 3 h (Oct.)
			15 (spate)	5 (spate)	15 (spate)	3.0 (spate)	5 h (Jul.)
[34]	Oriège	R	4	0.7	11	15.7	n.a.
[35]	Fontaulière	R	12	1.4	20	14.1	UR = 20 min
				0.1	13 to 20	108.3 to 166.7	n.a.
[14]	Noce Bianco	R	n.a.	1.0	7	7.0	UR = 10 min
[36]	Italian Alpine streams	n.a.	n.a.	5.0, 10, 20	50, 55, 65	10.0, 5.5, 3.5	UR = 0 min
[37]	Bævra	R	n.a.	0.0	11	-	UR = 5 min
[38]	Lundesokna	R	n.a.	1.0	21	21.0	UR = 2 min
[38]	Surna	R	46	15	39	2.6	n.a.
[39]	Upper Rhone	ROR	0.3 (January–March) 8.6 (July–August)	0.2	2.6	13.0	UR + DR = 15 min
[40]	Hasliaare	R	35	3.1	42.2, 44.8, 45.4	13.6, 14.5, 14.7	$\Delta Q_U = 1.36, 0.86, 0.76$ $\Delta Q_D = -0.7, -0.37, -0.2$
[15,41,42,44]	Magpie	R	27	7.5	45	6.0	UR = <1 h
[43]	Saskatchewan	R	n.a.	75	90 (June)	1.2 (June)	UR + DR = 1 h (July)
					135 (July)	1.8 (July)	
					225 (August)	3.0 (August)	
					345 (September)	4.6 (September)	
[45]	Colorado	R	325	200	500	2.5	n.a.
[46]	Green	R	52	28	>75	2.7	UR + DR = 2–4 h
[47]	Chattahoochee	R	n.a.	21	210	n.a.	n.a.
[48]	Rio Grande	ROR	323 (wet) 111 (dry)	n.a.	481 (wet) 173 (dry)	n.a.	UR = 90 min

Accordingly, in studying the effects of hydropeaking on benthic macroinvertebrates, the spatial extent of the investigation should account for modifications both at the watercourse scale, at the mesohabitat scale and at the patch scale. The earliest studies on hydropeaking already documented ecological effects of peaking flows up to significant distance (i.e., several km) downstream of HP tailrace channels [29]. Accordingly, many of the studies considered in this review reported the results of macroinvertebrate samplings performed at increasing distance downstream of HP plants releases [14,15,29,30,32,41–45,47,52] (Table 4). This generally allowed the authors to notice the detectable impact of hydropeaking a long distance below the water release (a few kilometers up to 50 km, depending on river dimensions and morphology), even if, in many cases, longitudinal gradients of decreasing influence were highlighted.

Table 4. Direct methods: main characteristics of the study design and methodology. Ref = reference; type of sites: U = upstream, D = downstream, R = reference, i.e., a site in an unimpacted river different from the river where downstream sites are located; sampling technique: Dr = drift, Be = benthic; sampling schedule per each site: Hpk = hydropeaking, B = before hydropeaking, D = during hydropeaking, A = after hydropeaking, Uns = unspecified, BF = base flow, Rep = replicates; taxa resolution: O = order, F = family, G = genus, S = species, LP = lowest possible; n.a. = not available.

Ref	N and Type of Sites	Distance (km) Below dam/HPP	Sampling Technique	Sampling N and Schedule	Taxa Resolution
[14]	1U-3D	0.25–8	Dr	1 Hpk event: 4B-6D (3 Rep)	LP (O to S)
[15]	3R-3D	3–9	Dr-Be	4 Hpk events: Dr: 4–28D/Be: 8–10Uns	mainly F
[29]	1U-7D	n.a.	Be	n.a.	O to S
[30]	1U-3D	0.4–11	Be	3Uns—2 pre and 1 postmitigation period (6 Rep)	LP (mainly F)
[31]	2D	n.a.	Be	1Uns (6 Rep)	mainly F
[32]	1U-9D	0.03–4.4	Be	2A—during spate and low flow period (5 Rep)	F/G/S
[33]	1U-1D	0.7	Dr	2Uns—during spate and low flow (every 0.5–1 h over 24 h)	F/G
[34]	1U-1D	1	Dr-Be	During spate and low flow period: Dr: 2D—every 0.5–1 h over 24 h/Be: 2Uns (10 Rep)	O
[35]	1U-2D	<1–4	Be	3Uns—2 before and 1 after flood (6 Rep)	mainly G
[37]	2U-2D	0.15–1.9	Be	Surber: 2Uns (5 Rep in ramping and 5 in deep zone)	LP (F/G/S)
	3U-3D	0.3–2.3	Be	Kick: 11 in different flow regime (6 Rep)	
[39]	1U-1D	0.6	Dr-Be	5 Hpk events in pool and riffle: Dr: 1B/4D/1A (3 Rep)/Be: 5B (5 Rep)	mainly F
[41]	6R-1U-5D	2.5–10.5	Be	3Uns with and 3 Uns without restrictions on ramping rates (5 Rep)	F
[42]	19R-1U-3D	3–8	Be	2Uns—during high and low flow period (8–10 Rep)	mainly G
[43]	3R-5D	2–50	Be	5Uns—one per ice-free month (3 Rep)	G/S
[44]	3R-1U-2D	6–20.5	Be	10Uns—one per year, in August	F
[45]	1D	11–19	Dr-Be	20 Hpk events: Dr: 3–5D (3 Rep)/Be: 1B	F/G
[46]	1U-2D	<1–10	Dr-Be	2 before and 5 during double-peaking: Dr: 6–8D (7 Rep)/Be: 1BF + long-term series	mainly G
[47]	4D	1–45	Be	4Uns over 11 years (3 Rep)	LP (mainly G)
[48]	1D	5	Dr	In wet and dry season: 12BF-12D (3 Rep)	F
[49]	8R-6D	<5–80	Be	1Uns (6 Rep)	LP (F/G)

Regarding site selection, in most of the mentioned papers, macroinvertebrates sampling was performed both upstream and downstream of the flow disturbance source [14,29,30,32–35,37,39,41,42,44,46,49] (Table 4). This choice is always recommended when studying the effects of a local source of impairment on macroinvertebrate communities, because it helps identify if measured modifications in the studied communities are related to the studied perturbation or to larger scale disturbance, such as meteorological events. However, the upstream–downstream comparison of communities may be poorly representative, for instance when an excessive difference in altitude (and thus geomorphology, hydrology and climate) between the reference and the impacted sites could induce different biological assemblages, regardless of dam-induced hydrological alterations [53]. In these cases, sites

located on nearby watercourses with similar physical natural characteristics can be selected as a reference, as already done in studies about hydropeaking [15,41,42,44,49] (Table 4) and on general HP-induced hydrological impairment [7].

Since hydropeaking primarily entails the modification of instream hydraulic parameters, local hydraulic patterns within the river channel can result in differently affected abiotic and biotic conditions. As a consequence, the specific location (in terms of mesohabitat selection and sampling area selection within lateral river transects) where to perform macroinvertebrate sampling is crucial in determining the results of a study. Unfortunately, these aspects were often neglected within the available literature, except for some recent papers. Regarding mesohabitat selection, some studies were conducted choosing the most common mesohabitat within the studied reaches [41,49], while others explicitly accounted for the variability due to the presence of different mesohabitats [35,39,44] or different levels of channel confinement due to valleys morphology [46]. In particular, Aksamit et al. [39] underlined the importance of local mesohabitat configuration and suggested to avoid focusing only on riffle areas (which are generally preferred in macroinvertebrate monitoring), since they appear to be least affected by hydropeaking, compared to areas characterized by lower flow velocity.

Regarding cross-sectional variability, many studies were based on samplings performed in different positions along selected transects [15,37,42]. This effectively allowed the authors to identify different effects on macroinvertebrate communities according to their position along the cross-section, with communities in the ramping zones (shores) particularly impacted by hydropeaking. Specifically, Kjærstad et al. [37] detected the presence, in the midchannel, of taxa adapted to high water velocity, compared to shore zones. In the case of large rivers, Mihalicz et al. [43] underlined the difficulty to take samples in the midchannel (i.e., the permanently wetted area) and indicated the necessity to identify specific sampling protocols for such watercourses. Other authors overcame the same problem by adopting different sampling techniques [45] or timing [42] for different areas within transects in large rivers.

The temporal frame of the study can also vary, according to the study objectives (Tables 2 and 4). When aiming to quantify the overall biological effects of hydropeaking, macroinvertebrate sampling is generally performed at base-flow conditions, i.e., after the fluctuation has settled [32,37,43,45–48], eventually integrating the study by samples collected shortly before the hydropeak, to provide a temporal reference. When feasible, macroinvertebrate sampling after repeated flow fluctuations or at different time spans after a single flow fluctuation could add information on community resilience [37,46,47].

Whether the study aim is to investigate the influence of specific hydraulic parameters or phases of the fluctuating flows, sampling is commonly performed during the fluctuation. Many authors [14,15,33,34,39,46] reported on differential effects on the macroinvertebrate community in different timeframes during fluctuations, driven by different hydraulic patterns. Specifically, the low-flow (before and after the peak), high-flow and ramping (up and down) phases, induced different macroinvertebrate response as documented by repeated sampling. Similar considerations are present in flume studies [26], thus confirming that sampling results can vary strongly in relation to the mentioned phases. Moreover, attention should be kept when investigating communities that are exposed to hydropeaking for the first time (ever or after long periods of non-hydropeaking flow management), since assemblages could probably be not adapted to withstand a highly varying hydraulic stress. These communities, as experimented by Bruno et al. [26] in natural flumes on a pristine watercourse, show significantly different and stronger effects during the first flow fluctuation, compared to the following repeated ones.

Finally, Mihalicz et al. [43] and Schulting et al. [16] observed possible season-driven differential effects of hydropeaking linked to species phenology and to photoperiod and temperature control on organisms' behavior (as also visible at the diel scale [16]), these aspects deserving proper consideration when a monitoring activity is planned.

Regarding the sampling techniques, two main approaches can be found in the available literature: the drift sampling and the benthic sampling (Table 4). The drift sampling consists of the collection of invertebrate organisms by positioning nets within the watercourse for a known timespan and it is aimed at catching individuals that (actively or passively) left the benthic environment and entered the water column, being then transported by the current. This sampling technique was preferred when investigating the differential effects of single phases during the flow fluctuation [14,15,33,34,39,45,46]. In fact, drift was reported as a major short-term effect of hydropeaking, particularly during the up-ramping and peak-flow phases [16,26].

The benthic sampling consists in the removal of the organisms from the streambed substrate by kicking or scrubbing the substrate upstream of a net, so that individuals are moved within the net by flowing water. This procedure can be performed (i) within a frame defined by the net structure (Surber sampler or Hess sampler), so that quantitative data are obtained pertaining to the defined sampling area, or (ii) without such a frame, on a kicking-time basis or on a visually estimated area (kick sampling), so that semiquantitative data are produced. Finally, a collection of macroinvertebrates colonizing “rockbags” filled with substrate collected within the sampling site and left within the channel for 60 days is also possible, as reported by Armanini et al. [41]. All these three methods are adopted to describe the benthic community and are generally applied when aiming at studying a hydropeaking management scheme as a whole and sampling is performed at base flow [29–32,34,35,37,39,42–47,49].

Both drift and benthic samplings support the assessment of modifications in taxonomical and functional community composition and in the density/abundance of individuals and biomass, in response to the changing flows. In particular, the reviewed literature allowed to identify some biological metrics as the most useful in detecting the degree of impairment of macroinvertebrate communities due to hydropeaking, as briefly summarized in the following.

Drift density appears useful at defining the sustainability of hydraulic stress in the different hydropeaking phases, reaching its maximum during the up-ramping and the peak phases [15,29,33,34,46]. Since drift composition was reported to change during the flow fluctuation [14,15,39], its measure allows for the identification of the most affected components of the community through passive or active drift. Moreover, based on flume studies, Bruno et al. [26] suggested to calculate the ratio between the incoming drift upstream of the impacted reach and the catastrophic drift at the end of the impacted reach, to assess the community resilience to hydropeaking.

Regarding benthic sampling, both total density and biomass were reported to decrease as a consequence of hydropeaking flows [30,32]. Moreover, taxonomical and functional composition of the assemblages at sites affected by hydropeaking resulted in being different from the reference conditions [32,41,47]. Hence, comparative studies on benthic communities at reference and impacted sites (eventually with a before–after–control–impact design, when feasible) could give useful information on the degree of impairment associated to hydropeaking HP plants. In particular, reduced abundances of taxa characterized by low ability at resisting the drift (e.g., limnophilic taxa [47] and weak swimmers without morphological adaptations for fastening to the substrate as the Diptera, Chironomidae [14,15,39]) or taxa with unfavorable life history traits (e.g., univoltines [47] or taxa laying eggs on substrates subject to drying [17]) could be monitored as specific indicators of the effects of hydropeaking operation.

Total density and assemblage composition were reported to be clearly different between the occasionally and permanently wetted areas [37,42] in hydropeaking watercourses. Moreover, benthic abundance and biomass resulted to be higher where instream morphological heterogeneity (i.e., gravel bars) determine locally lower flow velocity [30].

Finally, considering the taxonomical identification level, family or genus was selected in 9 out of the 15 papers reporting this information [14,15,34,39,41,42,46,48,49], while 3 papers report on data based on the lowest possible identification level [30,37,47], and

only 3 on the genus or species level [32,35,43] (Table 4). Though hydraulic preferences of benthic macroinvertebrates are sometimes variable between species within the same family, family-level resolution proved to perform well in identifying the main changes in assemblage structure due to environmental constraints (e.g., [54,55]) and the interesting results reported in the analyzed papers suggest the effectiveness of levels of identification higher than species in measuring main effects of hydropeaking, while adopting simple and rapid processing methods that could be easily implemented in official monitoring protocols.

3.2. Indirect Methods

As an alternative approach to directly monitoring macroinvertebrate assemblages' modifications in response to hydropeaking, some authors adopted predictive habitat modelling to determine the suitability for benthic macroinvertebrates of the hydrological conditions determined by the different hydropeaking phases [24,27,28,36,38]. This approach allows for the evaluation of alternative operational schemes or mitigation measures, based on expected invertebrate responses to specific hydraulic and/or morphological parameters, i.e., mainly on habitat suitability curves. The reliability of this method is dependent on the robustness of its bio-hydro assumptions. Specifically, it is acknowledged that the definition of habitat preference curves should be preferably site-specific, or based on transferable existing curves developed at geographically and typologically comparable watercourses, since organisms' responses to hydraulic conditions are influenced by numerous local biotic (e.g., predators) and abiotic (e.g., climate) factors [56,57]. This was the approach followed by Holzzapfel et al. [27] and Leitner et al. [28], who generated suitability curves for some macroinvertebrate taxa specifically selected to represent different hydraulic preferences and thus to test for the suitability of the instream habitat in the different phases of the hydropeaking cycle. These authors used depth-averaged flow velocity as the hydraulic variable controlling macroinvertebrate distribution and potentially driving drift during the up-ramping and peak phases. However, bottom shear stress, rather than mean flow velocity, is the hydraulic driver of macroinvertebrate drift [58]. Consequently, many authors (e.g., [56,59–61]) prefer to use this parameter when producing habitat suitability curves for macroinvertebrates, usually by adopting the FließwasserStammTisch (FST) hemispheres method proposed by Statzner and Müller [62] to measure the shear stress. In the specific field of hydropeaking studies, Schneider et al. [38] obtained habitat suitability curves with FST values computed based on field data on mean flow velocity, depth and substrate characteristics, complemented by 2D hydrodynamic models and GIS analyses. This method, firstly purposed by Kopecki [63], appears easier and less time-expensive in terms of field work than the FST hemispheres method, ensuring at the same time ecologically meaningful curves.

Regarding the selected macroinvertebrate taxa, Holzzapfel et al. [27] chose five different taxa (listed from the one preferring areas with low hydraulic forces, to that preferring higher hydraulic forces): the Trichoptera, *Allogamus auricollis* (family Limnephilidae), the Ephemeroptera, *Ecdyonurus* sp. (family Heptageniidae) and *Baetis alpinus* (family Baetidae), the Diptera, Simuliidae Gen. sp. and the Ephemeroptera, *Rhithrogena* sp. (family Heptageniidae). *A. auricollis* was selected by Leitner et al. [28] and Schneider et al. [38] as well, along with *Rhithrogena* sp. and the Trichoptera, *Hydroptila* sp. (family Hydroptilidae) and *Baetis rhodani* (respectively). All these studies were conducted in alpine watercourses, thus other taxa are probably more representative of instream hydraulic conditions when considering other geographical areas.

As already discussed in the previous Section 3.1, also when developing habitat suitability curves, the choice of the space and time frames to perform invertebrate sampling and measure of physical parameters should be carefully adapted to the study aims and local specificities.

Lastly, Tonolla et al. [40], based on the experience developed in Switzerland in the sustainability of HP management, proposed an evaluation method based on multiple

indicators of alterations of the macroinvertebrate assemblages (but also of fish and physical characteristics). In this method, the evaluation of possible alternative management schemes is performed by collecting macroinvertebrate data under the current management and predicting ecological changes following alternative solutions, based on literature-based indices or expert judgement. The same approach, with some additional indicators (including habitat suitability modelling for macroinvertebrates), has been adopted by the Swiss law and is currently applied as a mandatory tool for the evaluation of hydropeaking impacts of HP plants and mitigation measures identification [64]. It represents one of the few examples of inclusion in national monitoring protocols of methods specifically selected for the detection of the effects of hydropeaking on river benthic macroinvertebrates.

4. Conclusions

In this paper, we reported examples of available methods for the assessment of effects of hydropeaking on river benthic macroinvertebrates, and summarized possible solutions regarding monitoring methods, from the spatiotemporal planning to the metrics calculation.

The adopted sampling methods are fairly consistent, namely (i) drift sampling when focusing on responses to specific hydraulic variables and (ii) benthic sampling when the overall effects of hydropeaking are considered. However, sampling planning sometimes overlooked important aspects, such as the need to consider possible patchiness in the biotic response due to hydraulic differences along cross-sections or between different mesohabitats and the need to consider the timeframe for sampling in relation to hydropeaking cycles. In some instances, this is due to the application of standard monitoring protocols, not specifically designed to assess the hydropeaking impact. In studies applying the drift technique, the sampling protocol is generally developed to specifically analyze hydropeaking events. In contrast, the other studies adopted methods commonly used to investigate benthic macroinvertebrate communities in rivers. Specific methodologies should also account for the additional perturbations related to hydropeaking, including changes in river geomorphology [65] and water temperature [20].

Nevertheless, the key aspects of a sound monitoring are fully described in the available literature, providing many examples of solutions and overall representing a good scientific basis for the development of monitoring plans.

As already evidenced by Moreira et al. [4], to date few countries have already included thresholds for hydropeaking operation in their legislation, while the ongoing development of HP urgently calls for the adoption of regulating rules and related monitoring of mitigation measures, which are ecologically sound. Given the documented negative effects of hydropeaking on macroinvertebrates, these methods shall include the monitoring of this fundamental component of lotic ecosystems, as already applied in Switzerland, one of the most productive countries for scientific research and legislation regarding HP sustainability.

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