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Review

Impacts of hydropeaking: A systematic review

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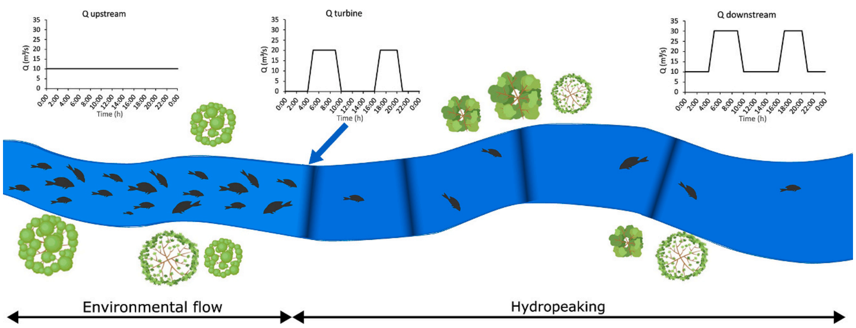
HIGHLIGHTS

- Hydropeaking affects the downstream ecology regarding fish and benthos habitat.
- Altered flow regimes can affects the sediment transport.
- DPSIR framework was used for addressing the complex issues related to hydropeaking.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydropower is commonly considered a renewable energy source. Nevertheless, this does not imply an absence of impacts on the riverine ecosystem, the extent of which is expected to increase in the coming years due to the energy transition from fossil fuels to renewable sources and for the climate change. A common consequence of hydroelectric power generation is hydropeaking, which causes rapid and frequent fluctuations in the water flow downstream of hydropower plants. The review incorporates 155 relevant studies published up until November 2023 and follows a systematic review method, Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), which is a multi-stage systematic procedure for the identification and selection of research documents. The selected studies highlighted several prominent impacts of hydropeaking on aquatic environments. The primary effects include alterations in flow patterns, modification of water temperature, changes in sediment dynamics and fluctuations in dissolved gas levels. These alterations have been found to affect various aspects of aquatic ecosystems, including fish growth, behavior, reproductive success, habitat, and migration patterns, and benthic macroinvertebrate communities. Furthermore, hydropeaking can also lead to habitat fragmentation, erosion, and loss of riparian vegetation, thereby impacting terrestrial ecosystems that depend on the aquatic environment. Despite the body of literature reviewed, several knowledge gaps were identified, underscoring the need for further research. There is limited understanding of the long-term ecological consequences of hydropeaking and its cumulative effects on aquatic ecosystems. Additionally, there is lack of consensus regarding the quantification of ecosystem services, economic impact, soil moisture content, and weighted usable area due to flow fluctuation and global evolution of energy production from renewable energy sources. Addressing the identified research gaps is crucial for achieving a balance between energy production and the conservation of freshwater ecosystems in the context of a rapidly changing global climate.

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1. Introduction

The global demand for electricity is rapidly increasing due to population growth, urbanization, and modernization (Bejarano et al., 2018). In response to climate change, there has been a decline in the use of non-renewable energy sources like fossil fuels and nuclear power, while the utilization of renewable energy sources such as solar, wind, and hydro power is on the rise (Schmutz et al., 2015). Currently, renewable energy sources account for approximately 19 % of global final energy consumption (REN21, 2016). Among renewable energy forms, hydropower is the leading source in states with water availability from catchment areas, providing 76 % of renewable energy and 16.4 % of global electricity (REN21, 2016). Hydroelectricity is recognized as a suitable renewable energy source due to its lower greenhouse gas emissions compared to hydrocarbon-based power generation, and it possesses the capacity to rapidly meet high electricity peak demand periods (Jones, 2014) when the energy production from other renewable sources (e.g., solar and wind production) is low. Consequently, efforts are being made to enhance the efficiency of hydropower generation in Europe (RES, 2009) and North America, while new hydropower projects are planned in Southeast Asia, Africa, and Latin America (Lees et al., 2016). New hydropower projects can also have a role in the growth of the renewable market storing a part of the energy during minimum demand request and releasing it during peak demand (Guruprasad et al., 2023).

However, while hydropower is commonly regarded as a clean energy source, it has various adverse environmental and social effects. The construction of dams leads to direct and indirect alterations in the fluvial geomorphology of rivers, disrupting the longitudinal continuum in sediment transport (Kondolf, 1997), affecting the structure and composition of aquatic communities and modifying the distribution and availability of riverine habitats (Bunn and Arthington, 2002). In addition to the modifications to the river habitat caused by damming the river to install hydropower plants, further impacts can arise from their operations, including sediment flushing (Folegot et al., 2021) and hydropeaking employed to meet the electricity demand by generating peaks in the power production at a sub-daily basis (Smokorowski, 2022), causing as a side effect rapid and frequent changes in discharge, associated with intermitting inundation and dewatering. Identified as one of the primary human-induced disturbances in river networks (Elgueta et al., 2021), hydropeaking is considered highly ecologically destructive due to its impact on downstream biota (Smokorowski, 2022), for its effect on the chemical, thermal, and hydraulic characteristics of the natural flow. Indeed, frequent hydropeaking leads to changes in the biogeochemistry of water bodies, to the reduction in abundance and diversity of taxa, and to a diminished interstitial habitat (Bruno et al., 2009). Hydropeaking sites exhibit significantly higher and longer-lasting saturation of total dissolved gas (TDG) (Pulg et al., 2016), and a reduce germination of riverbank vegetation (Baladrón et al., 2023, 2022; Bejarano et al., 2020; Gill et al., 2018; Gorla et al., 2015; Liu and Xu, 2022; Markwith and Parker, 2007). Chlorophyll-a (Chl-a) concentration in hydropeaking flows is lower than in the average base flow, with an increase in concentration observed further downstream of the hydropower plants (Rossel and de la Fuente, 2015). The magnitude of hydropeaking directly affects thermopeaking as well, causing water temperature fluctuations within a range of ±2.0 °C during 1 cycle of peaking operations (Bakken et al., 2016). Furthermore, a study conducted in an Alpine stream in Trentino, Italy, by Bruno et al. (2009) revealed that hydropeaking led to seven-fold higher discharge. Such alterations on the flow regime endanger the fish community through fish stranding, drift, and dewatering of spawning grounds, which occur during up-ramping, down-ramping, and peak flow (Auer et al., 2017). Hydropeaking can also lead to frequent changes in the Water Surface Elevation (WSE) at rates exceeding 1 m/h, resulting in significant fish stranding during rapid flow decreases (Hauer et al., 2017a; Higgins and Bradford, 1996). Such stranding events, if repeated, can lead to population declines and to an alteration of fish movement and migration (Auer et al., 2022; Boavida et al., 2021; Glowa et al., 2022; Jelovica et al., 2022; Pander et al., 2022b), while single stranding events can cause substantial fish mortality (Higgins and Bradford, 1996). Hydropeaking-induced discharge variations act also as potential stressors that inhibit fish growth and contribute to higher mercury concentrations in downstream fish (Green et al., 2020). Flow fluctuations during hydropeaking have a significant effect on the macroinvertebrate community (Elgueta et al., 2021), leading to increased macroinvertebrate drift during the up-ramping phase (Schülting et al., 2022; Tonolla et al., 2022) and stranding during the down-ramping phase (Tonolla et al., 2022). As a result, downstream of hydropeaked reaches, there is a decrease in aquatic insect richness, abundance, and biomass, particularly in sensitive taxa (Abernethy et al., 2021). Other impacts of hydropeaking are related to river-bed particles movement, sediment infiltration (Hauer et al., 2019; López et al., 2023, 2020; Vericat et al., 2020), hydrology, i.e., flow regime, discharge, hydrodynamics (Buček et al., 2021; Figueiredo et al., 2021; Gierszewski et al., 2020), and sediment transport (Szmańda et al., 2021; Vanzo et al., 2016).

Although several reviews have summarized hydropeaking impacts on different aspects, to our knowledge there is not a synthesized review on the overall impacts exerted by hydropeaking in the downstream river. Additionally, no previous review works have been conducted following a systematic review approach, i.e., PRISMA (Page et al., 2021). To fill this gap, this study aims to carry out a review work following a systematic approach to conceptualize the overall impacts of hydropeaking in the downstream river.

2. Methodology

2.1. Literature search strategy

A comprehensive literature review was carried out based on the PRISMA guidelines (Page et al., 2021), which is a multistage systematic procedure for the identification and selection of research documents, as follows: (1) Identification, (2) Screening and (3) Inclusion. The literature search for the review was based on the Scopus database with search string ‘TITLE-ABS-KEY’ and on Web of Science (WoS) Core Collection database with search string ‘Topic’. The first article search was carried out on 28th January 2023, and the final on 24th November 2023. Basic searches were performed using two different search terms linked by the “AND” and “OR” connectors. In both search engines, the search strategy contained a combination of the following fields of research:

1. “hydropeaking” OR “pulsed flow*” OR “rapid flow alteration*” AND “impact*” OR “effect*” OR “consequence*”; and search criteria 1 combined with the followings:
2. “biota” OR “eco*” OR “communit*” OR “flora AND fauna”
3. “human” OR “people*” OR “soci*”
4. “hydrolog*” OR “morpholog*” OR “sediment*” OR “erosion*” OR “filtration*” OR “fluvial*”
5. “temperature” OR “therm*”
6. “water AND quality”
7. “water”
8. “environ*”

As hydropeaking is also referred to as pulsed flow or rapid flow alteration, articles were also searched in Scopus using these additional two keywords.

After combining the articles from different search keywords, a total of 1272 articles were found in Scopus and 1443 in Web of Science.

2.2. Screening process

Table 1 shows the criteria adopted to select the articles reviewed in this study, among those emerged from the database search. After screening duplicates, language, review articles, title and abstract, 169 articles from Scopus and 202 articles from Web of Science were selected for full text screening. After removing duplicates, 211 articles were selected for full text screening, based on the possible presence of a focus on hydropeaking and thermopeaking impacts. The full text screening finally identified 155 articles in line with the topic object of this review (Fig. 1). The excluded paper focus on some specific characteristics of hydropeaking, but not on its overall impact assessment. For instance, Pisaturo et al. (Pisaturo et al., 2017) describes habitat modelling on hydropeaking events, but the focus is on the effectiveness of its 3D vs 2D hydraulic modelling.

2.3. Development of an impact review framework

A framework was developed to carry out the review of hydropeaking impact assessment and named as Impact Review Framework. Following the guidelines prepared for this framework, the review of each article was carried out. The framework is comprised of the following sections:

- general information, including authors, years of publication, journal, document type;
- methodological information, including study area, method(s) and tools used in the article, field of study;
- result-based information, including ecological, sediment, environmental, social, economic, degree of assessment and research gaps and recommendations addressed in the study.

The main elements of the frameworks and the respective considerations are shown in Table 2.

2.4. Data extraction

The information extracted from the studies was compiled in the synoptic table. The synthetic information, the graphs and the tables were prepared using WPS Excel to conceptualize the state-of-the-art on the current knowledge on the ecology, sediment, environment, and social impacts of hydropeaking and thermopeaking.

2.5. DPSIR framework

The system approach framework “Driving Forces – Pressures – State –Impacts – Responses (DPSIR)” highlights the interaction between the systems and resources of environment and society (Lewison et al., 2016). Although developed in social sciences, it has been used as a multidisciplinary tool for analysing environmental conflicts aiming at sustainable resource use solutions (Rounsevell et al., 2010), as an extension of the Pressure-State-Response (PSR) model developed in 1970 by Friend and Rapport (Friend and Rapport, 1979). Among others, it has been adopted by the Organization for Economic Cooperation and Development's (OECD) and the European Environmental Agency (Stanners et al., 1995). The DPSIR model is a flexible mechanism bridging between the conceptual understanding of scientists, academicians, practitioners, managers, and key stakeholders, for a shared decision making. It is a framework with cause-effects interlinkage that starts with drivers - the social and natural systems and actions, indirectly affecting the environment and ecosystem. The DPSIR framework was applied to this study as a tool to aid a simplified overview of the overall socio-ecological impacts of hydropeaking through summarising dynamic interlinkages between the different sources of multiple stressors, impacts and responses at global scale. Following the method used in Smeets et al. (1999), the indicators of DPSIR framework have been defined as follows:

Table 1
Inclusion criteria for reviewing the studies.

Criteria	Inclusion	Exclusion
Language	English	Other language
Types of study	Peer-reviewed articles, conference proceedings	Review articles, editorial materials, book chapters
Study focus	Impacts of hydropeaking	Hydropeaking characterization, methods, hydropeaking impact mitigation

- Drivers: overarching socio-economic mechanisms resulting from emerging energy demands;
- Pressures: installation and operation of hydropower plants;
- State: changes in hydro-geomorphological characteristics of the downstream channel;
- Impacts: changes in sediment transport, environment, ecology and social aspects;
- Response: responses to driving forces, pressures, state changes and impacts, aiming to control or compensate the negative consequences of hydropeaking operations.

The illustration of DPSIR framework has been carried out using an open-source tool called “draw.io” (https://www.drawio.com/).

3. Results

3.1. Overview of the research on hydropeaking

The investigation on the impacts of hydropeaking is relatively recent. The articles search in Scopus and WoS showed records from 1995 (Fig. 2A). However, most of the studies were carried out from 2013 onwards, with the highest number of publications occurring in 2016, followed by 2021 and 2023. A great contribution on hydropeaking research was provided by the Special Issue on Science of the Total Environment journal (Hauer et al., 2017b) (2016) and by the Special Issue: “The Innovations in Hydropeaking Research” on the River Research and Applications journal (Vanzo et al., 2023) (2023). In terms of geographical distribution, the literature on hydropeaking is not evenly spread. The highest number of articles was recorded in Europe (62.58 %), followed by North America (25.81 %), South America (5.16 %), and Asia (3.87 %). To our knowledge, there is no recorded literature available from Africa and Australia. Among the studies that we reviewed, the highest number of studies was carried on in Canada (12.90 %), and United States (12.90 %), followed by Norway (10.97 %), Austria (7.74 %), France (7.1 %), and Italy (5.16 %) (Fig. 2B). Despite being major producers of hydropower, Asia and South America had limited representation in the hydropeaking literature. For instance, China, the largest hydropower producer in the world (Association, 2021), reported only one English article, while Korea, Vietnam and Cambodia had 3, 1 and 1 articles, respectively. Notably, no articles were recorded from other significant hydropower producing countries in Asia, such as Japan, India, Pakistan, and Russia. Among South American countries, the highest number of articles were found in Chile (4 articles), followed by Brazil (3 articles), and Colombia (1 article). Interestingly, most of the studies are in areas that also have a high Environmental Performance Index (Wolf et al., 2022) and have no significant plans to build new hydropower plants (Zarfl et al., 2015).

The assessment of hydropeaking impacts encompasses various sectors such as ecology, hydro-morphology, environment, and society, with a predominant focus on ecology (Fig. 2C). Nearly half of the publications specifically address the effects of hydropeaking on fish (56.13 %). Following fish, the main sectors of interest are invertebrates (16.77 %),

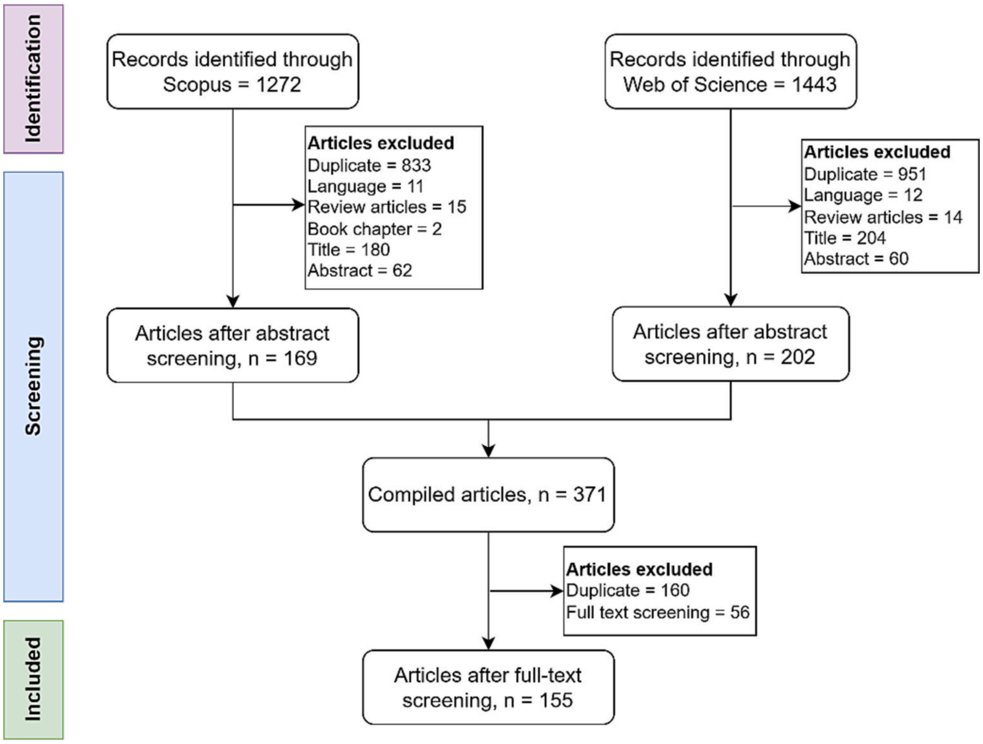

Fig. 1. Diagram illustrating the steps followed in the article screening process based on PRISMA method.

hydrology (4.52 %), riverine plants (4.52 %), and water quality (3.23 %). Among the fish species, over half of the studies concentrates on the Salmonidae family (54.35 %), followed by other species (18.48 %) and Cyprinidae family (17.4 %) (Fig. 2D). Fewer studies focus on fish species under the family of Esocidae, Catostomidae and Prochilodontidae, whereas the studies that consider more than three fish species were categorized as "Others".

3.2. Research approaches

Based on the methods and approaches used for the hydropeaking impact assessment, studies were classified into three types: empirical, experimental, and modelling research. Empirical research involves data collection from the field, experimental research is carried on in laboratory facilities, and modelling research employs modelling techniques (Table 3). More than half of the studies have adopted an empirical research approach (56.77 %), followed by experimental (23.87 %) and modelling approaches (19.36 %). In each study approach, impact assessments have been mainly carried out using statistical analysis, spatial analysis, hydraulic modelling, ecological modelling, and habitat modelling.

For the statistical analysis, different studies have adopted different speciation of regression analysis, parametric and non-parametric tests. Regression has been employed to evaluate various aspects, including fish and larval stranding (Führer et al., 2022; Glowa et al., 2022), drift (Bruno et al., 2013), survival (Valentin et al., 1996), fish length (Earley and Sammons, 2018), growth pattern (Céréghino and Lavandier, 1998a, 1998b), the relationship between drift intensity and stranding density (Tonolla et al., 2022), growth performance (Puffer et al., 2017), aquatic plant and animal composition (Bowen et al., 1998; Kjærstad et al., 2018), particle entrainment (López et al., 2020), discharge ratios, fine sediment infiltration (Hauer et al., 2019), and water quality in response to hydropeaking (Feng et al., 2018). Among the parametric tests, different speciation of ANOVAs have been used to assess biomass richness (Liu and Xu, 2022), fish length (Rocaspana et al., 2019), habitat (Rato et al., 2021), drift (Bruno et al., 2013), benthic communities composition (Tonolla et al., 2022), egg and larval mortality (Pander et al., 2022a), fish movement (Rocaspana et al., 2019), hormone production (De Fex-Wolf et al., 2019), and invertebrate abundance and richness (Mihalicz et al., 2019), while *t*-test has been employed for fish stranding (Halleraker et al., 2003). On the other hand, among the non-parametric tests, Kruskal-Wallis has been utilized to assess the impact on habitat (Pander et al., 2022b), mussel activity (Rato et al., 2021), and movement of aquatic fauna (Harvey-Lavoie et al., 2016), whereas Mann–Whitney *U* test has been utilized to evaluate drift intensity (Tonolla et al., 2022).

Spatial analysis, including DEM, KIB, and linear interpolations have been applied to simulate river flow (Vericat et al., 2020) and interpolate water quality (Ferencz et al., 2021). Additionally, habitat mapping, movement, intra-annual variation in habitat preferences and home range (Boavida et al., 2017), as well as visualization of research outcomes have been also conducted using spatial analysis (Alexandre et al., 2016).

Telemetry techniques have been used to assess hydropeaking impacts on fish populations. Seasonal movement, home range, distance and position of fish were investigated using radiotelemetry, (Rocaspana et al., 2019; Scruton et al., 2005, 2003; Mark K. Taylor et al., 2014). Passive Integrated Transponders (PIT) were also used to monitor fish movement (Bartoň et al., 2021), (Boavida et al., 2021) and specific location of the flow-refuge (Boavida et al., 2021). Rato et al. (Rato et al., 2021) used electromyogram telemetry to track the activity of tagged fish.

Different types of hydraulic models have been used to evaluate the hydrological, morphological, and ecological impacts, i.e., 1D, 2D and 3D hydraulic model for flow hydraulics (Choi et al., 2017; Halleraker et al., 2003; Vericat et al., 2020). For example, River 2D model has been applied to perform flow analysis (Choi et al., 2017), to assess physical habitat (Vehanen et al., 2003), to identify fish habitat change (Boavida et al., 2013), and to evaluate behavioural response of aquatic fauna (Scruton et al., 2003), whereas ELCOM model has been used for modelling reservoir hydrodynamics (Ibarra et al., 2015). Hydraulic methods such as IHA (Indicators of Hydrologic Alteration) have been

Table 2
Review framework for the assessment of hydropeaking impacts.

Ecological, sediment and social impacts of hydropeaking: a systematic review		
Criteria of the framework		
Type of information	Label	Information to be recorded from the reading of the papers
Code	Code	Number assigned to paper according to the year and alphabetic order within the year in the final list of papers
General information	Authors	List first three authors; add “et al” if more than three authors
	Title	Article's title
	Year	Publication year
	Journal	Name of the journal
	Publisher	Name of the publisher
	Document type	Article, book chapter, conference paper
Introductions	Aims	Purpose of the study
Methods	Study area	Location
	Study type	Type of study: empirical; experimental and modelling
	Method	Methods used for spatial, statistical analysis and modelling approaches
	Tool	Tools used in method
	Data	Primary or secondary
	Data period	Time period of the data set used in the study
	Sector	Type of wording the article refers to address hydropeaking impact: biota, human safety, sediment transport, filtration in the ground, temperature (thermopeaking), etc
Results	Ecological	Has the paper assessed impacts on plants and animals?
	Sediment	Has the paper assessed impacts on discharge, sediments, filtration, erosion?
	Environmental	Has the paper assessed impacts on water temperature and other water quality parameters?
	Social	Has the paper assessed impacts on human safety and other social dimensions?
	Economic	Has the paper assessed economic valuation?
	Degree of assessment	At what level the assessment has been carried out: basic, intermediate, full extent?
Conclusion	Research gap	Future research direction addressed
Comments		If reviewer has any comment

used for the assessment of hydrological regime (Szmańda et al., 2021).

Among the ecological models, growth model and species distribution model have been employed for modelling fish growth (Flodmark et al., 2004) and biomass pattern (Liu and Xu, 2022), SIMPER model and TWIN SPAN model for habitat variables, benthic community composition (Rato et al., 2021; Tonolla et al., 2022) and community structure (Brabec, 1998). On the other hand, habitat suitability modelling has been used for identifying weighted usable area for fish and other aquatic fauna (Boavida et al., 2013). Inter and intra-river model has been used for modelling fish movement (Harvey-Lavoie et al., 2016) and PHABSIM model for habitat evaluation (Hauer et al., 2017a).

Tools and platforms used to carry out the analysis and modelling works in the hydropeaking impact assessment studies have been summarized in Table 3.

3.3. Impacts on fish and amphibians

Hydropeaking has substantial implications for fish and other aquatic animals. The fluctuating water levels and unpredictable flow patterns can directly impact fish populations' abundance, growth, distribution, habitat, movement, drifting, stranding, survival, and so on.

Overall, studies show that the immediate downstream area of the hydropower outlets exhibits the lowest density and diversity of fish species compared to both sites located further downstream and upstream (Enders et al., 2017; Liebig et al., 1999; Rocaspana et al., 2016a; Vehanen et al., 2005). R. Rocaspana et al. (2016a) stated that hydropeaking sites especially show a lower density of juvenile fish, while they did not observe a significant impact on the density of fry and adult fish. Pragana et al. (2017) conducted a study to assess hydropeaking effects on brown trout habitat considering the Weighted Usable Area (WUA) downstream of the tailrace of the small hydropower plant (SHP) and observed a lower habitat area for juvenile brown trout during the hydropeaking compared to no-production period, and the opposite pattern for adult fish.

One of the drivers for fish density reduction is related to the risk of stranding. Le Coarer et al. (2022) found that rapid decreases in discharge during hydropeaking events may impede fish to reach the centre of the channel in time to find refuge, leading to fish mortality from stranding and/or trapping, and that such a tendency is aggravated in dewatered habitats. Furthermore, the process of dewatering was found to be responsible for the desiccation of crucial nursery areas, and to the subsequent decline in the successful reproduction and survival of endangered fish species that inhabit rivers (Pander et al., 2022b). Another study by Führer et al. (2022), stated that stranding rate depends on different factors, such as banks slope, hydropeaking phase or daytime. In particular, a higher fish stranding rate was observed at lower sloped banks than steeper ones, during the down-ramping phase, and at night.

Another disturbance on fish is caused by the noise produced by turbines: according to Lumsdon et al. (2018), hydropeaking affects soundscapes, causing notable homogenization. They observed that sound pressure levels closely relate to turbine discharge, resulting in sudden and substantial spikes in low-frequency amplitudes. These spikes occur multiple times and fall within the audible range for typical fish species.

Looking at the fish characteristics, different species show both positive and negative growth and biomass pattern in hydropeaking sites. Bond et al. (2016) compared the growth, mass-at-age, weight–length relationships, age-at-maturity, and size-at-maturity of sculpin in the regulated and natural rivers and found that Slimy sculpin grew faster and were in better condition in hydropeaking impacted river than natural river. Additionally, they found that, within the hydropeaking impacted sites, sculpin at sampling sites near the dams had rapid growth, earlier maturity and attained a larger size-at-age than sculpin at sites farther downstream or in natural systems. (Kelly et al., 2017a, 2016) also found the same growth pattern of Slimy sculpin but mentioned that the growth was not significant among the regulated sites. However, the opposite growth and biomass pattern of fish species have been observed in different studies (Earley and Sammons, 2018; Fette et al., 2007; Hajiesmaeili et al., 2023).

Hydropeaking also has influence on the whole reproductive process of fish. Thermal effects of hydropeaking (thermopeaking) on the early life stage of salmonids were studied by Casas-Mulet et al. (2016), who observed that fish in the hydropeaking site experienced a delay in hatching (with a 12-day delay in the ramping zone of dewatering) and

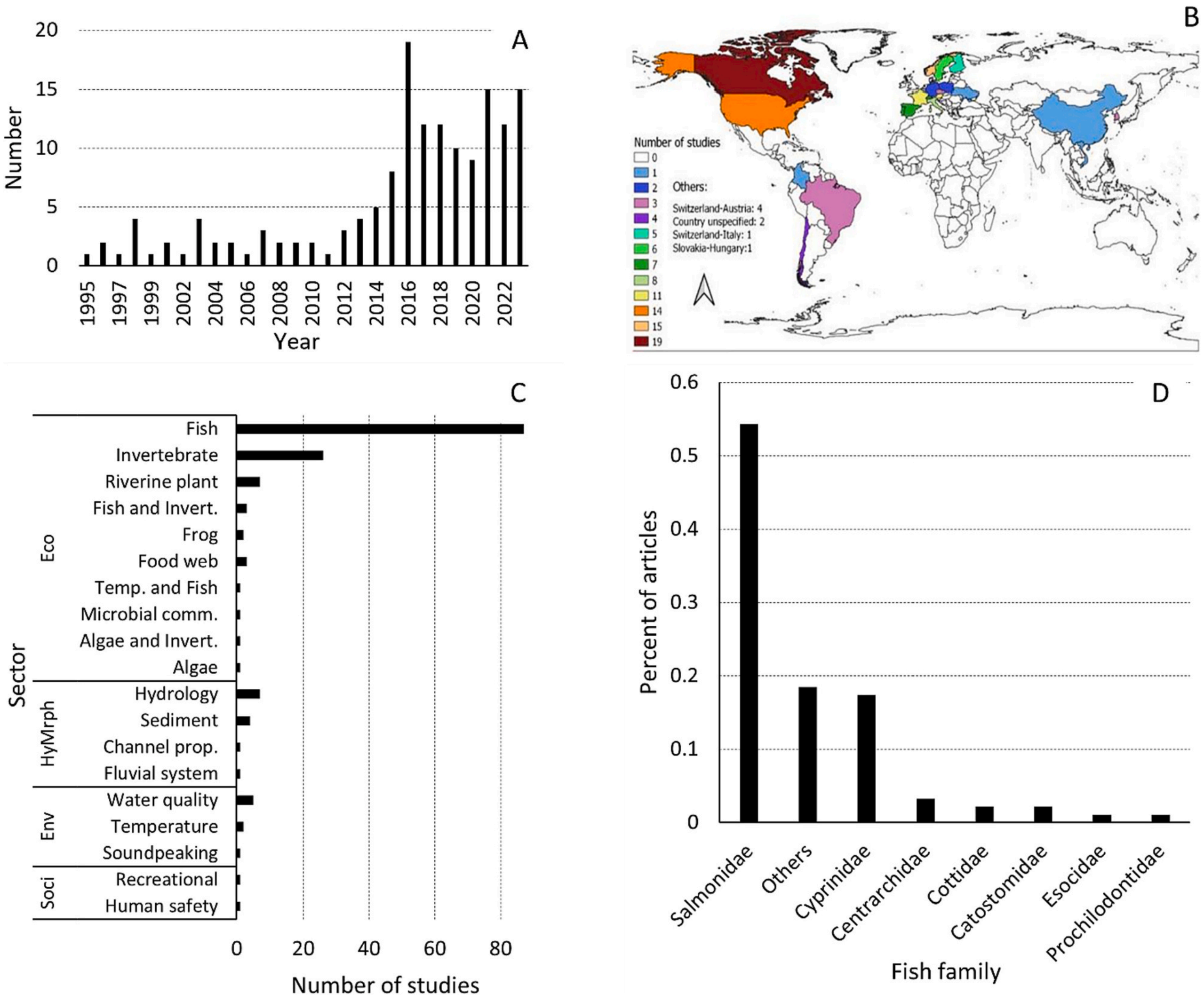

Fig. 2. Number of studies based on (A) year-wise distribution, (B) country-wise distribution, (C) sector-wise distribution and (D) number of studies based on fish family; Note: Eco: Ecology, HyMrph: Hydro-Morphology, Env: Environment, Soci: Social.

swim-up compared to the unregulated site. Within the hydropeaking site, hatching and swim-up occurred earlier in the permanently wetted zone, with a difference of up to 16 days and 6 days, respectively, compared to the ramping zone subject to dewatering. Bakken et al. (2016) also mentioned that the thermal fluctuations resulting from hydropeaking affected the development of salmon eggs, causing a delay of 2-4 days in hatching and approximately 2 days in the swim-up date. According to Vollset et al. (2016), in their case study, when water discharge fell below 5 m^{3}s^{-1} during daytime, both *S. salar* and *S. trutta* exited the spawning area. *S. salar* did not engage in nest preparation when the average hourly discharge dropped below 15.6 m^{3}s^{-1}, whereas *S. trutta* were observed preparing nests at a minimum hourly average discharge of 5.7 m^{3}s^{-1}. In case of hormone production, De Fex-Wolf et al. (2019) observed that hormone production associated with reproduction of the potamodromous fish was sensitive to changes in water level and discharge. Furthermore, fish exposed to hydropeaking received ambiguous stimuli that affected hormone production, reproduction synchronization with environmental cues, and ripening, which are essential for reproductive success.

Only few articles studied the impact of hydropeaking on other animals and in particular on amphibians. The main results show a lower density, habitat, and egg survival for frogs (Kupferberg et al., 2012; Yarnell et al., 2012).

Table 4 summarizes the main impacts on fish due to hydropeaking events, subdivided by “positive”, “negative” and “no impacts”. In cases in which the distinction in positive or negative impacts is not possible or ambiguous, the authors choose the terms “increased” and “decreased”.

3.4. Impacts on invertebrate, algae and microbial community

3.4.1. Invertebrate

Flow regime alteration on the functional trajectory of an aquatic invertebrate metacommunity was observed by Ruhi et al. (2018). According to the study, the impact of hydropeaking on the invertebrate metacommunity resulted in reduced trait characteristics, including body size, body shape, attachment, armor, feeding habits, rheophily, voltinism, adult lifespan, and adult flying, regardless of whether the metacommunity exhibited asynchronous or synchronous structure. Bruno et al. (2009) analysed hydropeaking impact on hyporheic invertebrates and stated that the occurrence of repeated hydropeaking events leads to modifications in the physical-chemical attributes of the hyporheic habitat, consequently impacting the observed faunistic pattern. According to Schneider et al. (2017), *B. rhodani* has better habitat in high flow, while *Hydroptila* in low flow.

Sidler et al. (2018) studied the behavioural response of the freshwater cyclopoid copepod *Eucyclops serrulatus* to hydropeaking and thermopeaking founding that temperature fluctuations have no impact on the velocity of copepods within the sediment bed. However, a

Table 3
Summary of methods and tools/platforms used for hydropeaking impact assessment.

Study type	Summary methods	Summary tools
Empirical	Statistical analysis: Correlation analysis, Regression analysis, Parametric test, non-parametric test, Bayesian method, Bray-Curtis's dissimilarity matrix, Gaussian kernel density estimation, Likelihood cross-validation, decision tree analysis (CRT), ARMA models, Wavelet analysis, MDS/NMDS, CCA/DCA/PCA/PCO, Kaiser–Meyer–Olkin (KMO), Wilks's λ method, Coinertia Analysis, RDA	R programming, SPSS, PRIMER, STATISTICA, SigmaPlot, OpenBugs, Matlab, COMSOL software, CANOCO, PC-ORD, MASS, SYSTAT, Dell Software, SonarView software, GME software, PROC MIXED, Python, STATA, TREEVIEW software, Arlequin, SAS, STAT
	Spatial analysis: DEM, LiDAR, DTMs, IDW interpolation method, KIB, linear interpolation	ArcGIS, QGIS, SAGA, HABBY software, ToPCAT algorithm, Leica Geo Office software
	Telemetry techniques	Radiotelemetry, Passive Integrated Transponders (PIT), electromyogram telemetry
	Ecological model: ELCOM model, patch scale analysis, JSDM technique, HMSC, SIMPER, TWIN SPAN analysis	ECOSIM
	Hydraulic modelling: 1D modelling, IARHIS, Inter and intra river Model, 1-D and 2D Saint Venant Equation, 2D hydraulic simulations, van Genuchten model, DuBoys equation, Shield's equation	2D hydrodynamic model, Iber 2D hydraulic model, Hydro-as-2d software, SMS (Surface Modelling System) software, HydroSignature software, QINSy, HEC-RAS, ELCOM software
	Habitat modelling	Habitat suitability curves (HSC)
	Genetic analysis	TETRASAT program, PAUP
	Hydraulic method: IHA (Indicators of Hydrologic Alteration)	IHA software
Experimental	Statistical analysis: Correlation analysis, Regression analysis, Parametric test, non-parametric test, CCA, decision tree-based model, NMDS	R programming, SPSS, MATLAB, SAS, SigmaPlot, GIMP, HyTEC, STATISTICA, PRIMER, Oriana, T-REX software, T-Align software, Cytoscape
	Spatial analysis: Data visualization/mapping, movement and home range analyses	QGIS, MapInfo, Arcview
	Hydraulic modelling: 2D and 3D hydraulic modelling	SSIIM, Basement, River2D
	Ecological modelling: growth model, SIMPER	R programming
	Image analysis: Optical analysis, image analysis	LabVIEW, ImageJ and AVIZO FIRE software
	Genetic analysis	GeneMapper Software
Modelling	Statistical analysis: Regression analysis, Parametric, non-parametric, Gaussian function	R programming, Matlab
	Spatial analysis: satellite image processing, optical remote sensing method, Topographic and bathymetric surveys, TIN model, 3D topography, DEM, LiDAR, DTM	QGIS, ArcGIS, ArcMap
	Hydraulic modelling: 1D, 2D and 3D hydrodynamic model, Sediment transport models, Mekong Mainstream Model, Delta Model, CMS-Flow model, hydrological model, unsteady flow model, shallow-water numerical model, channel networks modelling, 3D unsteady Reynolds-averaged Navier-Stokes equations, hydrodynamic numerical model, Hydropower production modelling	HEC-RAS software, Hydro_AS-2d model, Delft3d, ELCOM software, CAEDYM software, 2D model CCHE, S-HYPE software, BASEMENT software, SMS software, ORSA2D software, MIKE model, EcoLab model, SWAT, CFD-model, COSH-Tool, Coastal Modelling System-Flow model, GIAMT2D, Ansys
	Habitat modelling: fish habitat modelling, Aquatic Habitat Modelling, 1D habitat simulation model, fuzzy rule-based physical habitat model, HSCs, HIS, IFIM, GEP model	2D habitat model, CASiMiR, PHABSIM, GEP (Gene Expression Programming) software, GeneXpro-Tool
	Ecological model: Fish 2D model, IBM approach	InSTREAM, Crisp model
	Water temperature modelling, Water quality modelling, EcoLab	Energy balance model, air2stream model, MIPUC software
	Fuzzy-logic framework	Fuzzy-logic framework
	Escaping model: Dijkstra's algorithm	Dijkstra's algorithm

decrease in temperature significantly reduces their counter-current swimming effort, potentially leading to increased drift. Conversely, the influence of rising temperatures on copepod behavior was not evident.

In the case of macroinvertebrate drift density associated with hydropeaking, Timusk et al. (2016) provided evidence that the average density of invertebrate drift in a regulated river subjected to hydropeaking was found to be 1.5 times higher compared to a river with natural flow. In a study of short time-scale impacts of hydropeaking on benthic invertebrates, Bruno et al. (2010) selected 3 study sites affected by hydropeaking (0.25, 6 and 8 km downstream from the power plant) and found that drifting was higher in the middle section compared to immediate downstream and the farthest downstream site. Total number of benthic invertebrates lost to drift was 92 ind m^{-3} s^{-1} at first site (26 taxa), 153 ind m^{-3} s^{-1} at middle section (33 taxa), and 91 ind m^{-3} s^{-1} (20 taxa) at last site. Similar impacts were also reported by Ruhi et al. (2018). In (Schülting et al., 2022) study, drift was notably higher when the up-ramping rate exceeded 1 cm/min, whereas no drift was observed when the up-ramping rate was equal to or <1 cm/min. Furthermore, the drift phenomenon was evaluated as more prominent among taxa inhabiting the surface and lentic habitats compared to those found in lotic and interstitial habitats. In (Tonolla et al., 2022) work, the occurrence of macroinvertebrates stranding exhibits a positive correlation with drift, particularly during the up-ramping phase. Elevated discharge, flow velocity and up-ramping rate leads to an augmentation in the drift of macroinvertebrates associated with lentic environments (Schülting et al., 2023, 2019), higher at night (Schülting et al., 2019, 2016), while flow ratio and down-ramping rate contributes to the stranding phenomenon (Tonolla et al., 2022).

Kjærstad et al. (2018) in their study observed that a ramping zone subjected to hydropeaking exhibits a different invertebrate community composition and a lower benthic density compared to other areas. Specifically in the hydropeaking site, they found a higher density of gatherers/collectors and a lower density of mayflies, chironomids, and filter feeders. Castro et al. (2013) reported that in the hydropeaking site, density was higher in wet season and lower in dry season. However, in the long run, hydropeaking did not significantly diminish the benthic density of most taxa, as observed also by Tonolla et al. (2022).

The main impacts on invertebrates, subdivided in “positive” - “negative” - “no impacts”, are summarized in Table 5, alongside that on algae and microbes, described in the following sections.

3.4.2. Algae

Streams subjected to hydropeaking show a reduced biomass development compared to the non-hydropeaked ones. During periods without hydropeaking, studied sites show a higher percentage of Chlorophyta, while during hydropeaking they exhibit a greater percentage of diatoms and cyanobacteria (Bondar-Kunze et al., 2016). Additionally, hydropeaked sites downstream of hydro power plants were found to display significantly higher epilithic biomasses in comparison to the upstream sites where the natural flow is running (Valentin et al., 1995).

Table 4

Hydropeaking impacts on fish and amphibians. Note: Asp = Asp (*Leuciscus aspius*), Ab = Alabama bass (*Micropterus henshalli*), As = Atlantic salmon (*Salmo salar*), Bot = Brook trout (*Salvelinus fontinalis*), Bt = Brown trout (*Salmo trutta*), But = Bull trout (*Salvelinus confluentus*), Cs = Chinook salmon (*Oncorhynchus tshawytscha*), Cn = Common nase (*Chondrostoma nasus*), Eg = European grayling (*Thymallus thymallus*), Ib = Iberian barbel (*Luciobarbus bocagei*), Ic = Iberian cyprinid (*Luciobarbus bocagei*), Ld = Longnose dace (*Rhinichthys cataractae*), Mt. = Marble trout (*Salmo marmoratus*), Np = Northern pike (*Esox lucius*), Oth = Others (Studies those considered four or more than four fish species are mentioned as others), Pc = Pale chub (*Zacco platypus*), Ps = Pink salmon (*Oncorhynchus gorbuscha*), Pm = *Prochilodus magdalenae*, Rt = Rainbow trout (*Oncorhynchus mykiss*), Rb = Redeye bass (*Micropterus coosae*), Rr = Robust redhorse (*Moxostoma robustum*), Sls = Slimy sculpin (*Cottus cognatus*), Sp = *Salmo* sp., Ss = Spottail shiner (*Notropis hudsonius*), St = Sea trout (*Salmo trutta*), Tp = Trout-perch (*Percopsis omiscomaycus*), Vr = V-lip redhorse (*Moxostoma pappillosum*).

Sub-sector	Impacts	Reference	Note
Growth	Positive	(Feng et al., 2018) (Bt), (Kelly et al., 2017a) (Ld, Sls, Tp), (Bond et al., 2016) (Sls), (Kelly et al., 2016) (Sls), (Flodmark et al., 2004) (Bt at high stable flow)	- Growth: hydropeaking > natural flow ((Kelly et al., 2017a) Ld, Sls, Tp) - Did not differ within hydropeaking sites ((Kelly et al., 2017a) Ld, Sls, Tp) - Growth decreased with increasing distance from the dam, but the decreasing rate was not significant ((Kelly et al., 2016) Sls) - No significance difference in age-length relationships ((Enders et al., 2017) Oth) - Growth rate reduced by 10 % in summer ((Puffer et al., 2015) As)
	Negative	(Addo et al., 2022) (Bt), (Hajiesmaeili et al., 2023) (As, Bt), (Earley and Sammons, 2018) (Ab, Rb), (Puffer et al., 2015) (As), (Weyers et al., 2003) (Rr, Vr),(Flodmark et al., 2004) (Bt at fluctuating and low stable flow+ thermopeaking)	
	No impact	(Addo et al., 2022) (As), (Enders et al., 2017) (Oth), (Flodmark et al., 2006) (Bt), (Watz et al., 2023) (As, Bt)	
Length	Positive	(Rocaspana et al., 2019) (Bt), (Enders et al., 2017) (Oth), (Kelly et al., 2017b) (Bot), (Rocaspana et al., 2016a) (Bt), (Rocaspana et al., 2016b) (Bt)	- Fork-length is significantly correlated with invertebrate drift density ((Rocaspana et al., 2016b) Bt)
	Negative	(Puffer et al., 2017) (As)	
	No impact	(Alexandre et al., 2016) (Ib), (Puffer et al., 2015) (As in winter)	
Biomass	Positive	(Rocaspana et al., 2016a) (Bt: adult)	- Final length and body mass decreased by -9 % and -7 %, respectively ((Puffer et al., 2017) As) - No effect on variability of mass ((Addo et al., 2022) As) - No impact in winter, while lower in summer ((Puffer et al., 2015) As)
	Negative	(Hayes et al., 2021) (Eg), (Puffer et al., 2017) (As), (Rocaspana et al., 2016a) (Bt: fry and juvenile), (Rocaspana et al., 2016b) (Bt), (Puffer et al., 2015) (As in summer), (Fette et al., 2007) (Bt: weight)	
	No impact	(Addo et al., 2022) (As), (Puffer et al., 2015) (As in winter)	
Body lipid content	Positive	(Puffer et al., 2017) (As)	- Increased by +2 % ((Puffer et al., 2017) As)
Density	Negative	(Judes et al., 2021) (Oth), (Saltveit et al., 2020) (Bt), (Pearce et al., 2019) (Oth), (Hedger et al., 2018) (As), (Enders et al., 2017) (Oth), (Rocaspana et al., 2016a) (Bt: juvenile), (Rocaspana et al., 2016b) (Bt), (Sauterleute et al., 2016) (As), (Vehanen et al., 2005) (Oth), (Liebig et al., 1999) (Bt), (Kupferberg et al., 2012) (Frog)	- Density: no impact on fry and adult, while decrease for juvenile ((Rocaspana et al., 2016a) Bt) - Within hydropeaking sites, density increases over distance ((Vehanen et al., 2005) Oth, (Liebig et al., 1999) Bt) - Five time smaller frog density ((Kupferberg et al., 2012) Frog)
	No impact	(Rocaspana et al., 2016a) (Bt: fry and adult)	
Diversity	Positive	(Schmutz et al., 2015) (overall fish richness)	- Diversity: Further downstream > reference site > immediate downstream ((Enders et al., 2017) Oth)
	Negative	(Enders et al., 2017) (Oth), (Boavida et al., 2015) (Ib), (Vehanen et al., 2005) (Oth)	
Habitat	Positive	(Pragana et al., 2017) (adult Bt)	- WUA: Reference site > HP initial discharge > HP peak flow ((Boavida et al., 2013) Ib) - Habitat impact: Juvenile > adult ((Jelovica et al., 2022) Bt, Eg; (Pragana et al., 2017) Bt; (Boavida et al., 2013) Ib) - Disturbed fish choice of mesohabitat ((Liebig et al., 1999) Bt) - During hydropeaking, fish prefer shaded habitat closer to bank ((Rato et al., 2021) Ib; (Earley* and Sammons, 2015) Ab) - Habitat persistence was lower ((Freeman et al., 2001) Oth) - Delay in fish migration ((Coutant, 2023) Cs) - Frog habitat was lower ((Yarnell et al., 2012) Frog)
	Negative	(Jelovica et al., 2022) (Bt and Eg), (Antonetti et al., 2022) (Bt), (Choi and Choi, 2018) (Pc), (Pragana et al., 2017) (juvenile Bt), (Choi et al., 2017) (Pc), (Choi and Choi, 2016) (Pc), (Boavida et al., 2015) (Ib), (Boavida et al., 2013) (Ib), (García et al., 2011) (Oth), (Liebig et al., 1999) (Bt), (Valentin et al., 1996) (Bt), (Freeman et al., 2001) (Oth), (Coutant, 2023) (Cs), (Ngor et al., 2018) (Oth), (Yarnell et al., 2012) (Frog)	
Survival	Negative	(Le Coarer et al., 2022) (Oth), (Hajiesmaeili et al., 2023) (As, Bt), (Hedger et al., 2018) (As), (Kelly et al., 2017a) (Ld, Sls), (Puffer et al., 2015) (As), (Fisk et al., 2013) (Rr), (Scruton et al., 2008) (As), (Saltveit et al., 2001) (As, Bt), (Weyers et al., 2003) (Rr, Vr)	- Impact: Smaller > adult ((Hajiesmaeili et al., 2023) As, Bt)
	No impact	(Kelly et al., 2017a) (Tp), (Puffer et al., 2017) (As, Bt), (Puffer et al., 2015) (As), (Watz et al., 2023) (As, Bt)	
Metabolism	Positive	(Kelly et al., 2017b) (Bot)	- Glucose and Lactate content did not respond to hydropeaking event
	No impact	(Moreira et al., 2020) (Ib)	
Drifting	Negative	(Auer et al., 2022) (Eg), (Auer et al., 2017) (Eg), (Rocaspana et al., 2016b) (Bt), (Mameri et al., 2023) (Cn)	- Drift density: After flow pulses > between pulses > control site ((Rocaspana et al., 2016b) Bt) - Higher at cold thermopeaking ((Auer et al., 2022) Eg) - cold thermopeaking may increase drift in the early life stages ((Mameri et al., 2023) Cn)
Stranding	Negative	(Pander et al., 2022b) (Oth), (Auer et al., 2022) (Eg), (Glowa et al., 2022) (Oth), (Le Coarer et al., 2022) (Oth), (Antonetti et al., 2022) (Bt), (Espa et al., 2022) (Mt), (Führer et al., 2022) (Cn), (Burman et al., 2021) (Eg, As, Bt), (Juárez et al., 2019) (Bt), (Hedger et al., 2018) (As), (Auer et al., 2017) (Eg), (Hauer et al., 2017a) (Eg), (Sauterleute et al., 2016) (As), (Tuhtan et al., 2012) (Eg), (Halleraker et al., 2003) (Bt), (Saltveit et al., 2001) (As, Bt), (Hedger et al., 2023) (As), (Glowa et al., 2022) (Oth), (Hauer et al., 2023) (Oth), (Hayes et al., 2023) (Cn), (Alfredsen and Tekle, 2023) (Oth)	- Stranding impact: Juvenile > small fish > large fish ((Pander et al., 2022b) Oth; (Glowa et al., 2022) Oth) - Stranding rate: Cold TP > warm TP ((Auer et al., 2022) Eg; (Saltveit et al., 2001) As, Bt); opposite ((Glowa et al., 2022) Oth) Night > day ((Führer et al., 2022) (Hayes et al., 2023) Cn); opposite ((Saltveit et al., 2001) As, Bt) Higher at higher down ramping ((Führer et al., 2022) Cn; (Tuhtan et al., 2012) Eg; (Hedger et al., 2023) As) Increase over distance ((Glowa et al., 2022) Oth; (Burman et al., 2021) (Eg, As, Bt); (Tuhtan et al., 2012) Eg) Higher during day in winter, while at night in summer ((Saltveit et al., 2001) Bt) Longer spill gate closing time, lower stranding density ((Burman et al., 2021) (Eg, As, Bt); (Saltveit et al., 2001) As)

(*continued on next page*)

Table 4 (*continued*)

Sub-sector	Impacts	Reference	Note
			Smolt production is highly sensitive to stranding mortality ((Sauterleute et al., 2016) As) • Coarsening of substrate increases the stranding risk ((Hauer et al., 2023) Oth)
Larvae, eggs	Negative	(Pander et al., 2022a) (Bt), (Bartoň et al., 2021) (Asp), (Fisk et al., 2013) (Rr), (Yarnell et al., 2012) (Frog)	• Negative impact on eggs density ((Bartoň et al., 2021) Asp) • High potential for scour of egg masses or tadpoles ((Yarnell et al., 2012) Frog)
Movement, displacement	Increased	(Judes et al., 2022) (Oth), (Watz et al., 2020) (Eg), (Rocaspana et al., 2019) (Bt), (Harvey-Lavoie et al., 2016) (Np), (Alexandre et al., 2016) (Ib), (Rocaspana et al., 2016a) (Bt), (Costa et al., 2016) (Ic), (Puffer et al., 2015) (As in summer), (Korman and Campana, 2009) (Rt), (Scruton et al., 2008) (As), (Vehanen et al., 2003) (Eg)	• Emergence of swim-up: Control > hydropeaking site ((Casas-Mulet et al., 2016) As) • Emergence of swim-up within hydropeaking sites: Permanently submerged area > dewatering zone (6 days difference) ((Casas-Mulet et al., 2016) As) • No impact in winter, while higher in summer ((Puffer et al., 2015) As)
	Decreased	(Jones and Petreman, 2015) (Ps; upstream movement), (Casas-Mulet et al., 2016) (As: delay), (Bakken et al., 2016) (As and St: delay)	
	No impact	(Earley* and Sammons, 2015) (Ab, Rb), (Puffer et al., 2015) (As in winter), (Mark K. Taylor et al., 2014) (But), (Flodmark et al., 2006) (Bt)	
Muscle activity	Positive	(M. K. Taylor et al., 2014) (But)	• Decreases with increasing discharge magnitude ((Rato et al., 2021) Ib)
	Negative	(Rato et al., 2021) (Ib)	
Feeding	Positive	(Rocaspana et al., 2016b) (Bt), (Gandini et al., 2014) (Rt, Bt), (Flodmark et al., 2004) (Bt at high stable flow), (Lauters et al., 1996) (Bt)	• Significantly higher taxonomic richness in individual stomachs ((Rocaspana et al., 2016b) Bt)
	Negative	(Gandini et al., 2014) (Oth), (Flodmark et al., 2004) (Bt at fluctuating and low stable flow),	• Higher mercury and lower triglyceride concentration ((Green et al., 2020) Ss)
	No impact	(Flodmark et al., 2006) (Bt), (Flodmark et al., 2004) (Bt, thermopeaking)	• Higher cortisol ((Earley et al., 2019) Ab)
Spawning area	Positive	(Hauer et al., 2017a) (Eg)	• Higher the distance from dam, lower the potential spawning area ((Burman et al., 2021) Eg, As, Bt)
	Negative	(Bartoň et al., 2022) (Asp), (Burman et al., 2021) (Eg, As, Bt)	
Home range	Increased	(Rocaspana et al., 2019) (Bt), (Alexandre et al., 2016) (Ib)	
	Decreased	(Holzapfel et al., 2017) (Bt)	
Hatching/ spawning/ breeding	Decreased	(Vollset et al., 2016) (As, Bt), (Bakken et al., 2016) (Sp), (Casas-Mulet et al., 2016) (As: delay), (Bakken et al., 2016) (As and St: delay)	• Emergence of hatching: Control > hydropeaking ((Casas-Mulet et al., 2016) As) • Emergence of hatching (within hydropeaking): Permanently submerged area > dewatering zone (delay upto 16 days) ((Casas-Mulet et al., 2016) As) • Impact on early life stages: hydropeaking > control site ((Casas-Mulet et al., 2016) As) • Nest preparation: *S. salar* at high flow and *S. trutta* at minimum flow ((Vollset et al., 2016) As, Bt)
Hormone production	Negative	(De Fex-Wolf et al., 2019) (Pm)	• Sensitive to changes in water level and discharge ((De Fex-Wolf et al., 2019) Pm)
Body fat	Negative	(Puffer et al., 2015) (As in summer)	• No impact in winter, while reduction of 16 % in summer ((Puffer et al., 2015) As)
	No impact	(Puffer et al., 2015) (As in winter)	
Use of flow-refuge	Negative	(Boavida et al., 2021) (Oth), (Shen et al., 2010) (Bt)	
Food web	Negative	(Holzapfel et al., 2017) (Bt), (Sabo et al., 2018) (Oth)	• Seasonal discontinuities in food-wed structure in terms of allochthony, food-web diversity and food chain length ((Sabo et al., 2018) Oth)
	No impact	(Pearce et al., 2019) (Oth)	

3.4.3. *Microbial community*

Frequent pulsed flow rates can lead to a different composition of bacterial communities in floodplains over an extended period. Doering et al. (2021) conducted a study to compare the spatial and temporal variation of microbial communities among different floodplain habitats (natural flow, residual flow, hydropeaking flow). The experimental flood event analysed in the study (to mimic a natural high flow event) induced a temporary alteration in microbial communities, as it released microbes from the reservoir and redistributed them across various floodplain habitats. However, the shift in community structures caused by the flood was found to be transient, as pelagic bacteria did not persist within the floodplain habitats over time.

3.4.4. *Impacts on riverine plants*

Comparing different studies shows that the effect of hydropeaking varies significantly according to plant species. According to Gill et al. (2018), obligate riparian plants, which have specific flow requirements within stream ecosystems, are frequently adversely affected by river regulation. As ecological specialists, they are more vulnerable to the river damming and flow regulation. In contrast, facultative riparian plants are generalists and may have a lower vulnerability to river regulation. In fact, they can benefit from increased flows that alleviate drought stress during periods of high temperature and low precipitation. Bejarano et al. (2020) conducted a study to evaluate the effects of hydropeaking on the germination and establishment of seedlings of riverbank vegetation. According to the study, flood-intolerant species experience pronounced impacts during the germination stage, while flood-tolerant species are capable of germination and survival. However, the erosion caused by hydropeaking ultimately also affected the latter group. In the study, the success of germination was greatly influenced by the rates at which water levels rose and fell, providing a key explanation for the observed variations. According to the study conducted by Gorla et al. (2015), the daily fluctuations in hydropeaking had a minimal impact on the growth and photosynthesis of *S. viminalis* cuttings. However, they found that weekly patterns, such as extended dry periods during weekends, could have more severe effects. Markwith and Parker (2007) reported that the population of *H. coronaria* that was unaffected by hydropeaking exhibited a smaller average population size (63 bulb clumps ±143) compared to the population that experienced the impacts of hydropeaking (140 bulb clumps ±363). Table 6 summarizes the impacts observed on riverine plants in hydropeaking sites.

3.5. *Impacts on sediment transport, environment, and social aspects*

3.5.1. *Sediment transport*

The sediment-depleted water released by hydropower plants is at the same time capable of exerting high shear stress on the river bottom, further amplified by the rapid and frequent flow changes in the

Table 5
Hydropeaking impacts on invertebrate, algae, insect, and microbial community. Note: (+) = Positive impact and (-) = negative impact.

Variables	Invertebrate	Algae	Microbs
Growth	(-): (Céréghino et al., 1997)		
Length	(-): (Ruhi et al., 2018)		
Biomass	(+):(Lauters et al., 1996) (June) (-): (Leitner et al., 2017), (October) (Lauters et al., 1996), (Valentin et al., 1995), (Céréghino and Lavandier, 1998a, 1998b), (Céréghino et al., 1997), (Abernethy et al., 2021) (insect) No impact: (Abernethy et al., 2021)	(+): (Valentin et al., 1995) (-): (Bondar-Kunze et al., 2016)	
Diversity	(+): (Elgueta et al., 2021) (-): (Mihalicz et al., 2019), (Ruhi et al., 2018), (Castro et al., 2013), (Leitner et al., 2017), (Miller and Judson, 2014), (Abernethy et al., 2021) (insect), (Bruno et al., 2009)		(-): (Doering et al., 2021)
Density	(+): (Mihalicz et al., 2019) (July to September), (Kjærstad et al., 2018) (gatherers/collectors), (Castro et al., 2013) (wet season), (Bruno et al., 2009) (stygobites), (June) (Lauters et al., 1996) (-): (Bruno et al., 2009), (Valentin et al., 1995), (Abernethy et al., 2021) (insect), (Céréghino et al., 1997), (Lauters et al., 1996) (October), (Céréghino and Lavandier, 1998a, 1998b), (Castro et al., 2013) (dry season), (Kjærstad et al., 2018) (mayflies, chironomids, filter feeders), (Elgueta et al., 2021), (Paetzold et al., 2008), (Céréghino et al., 2002),, (Van Looy et al., 2007) No impact: (Tonolla et al., 2022)		
Drifting	(-): (Timusk et al., 2016), (Schülting et al., 2023), (Bruno et al., 2010), (Ruhi et al., 2018), (Lauters et al., 1996), (Céréghino and Lavandier, 1998a, 1998b), (Miller and Judson, 2014), (Kjærstad et al., 2018), (Tonolla et al., 2022), (Schülting et al., 2019), (Schülting et al., 2016), (Bruno et al., 2016), (Bruno et al., 2013) (Hydropeaking + cold Thermopeaking)		
Stranding	(-): (Tonolla et al., 2022), (Hauer et al., 2017a)		
Movement	(+): (Sidler et al., 2018) (velocity), (Céréghino et al., 1997) No impact: (Sidler et al., 2018) (due to thermopeaking)		(+): (Doering et al., 2021)
Hatching period	(-): (Céréghino et al., 1997)		
Habitat	(+): (Schneider et al., 2017) (*B. rhodani* in high flow and *Hydroptila* in low flow) No impact: (Vanzo et al., 2016) (in braided channel)		
Survival	(-): (Richards et al., 2014)		
Larvae	(+): (Ruhi et al., 2018)		
Dietary analysis	(-): (Ruhi et al., 2018)		
Functional structure	(-): (Ruhi et al., 2018), (Kjærstad et al., 2018)		

discharge induced by hydropeaking, increasing the entrainment of sediments, and ultimately altering the bed geometry (López et al., 2020). Although the effect of hydropeaking on the sediments' cycle is to be considered less significant compared to that caused by the presence of the dam itself, and it may be difficult to precisely discriminate its role due to the overlapping causes (Gierszewski et al., 2020; Szmańda et al., 2021), we believe that it could still be of interest to include in this review the studies that analyse alterations to the transport mechanisms and morphology in hydropeaked sites. Béjar et al. (2018) found that the suspended sediment load increased by up to 25 % in hydropeaking sites compared to undisturbed ones. According to Ziliotto et al. (2021), hydropeaking strongly enhances the spreading and mixing in the subsurface (up to 249.5 % and 41.8 % in their experiments). Hauer et al. (2019) conducted a study on alpine rivers impacted by hydropeaking to quantify Fine Sediment Infiltration (FSI) in their vertical stratigraphy. The study revealed distinct vertical FSI variations between wet areas and dewatering zones flooded only during peak flows. Surface blockages were found solely in dewatering zones, with finer sediments decreasing deeper into the substrate. Permanently wet zones had minimal surface fine sediment, while hydropeaking intensity showed no significant correlation with FSI rates. In the case of particles entrainment under frequent hydropeaking, López et al. (2020) provided circumstantial evidence that the hydropower station's peak discharge primarily impacted the adjacent downstream river section, causing the entrainment of fine to medium-sized gravels. The movement of finer sediment fractions from the riverbed termed as partial transport, involving selective transportation downstream of the hydropower plant. This process gradually shifted sand and smaller gravel to more distant points downstream. The effects of hydropeaks on river-bed particle mobility was also observed by Vericat et al. (2020). The study observed that entrainment occurred solely downstream of the plant, with no movement observed 2 km away from the plant. Hydropeaking induces frequent and selective bed movement, depleting fine sediment patches on the riverbed and causing the gradual loss of intermediate fractions, including medium-sized gravel. While the substantial structural components like boulders within the channel remain stationary, sand and finer gravel in bed patches are consistently washed away, and intermediate to larger gravel fractions eroded from inner spaces. Buček et al. (2021) also stated that hydropeaking had negligible effect on the bedload transport in the studied cross section, located 23.42 km downstream from power plant. On the other hand, López et al. (2023) stated that the peak discharge from the hydropower plant mainly affected the most distant downstream portion, situated at approximately 17 km downstream. There, finer fractions of the riverbed were entrained, including coarse gravels. Hydropeaking induced size-based selective partial transport downstream, shifting sand and small gravel, enhancing armor on the riverbed, and decreasing fine sediment presence.

Szmańda et al. (2021) investigated the fluvial changes on the Dnieper River and showed the distinct difference in the fluvial system before the dam was built (pre-dam period), with hydropeaking, and in a run-of-river system. According to the findings, during the pre-dam period, the downstream section of the river was characterized by an undisturbed sand-bed channel, while the intensification of erosion processes due to the dam and the hydropeaking operations caused the incision and narrowing of the channel and transformed interchannel areas into islands. The subsequent conversion of the power plant to a run-of-river system merged the islands back into interchannel regions. A different study by Gierszewski et al. (2020) also observed the formation of a deeper and narrower river channel downstream of the power plant due to hydropeaking fluctuations. In this case study however, a resistant formation on the riverbed caused the erosion process to migrate from bottom to lateral, widening the river channel and shifting back the process to an anabranching type system. Trung et al. (2020) observed that the diurnal nature of hydropeaking resulted in the variation of downstream flow velocities and water levels, which led to severe erosion and negative outcomes downstream of the power plant and the effect diminished as distance increased. The river section closest to the dam experienced the most pronounced impact from fluctuating flows and water levels. In addition, Shen et al. (2010) reported that hydropeaking

Table 6
Impacts of hydropeaking on riverine plants.

Impacts	Ref.
Expansions of herbs to higher elevation and shifting species dominance at low elevations	(Liu and Xu, 2022)
Negative effects on assemblage composition and biomass allocation, more biomass allocation to belowground part	
Negative impact on germination and biomass, growth rates, stem and root length, physiological stress	(Baladrón et al., 2022)
Highest ^{13}C abundances were found under the highest hydropeaking intensities	
Flood-intolerant species and their germination were affected mostly	(Bejarano et al., 2020)
Impact on seedling survival due to erosive process	
Higher hackberry cover at lower slope region	(Gill et al., 2018)
Higher hackberry abundance due to hydropeaking	
Reduced growth, leaf yellowing and mortality due to dewatering	(Gorla et al., 2015)
Negative effect on root amount and distribution	
No significant effect on *H. coronaria* populations located downstream of the dams	(Markwith and Parker, 2007)
H. coronaria has higher average population size in hydropeaking site	
Grasses were the most resistant to inundation and water fluctuation. Trees, and shrubs most resistant to water stress.	(Baladrón et al., 2023)
Forbs were rather vulnerable to all the hydropeaking disturbances	

caused significant erosion near exposed boulders and submerged rocks.

Table 7 reports the main impacts of hydropeaking on sediment transport, alongside that on the environmental and social characteristics of a river, outlined in the next sections.

3.5.2. *Environment*

Hydropeaking has further effects on the riverine environment, caused by its influence on the chemical (e.g. (Rossel and de la Fuente, 2015)) and thermal (e.g. (Ferencz et al., 2021)) characteristics of rivers, and on the levels of dissolved gas (e.g. (Pulg et al., 2016)). Thermopeaking in alpine streams is known to intermittently cool down the river water in summer and to warm it up in winter (Feng et al., 2018).

Rossel and de la Fuente (2015) studied the impact of hydropower plant operation (hydropeaking) on water quality. Their findings indicated that Chl-a concentration in the hydropower plant outflow was lower during hydropeaking than during average base flow. Beyond chemical impacts, medium to high changes in salinity intrusion may occur due to hydropeaking induced water flow changes in dry season (Trung et al., 2020).

Ferencz et al. (2021) investigated hydropeaking's impact on riverbed temperatures in a regulated river. They identified two distinct thermal regions: cooler temperatures near the left bank due to advective heat transport, and 3–6 °C warmer riverbed temperatures elsewhere, primarily explained by conductive heating. Groundwater conditions and sediment hydraulic conductivity influence thermal zones. High conductivity favours dynamic zones near banks, while low conductivity and neutral/losing groundwater conditions results in less temperature fluctuations. Thermopeaking's impact on alpine river thermal response during heatwaves was investigated by Feng et al. (2018) by comparing "unpeaked" and "peaked" station types. Peaked stations, due to the homogenizing effect of thermopeaking exposed to reduced natural temperature variability, exhibited weaker correlations between river and air temperatures. These stations demonstrated a less pronounced response to heatwaves compared to unpeaked stations.

Pulg et al. (2016), in their study, observed the hydropeaking case study site to have notably higher and more prolonged Total Dissolved Gas (TDG) saturation levels than the reference site. TDG levels at the hydropeaking site ranged from 99 % to 108 % (median of 105 %), while the reference site ranged from 99 % to 105 % (median of 101 %). Around 73 % of gas saturation variation at the hydropeaking site was attributed to power station discharge, compared to about 37 % at the reference site. Gas saturation increased within 30 to 60 min after an up-ramping event and decreased 2 to 4 h after a down-ramping event.

3.5.3. *Social aspects*

Only a minority of the studies on hydropeaking focuses on its social impacts. However, more generally, hydropower is known to influence the population living near watercourses. These effects are due to an alteration of the hydrological regime and the consequent alteration of the ecosystem services on which the population relies. The most affected sectors are agriculture, economy, and health (Kirchherr and Charles, 2016; Mubondo and Bezuidenhoudt, 2020). Agriculture could undergo changes due to the altered management of water resources, resulting in a reduced productivity and soil fertility. Looking at the economic perspective on the local communities, after an initial opening of job opportunities for the construction of the hydropower plant, a phase of reduced tourist attractiveness and a reduction in economic activities based on outdoor activities (hunting, fishing, etc.) could follow. For example, Carolli et al. (2017) developed a modelling-approach to assess flow requirements for white-water rafting suitability in a hydropower regulated Alpine River and stated that hydropeaking-induced peak flows provides favourable conditions for rafting activities during the late summer, showcasing the dual role of hydropeaking in regulated river systems. However, the suitability for rafting experiences was found to be slightly diminished under regulated flow conditions imposed by hydropower operations. They anticipated that localized water extractions for small-scale run-of-river hydropower plants would have an adverse impact on the suitability of rafting activities.

Hydropeaking can also pose a risk to hydraulic safety: Pisaturo et al. (2019) carried out a study on the interaction between hydropeaking and human safety and proposed a possible investigational tool to evaluate and parameterize the risk for the population during hydropeaking events through quantitative indices. According to the study, in the identification of escape routes, the water depth and the flow velocity emerged as the most crucial factors when compared to steepness and roughness. Areas that exhibited favourable and highly suitable conditions for escape were primarily concentrated along the riverbanks, while the middle of the river showed the least readiness in terms of escape options.

4. Discussion

Within the studies relating fish and hydropeaking, articles focusing on habitat almost unanimously agree on its degradation (16 studies out of 20, Fig. 3A). Literature also agrees on the overall negative effect of hydropeaking on fish density (13 studies out of 14), stranding (10 studies), survival (8 studies out of 11), diversity (3 studies out of 4) and spawning (4 studies). On the other hand, the impact of hydropeaking on fish length, growth, and dietary activities is more debated, as the ratio between studies claiming a negative or positive/null effect is more balanced. A separate discussion should be made about fish movement, which has been reported to be increased due to hydropeaking by 11 studies out of 17. However, the increase or decrease of fish movement is not parallel to a positive or negative effect, due to its relation with different aspects as feeding, spawning, or migration.

Almost all the reviewed studies agree on hydropeaking having negative effects on the biophysical and behavioural characteristics of invertebrates (Fig. 3B), with the highest number of articles focusing on

Table 7
Sediment transport, environmental and social impacts of hydropeaking.

Sector	Sub-sector	Note/impacts	Ref.
Sediment transport	Sediment	For fine sediment, higher effect with increasing distance from hydropower plant	(López et al., 2023)
		Mostly fine sediments are entrained	(López et al., 2023), (López et al., 2020), (Vericat et al., 2020)
		Suspended sediment load increased by 25 %	(Béjar et al., 2018)
		Higher effects in immediately downstream site	(Trung et al., 2020), (López et al., 2020)
		Enhances spreading and mixing in the subsurface	(Ziliotto et al., 2021)
		Negligible effect on bed-load transport in 23.42 km downstream	(Buček et al., 2021)
		Negligible impact on FSI	(Hauer et al., 2019)
	Erosion	Intensify erosion processes, widening immediate downstream and narrowing furthest downstream channels and channels anabranching and form island	(Szmańda et al., 2021), (Trung et al., 2020), (Gierszewski et al., 2020)
		Erosion near boulders and submerged rocks	(Shen et al., 2010)
	Channel width	Negligible impact in braided channel	(Vanzo et al., 2016)
	Flow	Increase water flow dynamics	(Szatten et al., 2021), (Watz et al., 2020)
		Alter flow dynamics	(Figueiredo et al., 2021), (Trung et al., 2020), (Casas-Mulet et al., 2016)
		Extended drought	(Baladrón et al., 2022)
	Hydrodynamics	Enhance vertical mixing in reservoir	(Ibarra et al., 2015)
	Water yield	Hydropeaking increases annual water yield by four-fold	(Béjar et al., 2018)
Environmental	Temperature	Temperature changes of riverbed is higher in near the bank. Bank riverbed showed cooler temperature.	(Ferencz et al., 2021)
		Increase thermo-peaking	(Bakken et al., 2016)
		Water temperatures varied greatly	(Casas-Mulet et al., 2016), (Bakken et al., 2016)
		Peaked stations showed a much weaker response to heatwaves, and weaker correlation between air and water temperature	(Feng et al., 2018)
	Water quality	Dissolved load and nutrients removal increased	(Szatten et al., 2021)
		Higher concentration of benthic chl-a and DOC	(Mihalicz et al., 2019)
		Chl-a decrease	(Rossel and de la Fuente, 2015)
		Salinity intrusion (in coastal river)	(Trung et al., 2020)
		Higher TDG saturation for longer period	(Pulg et al., 2016)
		Lower concentration of turbidity, TSS, TP and suspended chl-a	(Mihalicz et al., 2019)
	Sound peaking	Sound pressure levels increase	(Lumsdon et al., 2018)
Social	Health	Affect human safety	(Trung et al., 2020)
		Difficulty in escaping increases with the flow rate	(Pisaturo et al., 2019)
	Economy	Peak flows support rafting activities in late summer	(Carolli et al., 2017)

density and drifting, followed by biomass and diversity. Regarding riverine plants, although less studies addressed them compared to fish and invertebrate, the reviewed articles agree on hydropeaking having negative impact on germination, biomass, root and survival.

In case of the impacts on sediment transport, environment, and social aspects downstream the hydropower plant, the studies agree on negative effects on all the sub-sectors. The only positive impact upstream the dam is related to the hydropower production that can increase the vertical water column mixing in artificial reservoirs (Fig. 3C).

Once all the impacts due to hydropeaking are identified, a comprehensive view of the phenomenon can be gained by relating them to the drivers that push for hydropower production using the DPSIR framework. The graphical results from the DPSIR method are depicted in Fig. 4. Population growth, economic development, and the rising demand for renewable energy are the primary drivers that contribute to the increasing of the installed hydropower capacity by plant revamping or by constructing hydropower plants along rivers, enabling the operation and electricity generation through hydropeaking (Ruokamo et al., 2024). All the impacts overviewed in the DPSIR scheme could be reduced through indirect (i.e., increasing the river habitat availability and the possible refugial areas) and direct (i.e., operating on the hydropower production strategies) mitigation measures. According to the choice taken, the mitigation measures can also have effects on the initial drivers, modifying the subsequent pressure on hydropower production. In the following example, we illustrate how DPSIR can highlight the connections to key stakeholders and managers: the population growth in a certain area (DRIVER, labelled in orange in Fig. 4) might push for the installation of a new hydropower dam (PRESSURE, labelled in blue in Fig. 4), operated through hydropeaking, which is known to alter temperature and flow regime in the downstream reach (STATE, labelled in purple in Fig. 4). This might generate various impacts (labelled in red in Fig. 4), requiring diverse mitigation strategies. Let ecology be the focus of this case: the scheme suggests indirect measures (left side of RESPONSE, labelled in green in Fig. 4), like creating refugial habitats or improving the existing ones. However, it is essential to note that while these measures also benefit morphology, they will not directly address environmental or social aspects, as they do not alter the STATE.

4.1. *Possible mitigation measures*

Hydropeaking can be mitigated by structural, operational and morphological measures (Bruder et al., 2016; Brunner and Rey, 2014; Moog, 1993; Niu and Insley, 2013), as well as by reducing energy demands by means of behavioural changes, energy efficient technology use, such as electric vehicle energy storage (Román et al., 2019). The proper evaluation of the effects of different mitigation strategies requires a methodological approach that includes the formulation of a conceptual framework and a set of indicators for assessing their effectiveness on the river ecosystems under study (Bruder et al., 2016).

4.1.1. *Structural measures*

Common structural measures often involve the incorporation of a retention volume designed to both capture the peak discharge and create a gradual water release into the downstream river. This can be achieved through various means, such as using basins or caverns located at the power plant's outlet (Bieri et al., 2014). These measures primarily serve to mitigate abrupt changes in discharge rates during hydropeaking. Additionally, they may be employed to establish a preliminary surge before the main discharge peak, allowing river organisms to adapt. When the retention volume is sufficiently large, it can even reduce the maximum discharge levels (Meile et al., 2011; Parasiewicz et al., 1998; Person et al., 2014). In certain scenarios, diverting the discharge peak towards larger downstream waterbodies, such as lakes or rivers with ample capacity, or directing it into parallel channels with lower

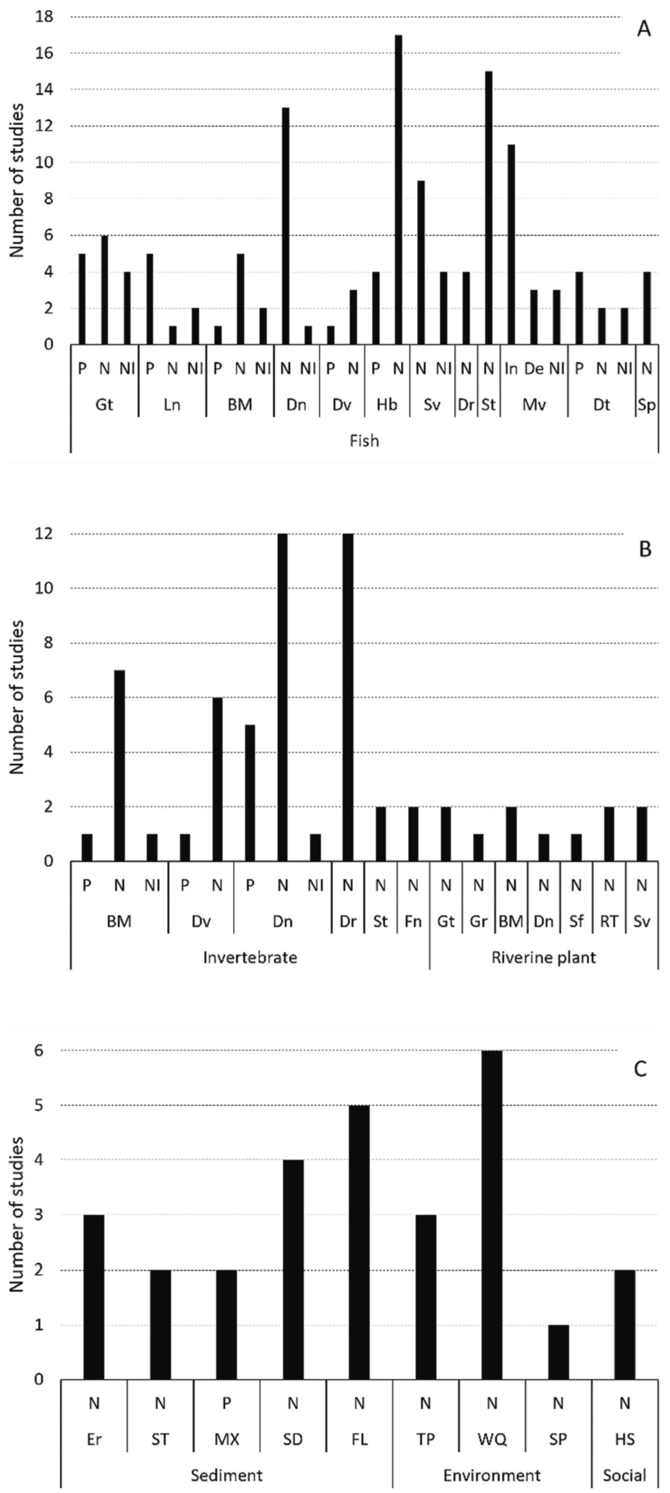

Fig. 3. Impacts of hydropeaking on (A) fish variables, (B) invertebrate and riverine plant, and (C) Sediment, Environment and Social variables based on the number of studies. Note: N: Negative, P: Positive, NI: No impact, In: Increasing, De: Decreasing. Gt: Growth, Ln: Length, BM: Biomass, Dn: Density, Dv: Diversity, Hb: Habitat, Sv: Survival, Dr.: Drift, St: Stranding, Mv: Movement, In: Increased, De: Decreased, Dt: Dietary analysis, Sp: Spawning or hatching activity, Fn: Functional activity, Gr: Germination, Sf: Shifting, RT: Root, Er: Erosion, ST: Sediment transport, MX: Mixing, SD: Sediment deposition, FL: Flow, TP: Thermopeaking, WQ: Water quality, SP: Sound pressure, HS: Human safety.

ecological sensitivity, may also present viable alternatives (Brunner and Rey, 2014).

In a case study conducted in the Swiss Alps, Tonolla et al. (2017) examined various retention volumes as potential mitigation measures to alleviate the impacts of hydropeaking on river ecosystems. The investigation encompassed four different retention volumes: 50,000m^3, 60,000m^3, 80,000m^3, and 100,000m^3. The findings indicated that as the retention volumes increased, the rates of flow ramping decreased, leading to reduced macroinvertebrate drift and, consequently, facilitating a long-term recovery in their biomass. Consequently, the benefits in terms of preventing fish stranding and enhancing macroinvertebrate biomass were rated as very favourable for the larger volumes of 80,000 m^3 and 100,000 m^3, and good for retention volumes of 50,000 m^3 and 60,000 m^3. However, the largest retention volume was deemed impractical due to disproportionately high costs when compared to the 80,000 m^3 volume.

4.1.2. Operational measures

Operational measures aim at reducing the hydrological effects of hydropeaking by adapting the production scheme (Person et al., 2014) to (i) reduce the ratio between peak and base flows, (ii) reduce rates of change in discharge, (iii) reduce the frequency of peaks, (iv) create a stepwise discharge increase (i.e., a pre-surge), and/or (v) by anticyclical production of sequential power plants. However, because operational measures influence both the overall electricity production capacity and its flexibility, they may have adverse effects on the economic sustainability of the power plant and the stability of the electricity grid (Niu and Insley, 2013; Person et al., 2014). Nonetheless, in certain socioeconomic contexts, operational measures, or a combination of structural and operational measures, can effectively mitigate hydropeaking effects without negatively impacting economic sustainability (Fette et al., 2007). To evaluate the reduced discharge, Casas-Mulet et al. (2016) proposed three mitigation options related to discharge management to decrease the risk of early life stage mortality among salmonids. All three options involved releasing the minimum discharge required during critical conditions for the pre-hatch stage of eggs and the hatch-to-swim-up stage of alevins. Option B additionally included a reduction in flows during the preceding 15 days, while option C extended this reduction to the previous month. The costs associated with these three mitigation options were relatively low when compared to the annual revenue generated from production. Options that combined reduced flows during spawning (B and C) with minimal flows during development (A) were deemed more effective for the survival of eggs and alevins. However, options B and C faced limitations due to water availability in the system during certain years, making option A the consistently feasible choice. Another study by Reindl et al. (2023), applied in the Western Tyrol area with a catchment area of 4650 km^2 and the Inn River as the main watercourse, explored the effects of hydropeaking mitigation by employing a combination of buffer reservoirs (impoundments), diversion hydropower plants, and retention basins. This approach yielded an additional production capacity of approximately 1800 GWh per year and simultaneously improved the ecological conditions of the downstream river. These combined measures successfully mitigated hydropeaking and reduced gradients to <15 cm/h during upramping and <12 cm/h during downramping in critical periods.

4.1.3. Morphological measures

Rehabilitating the river morphology downstream hydropower plants outlets has the potential to mitigate some of the adverse consequences linked to hydropeaking or could function as a means of ecological restoration within the watershed. Frequently, hydropeaked reaches undergo artificial modifications to conform to a predetermined channel design, thereby diminishing the natural heterogeneity in habitat shape

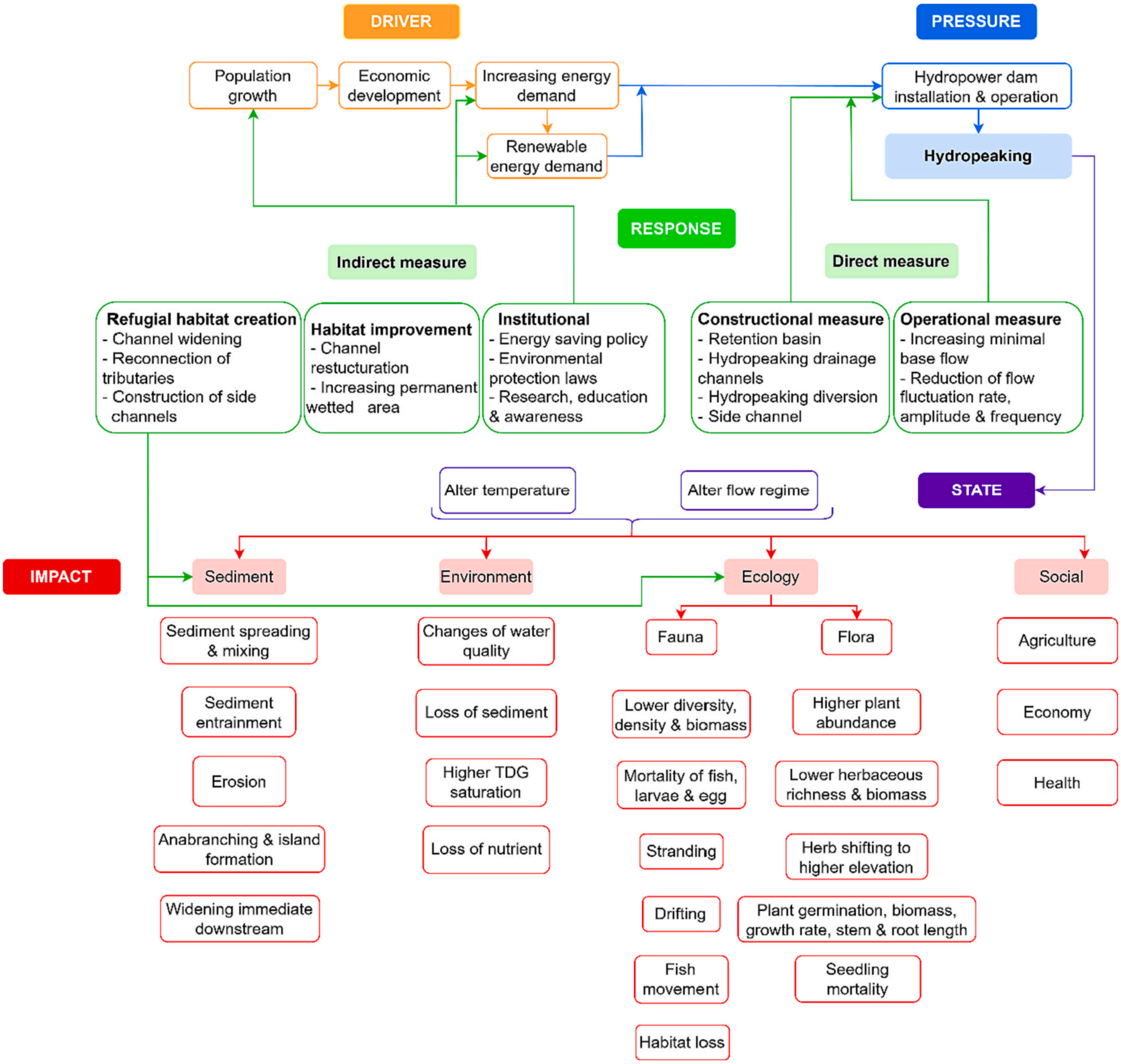

Fig. 4. DPSIR Framework addressing the drivers, pressures, states, impacts released due to hydropeaking and response mechanisms.

and diversity (Ribi et al., 2014; Zeiringer et al., 2014). In channelized reaches, efforts to mitigate the effects of hydropeaking may result in improvements to the ecological state at least marginally, which can be exemplified by the case of Person et al. (2014) in the Hasliaare.

4.1.4. *Cut-off of energy demand*

An innovative proposal was made by Román et al. (2019) who highlighted the potential of electric vehicle (EV) energy storage as a mitigation strategy for hydropeaking, achieved by reducing peak energy demands. The study proposed that forthcoming Plug-in Electric Vehicle (PEV) energy storage systems could effectively address hydropeaking challenges. With adequate PEV energy storage capacity in place, hydropower plants could stabilize their energy production by extending the unit commitment interval, thus reducing the need for a higher number of turbines. Consequently, the integration of PEV energy storage helps alleviate the hydrological fluctuations that contribute to the adverse impacts of hydropeaking, eliminating the necessity for implementing costly measures to mitigate its side effects. This, in turn, renders additional expenses for mitigation and compensation activities unnecessary.

5. Research gap

While numerous studies have examined the environmental and ecological impacts of hydropeaking, there still exist several significant research gaps that need to be addressed to enhance our understanding of its effects on aquatic ecosystems. Below are some key research gaps on “hydropeaking impacts”:

1. Reproducibility and comparative studies: many hydropeaking impact studies are site-specific and lack standardized methodologies, making it challenging to compare results across different regions and settings. Conducting reproducible and comparative studies will provide a more comprehensive assessment of the variability in hydropeaking impacts and enable the development of generalizable management strategies.
2. Surface-groundwater interaction: Hazas (2023) addressed the effect of hydropeaking on the dissolved solid mixing at the transient boundary conditions at surface-groundwater interface. However, the overall impacts of hydropeaking on the groundwater hydrodynamics/hydraulics are still unexplored. Additionally, the condition

of soil moisture content due to hydropeaking induced water level fluctuation is yet to be investigated.

3. Even though the transient nature of hydropeaking is considered in the unsteady hydraulic modelling, only few studies focusing on its ecological effects take into consideration this aspect, and they are applied to the fish stranding only (Burman et al., 2021). The current standard to perform habitat suitability models is rather based on steady-state conditions or on a sequence of steady-states. Further efforts should be put in considering the characteristic unsteady behavior of hydropeaking.
4. Interaction with other stressors: aquatic ecosystems are subjected to multiple stressors, such as pollution, habitat loss, and climate change. Understanding the synergistic effects of hydropeaking in combination with other stressors is essential to develop comprehensive management approaches that address multiple impacts simultaneously.
5. Thresholds and tipping points: determining ecological thresholds and tipping points is crucial for understanding when the effects of hydropeaking become significantly detrimental to aquatic ecosystems. Research is needed to identify critical flow thresholds beyond which irreversible ecological damage occurs, guiding the establishment of flow regulations that ensure the preservation of river health.
6. Social and Economic implications: among the terrestrial and aquatic ecosystems, riverine ecosystems play vital role in human livelihood and economic development by means of providing supply of goods and services. The ecosystem services offered by streams and rivers span on broad categories of human societal needs, including resource provisioning (e.g., fisheries, medicine, gravel, sands), consumptive use of water (domestic, agricultural and industrial), non-consumptive use of water (transportation/navigation, power generation, regulating services such as flood mitigation and water filtration), climate regulation, maintenance of water quality, pollution and waste assimilation, supporting services (e.g., maintaining riparian wildlife habitat and biodiversity), regulation of biogeochemical cycles, and, finally, providing cultural values such as recreation and aesthetics (Alan Yeakley et al., 2016). Although the articles reviewed in this work agree on the negative consequences of hydropeaking on the downstream riverine ecosystem and therefore on the supply of ecosystem services, no study has been found focusing on the quantification of such a loss, from an economic perspective as well.
7. Global impact: In summary, this systematic review addresses hydropeaking impact on ecology, sediments, environment, and society. However, to understand the global evolution of this effects, a comprehensive meta-analysis and/or a multi-criteria analysis should be taken into consideration. Moreover, Investigating the cumulative effects over extended periods is essential to identify potential shifts in ecological processes and understand the resilience of aquatic communities.

6. Conclusion

Hydropower has gained a reputation as a clean and sustainable energy source with low life cycle emissions and manageable local impacts, although these impacts vary depending on the type of the hydropower scheme (Kumar et al., 2011). However, literature suggests that hydrological modifications caused by hydropeaking, particularly sub-daily flow fluctuations, have a detrimental effect on aquatic organisms, leading to habitat degradation, species displacement, and ecosystem destruction (Bejarano et al., 2017). This systematic review on the assessment of hydropeaking impacts sheds light on the significant consequences of hydropeaking operations on the sediment, ecology, and environment of affected river reaches. In summary, hydropeaking operations, characterized by rapid and frequent changes in water flow, have substantial environmental and ecological effects. These include alterations in water temperature, dissolved gas levels, and sediment transport, which disrupt the natural balance of river ecosystems, resulting in reduced biomass, diversity, density, and survival rate of aquatic fauna, as well as increased drifting and stranding. Similarly, hydropeaking negatively affects the growth, germination, biomass, and density of flora. Similarly, hydropeaking negatively affects the growth, germination, biomass, and density of flora, and it alters the natural mobility of fish and invertebrates. Based on the knowledge gained from this review, a DPSIR framework was developed to illustrate the overall response to hydropeaking. However, it is important to note that the available literature on hydropeaking impact assessment is still limited in certain aspects and in specific regions or hydropeaking projects making it challenging to generalize the cumulative impacts across different geographic areas. Furthermore, long-term monitoring and evaluation of hydropeaking impacts are often lacking, which hinders our understanding of the ecological recovery potential after implementing mitigation measures. In conclusion, this systematic review underscores the need for further research, standardized methodologies, and the implementation of adaptive management strategies to address the gaps in knowledge. By doing so, we can enhance our understanding of hydropeaking effects and work towards minimizing the ecological impacts associated with hydropower operations.

CRediT authorship contribution statement

Nusrat Jahan Bipa: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Giulia Stradiotti:** Supervision, Validation, Writing – review & editing. **Maurizio Righetti:** Conceptualization, Funding acquisition, Resources, Supervision. **Giuseppe Roberto Pisaturo:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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