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Introducing HyPeak: an international network on hydropeaking research, practice, and policy

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Abstract

An increase in the demand for renewable energy is driving hydropower development and its integration with variable renewable energy sources. When hydropower is produced flexibly from hydropower plants, it causes rapid and frequent artificial flow fluctuations in rivers, a phenomenon known as hydropeaking. Hydropeaking and associated hydrological alterations cause multiple impacts on riverine habitats with cascading effects on ecosystem functioning and structure. Given the significance of hydropeaking's ecological and socio-economic implications, mitigation requires an inter- and transdisciplinary approach. An interdisciplinary network called HyPeak has been conceived to enrich international research initiatives and support hydropower planning and policy. HyPeak has been founded based on exchange and networking activities linking scientists from several countries where hydropeaking has been widespread for decades and numerous studies dedicated to the topic have been carried out. HyPeak aims to integrate members from other countries and continents in which hydropower production plays a relevant role, and grow to be a reference group that provides expert advice on the topic to policy-makers, as well as researchers, stakeholders and practitioners in the field of hydropeaking.

Keywords: hydropower, flow management, interdisciplinary network, flow fluctuations, mitigation measures, anthropogenic impact, rivers

1. Hydropeaking and hydropeaked rivers

Hydropower is the largest source of renewable energy (71% as of 2016; Moran et al., 2018), generating 4370 TWh with 1330 GW of installed capacity globally in 2020 (IHA, 2021). Still, energy generation from hydropower must double by 2050 to meet the target of limiting global warming to 2°C (IEA, 2021). In addition to providing renewable energy, hydropower offers flexibility to the energy system at timescales ranging from seconds to seasons, which is important for the integration of variable renewable energy from wind and solar technologies (IEA, 2021). Depending on the site, technical layout, and operation mode, hydropower production may also have significant environmental and social impacts. When hydropower plants operate with rapid and frequent changes in generation to meet demands for flexibility, they cause rapid and frequent fluctuations of flow in outlets. Hydropeaking is the term used to describe rapid and frequent artificial flow fluctuations caused by flexible reservoir-operated hydropower production (Moog, 1983). The outlet flow may be delivered to reservoirs, lakes, or the sea, but the downstream effects are by far most pronounced when the outlets discharge directly to rivers, which is the focus of this paper.

Flow fluctuations can be characterised by changes in one or more of the flow regime components (i.e., flow magnitude, flow ratio, frequency, rate of change, and timing), which exceed those of the natural variability and intensity of the flow regime. Importantly, it is often the combination of these parameters that creates the most harmful effects (Harby & Noack, 2013; Hayes et al., 2019). Specifically, hydropeaking and associated hydrological alterations may result in thermal fluctuations (thermopeaking), geomorphological alterations (i.e., changes in sediment transport and in bed-material grain-size distribution), and changes in hydraulic habitat conditions (Table 1), the nature and extent of which will depend on the hydro-morphological characteristics of the downstream river (Vanzo et al., 2016). In turn, these changes cause numerous adverse impacts on aquatic biota and ecosystem processes (Table 1). Furthermore, changes in hydrological conditions from hydropower may lead to socio-economic impacts related to water availability for irrigation, tourism, and recreational opportunities, the aesthetic value of rivers, and increased risks to local populations (Table 1).

As future demand for flexible hydropower operation is expected to increase, we must find ways of operating hydropower plants that limit negative impacts on downstream river ecosystems (Jones, 2014; Batalla et al., 2021). Currently available mitigation measures can be categorised into: (i) measures that directly modify the dynamics and intensity of hydropeaking flow, (ii) indirect measures that reduce impact on river habitat and hydro-morphological conditions, and (iii) complementary approaches (Hayes et al., 2022). The first group includes operational measures, such as lowering ramping rates by turbine flow restrictions, and structural measures, such as the construction of re-regulation reservoirs or compensation basins (Bruder et al., 2016). The second group of measures encompasses morphological improvements of the hydropeaked section through river restoration or addition of instream structures, as well as its reconnection with tributaries characterized by natural flow and sediment regime and/or presence of potential source populations (Baladrón et al., 2021; Costa et al., 2019; Greimel et al., 2018; Hauer et al., 2017). Finally, complementary measures include new approaches to coupling hydropeaking-based power production with alternative energy storage technologies (e.g., batteries, supercapacitors) or other renewables (i.e., solar, wind) (Haas et al., 2019; Hayes et al., 2022).

A common understanding of sustainable hydropeaking mitigation has emerged in several European countries related to the implementation of the Water Framework Directive (Halleraker et al., 2016), but no common legal framework for hydropeaking thresholds exists. For instance, only the Alpine region has yet established legal regulations (i.e., on the national level in Austria and Switzerland and on the regional level in Bolzano, Italy). Some countries or regions (e.g., Spain and the state of Baden-Württemberg in Germany) include hydropeaking mitigation recommendations in their river basin management plans, while others still work on a case-by-case basis (Moreira et al., 2019).

With the exception of base flow requirements, which exist in many countries, the implementation of mitigation measures and thresholds for ramping restrictions are rare (Hayes et al., 2022; Tonolla et al., 2017).

2. Challenges and needs of studying hydropeaked rivers

Given the complexity of transnational electricity markets and increasing electricity demand combined with the multifaceted impacts of hydropeaking, interdisciplinary and transdisciplinary scientific research is needed to support sustainable management and regulation of hydropeaking-based hydropower production. Developing such knowledge is challenging for several reasons: (i) the high and often unpredictable hydrological dynamism of mountain rivers, where hydropeaking typically occurs, renders field studies complex to carry out, and (ii) the highly variable geographic and geomorphological settings, technical approaches, and legal regulations adopted at national and regional scales limit the transferability of results. Finally, (iii) stronger links between disciplines are urgently needed, but have yet been poorly developed. This concerns in particular, the social sciences, which should be integrated into biophysical research on hydropeaking (e.g., risks to local populations, public acceptance, power markets projections based on climate change). At the same time, an increasing number of research tools and decision support tools have been developed in recent years and offer new approaches to key disciplines related to hydropeaking and to hydropower production planning (Appendix Table ST1).

In this context, several tasks appear to be of high research priority for the scientific community working on the topic of hydropeaking:

1. Compile an overview of the localization and typology of hydropeaking at a large scale (continental). For instance, no geo-database including source and severity of hydropeaking impacts across Europe exists. Standardization of tools used for characterizing the hydropeaking hydrological regime would be necessary for this task.
2. Identify the most informative indicators for assessing hydropeaking impacts on rivers. While a number of biophysical indicators have already been suggested for this purpose (e.g., water temperature, sediment transport, invertebrate drift, fish stranding; see Bruder et al., 2016), further indicators, covering other types of organisms and life stages, levels of biological organization (e.g., food webs), ecosystem functions and associated services (e.g., carbon retention and greenhouse gas emissions), geomorphological processes (e.g., river-bed degradation, bed-material winnowing, armouring, habitat degradation), and societal needs (e.g,. recreational opportunities), need to be developed.
3. Continue to develop technical approaches to limit negative impacts of hydropower plant operation on river ecosystems and develop procedures to select the most locally-appropriate ones, evaluate their feasibility by implementing cost-benefit (ecological, social, etc.) analyses and assess their efficiency.

4. Elaborate inter- and transdisciplinary approaches for finding compromises between hydropower plant operation and ecological sustainability, to achieve an economic sustainability of mitigation measures and carbon-free energy production, in view of the pressures of energy markets, private and public interests, as well as the challenges imposed by climate change. This issue needs to be addressed in a general framework of energy planning and requires increasing the flexibility in the power system and coupling different renewable energy sources.
5. Create and reinforce functioning links between research and application (researchers of various disciplines, legislators, public river managers, hydropower producers). This implies an efficient reciprocal transfer of knowledge and tools between researchers and practitioners to support the development of informed policies, the choice of technical solutions, and the assessment of their efficiency at different scales (local, river basin, national, international).

Several of the listed tasks require a systematic inter- and transdisciplinary approach. Moreover, exchanging tools and experiences across countries appears crucial to advance towards sustainable hydropeaking management on a large scale (e.g., Pittman et al., 2016). International and interdisciplinary networks are essential for improving the transfer of knowledge across borders and from science to practice. In Europe, several recent networks and projects (e.g., smires.eu, converges.eu, FitHydro.eu) have succeeded in creating key scientific consortia in aquatic environmental research, building strong links across borders and disciplines, and supporting the development of environmental policies (e.g., Brils, 2020). In the case of hydropeaking, hydropower operators, public decision-makers and stakeholders must be involved in such networks to promote knowledge-sharing and dialogue concerning the degree of hydropeaking impacts on the environment and the selection of the best cost-effective mitigation measures (Barillier et al., 2021).

3. Founding and activities of the HyPeak Network

The interdisciplinary network on Hydropeaking Research (HyPeak) was founded after an interactive and well-attended webinar held during the 13th International Symposium on Ecohydraulics in November 2020, with the intention to propose a framework for crossing interdisciplinary perspectives on hydropeaking (Figure 1). In 2021, the network started to operate with the core group of European researchers covering a wide range of disciplines (hydrology, geomorphology, hydraulic engineering, ecology, economics) and countries. The first steps consisted in reaching an agreement on the exact mission of the network, its organization, and enrollment/operational rules indispensable before opening it up to interested future members. This resulted in a formalised HyPeak Charter (https://www.researchgate.net/project/HyPeak-Hydropeaking-Research-Network), which identified the overall goal of HyPeak as one of becoming a reference group of experts to support evidence-based guidelines and legislation at different levels (national to international) and enhance the value of the interaction between research and policy. Therefore, our activities focus on collaborations among researchers and the creation of strong bridges with practitioners (hydropower producers, environmental agencies, consultants, or legislators). Our key mission is to stimulate integrative hydropeaking research across disciplines to support:

(i) assessment of environmental effects and related socio-economic issues of hydropeaking at various spatial and temporal scales;
(ii) fundamental understanding of hydropeaking dynamics and related biophysical processes;
(iii) improvements of mitigation measures and management strategies;
(iv) promotion of environmentally sustainable approaches to hydropeaking;
(v) providing recommendations for national and international policies and supporting their integration.

Involvement in the HyPeak Network is possible at several levels : (i) as a General Member: adhering to the principles of the network and following its activities via email newsletter; (ii) as a Core Group Member: getting actively involved in specific activities of the network (see below); (iii) as a member of the Executive Board: centralizing the activities of the network and assuring continuity of the Core Group meetings. Importantly, our choice is to keep the HyPeak network independent of any funding other than funding for scientific research.

We envisage a wide range of activities according to the above-stated key mission in the upcoming years aiming at:

(i) keeping the members informed of news in relation to hydropeaking across countries and research fields (new legislation, new research results, conferences, etc.);
(ii) preparing collaborative international research initiatives to optimise acquisition and dissemination of knowledge (co-supervision of doctoral students, conducting parallel experimental approaches across continents/hydro-bioregions, working on transboundary study cases, sharing/enlarging datasets for cross-continental or global impact analyses);
(iii) exchanging knowledge and enhancing the common understanding across disciplines (e.g., river ecology and economics);
(iv) fostering the involvement of managers in defining research guidelines;
(v) expanding the geographic coverage of the network well outside of Europe.

Analysing current knowledge gaps and key expectations of practitioners and legislators towards the scientific community belongs to our key short-term objectives. Therefore, one of HyPeak's first activities consisted in conducting an extensive online survey targeting hydropower stakeholders and researchers working on the topic of hydropeaking (released in December 2021). Together with a follow-up Delphi study, the aims of this work are to gather global research priorities, emerging issues related to hydropeaking impacts and their mitigation, and to analyse stakeholder perceptions of the hydropeaking effects on the ecosystem services in rivers. Key research questions relevant for the practitioners identified through this survey will allow us to adjust the baseline for future activities of the HyPeak network and beyond, such as the prioritization of future research to meet the policy and management needs of hydropeaked rivers. Additionally, the lessons from the stakeholder perceptions of the ecosystem service effects of hydropeaking will support science, governance, and management in the effective communication of impacts and necessary mitigation approaches.

The preparation of the special issue "Innovations in Hydropeaking Research" in *River Research & Applications*, led by an editorial board of HyPeak Core Group members represents another activity fostering communication of current research in the field. In the same line, a series of open webinars about sustainable hydropeaking is organised by HyPeak starting from 2022 (HyPeak Webinar Series 2022). The idea is to present both researcher and practitioner perspectives on hydropeaking through a selection of speakers with different professional backgrounds and geographical origins.

4. Conclusions

Our current knowledge on how many rivers are exposed to hydropeaking across continents, the severity of the resulting impacts and their dependence on the specific boundary conditions (river type, geographic setting, management scheme, or history of hydropeaking), is currently extremely limited. A joint effort enabled by an international network in the long term could help collect, standardise and share data on hydropeaked rivers (hydrological, geomorphological, ecological, legal, social…) on a large scale. These data could be used, for instance, to produce maps of hydropeaked rivers across continents and allow us to have a global overview of the hydropeaking phenomenon and status updates about ecological effective mitigation measures. Similarly, a future task would be to launch comparisons and knowledge transfer across borders in terms of hydropeaking extent and impact, the weight of this type of energy production in the energy mix, legislation, monitoring tools, and mitigation approaches as well as public perception.

As stated in the HyPeak Charter, our network is independent and based on the voluntary contributions of its members. The HyPeak Network is open to new members interested in participating in it, at the desired level of commitment as stated in Annex 1 of the Charter. The first step for any interested person is to enrol as a General Member by filling the form available at https://forms.gle/CsahiE6dWB5SuLaAA.

Appendix: Table ST1. Novel research tools expanding the opportunities in the research on hydropeaking

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Tables

Table 1. Main documented impacts of hydropeaking and list of representative recent papers for each impact (distributed according to different typologies).

Type of impact	Impact	Literature (examples)
Physical	Temperature: thermopeaking	Carolli et al., 2012 ; Zolezzi et al., 2011
	Riverbed clogging	Hauer et al., 2019
	Changes in gas saturation: saturopeaking	Pulg et al., 2016
	Changes in underwater soundscapes: soundpeaking	Lumsdon et al., 2018
	Changes in grain-size distribution, bed-armouring and particles' mobility, and winnowing of sand and fine gravel	Béjar et al., 2018; López et al., 2020 ; Vericat et al., 2020
	Changes in flow turbidity	Béjar et al., 2018; Hauer et al., 2019 ; Lobera et al., 2016
	Hydraulic impacts i.e. increase in water velocity and turbulence, and sudden and rapid changes in flow depth	Hauer et al., 2017; Shen & Diplas, 2010; Vanzo et al., 2016
Biological	Invertebrates: drift, stranding, community composition, habitat use, egg mortality	Aksamit et al., 2021; Bruno et al., 2016; Kennedy et al., 2018; Kjærstad et al., 2018; Miller & Judson, 2014; Ruhí et al., 2018; Schülting et al., 2018
	Fish: drift, stranding, egg mortality, population integrity, behaviour, habitat selection	Auer et al., 2017; Béjar et al., 2018; Boavida et al., 2017, 2020; Capra et al., 2017; Casas-Mulet et al., 2015; Costa et al., 2019; Hayes et al., 2019, 2021; Judes et al., 2020
	Periphyton: reduced biomass, compositional changes, reduced nutritional quality	Bondar-Kunze et al., 2016; Cashman et al., 2017
	Macrophytes and riparian vegetation: communities composition, structure, and persistence	Bejarano et al., 2018, 2020 ; Gorla et al., 2015
	Foodwebs	Holzapfel et al., 2017; Pearce et al., 2019
Socio-economic	Risks to local populations	Premstaller et al., 2017; Venus et al., 2020
	Recreational opportunities (e.g. swimming, boating and fishing)	Carolli et al., 2017; Venus et al., 2020; Venus & Sauer, 2022
	Aesthetic value of rivers	Pflüger et al., 2010
	Water availability for irrigation	Bryan et al., 2013

Table 2. Novel research tools expanding the opportunities in the research on hydropeaking

Aspects assessed	Tools	Some representative references (illustrating application in the field of hydropeaking)
Physical processes	Hydraulic, hydrological and topographical modelling including simulations, particle tracking techniques, assessment of river topography and morphology through geomatics, thermal imagery, remote sensing, experimentation in hydraulic laboratories	Brasington et al., 2012; Carolli et al., 2015; Sauterleute & Charmasson, 2014
Biology	Habitat and population modelling; underwater cameras and telemetry for behavioral observations; experimentation in hydraulic laboratories and open-air flumes; impacts classification systems	Bakken et al., 2021; Boavida et al. 2021; Bruno et al., 2016; Capra et al., 2017; Costa et al., 2019; Hedger et al., 2018; Holzapfel et al., 2017; Leitner et al., 2017; Person et al. 2017; Schneider et al., 2017; Schülting et al., 2016
Optimising hydropower plant operation	Market models, power system analyses, decision support tools	Kong et al., 2020

Figures

Figure 1: A schematic representation of the multidisciplinary approach required to tackle hydropeaking impacts on the different components of socio-ecosystems and propose mitigation strategies.